Geoffrey R. Dixon · David E. Aldous
*Editors*

# Horticulture: Plants for People and Places, Volume 1

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*We dedicate these Books to our wives;*
*Mrs. Kathy Dixon and Mrs. Kaye Aldous*
*in gratitude for their lifetimes of unstinting*
*support, forbearance and understanding*

*Professor David E. Aldous – deceased 1st November 2013.*

*The concepts underlying the Trilogy Horticulture—Plants People and Places were developed by David Aldous and me during the International Horticultural Congress 2010 in Lisbon, Portugal. These Books celebrate our common views of the scholastic and intellectual depth and breadth of our discipline and the manner by which it is evolving in response to the economic, environmental and social challenges of the*

*21st Century. Jointly, over more than two years we enlisted international authorities as lead authors, reviewed drafts and edited final texts. Despite there being half the world between us we formed a deep rapport. His sudden and wholly unexpected death from a brain aneurysm came as a shattering blow leaving me with the tasks of seeing our work through to completion. This Trilogy stands as a legacy to horticulture as "the first of all the Arts and Sciences" from an internationally acclaimed, respected and much loved: scientist, educator and author. It is appropriate that the Trilogy should be dedicated to David united with our original intention of paying tribute to our respective wives.*

*Professor Geoffrey R. Dixon*

# Preface

This Trilogy of books answers the question “What is Horticulture?”. Their contents span from tropical plantations growing exotics crops such as cocoa, pineapples and rubber through to the interior landscaping of high-rise office tower blocks and other landscape applications which encourage physical and mental health. The common thread uniting this Discipline is the identification, breeding, manipulation of growth and stimulation of flowering and fruiting in plants either for food, environmental or social improvement. Understanding the scientific principles of why plant productivity increases following physical, chemical and biological stimuli has fascinated horticulturists for several millennia.

Epicurus (341BC-270BC) the Athenian philosopher of the 3rd century BC believed that plants achieved “the highest good was calmness of mind”. Calmness comes to some Horticulturists with the satisfaction of entering vast hectarages of bountiful orchards, to others from well designed and carefully maintained landscape while others are entranced by participation in conserving components of the Earth’s fragile biodiversity. Horticulture, while being a scientific discipline, has much wider and deeper dimensions. There are historic, artistic and cultural facets which are shared with the Humanities and these aspects are included within this Trilogy. Wherever Horticulturists gather together they share a common language which interprets useful scientific knowledge and cultural understanding for the common benefit of mankind. For while Horticulture is about achieving an intensity of growth and development, flowering and fruiting, it is wholly conscious that this must be achieved sustainably such that the resources used are matched by those passed on for use by future generations.

The structure of this Trilogy is such that it traces the evolution in emphasis which has developed in Horticultural philosophy across the second half of the 20th and into the 21st century. Following the worldwide conflicts of the 1940s the key necessities were the achievement of food sufficiency and the eradication of hunger from the planet. In the increasingly affluent and developed world there is now food sufficiency *par excellence*. Never before has such an array of plenty been made available year round. This plenty is nowhere more evident that in the fresh fruit and vegetable aisles of our supermarkets. Horticulture has given retail shoppers the gift of high quality and diversity of produce by manipulating plant growth, reproduction and postharvest care across the globe.

This first volume illustrates in considerable depth the science, management and technology which underpins the continuous production of Horticultural Produce. Firstly there is a consideration of aspects of industrial development based on basic scientific discoveries. This is followed by chapters written by acknowledged world experts covering the production of: Field Vegetables, Temperate Fruit, Tropical Fruit, Citrus, Plantation Crops, Berry Crops, Viticulture, Protected Crops, Flower Crops, Developing New Crops, Post-harvest Handling, Supply Chain Management, and the Environmental Impact of Production. Crop Production Horticulture may now be found supporting the economies of less developed nations, consequently the final Chapter focuses especially on the impact of Crop Production Horticulture in Africa.

Subsequent volumes in this Trilogy cover Environmental Horticulture (volume 2) and Social Horticulture (volume 3). Once food sufficiency was achieved in many developed countries, Horticulture from about the early 1980s onwards, became concerned with the manner by which it influences the human environment. Some might argue that this is a return to Horticulture's role in the 17th to early 20th Centuries, when plants were used very effectively to change local environments. Volume 2 assesses the activities and achievements of Environmental Horticulture in detail. It covers in considerable depth the scientific, management and technological concepts which underpin Environmental Horticulture. It covers considerations of: Horticulture and the Environment, Woody Ornamentals, Herbs and Pharmaceuticals, Urban Greening, Rural Trees, Urban Trees, Turfgrass Science, Interior and External Landscaping, Biodiversity, Climate Change and Organic Production. Volume 3, Social Horticulture, brings the evolution of the Discipline firmly into the 21st Century. It breaks new ground by detailed analysis of the value of Horticulture as a force for enhancing society in the form of social welfare, health and well-being, how this knowledge is transferred within and between generations, and the place of Horticulture in the Arts and Humanities. Volume 3 contains considerations of: Horticulture and Society, Diet and Health, Psychological Health, Wildlife, Horticulture and Public Welfare, Education, Extension, Economics, Exports and Biosecurity, Scholarship and Art, Scholarship and Literature, Scholarship and History and the relationship between Horticulture and Gardening.

The value of Horticulture for human development was emphasised by Jorge Sampaio (United Nations High Representative for the Alliance of Civilisations and previously the President of the Republic of Portugal) in his opening address to the 28th International Horticultural Congress held in Lisbon, 2010. He stated that Horticulture can achieve "a lot…to overcome hunger and ensure food security". In the face of estimates that the world's population, particularly in developing counties, will reach 9.1 billion by 2050 and in this Horticulture has an especially important role. Intensive plant production has much to offer as urbanization continues at an accelerating pace. Shortly about 70 % of the world's population will choose to live in the urban and peri-urban areas of many countries. In contrast with the developed world many millions of the world's population continue to be undernourished and in poor health. Horticulture can help massively to change this situation. Climatic change, over-population, soil degradation, water and energy shortages, pollution and crippling destruction of biodiversity are the challenges facing humanity. Horticulture in its Production, Environmental and Social roles offers important knowledge and expertise in these areas. This is well explained in “Harvesting the Sun” a digest recently published by the International Society for Horticultural Science. In summary form the international interactions between horticultural science, technology, business and management are displayed. This offers pointers as to how over the early part of the 21st Century world food production must rise by at least some 110 % to meet the demands of expanding populations in countries such as China, India, parts of Asia and in South America.

Considerable breadth and depth of intellect are demanded of those who seek an understanding of horticulture. This is not a discipline for the faint-hearted since the true disciple needs a considerable base in the physical, chemical, and the biological sciences together with a knowledge of natural resources linked with an understanding of the application of economics and engineering and the social sciences. Added to this should also comes an appreciation of the artistic, historical and cultural dimensions of the Discipline. The teaching of fully comprehensive horticultural science courses in higher educational institutions has regrettably diminished worldwide. It is to be hoped that this Trilogy may go some small way in providing an insight into the scale, scope and excitement of the Discipline and the intellectual rigour demanded of those who seek a properly proportioned understanding of horticulture and horticultural science.

Enormous thanks go to all those who have contributed to these three volumes. Their devotion, hard work and understanding of the Editors’ requests are greatly appreciated. Thanks are also due to our colleagues in Springer for all their continuing help, guidance and understanding. In particular we would like to thank Dr. Maryse Walsh, Commissioning Editor and Ir Melanie Van Overbeek, Senior Publishing Assistant.

Professor Geoffrey R. Dixon affectionately records his thanks to his mentor Professor Herbert Miles, then Head of the Horticulture Department of Wye College, University of London (now Imperial College, London) who challenged him to “define Horticulture”. Regrettably, it has taken half a century of enquiry to respond effectively.

Sherborne, Dorset, United Kingdom G. R. Dixon
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August 2013

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# Chapter 1
# An Introductory Perspective to Horticulture: Plants for People and Places

**Geoffrey R. Dixon and David E. Aldous**

**Abstract** Horticulture is "the first of all the arts and sciences". This definition indicates both the breadth and depth of the discipline and its early inception as mankind changed from being hunter-gatherers to cultivators. Intensive crop production which is a form of horticulture preceded more extensive agricultural practices. From that time onwards the intricate involvement of horticulture in man's life has become very apparent by its multitude of applications and the interests of those involved. These extend from the provision of foodstuffs and nutritional benefits through pharmaceuticals to aspects of rest and relaxation onto encouraging physical and mental well-being. Horticulture is therefore, a discipline with many components and as such that it can mean different things in the varying context of its use. This chapter introduces the meanings of horticulture as expressed by the authors who have contributed to this Trilogy of Books. They have analysed in considerable depth "Horticulture" as expressed in its facets of production, environment and society. Horticulture has impact and expression in each of these fields of human activity. This chapter also sets Horticulture into the wider context of the world of plants and their intensive cultivation both in their use by mankind and in the natural world. The aim is to demonstrate the depth and breadth of human activity associated with this discipline for it stretches from crop production, through landscape design and maintenance and into aspects of society and its expression in the arts and humanities. Horticulture touches almost every aspect of human activity. Increasingly Horticulture has significant importance in contributing towards the mitigation of the major problems which now face life on Earth such as:- climate change, food security, the loss of natural biodiversity, pollution, resource erosion and over-population. Indeed despite or perhaps because of its antiquity and therefore its strong connection between science, technology and practice horticulture can offer solutions that might allude other disciplines.

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Professor David E. Aldous – deceased 1st November 2013

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## Introduction

Plants are fundamental for the existence of life on Earth. In partnership with the microbes, plants make the Earth habitable for all other forms of life including mankind. The fundamental importance of plants as the base of the world's ecological network has been recognised scientifically for the past century as described for example by the father of their ecological study, Arthur Tansley (1949). These interconnections and interactions interlace with James Lovelock's (2000, 2003) propositions in his theory of Gaia where he explores firstly the fine balances upon which life depends and secondly the physical, chemical and biological forces and stresses which drive evolution (see also Lenton 1998) which is now codified in economic terms of the costs and benefits of eco-systems analysis. This builds on Margulis (1999) who describes the natural world as a unified symbiotic system. It is accepted however, that some authors cast doubt on the extent of these interconnections (Tyrrell 2013). Nonetheless, there is immense significance in the role of plants in supporting all human and other life, what Dawkins (2009) called "The greatest show on Earth". Regrettably, this is not appreciated or understood by the vast majority of people. Some academics, most notably the historian Simon Schama (1995) have attempted to explore this relationship from a sociological and historic perspective. He shows the interdependence of people and plants and the manner by which this has resulted in many of the semi-natural landscapes which occupy much of rural areas worldwide (Fig. 1.1).

For particularly in the developed world there are now very few examples left of entirely natural landscapes unaffected by the hand of man even in the wildernesses of the Arctic and Antarctic. A prime example of the manner by which man has moulded a landscape is described by Pryor (2010) in a discussion of Great Britain and the development of its rural areas from the earliest farming communities through to "sat-nav Britain".

Despite the daily significance of plants as an ingredient of almost any meal there is a suspicion of plants in the general population. This phobia was vividly described by Michael Leapman (2000) where he touched on the antagonisms between botanists and horticulturists because of their involvement in plant hybridisation in the 18th century. More recently, it was also noticeable that even in early attempts to engage general television audiences' interest in the biological world these largely omitted references to plants, for example Jacob Bronowski' "The Accent of Man" (1973). Encouraging an understanding and appreciation of plants as biological entities among the broader population is an essential prerequisite for ensuring their care, conservation and survival and recognition of their economic value. In this respect the more recent work of eminent biologists and gifted communicators is

**Fig. 1.1** Wild flower meadow Guernsey, channel Islands

vital. Few people have achieved this more eloquently and effectively than Sir David Attenborough with his television series "The Private Life of Plants" (1995).

## The Development of People and Plant Interactions

The Neolithic people, 10,000 years ago were consumers of plants as they followed animal herds. They gathered wild plants in season for food, clothing, shelter and medicine (Solecki et al. 2004; Janick 2014). Later these folk developed into small family groups with more permanent settlements leading to the first stages of economic and social structure involving the early stages of horticulture, the intensive cultivation of plants. As permanent settlements grew crop surpluses were created. This released some people from the routine of horticulture practices to take on a wider range of roles and responsibilities in the community such as trade, education, literature and government.

Permanent settlements began emerging in about 2,800BC in the river valleys of the Tigris-Euphrates, Indus and Nile. They developed orchards, vineyards and vegetable growing enterprises, as well as formal and semi-formal gardens (Singer et al. 1954; Janick 2002). Early civilizations encouraged the broader appreciation of horticulture as with the Hanging Gardens of Babylon once the initial need for a food supply had been satisfied. This provided trees for food, fibre and shade (Anon 2013b). Some of the early Kings of Assyria used the land adjacent to the Upper River Tigris for parkland intended for rest and relaxation. Researchers such as Janick (2008, 2014), Sansavini (2014), Warrington and Janick (2014), describe the development of cropping enterprises and care for the environment in the ancient civilizations of Sumeria, Egypt, Greece, China, India, and Italy. These civilizations exploited the use of science and technology. They lived adjacent to rivers consequently early developments involved irrigation using the shaduf and other devices for moving water. The shadulf originated in the Mesopotamian area of south-western Asia between 3,000–4,000 years ago. Later the Persian water wheel or typanum, the Archimedean screw, which has been attributed to Archimedes (c.287BC-212BC), and the Roman screw were used to move water in early Spain. Some initial teachings of horticulture from ancient Persian rulers such has Cyrus the Great (c.600BC or 576 BC-530BC) and scholars like Theophrastus (c.371-c.287 BC) (Anon 2013d) and Hippocrates of Kos (ca. 460BC—ca. 370BC) from ancient Greece have survived. Consequently, long before the time of Christ, horticulture was well established and capable of producing food surpluses and offering areas for rest and relaxation. The general principles of husbandry and marketing had been established. This knowledge and skills were also developed in Asia especially in China and Japan and in the South American civilisations (Swaminathan and Kochhar 1989). Plants and their products became traded commodities, were valued as means for environmental improvement and as sources of medicine.

The economic and environmental significance of plants developed still further during the Arabian (8th–13th century) era and into monastic and medieval periods. In Europe by 15th century there was very active trade in the products of nurserymen supplying grafted fruit trees. There were also needs for the regulation of the trade which supplied fruit and vegetables into the developing towns and cities. For example the Worshipful Company of Fruiterers of the City of London licensed their liverymen with the rights as the sole traders within the City. Radical social changes started with the British (17th–19th century) agricultural and subsequent industrial revolutions. Huge numbers of people moved into the developing factory towns and required food which the rural areas serviced aided by a developing railway network. Progressive employers recognised the importance of rest and relaxation and that resulted in the urban parks movement which progressed across Europe. The creation of parks for use by the general public and even earlier as possessions prized by wealthy landowners brought horticulture and the arts clearly into fruitful partnerships as described by Strong (2000). Landscapes began being viewed as works of art in their own right.

Into the 20th and 21st centuries urbanisation has increased and now predominates in the modern world. Increasingly, food supplies particularly fresh fruit and vegetables are becoming worldwide traded commodities. These reach the ultimate retail consumer through huge multinational corporations known as supermarkets. The challenge in this for horticulture comes in developing continuing capacities and capabilities for effectively and safely managing food supply chains for an increasing world population concentrated in ever larger urban conurbations. These populations demand not only sufficient food calories but also greater nutritional value, interest and increasingly health benefits (Fig. 1.2).

Additionally consumers demand that the plants are grown in a greener and more sustainable economy. Chapters in this trilogy “Horticulture-Plants for People and Places” discuss these issues (Dixon et al. 2014a).

**Fig. 1.2** Supermarket apple display

## The Problems of Success

As the use of plants for man's benefit developed both production and environmental horticulture have been greatly influenced by contributions from the sciences, technology, research, teaching and extension. Now mankind faces increasingly more difficult problems resulting from global climate change (Moore 2006; Dixon et al. 2014b). For horticulture there is a catalogue of issues which will influence its capacities and capabilities over the next half century. These challenges include:- an increasing world and urban population, greater water scarcity, exploitation and loss of our natural habitats, energy shortages, and the invasion of exotic or invasive species. These continue to threaten the sustainable use of horticultural food systems, biodiversity, and the benefits we receive from connecting with our natural resources. Degradation of the rural landscape has come about from adverse land–use practices, extensive erosion, emerging light industry and housing development (Uzun and Bayira 2009), all of which has resulted in loss of productive land, tree cover, native bush, and grasslands. It has been estimated that 40 % of the world's food now comes from only 18 % of global irrigated land for food production, yet there is the challenge of feeding an extra 80 million people per year (Borlaug 2001). Similarly, in urban areas there is clear scientific evidence that the removal of the vegetation results in soil losses due to: erosion, reduced nutrient and water supplies and losses of the habitat to pest-eating birds.

Climate change has been shown to influence the integrity of our environmental and health systems. Emerging groundwater shortages affect basic sanitation, the safety of drinking water and provision of an adequate and safe food supplies particularly in many developing countries (Anon 2002; Dixon et al. 2014b). The major threats to human health and well-being in less developed countries include those of poor nutrition and disease, and in developed countries, obesity, declining physical activity, growing rates of mental illness, high levels of family breakdown and declining community cohesion. The clearing of rural and especially forested land can significantly add to the emissions of carbon dioxide, the main greenhouse gas, and as a result reduce the benefit of renewing oxygen and providing cleaner air.

Elevated temperatures have been recorded in urban landscapes devoid of vegetation (Bowler et al. 2010). In addition urban landscapes lacking trees, turf and other vegetation, and that are overcrowded and isolated from the natural environment, are often given as causes for aggression, depression, and stress (Bennett and Swasey 1996; Lohr et al. 1996) in modern society.

The loss of biodiversity is part of the pattern which accompanies climate change and the scientific evidence suggests that this threat is a global phenomenon. Hajkowicz (2012) reports that globally biodiversity continues to be in rapid decline Research shows that long-term environmental conditions can play a significant role in defining the function and distribution of plants and animals in a tropical forest landscape (Stork and Turton 2008). Climate change, increasing world population, and unprecedented urban growth are the major drivers of changing biodiversity patterns (Prance et al. 2014).

Water sources, another natural resource, are important for growth and food security; however some are not sustainable, with some large river systems no longer reaching the sea (Postel 2010). Continued dry conditions have been shown to affect both rural and urban environments and communities. Local government agencies must now seek alternative water sources, other than potable water, for irrigation purposes. The concepts of “water footprints” and “virtual water” are now under discussion providing better understanding of the use of scarce water supplies (Anon 2012). The impact of invasive plant, animal and microbial species, which have demonstrated environmental, social, economic and health consequences was discussed by Rotherham and Lambert (2011).

An emerging conflict as described by Markham (2013) provides an example involving the regional islands of the Pacific region. An increasing population, principally arising from increasing tourist numbers, a growth in urban migration, poor land-use planning, alternating cycles of El Niño and La Niña weather patterns that bring periods of drought or excessive rainfall that last for several years, shortages of fresh water, contamination from rising sea water levels, and challenges with exotic and invasive nematodes and diseases are resulting in a crisis leading to non-sustainable production in the Pacific region. The challenges and solutions in seeking sustainable development involve plant changes such as the introduction of improved cultivars. Social changes require the recognition of the importance of soil fertility, organic matter production or ‘conservation agriculture’ and introducing farmers to integrated pest management (IPM). This must also include introducing simple drip irrigation systems that counter climate-related problems and sustain soil health.

## Plants for Good and Evil

Fundamentally plants impinge on peoples’ lives initially as a source of food and then as society develops they provide far wider and more valuable products. The eminent Russian geneticist and plant breeder Nikolay Vavilov (1994) described the origins of horticultural plants based on his extensive expeditions aiming to find and study wild and semi-cultivated forms of basic crops. He concluded that much of agriculture, and that includes horticulture, arose in Asia. The need for plants as the basis for human diets and the manner by which this is achieved can be a powerful engine for economic development and good. Tragically, plants can also be abused as a source of much evil as is now being revealed through accounts of the devastations which beset the totalitarian world in the 20th Century. In the Soviet Union (Medvedev 1987), China (Jisheng 2012) and North Korea (Demick 2010), the abusive manipulation of plant production led to the death of many millions of people through deliberate starvation. Fortunately, in the majority of instances plants and the crops that they produce are used in the improvement of mankind's well being. Perhaps a classic example of this is Norman Borlaugh's breeding of dwarf wheat (Khush 2001) which helped raise cereal yields especially in developing countries and gave India food self-sufficiency for a generation. In the 10,000 years up to 1960 the world's cereal yields had reached 1 billion tonnes per annum, in the succeeding 40 years this was doubled. More generally the "agricultural revolution" between the 1940s and the late 1970s increased agricultural and horticultural production worldwide. Plant breeding and plant selection have continued to be vital tools bringing success in both agricultural and horticultural systems (North 1979; Hoisington et al. 1999, Leitão 2012).

## The Power of Horticulture

Plants are a power for enormous economic, environmental and social good as recently summarised by the International Society for Horticultural Science's publication "Harvesting the Sun" (Anon 2012). Export industries are powerful engines for the world's economy through the exchange of goods and services between nations. The total value of fruit and vegetables exchanged through worldwide exports in 2008 was $ US 180 billion. Exports represent less than 10 % of world production since it is calculated that 93 % of fruit and vegetables are used in home consumption with a total production of 2.4 billion tonnes. China has developed over the last 30 years into one of the world's biggest horticultural producers growing 19 % of all global fruit, 38 % of all global vegetable, 45 % of all global apple and 50 % of all global peach and nectarine production. Analyses of export trading show that the USA exported over $ US 10 billion worth of fruit and nuts in 2010 mainly sent to Asia, India and the European Union (EU); the Netherlands exported $ US 10 billion worth of live plants, bulbs and cut flowers in 2010 mainly to other members of the EU, it is well worth noting that much of this trade will involve handling produce coming from under-developed nations in Africa and South America; and the emerging economy of Turkey exported $ US 3.5 worth of fruit and nuts in 2010 mainly to EU states. As "Harvesting the Sun" notes "horticultural crop production is increasingly shifting from countries with high land, labour and energy costs to those with lower input expenses such as Kenya, Thailand, Vietnam, Mexico and Morocco". As illustrated in Table 1.1 China now dominates a considerable proportion of the

**Table 1.1** World fruit and vegetable production in 2009. (Source: Anon 2012)

| Production (millions tonnes) | Fruit | Vegetables | Total |
|---|---|---|---|
| China | 118 | 683 | 801 |
| India | 71 | 152 | 223 |
| Nigeria | 10 | 85 | 95 |
| USA | 29 | 61 | 90 |
| Brazil | 37 | 43 | 80 |
| Indonesia | 17 | 35 | 52 |
| Russian Federation | 3 | 48 | 51 |
| Turkey | 15 | 32 | 47 |
| Thailand | 9 | 34 | 43 |

world's horticultural export trade since it is the largest fruit and vegetable producer. In 2010 the United States farm gate value of fruits, nuts, and vegetables was valued at $ US 33.4 billion, representing almost one-half of the United States' crop farm gate value (Ingram 2012). That value excluded those commodities such as building materials, fibre, perfumes, dyes, and medicinal and pharmaceutical products. Neither was the value of production associated with community gardens (Twiss et al. 2003), green roof gardens (Kidd 2005; Kassim 2011), hydroponics, mini-farming and ranching (Simovic 1998) included. Kassim (2011) reported that the technological spin-offs from hydroponics and aquaculture now make the Republic of Singapore a world leader in rooftop production of fresh vegetables, fruit and flowers; certain types of seafood in specially designed containers; as well as making this city a greener, cleaner cityscape that contributes less to global warming.

The range and diversity of food products and commodities associated with horticultural production have become particularly important for improved human nutrition and in health, and play important roles in establishing the economic security and stability of many countries (Ingram 2012; Anon 2013c). In 2009 total world production of fruits and vegetables were calculated at 2.4 billion tonnes (Anon 2012) with Brazil, China, India, Indonesia, Nigeria, Russian Federation, Thailand, Turkey and USA, accounting for 51 % of the world's fruit and 65 % of the world's vegetable crops. Asia accounted for only 23 % of the world's fruit production in 1983, by 2005 this had risen to 76 % of the world's fruits and 82 % of the world's vegetables (Lee 2007).

In 2008 the value of environmental horticulture to North America, Latin America, Europe, the former Soviet Union, Asia and Oceania, the Middle East and Africa was worth almost $ US 290.0 billion, or approximately 1 % of Gross Domestic Product (Haydu et al. 2008), or worth some $ US 175.26 billion in total revenue (Hall et al. 2006; Hall and Hodges 2011). Additional research is required in determining the value of environmental horticulture projects such as is found in many green open space initiatives like parks and garden tours, eco-tourism and event management. Recognition of the value of greening to the environment has come about only recently in response to global warming (Dixon et al. 2014b) and rising urban populations (Figs. 1.3 and 1.4).

**Fig. 1.3** Walkers in a park

**Fig. 1.4** Greening tramway tracks in Angers France

The social, environmental, economic and health costs associated with providing these benefits such as the provision of shade, biodiversity conservation and safety of play are reported by Cooper (2010); Nowak et al. (2006); Wang (1999); Beard and Green (1994). In this Trilogy chapters by:- Wainwright et al. (2014); Lillywhite (2014); Desjardins (2014); Curtin and Fox (2014), and Lohr and Relf (2014) provide important information and analysis of the issues involved.

Considerable added value is generated in the supply chain as goods move along from the producer country to the retail consumer. The ultimate return to the grower is less than 10 % of the ultimate price paid by the retail consumer. Income, profits and employment are generated throughout the distribution chain as illustrated in Table 1.2. This ably demonstrates how horticulture creates wealth well beyond the basic processes of crop production.

## Horticulture and Knowledge Generation

Horticulture has a long established capacity for absorbing novel scientific discoveries and turning these very quickly into new technological processes (Dixon 2000, 2004). Previously this aspect was analysed in detail by Sansaveni et al. (1999), where these researchers recognised that there had in the past 50 years been a "green revolution" in horticultural crop production. The levels of output indicated in Tables 1.1 and 1.2 would not have been possible without enormous scientific advances in plant breeding, crop nutrition and protection, cropping systems and engineering. In the succeeding 15 years since 1989 the pace of this "horticultural green revolution" has accelerated. Additionally the emphasis has evolved into a much closer alignment between the facets of horticulture and the need for environmental care and conservation. Horticulture has accepted worldwide the need for sustainable forms of husbandry which rise to the challenge of producing crops with minimal impact on the environment. In particular the dangers inherent in the excessive use of pesticides (Carson 1963) have been well accepted in horticulture. The recognition of the interaction between horticulture and the environment could be interpreted as a return to values previously accepted by horticulturists and used for example in the earlier manipulation of crop fertility (Whyte 1960).

Most crops are now grown using stringent quality assurance standards with minimal pesticide residues frequently at concentrations well below those legally specified. This approach which links crop production in a partnership with the environment was highlighted in the International Horticultural Congresses of 2002 (Rom and Dixon 2004; Janick 2007; Janick et al. 2011) and the Symposium on Horticulture in Europe (Dixon 2009). These events amply demonstrated that horticultural husbandry is applying sound scientific principles which enable increasing volumes of output of high quality produce while harmonising with the natural world and particularly making considerable strides towards partnership with aerial and edaphic microbial flora as suggested by Dixon and Tilston (2010).

Horticulture has yet to make full use of the power of genetic modification. While it has long been recognised that biotechnology could provide substantial benefits for intensive production of fresh fruit and vegetables (Busch et al. 1991) there has been considerable reluctance driven by "anti-scientific phobias" in the general

**Table 1.2** Costs in the supply chain from grower to consumer for a carton of apples. (Example based on apples exported from the Southern Hemisphere and retailed at euro 17.00 per 12.5 kg carton in an European supermarket in 2008 (duty costs excluded). Source Anon (2012))

| Item | Cost (euro) | Logistics and other margins |
|---|---|---|
| Carton of apples retail | 17.00 | |
| Retail margin | 4.42 | 26 % retail margin |
| Destination costs | 2.72 | 3 % destination in-country transport<br>5 % importer's commission<br>8 % destination in-country logistics |
| Shipping freight and export costs | 3.74 | 15 % shipping freight<br>3 % exporter's commission<br>4 % insurance/port costs/finance/industry levies |
| Packing and materials | 2.72 | 10 % grading and packing costs<br>6 % packing materials |
| On-farm costs and grower profit | 3.40 | 2 % on-farm costs, excluding capital and finance<br>8 % fertilisers, chemicals and other production costs<br>10 % farm overheads and income per 12.5kg carton |

population to take advantage of the opportunities which are offered. This is despite attempts by those well versed in molecular biology in explaining in non-technical terms what is involved (Coen 1999). So far, however, the general public remains unconvinced of the opportunities on offer. Possibly, this is because the advantages currently exploited pertain to broad-acre agricultural crops where benefits appear to stop at the farm-gate. This may change when the enhancement of plant traits which provide direct benefits for human health and welfare come on the scene.

## The Facets of Horticulture

Horticulture has been described as the science, technology, and business associated with intensive plant production for human use (Doyle et al. 2012). In such restrictive definitions horticulture and horticultural science is focused narrowly on the producers or growers of horticultural products such as fruit, vegetables, ornamentals, flowers and turfgrass, as well as many other commodities, used as a fibre, pharmaceuticals, or essential oils, that have shown economic potential.

Horticultural production takes place (Singh et al. 2010; Aldous 2011) where the environmental conditions are conducive for growth and development and these are discussed in detail in this Trilogy. Suitable places for production are often determined by the climate, soil type and growing conditions most favoured in generating good

**Fig. 1.5** Intensive lettuce production

yields of high quality products. Where these conditions are not favourable the growing environment is often modified by the use of glasshouses and greenhouses and other techniques (Fig. 1.5).

Whereas Martinez et al. (2010) detailed the concepts, impacts and issues associated with cropping in the inner urban areas of cities, most high value commodities, like fruit (Costa 2014; Galan Sauco et al. 2014; Agusti et al. 2014), vegetables (Leskovar et al. 2014), ornamentals (Seaton et al. 2014; Read and Bavougian 2014; van Tuyl et al. 2014), medicinal and aromatic plants (Inoue and Craker 2014) and other forms of protected cropping (Gruda and Tanny 2014) are often located in the peri-urban or rural areas. Previously, this required close proximity to city centres to minimise the requirements for transport and to get the produce to market while it was still perceptibly fresh. Advances in post-harvest handling and storage now make this unnecessary. Produce associated with plantation (Diczbalis et al. 2014), berry (Brennan et al. 2014), viticulture (Guisard et al. 2014), and organic food horticulture (Pearson and Rowe 2014) cropping, is often grown much further afield, and uses artificial ripening methods, cool storage and refrigeration to reduce the problems in getting the produce to market in good condition (Toivonen et al. 2014; van der Vorst et al. 2014; Desjardins et al. 2014).

The consumer is defined as those people who benefit from the opportunities offered through the products and services of food production horticulture. This neglects the benefits derived from the provision of products and services of environmental horticulture such as green open spaces, urban parks, botanical gardens, household gardens and other areas of the contrived and semi-natural landscape. This approach mirrored the ideas of Rowe (1979) who separated horticulture into:-food production, amenity or environmental horticulture, and the associated support services.

The environmental horticulture sector has seen a number of name changes over the years from amenity, ornamental, environmental, urban, and more recently lifestyle horticulture. These changes frequently reflect shifts in educational fashion and attempts to encourage student interest. In this Trilogy the term environmental horticulture is employed. Mullins (1978) described environmental horticulture "as those people and organisations who are engaged in the production, sale and management of plants used for environmental, recreational and leisure purposes". These non-food crops embrace many of our ornamental plants that can be propagated and produced in nurseries for use in landscaping or horticultural production units such as seedlings for floriculture and cut flower production arboriculture, turfgrass production, aromatic and medicinal herbs, tropical foliage, as well as potted ornamental plants and bedding plants. The support industry dimensions are largely those people engaged in supplying non-plant products and services such as manufacturing, sales and services, education and training (Aldous et al. 2014a), and research and extension (McSweeney et al. 2014). These ensure that sustainable development is achieved in activities such as events, tourism, landscape restoration and conservation, landscape and garden design and construction (Figs. 1.6, 1.7 and 1.8).

This includes instances where plants are used as tools for intervention in recreational, educational, vocational, and rehabilitation programming, in the provision of therapy, as well as in socialization. This broader vision embraces the importance of plants not only as commodities and activities essential for human survival, but also where plants utilised in human goals provide considerable benefits for society as individuals, communities and cultures (Swaninathan and Kochlar 1989). In 2011 Aldous promoted a model where plants are of value as sources of fresh and processed food and drink, as well as beneficial amenity and environmental use, in servicing people, when they wish to access and utilize a place or landscape.

Green open spaces, have been described as any open space, vegetated land or water located and managed within the urban or rural environment (Anon 2013a). In this Trilogy plants needed for environmental horticulture, such as in sports turf and amenity grasses (Aldous et al. 2014), trees (Percival et al. 2014; Johnston and Hirons 2014), and ornamentals (Seaton et al. 2014; Read and Bavougian 2014; van Tuyl et al. 2014), or being used in gardening (Rae 2014) and in interior (Cameron 2014a) and in external landscaping settings (Groening and Hennecke 2014) are described. Green places in urban areas can range from public and private green open space, neighbourhood parkland, botanic gardens, flower shows institutional and hospital grounds, to grassed sporting and recreation facilities and semi-natural open space. Rural green open spaces include assets such as amenity grasslands, wild lands, protected areas, forest plantations, and well include a country's national, wilderness and conservation parks and continue to play a significant part in biodiversity (Prance et al. 2014) as well as providing a means of physical and mental health

**Fig. 1.6** Flower market Bruges, Belgium

(Cameron 2014b; Curtin and Fox 2014; Lohr and Relf 2014). These green open spaces, which are more often associated with our urban communities, are usually their only possible sources of connection with the natural world and need effective management (Baycan-Levent et al. 2002) (Fig. 1.8).

Social Horticulture is the newest dimension of horticulture and one which is gaining considerable credibility. Plants used in horticulture provide important social and human health services (Bird 2003; Lohr and Relf 2014) in addition to their environmental and ecological values (Kollin 2003; Moore 2009). Horticulture and its products improve physical health, reduce obesity, diminish the risk from chronic disease, improve the immune system, increase life expectancy, and reduce blood pressure in humans (Ulrich 1999; Bird 2007). Researchers such as Konijnendijk et al. (2013), Kendle and Stoneham (2014) and Lohr and Relf (2014), provide greater detail of these benefits to the community in this Trilogy. The model which integrates horticulture and health care was developed for example by Relf (2006) as a result of wide ranging research (Relf 1981, 1992, 1999; Relf and Kwack 2004). This links economic, environmental, social and health benefits with a culture of sustainable development (Jafari and Fayos-Sola 1996; Kidd 2005; Lohr and Relf 1993; Shoemaker et al. 2000). In many developed countries there is an obese population

**Fig. 1.7** Tintinhull garden National Trust England

**Fig. 1.8** Hampton Court Flower Show, England

accompanied by a decline in physical activity, community cohesion and human health, and resultant higher levels of family breakdown. By stark contrast in developing countries there remains poor nutrition, disease and potential starvation that resulted from a decline in the socio-economic status and human health of the population (Latham 1997). Both these community problems are susceptible to support from facets of Social Horticulture. Encompassing these triple descriptions of the Discipline of Horticulture broadens its vision to one that “encompasses all life and bridges the gap between science, art and human beings” (Janick and Goldman 2003; Janick 2014).

## Developing Benefits for People and Places

If production, environmental and social horticulture are to flourish then there is a need to describe the beneficial relationships that exists between people, plants, and places. This is firmly the purpose of this Trilogy. Each facet forms part of a platform which supports the concept of sustainable development that involves the increasingly urban lifestyle (Anon 2013c). Horticulture has been regarded as a rural entity. This concept must now change and accept a wider dimension since unlike agriculture it is well suited to providing benefits for an increasingly urbanised world population. This world’s population could well reach 9.1 billion by 2050, with particular impact in the developing countries such as Asia and Africa (Anon 2009b). Urbanization is likely to continue at an accelerating pace, with upwards of 70–80 % of the world’s population choosing to live in the urban and peri-urban areas of many countries (Anon 2006). Future trends indicate that the world’s population could exceed 5 billion people out of a total world population of 8.1 billion people by 2030. In 2012 China had 51 % of its population living in its towns and cities in just 3 years. According to the economic historians it took 200 years in Great Britain, 100 years in the United States and 50 years in Japan to reach the same stage (Anon 2013e). Increasing populations are placing substantial pressures on the world’s food supplies (Anon 2013c) as well as its environment and natural resources (Anon 2009a).

Achieving benefits from horticulture’s sectors requires a workforce. Earlier analyses identified groupings of food producers or growers, the environmental (amenity) horticulturists, and those providing support services that move products and commodities through the value added chain (Rowe 1979). People involved with food production are largely engaged in the production, processing, distribution and sale of fruit and vegetable crops, or other produce, largely consumed as food or drink. Environmental horticulture involves those people and organizations that are engaged in the production, sale and management of plants largely used for recreational and leisure purposes. Service personnel involve those people engaged in supplying the non-plant products and services within a community and as such can involve those in manufacturing, sales and service, education and training, research, extension, consultancy and management of these services.

Among the challenges that influence production horticultural performance will be our increasing world population. To feed our forecasted population of 9 billion people by 2050, we need at the present rate of production, to increase production from an annual 2.4 billion tonnes of fruit and vegetables to well over 3.1 billion tonnes. In South East Asia, Latin America and Africa, there are additional social and economic issues associated with increased production since improving the population's standard of living is also important and horticulture's position as a provider of employment (Sanyal 1985). Governments in these regions also recognize that they need to secure more production from their land, or increase productivity per unit area, so food security can be assured in the future as well as improve the quality of their populations' lives. Asian people have developed technology for securing more production from their land, based largely upon their varied experiences and traditional information (Lee 2007). Today there is greater discussion about how to retain the postharvest quality of our fruits and vegetables (Toivonen et al. 2014) and how they can be effectively marketed along the value supply chain (Murray-Prior et al. 2014; van de Vorst et al. 2014) both nationally and internationally (Maxwell et al. 2014). These new aspects of horticulture will contribute greatly to the twin goals of increasing production while also increasing the social standing of plant based foodstuffs.

The social facet of horticulture describes people's behaviour and how it relates to plants and places over time and space. Social horticulture largely defines the underpinning of the physical and psychological aspects, and other health benefits, which humans derive from living with and using plants, their products and services. Research shows that mankind is socially dependent on nature and green open space for psychological, emotional and spiritual needs (Maller et al. 2009; Dunnett and Qasim 2000). Urbanised green open spaces, although recently seen as sources of urbanised food production, but they also provide a range of social services for the public good. Plants provide social capital by fostering an active lifestyle, providing safe play areas for children, and providing instruction on conservation and environmental awareness (Patel 1992; Cammack et al. 2002). Green open space engages the community with structured and unstructured sporting activities, national and international events, all of which do contribute to a vibrant, populous and sustainable city. Similarly green open space can provide an environment that reduces crime and disorder, stress, aggressiveness and violence, builds interpersonal relationships between juvenile offenders and municipal officials, provides a safe environment for young people at risk and provides a reason for building civic pride and community spirit (Kuo and Sullivan 2001a, b). A stroll about or resting in green open space facilities can improve the health of people and enrich the culture of a nation as well as providing spiritual health and creative self-expression. Green open spaces can also improve the working environment, increase memory retention, reduce the recovery time after a medical procedure (Ulrich 1984) and the likelihood of stress-related depression (Kuo 2010; Elings 2006; Pretty et al. 2005, 2006; Rothert and Daubert 1981) and the potential for anger (Ulrich and Parsons 1992). More recently green open spaces have shown to provide significant health benefits and savings in medical care costs (McKenna 2003).

Among the changes that could influence the socio-economic performance are shifts in world demographics, such as age and longevity of the world population, and the level of unemployment and disposable income. In many western countries, life expectancy has increased by approximately 5 years over the past 20 years due to consuming healthier foods and improved lifestyles. In Europe the number of people aged 65 years and over will double from 17 % in 2012 to more than 30 % by 2050. For example, in Italy the age at which people retire in 2050 will need to be 77 years of age if the country is to maintain its worker to retiree ratio. These changing demographics have largely come about because of lower fertility rate. Similarly, Europe's share of the world's population in 2050 will be 7 %, compared with 12 % today, whereas a century ago Europe had 25 % of the world's population. These numbers have a significant impact on society and its needs for horticultural produce and the availability and quality of green spaces. From a production horticulture perspective in many less-developed countries consumers currently purchase fresh produce every day. But in western countries horticultural produce is purchased directly from a retail store or supermarket at irregular intervals on the presumption that it can be retained in refrigeration until it is needed. Also in these countries there is a demand for fresh produce to be available all the time. Retail consumers want complete convenience so that if they wish to shop during the night then that facility is available. The result is that the socio-economic composition and structure of human settlements is changing radically. This is forcing planners to rethink the connections between people, plants and places and will have considerable impact on all facets of horticulture.

## Horticulture's Future

Today horticulture stands at a crossroads. After a sustained period of improvement in food production and world crop yields, threats such as exacerbated climate change, water scarcity, food security, energy shortages, limited natural resources, and increasingly limited land resources all lead to a challenging and problematic production environments. A new global "green revolution", is required as described by Mittochner (2012) and by van Latesteijn and Andeweg (2011). This must strive for increased food production and wealth creation but in the context of a cleaner, healthier and sustainable environment. Horticulture is well placed for a substantial role in these social changes because of its environmental and social dimensions. Horticulture can justly claim considerable credit for the creation of rich environments in which people can live, work and play. There are considerable social attributes related to horticulture which are of increasing importance in an ever more crowded world. Horticulture provides for the social welfare and well-being of people and this aspect will come to be its dominant facet which will become the driver for both its production and environmental aspects. The challenge will be to learn from the past and provide through partnered research with a range of different scientific and humanitarian disciplines. The aim will be to develop smarter sustainable solutions which achieve sufficiency in nutritious food in a cleaner environment while adding to the world's store of resources.

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# Chapter 2
# Science Drives Horticulture's Progress and Profit

**Geoffrey R. Dixon, Ian J. Warrington, R. Drew and G. Buck-Sorlin**

**Abstract** Horticultural science linked with basic studies in biology, chemistry, physics and engineering has laid the foundation for advances in applied knowledge which are at the heart of commercial, environmental and social horticulture. In few disciplines is science more rapidly translated into applicable technologies than in the huge range of man's activities embraced within horticulture which are discussed in this Trilogy. This chapter surveys the origins of horticultural science developing as an integral part of the sixteenth century "Scientific Revolution". It identifies early discoveries during the latter part of the nineteenth and early twentieth centuries which rationalized the control of plant growth, flowering and fruiting and the media in which crops could be cultivated. The products of these discoveries formed the basis on which huge current industries of worldwide significance are founded in fruit, vegetable and ornamental production. More recent examples of the application of horticultural science are used in an explanation of how the integration of plant breeding, crop selection and astute marketing highlighted by the New Zealand industry have retained and expanded the viability of production which supplies huge volumes of fruit into the world's markets. This is followed by an examination of science applied to tissue and cell culture as an example of technologies which have already produced massive industrial applications but hold the prospect for generating even greater advances in the future. Finally, examples are given of

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nascent scientific discoveries which hold the prospect for generating horticultural industries with considerable future impact. These include systems modeling and biology, nanotechnology, robotics, automation and electronics, genetics and plant breeding, and more efficient and effective use of resources and the employment of benign microbes. In conclusion there is an estimation of the value of horticultural science to society.

**Keywords** Applied science · Impact · Industrial application · Environmental value · Social value · Food supply · Dietary provision

## Introduction

Horticulture is the controlled manipulation of plant reproduction, growth and fruiting applied to crop production, environmental care or social benefit. The word "profit" is deliberately used in the title indicating that scientific discovery is the basis for future profitability in the commercial sense but also in pursuit of environmental and social sustainability. This belief draws on the profits which have already accrued from discoveries and applications in horticulture and horticultural science and which are elaborated as part of this chapter. This may seem to be a utilitarian approach from the perspective of purist researchers but accurately reflects the desire of horticultural scientists for close collaboration with end-users. The definition does not however, adequately convey the intellectual depth of horticultural science which takes basic and fundamental discoveries and translates these into applicable and useful knowledge.

Controlled manipulation of plants requires access to and an understanding of scientific knowledge across multiple disciplines and then its synthesis into applied science and ultimately technological expertise. Horticultural science's reservoir of knowledge firstly evolved over many centuries from the original gathering of empirical principles garnered by mankind's founding social cultures. The advent of the sixteenth century "Scientific Revolution" ultimately produced qualitative and quantitative hypothesis and data-driven studies founded on basic research in biology, chemistry, physics, mathematics, electronics and social and economic disciplines. As a result, horticultural science has become an applied science which flourishes by cross-fertilization between itself and other disciplines. Excellence in horticultural science demands scholastic, intellectual capacities which are capable of identifying nascent discoveries across the basic sciences and integrating them into processes and procedures which possess industrial, environmental and social value. Horticultural science deals in both "why" natural processes happen and "how" they may be manipulated thereby producing ecologically sustainable social and economic growth. The knowledge gained in itself often contributes back to the fundamental sciences and enhances basic understanding.

Knowledge of the controlled manipulation of plants emerged long before the modern era of scientific experimentation. Horticulture is the oldest of all mankind's arts and sciences. From our earliest civilizations in Babylon, China and South

America mankind developed an understanding of the cultivation of food, medicinal and decorative plants. Knowledge of how plant form and function could be manipulated was passed firstly verbally and subsequently in written texts through into the sixteenth century. Quite probably forms of simple experimentation existed prior to this date. Initially it is quite likely that this involved the segregation of higher yielding forms of food plants and the evolution in cultivation of cropping variants which would, in turn, become semi-stable land races. This would have been supplemented with an understanding of the use and effects of irrigation water and animal fertilisers, seed saving and forms of asexual propagation, and plant protection. The identification of plants containing useful and beneficial compounds and their description required forms of systematic thinking and enquiry which culminated in the great herbals which were initially hand-written in monasteries and other religious establishments.

The first systematically recorded experimentally-based horticultural enquiry was that of Stephen Hales (1727). He carried through a series of well planned experiments, and demonstrated that a plant takes in large volumes of water through its roots provided that it has leaves from which the water may subsequently evaporate. He went so far as to suggest that "may not light also, by freely entering the expanded surfaces of leaves and flowers, contribute much to the ennobling the principles of vegetables?" A glimpse of an understanding of what much later was termed photosynthesis perhaps? Certainly, Hales provided the first scientific basis for the horticultural processes of irrigation, nutrition and plant manipulation and protection. That technology had been utilised empirically by mankind for centuries, possibly millennia. The ensuing "Scientific Revolution" produced increasing understanding of biological principles and processes. John Ray and Carl Linnaeus provided scientific structures for the nomenclature and taxonomic assessment of plants and their properties. That step related plant identification with structure and function (Dixon and Brishammar 2007a, b). Charles Darwin's seminal qualitative development of an understanding of evolution and speciation offered a logical basis for biological thought which is reverberating now as molecular science with ever increasing impacts in horticulture (Darwin 1862). Microbiology and mycology began emerging as important elements in horticultural thinking with Pasteur's recognition of the causal agents of vine diseases and subsequent studies which founded plant pathology. Along with entomology, the basis was laid for the emergence of key areas of biological science with enormous impact on the successful control of healthy plant growth.

A major step in quantitative understanding was Mendel's discovery of the principles of heredity using peas as an experimental model (Mendel 1866; Stern and Sherwood 1966; Orel 1996). Particular benefits come from the integration of physical and chemical scientific thinking into biology and subsequently leading to developments in horticultural science. An early example of this is the influence of Professor John Henslow's quantitative approach to speciation (Henslow 1830) which Kohn et al. (2005) postulated influenced Darwin's thinking. The rise of horticulture's productive capacities towards the end of the nineteenth century is firmly rooted also in industrial discoveries. Nitrogen fixation by artificial means allowed the manufacture of commercial quantities of fertilisers which resulted in increased levels of crop productivity of previously unachievable dimensions (Smil 2001). At about the same time, Mendel's work was rediscovered in 1900 (Bateson 1909) and formed a scientific basis for genetics and plant breeding leading to the development of higher yielding and better quality crop cultivars. This is a classic example of the convergence of commercial research and development providing fertilisers on the one hand and more basic academic studies providing new genetic forms capable of profiting from added nutrients on the other.

Throughout the ensuing twentieth and now twenty-first centuries, fundamental science has been and continues to be the foundation from which most developments and innovations in the art and science of horticulture spring. The pathways by which fundamental science is turned into horticultural science and subsequent technology are neither straightforward nor short term. Although many years may elapse between an initial basic "blue-skies" discovery and its translation into applied science and related technologies once these offer increased efficiency then changes are adopted by industry very quickly. The pathways for the thinking which translates science into application are complex, frequently indirect and most certainly not linear as some pundits regrettably and damagingly pretended in the 1980s. Horticulture, and agriculture and forestry for that matter, are rooted in industrial practice. Not infrequently that means that information derived by practitioners unlocks an understanding of science which then turns full circle formulating novel processes which resolve a practical problem.

The organisational structures within which horticultural science uses basic science and turns it into technology are changing in parallel with worldwide social, religious and political evolution. Nonetheless, the requirement for new basic scientific discoveries remains continuous. Without new science, horticulture itself cannot evolve and move forward, continuing the processes of wealth creation for society, conserving and safeguarding the environment, and enhancing human health and welfare. It is foolhardy in the extreme to pretend that mankind's urgent needs for horticultural production can be met by anything other than continuous evolution of new scientifically-based knowledge. This is exemplified by the huge advances that studies of molecular biology have brought in our basic understanding of how organisms are constructed and the delicate metabolisms which control their activities as, for example, described by Enrico Coen (1999). Horticulture has an enviable reputation for being capable of turning new science into technological improvements at least on a par with the pharmaceutical industry. This perhaps should not be surprising given the close origins and evolution of horticulture and pharmacy.

Social change is placing new demands on horticulture and satisfying these demands means altering the requirements for science and technology. In a very perceptive prediction Oosten (1999) (echoed by Warrington 2011) argued that major shifts in the world economy (globalization), society and technology would cause dramatic changes in Dutch horticulture and the attitude of the government towards research by 2010. He contended that the horticulture industry would change from a product-driven to customer-driven strategy while developing market-oriented product chains. Knowledge would become a critical factor in competition and applied research closely linked to industry would become the responsibility of private enterprise. In particular, he highlighted four developments in science and technology of great significance to the horticultural industry: molecular biology; information technology (IT); new concepts in the marketing chain; dynamics in health food relations and production ecology. The need for strengthening basic sciences was emphasised and those which he called "knowledge institutes" (universities and research institutes) would be faced with repositioning themselves for three roles:-knowledge creation; co-operating innovator; and knowledge brokering.

## Horticultural Science's Changing Focus

The marketing of horticultural produce has changed rapidly and monumentally in the past 25 years (Shepherd 2008) and continues doing so. Chains linking growers, traders, processors, retailers and consumers are now controlled to a very large degree by supermarket retailers. Supply systems are likely to evolve from largely price-based competition to innovation-based competition. Consumers are seeking increased localisation, regionality and identification of origin, as well as safe and healthy nutritional foods. Electronics, nanotechnology and robotics offer opportunities for interaction between primary producers and the ultimate consumers. Customers and producers will interact directly with confidence and trust. Only the largest producers will be capable of managing the infrastructure capable of servicing this relationship and its dialogue which will reach beyond national borders. These producers will own the intellectual property rights to production and supply systems and commission their own R&D from these assets. This applies currently with greatest impact on the supply of fresh and processed produce in food chains. As a result, applied horticultural science is moving towards private sector provision at the same time as the role of the crop producer is becoming more prominent in the consumer's mind as responsible for the delivery of safe, reliable and health-enhancing products. At the same time, aspects of research and development needed for environmental and social horticulture, as described in other chapters of this Trilogy, are emerging through economic evaluations of areas such as natural ecosystem services and the quantification of social care within communities. An example of this approach is the framework for environmental-economic decision-making which includes ecological sustainability criteria, environmental costs, natural resource scarcity prices and local peoples' preferences developed by Tiwari (2000). Here the geographic information system (GIS) technique was used for evaluating ecological criteria and integrating information for use in cost-benefit analysis. A cost-benefit analysis (CBA) embraced external costs, such as environmental costs and scarcity value of water, and ecological sustainability criteria. As stated by Hughes (2007), the *raison d'etre* of the global food industry is to satisfy the ever evolving requirements of consumers worldwide. The dominating trends affecting consumer behaviour include: demographic changes; concerns about safety, health, well-being and nutrition; and an inexorable search for convenience, particularly in urbanised communities. Across the globe, starting in developed and migrating to emerging countries, the growth of supermarket retailing is forming a principal link between food producing industries and their consumers. A relatively few, sophisticated international retailers are establishing businesses in both geographic hemispheres and, in doing so, are transforming the nature and operations of international supply chains. The implications of international horticultural supply chains being transformed from "supply push" to "demand pull" are profound for all stakeholders, including growers, exporters and importers, and the international research and development (R&D) community. Commodity markets are fragmenting into specific consumer segments. The R&D focus is shifting from input traits (e.g. yield or pest and pathogen resistance) to consumer-led output traits (e.g. taste, size, shape), and is becoming an increasingly private sector function. The challenge is to identify and commercialize product attributes that consumers' value and will pay premiums for.

Those businesses capturing the intellectual property associated with value-added products will take the lion's share of the consumers' dollars. The trend towards "privatization" of R&D will cause current supply chains, which are open and commodity-orientated to become closed, with exclusive providers of genetics and associated production systems linking with specific producers, exporters, importers and retailers. The horticultural industry will come under increasing price pressure in the future, as fewer, larger businesses control access to higher income consumers. Competition will evolve however, from solely price-based to innovation-based systems providing novelty in products, processes, and services. Successful horticultural businesses around the world will seek to build trust and longer-term commercial relationships with those who have immediate contact with the grower and consumer, bringing in an era of interdependence, rather than independence. This will steadily manifest itself in closer relationships between producers and the consumers. The latter are making it abundantly plain that they wish for contact with producers through increasing consumer demand for information regarding the origins and qualities of food. The internationalised food chains will have to accommodate growing demands by consumers for localisation of production, the provision of fresh and processed products carrying health and welfare benefits, minimisation of adverse environmental impacts in the production and delivery of food and other services, and a desire for a reconnection between urban and rural societies. Overlaying all of this will be the increasingly severe impacts of climate change, water scarcity and increased urbanisation on opportunities for horticultural production. This echoes Sumner's (2007) contention, that horticultural science has a dichotomy of purpose of serving the requirements of transnational corporations and supporting basic human needs, community survival and environmental sustainability.

Possibly a solution lies in what Larsson et al. (2009) now describe as their Triple Helix Concept of co-operation between academia, industry and government. That revives the founding principles of the American Land Grant Colleges and what were once the Scottish Schools of Agriculture. They resolved the dilemma whereby industry requires short term problem-solving research while there must be a provision of basic seed-corn research investing in studies which will only ripen into industrial technology over an indeterminate period. To some extent, in pursuit of these goals in the USA, Bewick et al. (2011) reported that the USDA has created a Specialty Crop Research Initiative (SCRI) for research, education and economics receiving $US 230 million over 5 years addressing the scientific needs of horticulture. The focus is to discover new knowledge and technologies which ensure a sustainable supply of horticultural products and services. Additionally, this programme emphasizes the need for education and training of both the current and future workforce. This is achieved through planning from university graduate to primary education which aims at inspiring youth into choosing horticulture as a career as described elsewhere in this Trilogy.

## Horticultural Industries Created by Science

The application of basic science into horticulture has succeeded by providing tools for the control of germination, growth, reproduction and post-harvest handling for commodity crops, the design, construction and maintenance of macro- and micro-landscapes, and the provision of plants which enhance physical and psychological health. In this section are examined a series of science-led advances in horticulture which have had and continue having enormous impact on profitability and sustainablility. These are but a few of the many such advances that have taken place over past decades. The perspective of history provides the identification of seminal advances in horticultural science in the early part of the twentieth century which laid the basis for industrial practices which have subsequently become common commercial uses. Much early scientific effort was invested in attempts to produce uniformity of growth in experimental material with the initial aim of providing regularity and reliability for research studies. The early researchers wished, in particular, for control and regularity with perennial crops. Darwin (1859) pointed to the two key sources of variation in biological systems, characteristics which are inherited from two parents in the genotype and the impact of the environment on their expression in the phenotype. Hence genotype (G) x environment (E) interaction results in the phenotype (P).

### *Refinement and Development of Top Fruit Rootstocks*

All top fruit trees, both pip and stone, consist of a rootstock onto which the scion fruiting cultivar is budded or grafted and which results in two sources of genotypic variation. The husbandry required for producing fruit trees formed from the union of a rootstock and a scion has been known in Europe at least since the fourteenth century and was developed to very high degrees of skill, particularly in part of the Spanish Netherlands in what is now separately Belgium and The Netherlands. Both the rootstock and the scion are influenced individually and collectively by the environments in which they grow and by interactions between them. Scion cultivars, the source of edible fruit, result from lengthy breeding and selection programmes and consequently possess highly defined characteristics. Rootstocks mainly result from even more lengthy selection programmes and are retained in commercial use for decades. Many of their characteristics began being identified in the late nineteenth century and variation within rootstocks is noted in Bedford and Pickering (1919) and amplified by Bunyard (1920) and Hatton (1920). Scion growth control via the manipulation of pip and stone rootstock vigour played and still plays a major role in increasing fruit quality and quantity. Bunyard (1920) noted the history of Paradise rootstocks and their origins. This was followed by several years of careful analysis of selections of these stocks demonstrating how the yield of the scion varied with different stocks. 'Lane's Prince Albert' when grafted and budded on stock number IX was the highest yielding (Hatton 1927). This work led on to the subsequent development of the 'Malling (M)', 'Malling-Merton (MM)' and 'East Malling-Long Ashton (EMLA)' clones as described, for example, by Preston (1955). Apple rootstocks selected by British research stations (East Malling, John Innes and Long Ashton) in the early part of the twentieth century currently still dominate commercial practice internationally. The rootstock known as Malling no. 9 (M9) is still to be found in almost every apple orchard worldwide. The studies of rootstock vigour and stabilisation of original selections taken from commercial material resulted in rootstocks with predictable and reliable properties. Recently, further sources of rootstocks have appeared from Eastern Europe and North America resulting from continuing studies aimed at engendering improved performance of the scion cultivars. None of these, however, have achieved the market dominance of the original British material, especially M9, to date. These rootstocks quite literally support a worldwide market in the single largest internationally-traded fruit commodity, the apple, and have done so for nearly a century.

## *Scion Sterility and Fertility Barriers*

Explanations of the biological processes of scion pollination across barriers of self-sterility and incompatibility were elucidated by Hatton, Amos, Hoblyn, Crane and Lawrence (Dixon 2006). These workers founded the science of cytogenetics resulting in an understanding of underlying incompatibility of fertilisation between cultivars of apple, pear and, in particular, cherries and plums. They recognised groups of cultivars which could be planted successfully so that pollination would be successful and those where it would fail. The result of this work has provided generations of fruitgrowers worldwide with the ability for designing orchard layouts which would ensure cross-pollination and successful high yielding and high quality cropping. Consequently, cultivars are now specified into their compatibility groups even where they are destined for hobby gardeners. Working out these groups required dedicated laboratory studies of the growth or failure of the pollen tube into the ovary and transmission of male gametes for successful pollination. This work extended into field vegetables in the 1950s showing that in *Brassica* spp. in particular the presence of specific sterility (S) alleles in the genotype regulated the success or failure of fertilisation and resultant development of seed crops. Prior to that step however, it was essential to understand what constitutes a brassica species. Detailed research by a Korean-born scientist working in Japan in the 1930s uncovered the plasticity of brassicas and the natural formation of new species through allopolyploidy (U 1935). As a consequence, brassicas now constitute the world's most important fresh food and industrial processing crops second only to the cereals in their importance in the diets of humans and domesticated animals (Dixon 2007).

## *Photoperiodism and the Control of Vegetative and Flowering Phases*

Investigations beginning in the 1920s revealed that plants may react to the duration of the light environment by reproducing or remaining vegetative (Garner and Allard 1920, 1923). Subsequently, plants were divided into short-day responsive, long-day responsive or day-neutral forms (Wareing 1956; Schwabbe 1950, 1951, 1952). Since these original discoveries, botanical science has invested huge amounts of time and effort into understanding the manner by which variations in light quality and quantity are perceived and translated into signals which result in the initiation of flowering or the retention of a vegetative state. Modern molecular biology explains these processes in terms of the genetic components of plants and the manner by which the signals are generated. In the intervening years however, huge multinational horticultural industries have developed which produce flower and foliage crops worldwide using artificial control of day-length (such as chrysanthemum, poinsettia, *Kalenchöe*, carnation and rose) (Bernier et al. 1981). Crops are grown on very precise schedules where flower production is predicted over the entire growing period to within a few hours to high degrees of quality and consequently financial value. Basic knowledge of the manner by which flowering is triggered created multibillion dollar, global industries growing cut flowers and flowering pot plants.

## *Rooting Media*

Original studies at the John Innes Institute in the 1920s, aimed at providing a root environment for potted experimental plants and germinating seed, which offered standardised structure and texture combined with regulated nutrient supplies. This aimed at limiting one of the variables which beset geneticists when studying the effects of breeding experiments. The results produced the John Innes series of potting and seed composts (Darlington 1949) which remain in common use, especially in the huge hobby markets today and are increasingly used where peat composts are not acceptable (Carlile and Waller 2013). These composts are based on standardised mixtures of sand and loam-based compost into which precise quantities of nutrient fertilisers and calcium carbonate (lime) were mixed. John Innes composts remained as research standards into the 1950s. A new industry developed that manufactured these composts for sale to plant propagators, nurserymen and hobby gardeners. This remains an active part of what has become the global plant media industry developed on the back of an initial desire by research workers for repeatable and regular growth patterns in their experimental material. The problem with John Innes mixtures is that the loam component is very difficult to standardise across large volumes of compost. Consequently, researchers in the University of California devised alternative formulations of media where loam is replaced by peat which became known quite simply as "UC mixes" (Baker et al. 1957). Mixtures of peat and sand are more easily standardised and formulated on a factory scale. They provide composts with better properties of air fill porosity and resultant reproducibility of crop growth. This Californian research initiative has resulted, over the last 50 years, in an entire revolution in the ornamental and nursery industries, whereby plant selling has changed from almost exclusively bare-root material which could only be sold in the period of plant dormancy, to almost year-round provision of container-grown and containerised shrubs, trees, perennials and annual plants. As a result, it is probably fair to claim that the entire shift from small local nurseries to massive garden centres has come about because of the characteristics of plants which the retail consumer can conveniently carry home and plant at any time of the year. This revolution, fired initially from the availability of convenient rooting media, has spawned a massive worldwide garden centre industry. The result is that this industry is now worth billions of dollars and has become part of the tourist industry in many countries, since retail customers use garden centres as part of their rest and relaxation during holidays and weekends. The revolution of continuously available plants permitted garden designers the freedom they needed for producing ever changing scenery in their urbanised clients' regard as "garden rooms".

## *Genetic Uniformity in Vegetable Crops*

Genetic uniformity has become the hallmark of field and protected vegetable crops and underpins growers' abilities for supplying supermarkets with high quality produce on a year-round basis. This has been achieved by an almost universal change to the use of $F_1$ hybrid cultivars. These provide uniformity of growth and maturity allowing the application of precision management techniques delivering controlled ripening and harvesting. Compared with open pollinated cultivars, where individual plants grew at differing rates and maturities and which were very unpredictable, $F_1$ hybrid crops have resulted in substantial financial gains across the industry worldwide and down the supply chain to retailers. From the plant breeders' perspective they also offer much greater security for their intellectual property rights (IPR) because they are far less accessible for duplication and copying. The seed of $F_1$ cultivars must be produced annually by crossing the inbred parental lines and self-saved seed from a commercial crop cannot easily reproduce the specified hybrid. Much of the development of $F_1$ hybrid vegetables can be traced back to genetic studies in Japan in the 1930s which resulted in the production of the Brussels sprout (*Brassica oleracea* var *gemifera*) cv Green Jade. This could not have come about without an understanding of the genetics of *Brassica* species and the manner by which allotetraploidy contributes to the formation of some species (U 1935).

Having achieved genetic uniformity, the industry has tirelessly sought environmental uniformity. This can be achieved very effectively in protected environments such as glasshouses and to a lesser extent by use of polyethylene covers. Engineering science has equipped growers of protected vegetables and flowering and foliage ornamentals with very sophisticated environmental control systems which ensure that crops mature with a synchrony that is predictable to within a few hours for an entire batch. That means that automated forms of cultivation and harvesting can be applied such that the whole crop is cleared and replaced very rapidly and immediately prepared for dispatch into the wholesale and retail markets with common quality standards achieved. This type of approach is sought for field crops and can be attained with root crops such as beetroot, carrots, onions and parsnip. Machine harvesting and subsequent cleaning followed by automated optical sorting means that entire crops can be cleared from land very efficiently. Leafy and flowering vegetables, particularly the brassicas, have proved more difficult because variations in maturity dependent on variations in the prevailing weather are still retained even where $F_1$ hybrids are available. For example, with Brussels sprouts unevenness is retained along the stem with the lower shoots (buttons) becoming over-mature well before the upper ones are mature. The biggest problems persist with cauliflower and calabrese (green broccoli) since flowering is more difficult to regulate meaning that, even under favourable environments, 60–70 % of the crop matures uniformly but 30 % trails behind.

Propagation of seedlings in modules under closely controlled glasshouse conditions results in much increased uniformity of field cropping especially where seedling vigour has been standardised. The horticultural seed industry has revolutionised genotype purity, seed quality, health and reliability based on basic research in seed development and maturation, processing, drying and packeting, pelleting, germination, purity and vigour testing (Joosen et al. 2010). The overall quality is such that the field vegetable industry has come to rely on defined vigour and germination as critical factors in the economic success of particular crops, especially the brassicas.

These five examples demonstrate how answering relatively simple basic biological questions in the late nineteenth and twentieth centuries provided the basis for whole industries which are key parts of today's horticultural economy and the social and environmental fabric of communities.

## Science Investment Leading Horticultural Industries

The amounts of money spent on research and development are often questioned with regard to the returns that are provided to investors, producers and society in general. Research budgets are frequently the subject of review, especially in the agricultural and horticultural sectors where, in many modern societies, food is regarded as being in plentiful supply and available at affordable prices. Furthermore, the influence of primary producers on governments in most countries is now minimal given the very small proportion of populations that are involved with food production—for example, in 1950 approximately 71 % of the world's population lived in rural locations while in 2010 this had declined to 50 % (or as low as 10, 18 and 22 % for the UK, the USA and France, respectively) and is projected to be as low as 30 % globally by 2050 (Anon 2007a). Convincing politicians and policy makers to invest in horticultural science is, therefore, becoming increasingly difficult.

Nonetheless, the reasons for investment in research and development in horticulture are compelling. The advantages to human health and wellbeing of diets balanced with a high intake of fruits and vegetables is widely accepted (Anon 2006). This emphasises the need to have such produce available to households year-round and at affordable prices—neither of which can be taken for granted. The need to deliver safe food free from human pathogens and other contaminants is also paramount but again cannot be taken for granted given the food safety compromises that have occurred globally over the past decade (Anon 2007b). Furthermore, the increase in the occurrence of significant climatic events, such as major droughts and storms, threaten many elements in the supply chain of horticultural crops some of which can be moderated through the application of research findings aimed at improving factors such as water use by crops. Finally, demands from modern societies for sustainable production practices and pesticide-free produce will be critically dependent on soundly-based research and development programmes. Continuing investment in research and development for horticultural crops and production practices will be essential if these continuing challenges are to be addressed in meaningful and timely ways.

There have been a number of studies into the returns achieved from investment in research and development in horticultural science. The examples provided here are drawn from experience within major horticultural sectors in New Zealand but they are directly relevant to other horticultural production areas around the world.

## *Breeding Kiwifruit*

The New Zealand horticultural industry first began exporting kiwifruit in 1952 (Earp 1990). For the following 50 years the industry was based on only one cultivar—'Hayward'—and on only one of over 70 different species (*Actinidia deliciosa* (A. Chev.) C.F. Liang et A.R. Ferguson) within the genus. The potential to introduce many new and different selections showing varying flesh and skin colours, fruit shapes, taste and nutritional characteristics, and skin hairiness was considerable. Government scientists (working within the then Department of Scientific and Industrial Research, subsequently The Horticulture and Food Research Institute of New Zealand Ltd, now The Plant and Food Research Institute of New Zealand Ltd.) introduced seeds of different species and selections from China in both 1977 and 1981 forming the basis of a modern fruit breeding programme. Within a decade, advanced progeny were available for initial selection and, from within the populations available, 'Hort16A' was selected. It had high yields, a novel golden flesh colour, a tropical "fruit salad" taste and fewer hairs than the green-fleshed 'Hayward'.

**Table 2.1** Grower returns and export sales volumes for ZESPRI™ GREEN, ZESPRI™ GOLD and ZESPRI™ GREEN ORGANIC kiwifruit from New Zealand, from 2003/2004 to 2011/2012. (Sources: Zespri Annual Reports 2003/2004–2011/2012 (http://www.zespri.com/userfiles/file/About_Annual_Report_2011–12.pdf)

| Season | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Cultivar | 2003–2004 | 2004–2005 | 2005–2006 | 2006–2007 | 2007–2008 | 2008–2009 | 2009–2010 | 2010–2011 | 2011–2012 |
| *Gross orchard gate returns: relative to green (=1.0)* | | | | | | | | | |
| Green | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Green organic | 0.95 | 1.06 | 1.15 | 1.21 | 1.46 | 1.30 | 1.33 | 1.16 | 1.07 |
| Gold | 1.16 | 1.53 | 1.65 | 1.69 | 1.92 | 2.03 | 2.81 | 2.60 | 2.75 |
| *Kiwifruit sold: trays equivalent (million)* | | | | | | | | | |
| Green | 49.6 | 59.1 | 62.5 | 58.8 | 67.9 | 72.7 | 71.9 | 69.9 | 73.3 |
| Green organic | 2.3 | 2.7 | 2.7 | 2.3 | 2.8 | 2.9 | 3.3 | 3.3 | 3.5 |
| Gold | 8.6 | 14.7 | 14.1 | 16.7 | 19.3 | 21.9 | 22.0 | 21.1 | 29.1 |

Sensory science evaluations showed that this selection was likely to be favoured strongly in Asian markets (Warrington and Weston 1990).

Industrial adoption of this new selection was initially slow—the first trial export shipments occurred in 1998 and the market launch occurred in 2000. A new cultivar required a change in thinking by the sector including adoption of suitable growing practices by producers, the development of maturity standards and post-harvest handling protocols, and the promotion of a completely new product in both traditional and potential new markets. The subsequent developments of this new cultivar have been very impressive. Gross orchard gate returns per hectare for producers of ZESPRI™ GOLD, through a combination of higher yields and higher sales returns, exceeded those of ZESPRI™ GREEN from the initial production volumes and subsequently by as high as 2.8-fold. New Zealand production volumes increased to 29.1 million trays in 2011/2012, becoming 27% of total industry production. By contrast to this major innovation through the introduction of highly appealing new cultivar, premiums from organic production and increases in production volumes were comparatively small (Table 2.1).

The underpinning reasons for the success of this new cultivar and the subsequent benefits to the industry can be identified with a number of key factors, including:

- An awareness of the fruit breeders involved of the diversity available from within the genus and an understanding of market opportunities for new cultivars that were attractive to consumers at a very early stage in the development of the breeding programme;
- The integration of a range of horticultural sciences relevant to the development of a new cultivar including: taxonomy, sensory science, postharvest management, and crop husbandry. These skills refined areas such as training and pruning methods, pollination requirements (kiwifruit is dioecious), pathogen and pest

management, maturity standards, storage requirements, and potential attractiveness to consumers in various global market segments;
- Co-investment by the fruit industry and Government in the cultivar development programme;
- The availability of plant breeders rights that allowed controlled release of the cultivar both within New Zealand and in alternative growing regions globally;
- Investment by the industry, including at the level of individual growers, in commercial scale production and in storage and shipping, to ensure that the cultivar could be produced reliably and marketed to a consistently high quality;
- Product promotion by the industry through major, highly professional marketing campaigns.

It is critical to note that cultivar development requires commitment and investment over long periods of time. In this instance, it was around 30 years between the initial collection of material that would serve as novel and important parents, through to the production of modest volumes of an elite new product. This commitment involved the active participation of a number of different sectors within R&D and of all of the participants in the supply chain.

The initial development of the cultivar, inclusive of breeding, production and sensory science research, was estimated in 2004 to be $NZ 20.5 million (Aitken et al. 2004a). Market development costs in excess of $NZ 50 million were paid for by the industry in the early phases of commercialisation over the 2000–2004 period. Cumulated export returns from ZESPRI™ GOLD kiwifruit up until 2003 were $NZ 344 million and forecasts were that earnings would be $NZ 1 billion by 2009 (Aitken et al. 2004a). Actual earnings by the entire industry in 2009 were $NZ 1.072 billion of which ZESPRI™ GOLD was 27% of total production volume. From an initial launch of this cultivar until 2012 the cumulative sales value of ZESPRI™ GOLD were approximately $NZ 4 billion. This new cultivar has, therefore, been a marked success, not just in New Zealand but in other countries such as Italy. It received widespread consumer acceptance and generated premium returns to individual growers and to the industry sector. It also provided options for sales given that demand for the gold-fleshed fruit was able to leverage sales of the more commonly-known green-fleshed cultivar. A consequence of this success was that the planted areas of both cultivars increased. While susceptibility to the bacterial disease *Pseudomonas syringae pv actinidiae* (PSA) is now having the effect of limiting production of 'Hort16A', the cultivar and the marketing efforts of ZESPRI International Ltd, have paved the way for the marketing of other novel, differentiated kiwifruit cultivars.

## Breeding Apples

New Zealand has a strong history of breeding and developing new apple cultivars. Both cvs 'Royal Gala' and 'Braeburn' were introduced internationally from such efforts. A characteristic of each however, was that they were not protected with plant variety rights (aside from subsequently selected strains) and consequently no proprietary revenues were secured reflecting the commercial successes that both had achieved. New Zealand scientists initiated apple breeding research in the 1960s and crosses were made between 'Royal Gala' (as the pollen parent) and 'Braeburn' (as the seed parent) in 1984–85. The initial selection of the seedling which would subsequently be named 'Scifresh' and marketed under the Jazz™ brand was made in 1990 and this was chosen for commercial advancement in 1995 following initial regional trials and evaluation. Assessments by consumers in European supermarkets in 1998 confirmed the outstanding prospects for this selection.

Plant variety rights were secured in both New Zealand (2002) and in overseas countries and the marketing name was also trademarked. Trial plantings were made in the USA (1999) and in France (2000) and following proven performance by 2003, 495,000 trees were planted in New Zealand, France, the United Kingdom and the USA (Aitken et al. 2004b). In 2011, the cultivar represented 11 % of the total New Zealand production (following 'Royal Gala' (27 %), 'Braeburn' (19 %) and 'Fuji' (11 %) representing an export production of 32,500 t (Anon 2012a). In 2012, it is estimated that some 17,000 t will have been produced in France alone. It is important to understand that the development of a new cultivar is not solely focused on the initial crossing of selected parents and the early selection of a desirable progeny. In fact, the successful release of Jazz™ ('Scifresh') included the integrated and collaborative efforts of plant breeders, tree physiologists who identified appropriate rootstocks and tree training methods, postharvest scientists who identified appropriate maturity standards and storage methods, plant protection specialists who managed all aspects of pathogen and pest management to meet stringent minimum pesticide residue requirements, and a specialised business unit who managed the cultivar protection and licensing requirements. The development of Jazz™ ('Scifresh') also involved the product development and marketing expertise of ENZA Ltd and close collaboration with the apple industry which co-invested in the original breeding programme, affirmed the selection criteria and managed the release of the trees to suppliers.

Royalties for Jazz™ are paid on the fruit sold from the orchard, not on the trees sold (which is the usual method used by breeders to collect plant royalties). Royalty fees from New Zealand and overseas producers come back to The Plant and Food Research Institute of New Zealand Ltd where they are used in tree management and integrated fruit production programmes, as well as the continuing apple breeding programme. The release of Jazz™ ('Scifresh') was driven through the ENZA Global Variety Development programme, which aimed to complement a production base in New Zealand with licensed production in other parts of the world. The advantages of these arrangements include the fact that the year-round supply of fruit to market can be managed by sourcing apples successively from New Zealand's southern hemisphere orchards, and in the counter season from northern hemisphere orchards. This approach provides a continuous and reliable supply of apples to supermarkets and to consumers worldwide. Suppliers are required to meet the New Zealand quality standards. In 2005, the estimate of the internal rate of return was 14 % and of net present value was $NZ 29 million based on the production projections for 2009 (Aitken et al. 2004b) (Fig. 2.1).

**Fig. 2.1** is a diagrammatic representation of the time-line involved in the breeding and development of Jazz$^{TM}$ apple. Global development of such new cultivars involves securing intellectual property protection, through the use of plant variety rights, in order to deliver an appropriate return on the costs of development. The time from initial crossing to commercial production can exceed 20 years. Since 2006 the cultivar has become significant within industries in a number of countries including New Zealand, Italy, France, the USA and the United Kingdom (Source: The New Zealand Institute of Plant and Food Research Ltd)

## *Tailoring Husbandry to Market Requirements*

Modern societies expect that the supply of fresh produce will be free from harmful pesticides and safe for human consumption. Significantly, supermarkets require such produce to meet critical standards that are set to have pesticide residue levels at barely detectable amounts. These fruit and vegetables are typically produced by methods such as Integrated Fruit Production (IFP). The New Zealand apple industry has been renowned internationally for its innovation through the adoption of new cultivars, such as 'Royal Gala' and 'Braeburn', and of new production methods. It has also been a leader in the development of new IFP and related practices. During the 1970s and 1980s scientists anticipated emerging market trends and recognised the need to find ways of reducing the use of agrochemicals within apple orchards. It is critically important to appreciate that much of the underpinning scientific studies that provided the basis for the subsequent development of robust orchard management technologies were completed during this period—successes that were only possible through the previous investment in research and the ongoing commitment by dedicated individual scientists over a 20–25 year period.

Anticipating the demands of supermarket customers, the apple industry committed to implementing an integrated fruit production (IFP) programme in 1995 as a step toward ensuring the continued entry of New Zealand apples onto the global market. The programme was led by the single desk marketing entity ENZA Ltd, as the exporter, with active participation and cooperation from scientists, producers, technologists and consumers. Some of the technology evolved during the programme.

The uptake of the subsequent IFP programme was rapid. It was introduced in 1995 and by 2000 most of the export crop was produced using IFP technology (Fig. 2.2). In 2009, 92 % of the industry used such methods while 8 % of producers used certified organic production methods. There was an immediate and marked reduction in the use of organophosphates on apple orchards in the late 1990s and also in the number of fungicide sprays applied during the mid- to late-summer period (Fig. 2.3) (Walker 2012; Wiltshire 2003).

These earlier programmes that were successful in markedly reducing pesticide use were subsequently continued to further ensure the competitiveness of the New Zealand apple industry and its ability to deliver produce to international supermarket chains and achieve premium returns—the "Apple Futures" programme (Kaye-Blake 2012; Walker 2012). This programme was designed to control pests and pathogens successfully whilst reducing residues on fruit to non-detectable levels that are significantly below those required by international market regulations. The programme combines computer modeling for pathogen prediction, monitoring of insect pests and beneficial organisms, and targeted spraying of pesticides allowing growers to intervene with optimised control methods only when required.

This programme was introduced in 2007 into the Central Otago and Hawke's Bay regions, then into the Nelson region in 2009. By the 2008–2009 season 65 % of apples produced were under the "Apple Futures" programme, meeting the requirements of over 65 countries and being residue-free or with average residues below 10 % of European Union (EU regulatory tolerances (noting that all other producers were producing fruit that was well within the EU standards).

Analysis by the New Zealand Institute of Economic Research (NZIER) has shown that the "Apple Futures" programme, developed by The Plant and Food Research Institute of New Zealand Ltd in conjunction with Pipfruit New Zealand, preserved up to $NZ 113 million of the pipfruit industry's revenue over the four years from 2008 to 2011 through achieving access to critical export markets for this industry. It was estimated that, in each year of the programme, industry net income

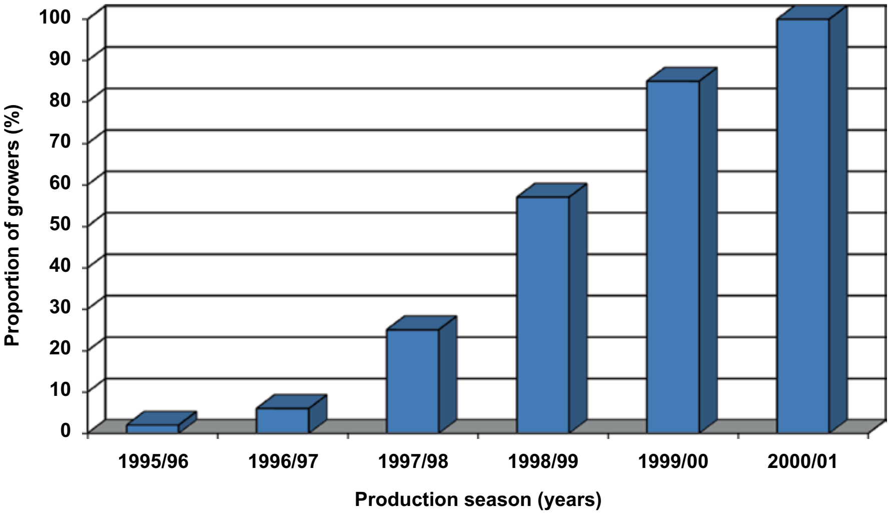

**Fig. 2.2** Proportion of growers adopting Integrated Fruit Technology (IFT) over time

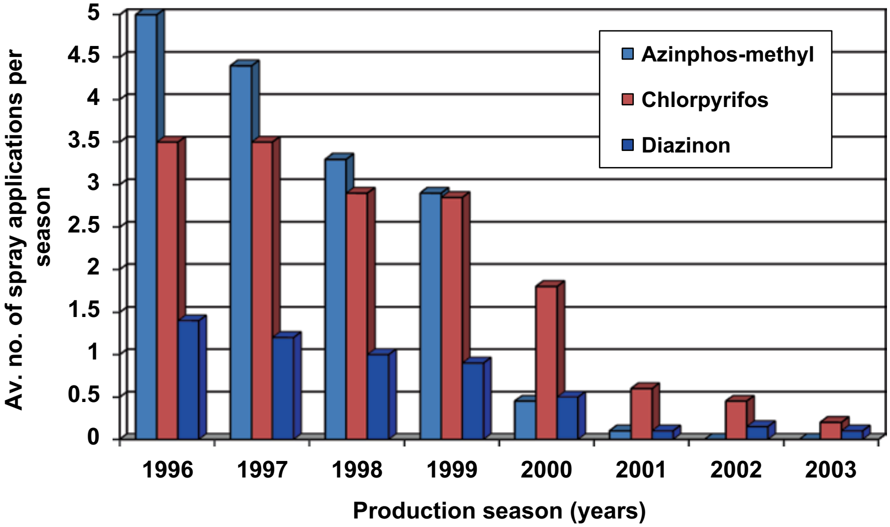

**Fig. 2.3** Integrated apple production (New Zealand): reduction in undesirable pesticide use—number of pesticide applications. (Source: Wiltshire 2003)

(revenues less costs) would have been between $NZ 25 and $NZ 35 million lower without "Apple Futures". These figures represent between 7 and 10 % of the industry's total revenue, or between 15 and 25 % of the industry's revenue from Northern Europe. The sector earns $NZ 350 million annually (Pipfruit New Zealand 2012). The research costs over the 2008 to 2011 were only $NZ 3.2 million. Benefit cost ratios (BCR) are shown in Table 2.2. The BCR is a ratio of the benefits produced

**Table 2.2** Benefit cost ratios (BCRs) for Apple Futures for different values of lost export markets and price elasticity. (Source: Kaye-Blake 2012)

| Elasticity | Closure to IFP fruit in northern European markets | | | |
|---|---|---|---|---|
| | 100% (base) | 75% | 50% | 25% |
| −0.3 (base) | 35.39 | 24.28 | 19.15 | 11.35 |
| −0.5 | 30.29 | 19.97 | 12.19 | 6.79 |
| −0.7 | 25.32 | 14.43 | 8.44 | 4.68 |

Note: Elasticity is the price elasticity of demand, which measures the price sensitivity of consumers

by a programme to its costs where a ratio greater than 1.0 indicates that benefits are higher than costs. The highest BCR was 35.39, assuming that Northern Europe would not accept any standard (IFP) apples from New Zealand and that consumers had a typical price sensitivity (Kaye-Blake 2012). This figure indicates that the value of the programme was over 30 times its cost. With the most relaxed assumptions, the impact of "Apple Futures" was $NZ 15.0 million and the BCR was 4.68. Regardless of the assumptions used, the programme is almost certain to have produced significant benefits for the industry.

## *Science Leading Current Industries with Future Prospects*

Over the past 100 years, fundamental research has investigated the mechanisms of cell growth and division, establishing how undifferentiated meristmatic cells could become functionally specialised, resulting in the formation of organs such as root, leaves, stems and flowers and tissues such as the vascular, cortical and epidermal layers. This research required methods whereby cells might be isolated, cultured *in vitro*, encouraged into differentiation and ultimately transferred back into *ex vitro* environments. That knowledge has provided foundations for subsequent studies in plant molecular biology and provided the basis for the controlled asexual propagation of ornamental plants. As a result the worldwide industry producing flowering and foliage pot plants and nursery ornamentals on a huge scale has developed. Controlling and subsequently culturing tissue growth demanded detailed understanding of the biochemistry of hormonally managed processes in plants. Growth regulation is a result of balances between a series of hormones within plants. Appropriate regulators control root growth, stem extension, cell multiplication, flower formation and fruit ripening. Understanding these processes has led to precision husbandry and controllable post-harvest storage. The latter permits worldwide transport of huge quantities of fruit and vegetables destined for receiving supermarkets.

## *Tissue Culture and Micropropagation*

Plant tissue culture has been the subject of research for more than 100 years following pioneer work of Harberlandt (1902) and Hannig (1904). Major applications to horticulture occurred in the latter half of the twentieth century following the work by scientists like Murashige (1964) and Nitsch and Nitsch (1956). Plant tissue culture was enthusiastically embraced as a method for clonal propagation in the 1960s; however, genetic instability following *in vitro* culture of many species limited its commercial application. The aim of micropropagation is to produce clonal or true-to-type plants of elite or selected genotypes *in vitro* (Debergh and Read 1991). New approaches to micropropagation, including those that are not prone to production of genetic off-types, have been applied where high levels of heterozygosity exist in breeding lines, for rapid release of new cultivars and for germplasm storage. A system that is genetically stable but has lower multiplication rates is based on production of micro-cuttings from axillary buds of nodal cuttings dissected from apically dominant shoots (Drew 1992, 1996). This protocol has been applied successfully to coffee, papaya, neem, passionfruit (Drew 1991, 1992, 1993, 1997, respectively) and to many other temperate and tropical species worldwide.

Meristem culture provided a unique way of producing virus tested plants and was applied to many horticultural crops following the pioneer work by Morel and Martin (1952) who produced virus-tested *Dahlia* plants. Genetic off-type plants produced after callus culture were a problem for those concerned with clonal micropropagation. However, this variation provided new sources of genetic material for the horticultural industry following the development of methods for i*n vitro* screening of cell suspension cultures. Many of the elite cultivars used in commercial horticultural practice are genetic variants that have occurred naturally in cultivated or wild populations and have then been clonally or vegetatively propagated. Examples such as the seedless navel orange, the spineless cayenne pineapple and the sweet kesington mango have made major contributions to commercial horticulture. Some *in vitro* techniques generate high levels of genetic variants and provided a method to produce stable, heritable changes and the potential to change one or two characteristics of an elite genotype without changing the remainder of the genome. *In vitro* selection of useful variants has resulted in a number of valuable new commercial lines of tomatoes (Tomes 1990). Useful somaclonal variants have been isolated from cultures of papaya (Sharma and Skidmore 1988), apple (Utkhede 1986), peach (Hammerschlag 1988), pear (Brisset et al. 1988), citrus (Ben-Hayyim and Goffer 1989; Spiegel-Roy et al. 1983) and many other crop species.

## *Haploidy, Embryo Culture and Plant Breeding*

Haploidy provided a technique for rapid production of doubled haploids for use in breeding programmes and to facilitate selection of mutations which are often recessive characters. Subsequently, *in vitro* screening for genetic variants in cell cultures derived from haploid cells has produced novel genotypes, e.g. *Xanthomonas* resistant pepper (Hwang et al. 1998). One of the original and noteworthy applications of haploidy was in asparagus breeding. All staminate populations that produce spears with low fibre content are desirable. *In vitro* androgenesis followed by diploidisation, produced 50 % homozygous YY “supermales” (Thevinin 1974). Fertile supermale homozygotes, when used as pollinators of homozygous diploid females, produced entire populations of male hybrids (Chase 1974). There have been reports of embryogenic callus and in some cases, successful plantlet regeneration, following androgenesis of tropical and subtropical fruit species, many of which are difficult to micropropagate e.g. *Annona squamosa* (Nair et al. 1983), *Carica papaya* (Tsay and Su 1985), *Euphoria longan* (Yang and Wei 1984), *Litchi chinensis* (Fu and Tang 1983), *Feijoa sellowiana* (Canhoto and Cruz 1994), *Pouteria lucama* (Jordan et al. 1994) and *Psidium guajava* (Babbar and Gupta 1986).

The culture of mature embryos is one of the easier *in vitro* techniques but it becomes progressively harder however, with immature or poorly formed embryos. Embryo culture has been used to culture recalcitrant species; to overcome problems associated with seed dormancy and incomplete embryo development (e.g. propagation of macapuno coconut); and to develop highly regenerable cultures for gene transfer systems (Hu and Wang 1986; Drew et al. 1995). The major application of embryo culture is, however, in the production of interspecific hybrids, where it has been used successfully to bypass post-zygotic incompatibility barriers. Hybrid plant production is often prevented by embryo abortion caused by embryo-endosperm incompatibility (Emsweller and Uhring 1962) or rapid deterioration of the endosperm before the embryo matures (Hu and Wang 1986). Embryo culture has been used to produce interspecific hybrids between *Carica papaya* and five wild relatives (Drew et al. 1998), and between commercial cucurbit species and *Curbita ecuadorensis* (Herrington et al. 1988, 1989).

Somatic hybridisation provides a non-sexual method of gene transfer but commercial applications are limited. Somatic hybridisation involves the fusion of protoplasts from different genotypes or species and was the first means of crossing plants while bypassing sexual reproduction and thus traditional methods of plant breeding. Although wide crosses have been achieved (e.g. potato x tomato; Melchers et al. 1978), useful applications to plant improvement have been limited by incompatibilities between species. A further limitation is that regeneration from protoplasts is arguably the most difficult *in vitro* procedure and has not been applied successfully to a wide range of species. The most noteworthy applications of this technique have been in *Citrus* species and these were reviewed by Ochatt et al. (1992).

### *Genetically Modified Cultivars*

Tissue culture methods offer a rich scope for creation, conservation, and utilization of genetic variability for the improvement of field, fruit, vegetable, and forest crops, and medicinal/aromatic plants (Gosal et al. 2010). Micropropagation technology ensures true-to-type, rapid and mass multiplication of plants that possesses special significance in vegetatively propagated plant species. This technology has witnessed a huge expansion globally, with an estimated global market of $US 15 billion/annum for tissue-culture products.

Vast amounts of research have also been undertaken to develop plant tissue culture techniques which underpin the new technologies that allow the production of genetically modified (GM) plants. Commencing in the 1980s genetic transformation brought the biggest technological advances in plant biology since the green revolution. The first generation GM plants were herbicide, insect and virus resistant genotypes and were widely adapted in agricultural species in the United States. The initial commercial success of this technology in horticulture was the Flavr Savr$^{R}$ tomato (Grierson and Fray 1994) which was initially widely accepted in the retail marketplace in both the United States and Great Britain. In this cultivar antisense technology was used to lower the level of poly-galacturonase enzyme during fruit ripening. By 1997, however the product was withdrawn from the market because of rapidly changing attitudes in consumer sentiment to genetically modified plants. Another example of gene transfer applied to a major disease of a horticultural crop was the development of papaya ringspot virus type P (PRSV-P) resistance in papaya. Although transgenic papaya genotypes were developed for many countries by use of coat protein-mediated resistance to induce silencing of viral genes (Gonsalves 1998), and the technology has been available for 20 years, they have been grown for commercial production only in Hawaii and in some regions of China.

Many markets, such as the EU and Japan still refuse to accept transgenic fruits. In addition, many governments are reluctant to allow commercial production of crops that are genetically modified by transgenetic engineering. The resistance has been fuelled by over-dramatised and unsubstantiated claims by green movements and consequential effects on many governments worldwide, who often depend on coalitions with green parties to stay in power. The twenty-first century has also seen a change in the attitude to science in some quarters from very positive to negative, and GM technology has been used as a scapegoat by many organisations intent on promoting negative views of science and its value to an ever-changing world. A tragic consequence of this attitude has been the refusal of numerous governments worldwide to accept golden rice (Potrykus 2001) as a solution to vitamin A deficiency. Six thousand children die daily from vitamin A deficiency; however, such is the hostility to GM foods that this obvious solution to the problem is being ignored.

Other factors in the GM debate show that acceptance or rejection of scientific breakthroughs is now based on more complex socioeconomic and political reasons. One objection to GMOs has been caused by the huge number of patents that have been applied to this technology. This has in part been caused by the pressure on scientists to control intellectual property (IP) on their discoveries, to produce income and profit, and reduce dependence on governments to provide funding for research. This has led to legitimate concerns on the effect of IP on the cost of food and longer term prospects of food monopolies and price control.

By contrast, the application of plant molecular biology that is making a major contribution to horticulture and is not embroiled in controversy is genomics, the use of molecular markers and a marker assisted breeding (Stephenson et al. 2010). Many plant genomes have now been sequenced and numerous molecular markers have been developed for a wide range of character traits. Following an analysis of the papaya genome sequence, all simple sequence repeats (SSR) markers have been identified (Wang et al. 2008). This example for papaya shows how quickly technology is progressing and the quantum leaps that are being and will be made in the future. Molecular markers are being used to evaluate genetic diversity, to identify genetic relationships within and between individuals, to develop genetic maps of particular species, to identify and clone particular genes of interest, to identify transgenes and in forensic science.

Both plant tissue culture in the 1950s and molecular biology in the 1980s started with much promise to make a huge impact in plant science in general and horticulture in particular. Plant tissue culture was not beset with the major problems and adverse reactions that have limited the commercial application of GM crops in horticulture. Plant tissue culture research has made a major contribution to horticulture in the production of new technologies and numerous examples of new cultivars of horticultural species. An example is the wide range of applications to tropical fruit species, many of which were considered recalcitrant *in vitro* in the twentieth century (Drew 2008). By contrast, despite a huge research effort, there has been limited commercial application of GM crops in horticulture. Successful examples include the Flavr Savr$^R$ tomato, PRSV-P resistant papaya in Hawaii and the production of some novel flowers such as purple carnations in South America.

As more genes and their related functions are identified on genome sequences, marker assisted selection will make a huge impact on plant breeding in the future. A limitation to the application of plant molecular biology has been biotechnologists working in isolation from other plant scientists. The technology still shows potential in the future particularly if scientists work in multidisciplinary teams that include molecular biologists, plant tissue culturists, plant breeders, horticulturists and other plant scientists. A model for this approach and the potential for success was demonstrated by Ingo Potrykus in his development of golden rice. Future research must include a sustainable approach to feeding an ever-growing world population given the limitations of land suitable for agriculture, the shortage of clean water and the need to preserve our environment (Juwarkar et al. 2010).

## Science Capable of Creating New Industries

### *Modelling and Integrative Biology in Horticulture*

Crop modelling is not new; in the 1950s and 1960s considerable effort was devoted in particular to developing "blue-print" growing, especially for glasshouse crops such as cucumbers and tomatoes. Subsequently, modelling crop responses to physical and chemical environments both in the field and under protection gained sophistication with the advent of desk top computing in the 1980s. In brassicas, responses defining nutrient and water demand by annual and perennial genotypes were established. Much more powerful computing now allows the description of biological systems as consisting of "layers of perception", in which each layer can be approached using a discipline and a dedicated set of data and processes (Fig. 2.4). A deliberate choice is made to perceive the system investigated through the filter of a discipline, one or two scales, and an appropriate "tool of the trade", measuring

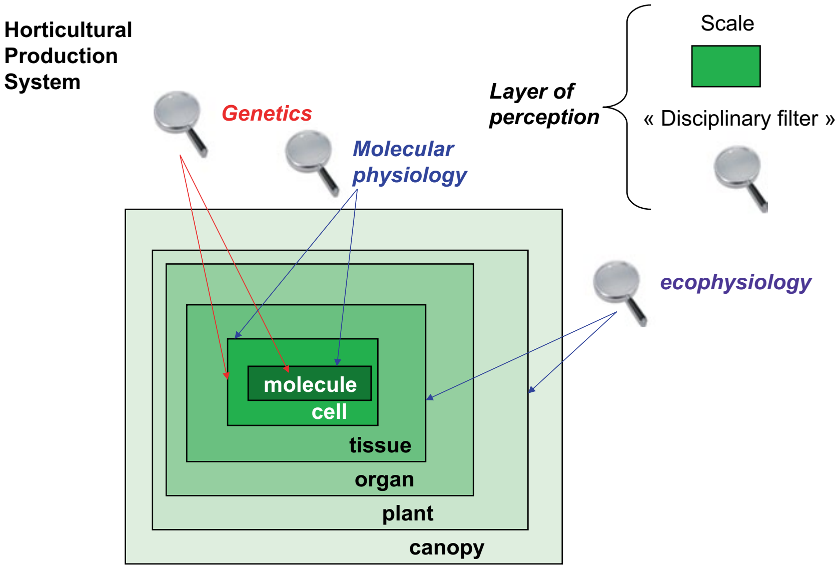

**Fig. 2.4** Multi-scaled view of horticulture, encompassing different "layers of perception" and "disciplinary filters". (Source: Xu et al. 2011)

a restricted set of output variables while neglecting most others. The same applies to horticultural production systems, yet horticulture is by its very nature multidisciplinary and multi-scaled: research in horticulture is carried out at the interface between different subjects (botany, genetics, agro-ecology, physiology, and physics) and at different scales (molecular, cellular, tissue, organ, shoot, plant, and crop population). Having already been applied to model the structural and physiological dynamics of a diverse range of agricultural and horticultural crop plants, functional-structural plant modelling (FSPM) is a paradigm which lends itself as a suitable tool in the quest towards horticultural systems biology. Horticultural production systems are artificial biological systems, which differ from natural biological systems in that their environment is more or less controlled and that restrictions are applied to the crop plants in terms of expression of physiological and morphogenetic processes (e.g. by treatment with chemicals to reduce the number of flowers or to manipulate shoot extension, or by mechanical removal of organs in order to enhance flowering). In current plant modeling, horticultural production systems are perceived as operating at different scales and through filters relevant to the particular scientific interests of the research worker. Thus while a physicist could be content to investigate the air movement within a greenhouse or the tensile stress in bending shoots, a molecular biologist will perhaps strive to understand bud break in rose as a function of the metabolic regulatory network of sugar-signalling; a physiologist might be interested in the relationships between source and sink organs, by characterizing photosynthesis and growth processes at the organ and plant level. In all these endeavors, the individuals involved largely remain within their disciplines and schools of thought, for practical or historical reasons or simply out of comfort coming from understanding within their peer-group. A key task for horticultural scientist is the integration of knowledge across these disciplines.

The advent of new regulations in horticulture (e.g. the Ecophyto 2018 round table of the French government, which is foreseeing a considerable reduction of pesticides) spells new challenges for all participants in the production chain, including researchers. Sustainable and "ecologically intensive" horticulture is to become the new standard, and this means that a different, "systems biology" perception of horticulture is required, which will be able integrate more effectively the information stemming from the different disciplines and levels, and in doing so help to solve the challenges lying ahead for global food production. Such an integrative biology for horticulture constitutes the insight that we are dealing with multi-scaled, modular, and complex systems, which cannot be satisfactorily described, explained, or optimized while remaining within the "comfort zone" as it were, of a single discipline. It rather implies the willingness to be radically multidisciplinary and interdisciplinary. Multidisciplinarity means that existing heterogeneous knowledge and information sources need to be linked and integrated with the help of suitable interfaces, while interdisciplinarity would go a step further by entering the well-known feedback loop of systems biology ("experiment → model → improved experimental design → experiment → …"), thereby moving towards *horticultural systems biology*.

## *Functional-Structural Plant Modelling: A Tool for Data Integration and Systems Analysis*

Functional-structural plant modelling (FSPM) refers to a paradigm for the description of a plant by creating an object-oriented computer model of its structure and selected physiological and physical processes, at different hierarchical levels: organ, plant individual, canopy, and in which the processes are modulated by the local environment. Structure comprises the explicit topology and geometry of the organs and the plant. At the individual level, this is also referred to as plant architecture. An FSPM may consider a change in organ and plant structure in time, thereby simulating the growth, extension, and branching processes of a given plant. This type of FSPM is referred to as dynamic. A static FSPM, in contrast, only considers an unchanging structure, one or several virtual plant individuals which are used as a model input in order to explain spatial and temporal heterogeneity in physiological processes (Buck-Sorlin 2012, in press).

A natural extension of the FSPM concept is the model representation of the genotype and the phenotype: whereas the "phenotype" thus constitutes the FSPM defined above (with explicit three-dimensional morphology, basic eco-physiological processes, transport, and environmental sensitivity), the "genotype" can be represented by a set of variables that stand for genes or quantitative trait loci (QTLs), or else a set of regulatory networks if appropriate. Furthermore, model provisions to link the core FSPM (phenotype) with the genotype are required.

A general yet very important question concerns the choice and number of physiological processes to be considered in the development of a model. This choice will have repercussions on the nature and number of model parameters. Many models end up having too few, too many or the wrong parameters, with respect to the initial intention of the modeller. A sound decision when asked to design a crop model or FSPM, seems to be to choose a combination of basic physiological processes involved in primary production (photosynthesis or growth for example) as a backbone, and then, according to the research problem identified and phrased as clearly as possible, to add processes suspected to exhibit genetic variability or processes suspected to be involved in yield traits. The upper limit in the number of processes and parameters should be a function of the ease with which the model may be calibrated. In other words, due to the computing power available at present, it is no longer necessary to strive for the simplest model with the fewest parameters (as indeed such a model might be too simple to be correct) but it is possible to introduce more complexity into a model in order to make it more widely applicable, more generic and thus closer to reality.

Regrettably, spatially explicit models, such as FSPMs, are still not widely accepted in the modelling community, as it is assumed that one can go a sufficiently long way using a combination of zero- or one-dimensional crop models and genotype information. It is by now established knowledge, however, that genes are having an effect on yield not directly, but by influencing processes (e.g. shoot formation, growth, branching, photosynthesis, transport) and that the amount of biomass and quality of harvestable yield depend on the architecture or morphology of the “carrier structure” which constitutes a central part of the production system. Structure strongly influences the environment, leading to spatial heterogeneity of processes, as can be seen in the example of the simulated light microclimate in a cut-rose production system (Fig. 2.5).

A further problem to be tackled is how to cope with the workload of the new postulated class of more complex models. The FSPMs potentially require many parameters and thus also have a higher data requirement. This requirement could be met by techniques currently developed in so-called high throughput phenotyping, yet plenty of problems remain as to which method(s) to apply to transform the raw data into model parameters. This class of problems belongs to statistical data analysis, model calibration and validation. Efforts to develop new techniques or adapt established techniques for data acquisition, analysis and automatic parameterisation will have to be made. As an example, Xu et al. (2011) developed an FSPM of rice in which certain model parameters were automatically retrieved from an output file of the QTLNetwork software. The latter calculates phenotype values for quantitative trait loci of mapping populations.

Horticulture comprises human activity involved with the growth of specialized crops (flowers, fruits, vegetables, ornamental and medicinal plants) under more or less controlled protected (greenhouse) or intensive field conditions, and with a varying degree of interaction with the husbandry used. This interaction, as well as the enormous diversity of husbandries, production systems and species distinguishes horticulture from agriculture and forestry. It is for this reason that we need

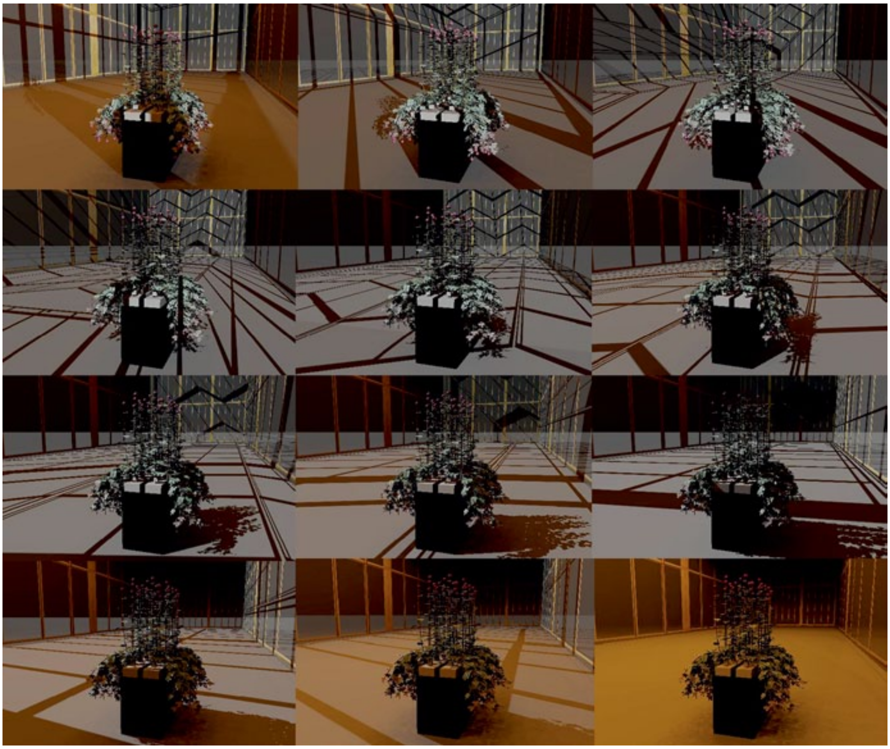

**Fig. 2.5** Simulation of a cut-rose production system in a greenhouse, with direct and diffuse daylight as well as light from high-pressure sodium lamps, reconstructing the light microclimate between 6:00 (up left) and 17:00 (down right) in winter. The model was created using GroIMP. (Source: Hemmerling et al. 2008)

to approach horticulture with a systems' view, in order to meet the global challenges that lie ahead. At the same time, the diversity of horticulture is a potential obstacle for a modelling approach as a model developed for one husbandry system (cultivar plus production methods) might only partially or not at all be transferable to another.

Horticultural production systems exhibit a high degree of diversity. Their complexity can be unravelled and their use improved using a method of choice—functional-structural plant modelling. Most examples for implemented FSPM explicitly only cover intermediate scale levels (e.g. that of the organ, the plant, and the canopy), whereas much lower (cellular and molecular) and much higher (field, region) ones are often not considered. As for the higher scales, their consideration would not make sense in a horticultural context, because of the high diversity of cultures. With respect to the lower scales, they have not yet been considered in horticultural FSPMs, for various reasons. Firstly, the knowledge base concerning the molecular and genetic control of physiological processes is still small and sketchy. Secondly, the reconstruction of the topology of regulatory networks from 'omics' data using bioinformatics tools is underway, and, therefore, linking these sketchy networks to higher scales in order to potentially increase the “genericness” of existing horticultural models, or to improve their predictive capacity, is currently not feasible. A promising direction to take, however, could be the modelling of the spatiotemporal dynamics of key growth regulators, such as auxins, cytokinins or gibberellins. These are known to control many physiological processes such as organ growth, extension, and branching and could be used in more advanced horticultural FSPMs.

## *Nanotechnology*

Nanotechnology, the application of atomic sized materials, is a vehicle for electronic control, product and process delivery. The properties of materials change substantially at atomic and sub-atomic particle sizes. This is creating whole new technologies which will have substantial impacts in horticulture. In recent years, multiple ways of interaction between the fields of nanotechnology and biology have been opened, mainly in biomedical research, with the development of tools for diagnosis and controlled delivery of substances (Corredor et al. 2010). By contrast, in the field of plant biology, the interaction between both disciplines has been less frequent. Most of the published work in this field has focused on the environmental impact of nanoparticles on crop growth and development; and also on the bioproduction of nanoparticles using plant extracts. There has been attention given to the development of nanodevices for controlled delivery of pesticides and other substances. As these developments take place they will spawn new applications in crop husbandry, protection and marketing.

Nanotechnology offers opportunities for extending product shelf life, by controlling the growth and development of micro-organisms, providing a new generation of packaging films and controlling the effects of gases and potentially harmful rays (UV). It will also enable the strength, quality and appeal of packaging to be enhanced and the use of multiple chips (nanobiosensors) for labeling products will be a step towards the automated control of degradation in stored produce (Yadollahi et al. 2010). Potentially there are applications of nanotechnology in all aspects of food sectors. These include food processing, packaging, monitoring, production of functional foods, development of foods capable of modifying their colour, flavour or nutritional properties according to a person’s individual dietary needs. More generically there will be the production of stronger flavourings, colourings and nutritional food additives (Alfadul and Elneshwy 2010). Developing smart packaging to optimize product shelf life using nanotechnologies is seen as a goal for many companies. Such packaging systems would be able to repair small holes and tears, respond to environmental conditions such as temperature and moisture changes, and alert the customer if the food is contaminated. Nanotechnology can modify the permeability of foils, increasing barrier properties (mechanical, thermal, chemical and microbial), improving mechanical and heat-resistance properties and sensing, as well as signaling, microbiological and biochemical changes. The creation of nano-biodegradable packaging is also likely to be possible. The development of food analytical methods for the detection of tiny amounts of a chemical contaminant, virus or bacteria in food systems is another potential use of nanotechnology. This will result in greater safety within the food processing system.

Within crops, nanotechnology will provide rapid and sensitive identification of pathogens, pests, nutrient and stress deficiencies. Crop protection and fertilisation remedies will be supplied and applied automatically in nano-packages by a commissioned supplier. Multiple chips, nano-biosensors, will offer fundamental steps forward in the automated control of production, storage and marketing. Predominantly, this satisfies consumers' demands for enhanced food quality, safety, stability, efficiency and traceability. As an example of what might be achieved in the field of food safety, a rapid and sensitive method was developed for separation and detection of multiple pathogens in a food matrix by magnetic surface-enhanced Raman scattering (SERS) nanoprobes. Silica-coated magnetic probes (MNPs@$SiO_2$) of ~100 nm in diameter were first prepared via the reverse micro-emulsion method using cetyltrimethylammonium bromide as a surfactant and tetraethyl orthosilicate as the silica precursor (Wang et al. 2011). In this system, pathogens were first immuno-magnetically captured with MNPs@$SiO_2$, and pathogen-specific SERS probes (gold nanoparticles) integrated with a Raman reporter. This was equipped with corresponding antibodies to allow the formation of a sandwich assay to complete the sensor module. The detection of multiple pathogens in selected food matrices could be achieved by changing the kinds of Raman reporters on SERS probes. In this research two key pathogens, *Salmonella enterica* serovar *typhimurium* and *Staphylococcus aureus*, were selected as models to illustrate the capacity of this scheme for detecting several pathogens. The lowest cell concentration detected in a spinach solution was $10^3$ CFU/mL. A blind test conducted in peanut butter established the limit of detection as $10^3$ CFU/mL with high specificity, demonstrating the potential of this approach in complex matrices.

## *Robotics, Automation and Electronics*

Since 1986 the rate of worldwide technological change has been breathtaking based on changes from analogue to digital electronic systems. Systems, devices and functions will get ever faster and smaller. This is the micro-age ($10^{-6}$) and fast approaching is the nano-age ($10^{-9}$) and by 2035 the pico-age ($10^{-12}$) age should be apparent. Electronic devices of atomic and sub-atomic scale will manage information exchanges, processes and product deliveries. A big advance is most likely to come from replacing silicon-based with carbon-based systems. These mimic DNA-RNA storage, transmission and function initiation, controlling data at faster and cheaper rates with increased efficiency. Delivery will be wireless and data will be shared and stored by cloud-computing which will handle huge amounts of data in nanoseconds. Fast biosensors will have the capacity to control crop growing, harvesting, storage and marketing.

Muscle powered work is disappearing from primary industries like horticulture. Robotics and autonomous systems are being developed for horticultural field production (Bechar 2010). These systems must be able to operate in unstructured agricultural environments without impairing the quality of the work in comparison with that achieved by current manual methods. The cost of robotic systems must be sufficiently low in order for them to be cost effective and additionally inherent safe and reliable. Detailed mapping of fields for soil structure, texture, nutrients, moisture content, pC and pH already allows precision automated and robotic husbandry. In turn, this exploits genomic characteristics of cultivars allowing precise predictions of sowing, planting, maturation and maturity, and harvesting. Intelligent robotic technologies will cope competently with continuously changing crop morphology and physiology and the environment. This demands information acquisition systems, including sensors, fusion algorithms and data analysis suitable for field conditions.

The combined interest in precision agriculture, information technology, and autonomous navigation has led to a growing interest in the generation of 3-dimensional (3-D) maps of mobile equipment surroundings (Rovira-Mas 2008). Creating three dimensional terrain maps is achieved by combining the information captured with a stereo camera, a localization sensor, and an inertial measurement unit, installed on a mobile equipment platform. The perception engine comprises a compact stereo camera that captures field scenes and generates 3D point clouds, which are transformed to geodetic coordinates and assembled in a global field map. Results have shown that stereo perception can provide the level of detail and accuracy needed in the construction of 3D field maps for precision agriculture and field robotics applications. An alternative system replaces stereo perception with global satellite and local positioning which may prove more accurate and reliable. In either case, the automated application of fertilisers, agrochemicals and water is now becoming a reality. The position of individual plants in rows and beds can be recorded into computerised memory banks and utilised many times over for automated husbandry and eventually harvesting operations. Protected crops can be produced by automated seeding, propagation, grafting, transplanting, maintenance, harvesting, sorting and packing. Already there are automated strawberry harvesters in Japan and rose harvesting and tomato de-leafing robots are in operation in the Netherlands. In China, a wireless apple harvesting robot is emerging. Image analysis applied in ornamental crops is being developed that will assesses leaf and flower cover, colour, uniformity, and canopy height, and enable harvesting, grading, storage and dispatch. Post-harvest processing imagery will be able to detect visual defects by applying optical and statistical methods identifying random colour and textures using multivariate image and principal component analyses.

Image analysis is being developed for ornamental crops and the bedding plant industries (Parsons et al. 2009). Feed-forward artificial neural networks have been used to segment top and side view images of three contrasting species of bedding plants. The segmented images provide objective measurements of leaf and flower cover, colour, uniformity and leaf canopy height. These systems may be applied for crop grading at marketing or for monitoring and assessment of growing crops within a glasshouse during all stages of production.

Glasshouse mechanization is being pioneered in The Netherlands (Henten 2006). Research demonstrates that the initial phases of plant production such as seeding, cutting, grafting and transplanting, and the final phase of sorting and packing the harvested produce can be mechanised. These tasks do not require much human intelligence and/or fast and accurate eye-hand coordination. Currently machines are largely based on principles of industrial automation consisting of mechanical solutions with only a limited amount of sensors and 'intelligence' being used. Crop maintenance and harvesting operations do rely on human intelligence and ability and are more difficult to automate. It is anticipated that in next 10 years will see the advent machines that will be based on the principles of mechatronics and robotics, combining smart mechanical design with sensors and "artificial intelligence" achieving the fast and accurate artificial eye-hand coordination needed for these difficult tasks. The slow progress in developing robotic harvesting is due largely to uncertainty in the working environment of the robot resulting from biological variability and the types of growing systems used. Progress requires innovations in robot technology, growing systems and plant breeding which collectively reduce biological variability and simplifies the tasks involved. In particular, the genetic profile of each cultivar will need to be known in minute detail. As a consequence the functions and processes controlling the abilities of each gene and, more importantly, perhaps their interactions will be matched with known responses to environmental factors. One consequence of this new level of sophisticated husbandry is to ask whether horticultural cropping will remain field-based?. In the past decade, soft fruit has moved under protection and the tree fruits are moving in that direction.

Considerable use is made already of automation and robotic technologies in the post-harvest and storage phases, particularly in the three major steps of grading, sorting and packing (Feng et al. 2010). Assembly lines emerged in horticultural packinghouses early in the 1900s. Major advances in the removal of manual labour have however, only arrived with the advent of electronic and optical systems which have operating speeds comparable with human eye decision making. Machines need to detect the colour, defects, size, shape, volume and density of produce. That can be achieved with techniques such as optical machine vision, near-infrared radiation, X-ray, and acoustic responses allowing 3-D machine evaluation of horticultural produce. Unlike industrial products, horticultural produce is variable in size, shape, volume, density and orientation. Automation and robotics must be able to cope with these factors. Frequently the unconstructed and tough environment in a packinghouse or the field at harvest challenges the operation and safety of the machines. Downtime resulting from machinery malfunctions must be minimised since loss of capacity in the packing house can have penal implications for the efficiency of the logistical systems designed to deliver produce into retailers' premises on a "just in time" basis. Machinery manufacturers are employing wi-fi technology which reports on the operating efficiency of equipment directly to control centres. These technologies issue alerts and fault diagnostic reports to mobile manufacturers' staff who are then able to prevent or minimise machinery downtime. In large scale post-harvest processing of crops such as *Citrus* one major problem is the detection of visual defects and the presence of undesirable matter (Lopez-Garcia et al. 2010). Species and cultivars of *Citrus* present a high rate of unpredictability in texture and colour. Detection of defects in real-time based on random colour textures, using multivariate image analysis and principal component analysis, potentially offers an accurate, unsupervised method which is readily calibrated. This type of technology is already used commercially in New Zealand. There is much developmental work required in order to improve the preservation of food quality after harvesting in the developing world Kitinoja et al. (2011). This requires science-based, simple methods for crop handling. These should include the characterization of indigenous crops in terms of their unique postharvest physiology (e.g. respiration rate, susceptibility to water loss, chilling sensitivity, ethylene sensitivity).

## *Genetics and Plant Breeding*

Since the rediscovery of Mendel's research identifying the principles of genetic inheritance in the 1900s, plant breeding has made an enormous contribution to all aspects of horticulture. Plant breeding is the fundamental means for coping with current and future economic and social problems facing mankind. The technology needed for the analysis and manipulation of genomes has advanced very rapidly in parallel with changes in the speed of electronics, automation and robotics. In the decade since the first plant genome (*Arabidopsis thaliana*) was sequenced, a central goal of research has been to assign functions to genes. The advent of high-throughput technology and robotics in biological research allows the study of gene function on a global scale, monitoring entire genomes and proteomes at once. Systematic approaches consider all possible dependencies between genes and their products. The science of proteomics characterizes biological processes which are under genetic control. Proteomic techniques now collect data for many proteins simultaneously. This identifies protein expression, modification, localization, turn-over and protein-protein interaction during each stage of physiological change or disease development. Recent advances the acquisition, storage and analysis of complex biological data sets provides detailed understanding of the mechanisms regulating plant development and responses to the environment. Over the next 25 years this information and that which follows will be applied to plant breeding. New cultivars will increase the efficiency of resource-use, develop pest, pathogen and stress resistance, and safeguard product quality.

Raising efficiency in the chloroplast is central to improving photosynthetic activity and increasing crop yields. Photosynthesis captures the sun's energy and converts it into yield and crop quality ultimately increasing growers' profits, the world food supply and its quality. Knowledge of photosynthesis and photorespiration has reached such an advanced state that application to crop improvement is now feasible (Armbruster et al. 2011). Engineering $C_4$ traits into $C_3$ plants, which include most horticultural crops, is an attractive means of crop improvement. The $C_4$ pathway of photosynthesis drives productivity in several major food crops and bioenergy grasses, including maize (*Zea mays*), sugarcane (*Saccharum officinarum*), sorghum (*Sorghum bicolor*), *Miscanthus* x *giganteus*, and switchgrass (*Panicum virgatum*) (Brutnell et al. 2010). Traits from these plants could be used to great advantage in horticultural crops. The gains in productivity associated with $C_4$ photosynthesis include improved water and nitrogen-use efficiencies. Thus, engineering $C_4$ traits into $C_3$ crops is an attractive target for crop improvement. The lack of a small, rapid cycling genetic model system to study $C_4$ photosynthesis, however, has limited progress in dissecting the regulatory networks underlying the $C_4$ syndrome. *Setaria viridis* is a member of the Panicoideae clade and is a close relative of several major feed, fuel, landscape and bio-energy grasses. It is a true diploid with a relatively small genome of ~510 Mb. Its short stature, simple growth requirements, and rapid life cycle will greatly facilitate genetic studies of the $C_4$ grasses. Importantly, *S. viridis* uses an NADP-malic enzyme subtype $C_4$ photosynthetic system to fix carbon and therefore is a potentially powerful model system for dissecting $C_4$ photosynthesis.

Recent advances in technology and in the ability to acquire, store, and analyze complex biological data sets have provided an unprecedented understanding of the mechanisms regulating the development and responses of organisms to the environment (Galbraith and Edwards 2010) and will bring substantial benefits for horticulture. Microarrays provide an early example of the productive integration of high-throughput technologies with biological inquiry. Proteomics provide a way of characterizing biological processes and is an important adjunct to micro-array approaches and DNA technology (Kumar and Yadav 2001). Proteomic techniques collect data for many proteins at once. They add rapidly to our knowledge of protein expression, modification, localization, turnover and protein-protein interaction during each stage of physiological change and disease. Because proteins are one step closer to function than are genes, these studies frequently lead directly to biological discoveries or hypotheses. The large-scale analysis of proteins is becoming an increasingly important post-genomic approach to understand gene function. Three major steps in proteome analysis are the separation of complex protein mixtures by two-dimensional protein gel electrophoresis (2D), characterization of the separated proteins by mass spectrometry (MS) and database searching. Protein interaction maps provided by the yeast two hybrid (Y2H) system on a genome-wide scale are being to assign functions to new proteins. Improvement in high-throughput techniques in proteome analysis, such as the development of robotic automation for recognizing and excision of protein spots from 2-DE gels, enzymatic digestion and transferring the digested 2-DE gel spots to a mass spectrometry target for MS analysis and generation of MPIs are now very much in vogue.

A central goal of post-genomic research is to assign a function to every predicted gene (Schoner et al. 2007). Because genes often cooperate in order to establish and regulate cellular events the examination of a gene has also included the search for at least a few interacting genes. This requires a strong hypothesis about possible interaction partners, which has often been derived from what was known about the gene or protein beforehand. It is now possible to study gene function on a global scale, monitoring entire genomes and proteomes at once. These systematic approaches aim at considering all possible dependencies between genes or their products, thereby exploring the interaction space at a systems scale. An example of this is seen in the manner by which genetically modified crops are emerging as a key weapon to fight the negative impact of abiotic stresses on agricultural production (Tuteja

2009). Cold stress mainly causes mechanical damage to the cell membrane, whereas salinity and drought disrupt the ionic and osmotic equilibria of cells. Cytosolic free $Ca^{2+}$concentration ($[Ca^{2+}]$cyt) increases in response to abiotic stress. The stress signal is first perceived at the membrane level by the receptors and then transduced in the cell to switch on various stress-responsive genes for mediating tolerance. The products of stress-inducible genes function both in the initial stress response and in establishing plant stress tolerance. Some genes have been reported to be upregulated in response to more than one stress, indicating the presence of cross-talk between the different stress signaling pathways. The generation of reactive oxygen species represents a universal mechanism in cellular responses to environmental stresses (Bauwe et al 2010). Plants also accumulate several osmo-protectants that improve their ability to combat abiotic stresses.

Unraveling the opportunities for increased photosynthetic efficiency and the mechanisms underlying stress disorders are two examples of the manner by which genetic studies and their application through plant breeding offer substantial avenues for the advancement of horticulture. Each increases the efficiency and effectiveness of biological processes thereby raising yield and product quality.

## *Resources and Befitting from Benign Microbes*

The study and application of plant pathology has been and continues to be hugely beneficial to horticulture. The unraveling of pathogen and pest biologies and life cycles, host-pathogen interactions, epidemiology and methods of control were some of the earliest benefits which science provided. The importance of such studies remains because regrettably pests and pathogens still cause substantial losses and control is costly. Environmentally induced stress disorders are now included with pests and pathogens since they cause considerable crop losses and have similar basic biological and biochemical pathways. The United Kingdom Horticultural Development Company (HDC), supported from an industrial levy, spends more on this aspect of husbandry than any other of its priorities and this distribution of funding seems unlikely to change radically in the immediate future.

Finely tuned diagnostics offers considerable opportunities for improving the prediction, the speed and efficacy of control of pests and pathogens. The discovery of the enzyme-linked immunosorbent assay (ELIZA) and the polymerase chain reaction (PCR) have, amongst other developments, greatly enhanced opportunities for the diagnosis of plant diseases and for charting epidemics of pathogens (Lauerman 2004). The mechanization of various aspects of the PCR assay, such as robotics, microfluidics and nanotechnology, has made it possible for the rapid advancement of new procedures. Real-time PCR, DNA microarray and DNA chips utilize these newer techniques in conjunction with specialized computer programs. Instruments for hand-held PCR assays are being developed. The PCR and reverse transcription-PCR (RT-PCR) assays have greatly accelerated the speed and accuracy of disease and pathogen diagnosis, making it possible to characterize genetically a microbial isolate inexpensively and rapidly for identification, typing and epidemiological comparison.

Deleterious organisms are only a small proportion of the aerial and edaphic microbial communities which surround crop plants. Many of these other micro-organisms are potentially valuable adjuncts for sustainable production, especially soil borne microbes. But currently there is relatively little understanding of soil properties, ecology and the microbes living in and around plant roots, the rhizosphere. Since the vast majority of soil microbes are benign, many must ultimately offer opportunities for aiding crop growth. There is a huge amount of nano-scale molecular signaling within microbial communities, with plant roots, and within and between plants themselves. Understanding these activities is the task of molecular microbiologists who are unraveling opportunities for the creation of new generations of fertilisers, crop stimulants, and protectant and eradicant treatments. These will be biologically-based and provide increased yields linked firmly with environmental sustainability. Already it is known that plants sense the approach of pests and pathogens and activate defense mechanisms. These processes are aided by benign soil microbes especially, but not exclusively, mycorrhizal types which themselves mobilise supplies of nutrients for their hosts. Free living microbes are being to be used in biological control and this trend will accelerate. It will also be possible to exploit characteristics of forms of self defense in plants. For example, some root exudates themselves suppress the growth of competitors and it has been recognised that some soils are naturally suppressive to disease-causing organisms and that this property stems from the cumulative effects of benign microbes. Understanding natural plant signaling and diverting it for the benefit of crop production is a possible sustainable pathway to increased yield and profits. It is becoming apparent also that there is an immense amount of signaling within individual plants that integrates responses to the environment and that finely tunes the plant's responses appropriately. Additionally there is signaling between plants which can detect and warn of approaching pests and pathogens and develop appropriate responses. Furthermore, research demonstrates that the plant's own defense compounds, like resveratrol in grapes, can form natural and ecological alternatives to chemical pesticides (Jimenez Sanchez et al. 2008).

Plants can, for instance, respond to feeding or egg deposition by herbivorous arthropods by changing the volatile blend that they emit (Mumm and Dicke 2010). These herbivore-induced plant volatiles (HIPVs) can attract carnivorous natural enemies of the herbivores, such as parasitoids and predators, a phenomenon termed indirect plant defense. The volatile blends of infested plants can be very complex, sometimes consisting of hundreds of compounds. Most HIPVs can be classified as terpenoids (e.g., (E)-beta-ocimene, (E, E)-alpha-farnesene, (E)-4,8-dimethyl-1,3,7-nonatriene), green leaf volatiles (e.g., hexanal, (Z)-3-hexen-1-ol, (Z)-3-hexenyl acetate), phenylpropanoids (e.g., methyl salicylate, indole), and sulphur- or nitrogen-containing compounds (e.g., *iso*thiocyanates or nitriles, respectively). One highly intriguing question has been which volatiles out of the complex blend are the most important ones for the carnivorous natural enemies to locate "suitable" host plants. Electrophysiological methods such as electroantennography have been used with parasitoids to elucidate which compounds can be perceived by the antennae. Different types of elicitors and inhibitors have widely been applied to manipulate plant volatile blends. Transgenic plants that were genetically modified in specific steps in one of the signal transduction pathways or biosynthetic routes have been used to find steps in HIPV emission crucial for indirect plant defense.

Knowledge of these interactions is increasing such that benign microbes and carnivorous insects are now being deployed as bio-control agents. Future crop protection will function in a wholly integrated manner. Knowledge of the genetic qualities of microbes will allow much greater specialised targeting of individual pests and pathogens using bio-controls based on specific microbes, plant products and biofriendly fertilisers which have properties supportive of crop growth and capable of preventing pollution. Integrated crop management will be founded on detailed computerised genetic profiles of the crop cultivar interacting with specific microbes and populations of groups of microbe. Crop nutrition could be founded around the properties of mycorrhizal organisms which are capable of extracting nutrient from the soil and passing them to growing plants (Shtark et al. 2010).

In particular this is likely to apply first to supplies of phosphorus. Warnings are already sounding that rock phosphate supplies are being depleted. Balancing the agricultural phosphorus (P) cycle is difficult, particularly for horticultural systems, where crop products are exported off-site (Stockdale et al. 2006). Sustaining soil phosphorus concentrations usually relies on the input of some form of fertiliser. These vary from those that are essentially unaltered to those that have undergone a high degree of processing to increase phosphorus solubility and enrichment. One of the major drawbacks associated with the direct use of rock phosphate is its poor solubility in circum-neutral and calcareous soils, which currently requires long-term and unnecessarily large application rates in order to satisfy crop demand. Opportunities exist whereby the solubility and therefore bio-availability of sparingly soluble rock phosphate can be enhanced without recourse to energy demanding processes. A range of root traits have been shown to be beneficial in improving the phosphorus-use efficiency of different crops and cultivars. These include: root properties (morphology and root hairs), uptake kinetics parameters and root-induced rhizosphere changes (pH, organic acids and acid phosphatase). These responses have a direct benefit for the crop itself, but may also have benefits for the crop rotation as a whole; if phosphorus is mobilized from recalcitrant soil fractions and mobilized, it is made available to following or adjacent crops. The mineralization of organic matter by soil microorganisms provides an important supply of available phosphorus for plant growth. Hence phosphorus supply may be related to microbial activity in soil. In addition, associations between plant roots and arbuscular mycorrhizal fungi are able to use the available forms of phosphorus in the soil solution more effectively than roots alone. A range of soil microorganisms including fungi and bacteria have the ability to solubilize mineral forms of phosphorus in culture and there is some evidence that this might also occur in soil (Dixon and Tilston 2010).

Horticulture, as with agriculture has benefitted for more than a century from the industrial discoveries which allowed the artificial fixation of atmospheric nitrogen and the consequent production of nitrogenous fertilisers. The entire world food supply now relies on the availability of these fertilisers since without them crop yields would be only tiny fractions of current output. Unfortunately no such benefit comes without penalties. In this case unrestricted use of particularly ammonia-

**Table 2.3** Regulation of nitrate formation related to dicyandiamide content in calcium cyanamide. (Source: Vilsmeier and Amberger 1978)

| Days from initial treatment | Milligram (mg) nitrogen/pot | |
|---|---|---|
| | DCD absent | DCD present |
| 40 | 7.0 | 0.1 |
| 100 | 14.3 | 0.4 |

Experimental details: each pot contained 100 g soil plus 20 mg of calcium cyanamide (granules), initially 11 % water saturation, calcium cyanamide incorporated after 20 days and then water saturation increased to 26 %, temperature 18 °C.

**Table 2.4** Regulation of nitrate formation related to dicyandiamide content in calcium cyanamide and soil water content. (Source: Vilsmeier and Amberger 1978)

| Days from initial treatment | Milligram (mg) nitrogen/pot in soil saturated with water % field capacity | | | |
|---|---|---|---|---|
| | 25 % field capacity | | 75 % field capacity | |
| | DCD absent | DCD present | DCD absent | DCD present |
| 40 | 1.8 | 0.6 | 8.1 | 0.5 |
| 60 | 9.4 | 0.5 | 8.8 | 0.0 |

Experimental details: each pot contained 100 gm soil plus 16 mgm calcium cyanamide, temperature 18°C.

based fertilisers leads to nitrification in the soil and the production of soluble nitrates which can leach through the soil profile percolating into waterways causing pollution and damaging the environment.

Fortunately there are forms of nitrogen fertiliser which do not cause these problems such as calcium cyanamide. Soil moisture encourages the dimerisation of cyanamide to dicyandiamide (Cornfoth 1971; Dixon 2009). Dicyandiamide (DCD) is recognised in the EU-Fertiliser Directive (2003/2003) amended November 8th 2008 as a nitrification inhibitor. Calcium cyanamide's initial DCD content and added amounts resulting from the presence of soil moisture and the effects of microbial activity, slows down soil nitrification and reduces the leaching of nitrates into groundwater (Vilsmeier and Amberger 1978; Rathsack 1978). See Tables 2.3, 4 and 5.

Dicyandiamide is decomposed by biotic and abiotic mechanisms in soil into ammonium ions, carbon dioxide and water as a consequence, nitrogen is only slowly released. Nitrate content of soils treated with calcium cyanamide was lower than those of untreated controls (Nõmmik 1958). Applications of calcium cyanamide increased the numbers of microbes in soil (Allison 1924; Mukerji 1932). Soil biological health as measured by the amount of enzyme activity increased where calcium cyanamide was used especially when this was compared with the effects of applying ammonium sulphate (Bosch and Amberger 1983). Calcium oxide may be released from calcium cyanamide and this raises alkaline soil pH which encourages microbial activity. The subsequent release of nitrogen via DCD encourages heterotrophic microbes (Nõmmik 1958). Hence the breakdown of calcium cyanamide increases the heterogeneity of soil microbe populations and in turn this increases fertility. This finding supports the contention of Crowther and Richardson (1932) that calcium cyanamide is most effective when applied annually. The liming effects

**Table 2.5** Rate of metabolism of dicyandiamide at three concentrations over time. (Source: Rathsack 1978)

| Treatment | Time (days) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Milligram (mg) DCD-nitrogen/100 g soil | 0 | 14 | 28 | 42 | 56 | 70 | 84 | 98 |
| 6 | 4.0 | 5.7 | 6.2 | 6.8 | 10.5 | 12.0 | 12.4 | 12.1 |
| 4 | 4.0 | 4.8 | 6.0 | 8.5 | 9.8 | 9.8 | 10.6 | 10.3 |
| 2 | 4.0 | 4.8 | 6.9 | 7.7 | 8.4 | 7.9 | 8.8 | 9.4 |
| 0 | 4.0 | 4.0 | 4.5 | 5.8 | 5.9 | 6.5 | 6.0 | 5.8 |

Soil source = Wietzenbruch

of calcium cyanamide linked with its useful combination of calcium and nitrogen and associated reduced rate of nitrification benefit soil fertility (Verona 1969). Intelligent application of fertiliser chemistry towards the greater exploitation of compounds such as calcium cyanamide will retain the capacity for feeding the burgeoning world population in ways which are environmentally sustainable.

## *Water Conservation*

Water is an increasingly scarce resource worldwide and irrigated broad acre agriculture remains one of its largest and frequently inefficient users (Costa et al. 2007). All intensive horticultural crops have very large demands for water in order to maintain yield, quality and appearance. In the environmental and social sectors the continuous availability of water in times of shortage in order to sustain the appearance of landscapes is a more questionable priority. Nonetheless once the structure of a landscape is damaged by drought it is hugely difficult to return it to its original status. Nonetheless low water-use efficiency (WUE) in some horticultural plants together with an increasing competition for water resources with other sectors (e.g. domestic uses, tourism or industry) is encouraging the adoption of new irrigation and cultivation practices that use water more judiciously. There have been very substantial improvements in the economy with which water is used in horticulture over the last 20 years. These have utilised fundamental scientific knowledge describing the manner by which plant growth regulators such as abscicic acid and cytokinins control water losses through the stomata (Davies and Zhang 1991; Wilkinson and Davies 2002; Davies et al. 2005).

In areas with dry and hot climates, drip irrigation and protected cultivation have improved WUE mainly by reducing runoff and evapotranspiration losses (Jones 2004). Greater precision in the control of water use is now being achieved by using deficit irrigation strategies such as regulated deficit irrigation or partial root drying have emerged as means of increasing water savings by allowing crops to withstand mild water stress with no or only marginal decreases of yield and quality. Deficit irrigation is where the volume of irrigation applied is less than that needed to replace all evapo-transpiration losses and hence there is a net depletion of water from the soil reservoir as the growing season progresses. Regulated deficit irrigation is a regime which purposely stresses the trees or vines at specific growth stages which are known to be least sensitive to water deficits outside these periods the trees are given full deficit replacement irrigation. Partial root drying is where there is alternate wetting and drying of either side of the crop row (Davies et al. 2000, 2005; Kang and Zhang 2004; Bravado 2005).

The efficacy of water saving irrigation systems as compared with overhead sprinkler methods has been demonstrated for example by Bowen et al. (2012). They investigated the effects of converting from overhead sprinkler to drip irrigation on the growth, leaf gas exchange, and fruit production of Merlot grapevines. The frequency of irrigation was 50 % higher using drip compared with sprinkler systems but 64 % less water was applied. Water-use efficiency as measured by transpiration was greater under drip than sprinkler irrigation and input water use efficiency averaged 2.5 times higher under drip irrigation over the 4 years. A further advantage of low level or below ground drip systems is that they can be used for the application of fertilisers. This reduces the quantities of fertiliser especially nitrogen that are required while increasing the efficiency of its use by plant roots (Granados et al. 2013; Ashraf et al. 2012). Further efficiencies in crop production may be gained by combining drip and low level irrigation with the application of mulches. This combination enhanced the growth, irrigation water use efficiency (IWUE), fruit yield, and quality of strawberry plants (Kumar and Dey 2012). In general these techniques have been most successfully applied so far with deciduous and evergreen fruit trees, vines and some soft fruit. Experiments with field vegetables and particularly potato crops have been less successful. Probably this reflects the shallow root systems and higher sensitivity to drought stress in these crops. Potato tuber yields and quality were substantially reduced by water deficits even when these were applied only briefly (Lynch et al. 1995; Shock and Feibert 2002; Liu et al. 2006). By contrast the application of water restriction husbandry in ornamentals could provide benefits. This has the potential for reducing excessive growth in woody plants such as *Cornus* and *Forsythia* spp (Cameron et al. 2004, 2006). In this research water consumption was halved. Further financial benefits accrued from more compact growth and less need for pruning.

Horticulture is responding to reductions in the availability of water which is a key resource by the innovative application of basic science. Understandings of the physiological mechanisms which govern water flow from the soil into roots, through the stem tissues into leaves and out via stomata in the evapotranspiration stream provide a sound scientific platform from which new and imaginative husbandries can arise. These are turned into practical realities by engineering new equipment.

## The Value of Horticultural Science

Over the past 25 years horticulture has demonstrated amazing robustness and capacities for trading in a global market with the very minimum of government support or even interest. Comprehensive evaluations of the value of horticultural research are rare. Hewett et al. (2005) for example suggested that New Zealand's exports of horticultural products have increased in value from $NZ 200 million to over $NZ 2 billion during the last 20 years. Fruit, flowers and vegetables are now exported from New Zealand to over 100 countries. Far from horticulture being a sunset industry, as viewed by some planners and analysts, these workers showed that science and innovation investment creates value for the local and national economy in New Zealand. Working at the cutting edge in many aspects of innovation, production, quality maintenance, distribution and marketing places the horticultural industry of New Zealand in the forefront as a world supplier of innovative products and cultivars. Recently, Anon (2012b) demonstrated that the annual contribution of fruit and vegetable to global trade exceeds $US 180 billion. Despite these huge volumes of fruit and vegetables exported through world trade still 93 % are grown and consumed locally. A recent comprehensive analysis however provides considerable detail as to the financial, environmental and value of horticulture worldwide. As examples of the importance of this trade, in 2010 the United States exported $US 10 billion worth of fruit and nuts while Turkey, a recent entrant to horticultural exports, had a trade in 2010 of $US 3.5 billion in these commodities alone. The Netherlands, one of the traditional power houses of horticultural exports, had a trade in live plants, bulbs and cut flowers worth $US 10 billion in 2010.

The need to invest in horticultural research and development is compelling (Dixon 2010). The advantages to human health and wellbeing of diets balanced with a high intake of fruits and vegetables is widely accepted (see elsewhere in this Trilogy) which emphasises the need to have such produce available to households year-round and at affordable prices—neither of which can be taken for granted. The need to deliver safe food free of human pathogens and other contaminants is also paramount but again cannot be taken for granted given the food safety compromises that have occurred globally over the past decade. Furthermore, the increase in the occurrence of significant climatic events, such as major droughts and storms, threaten many elements in the supply chain of horticultural crops some of which can be moderated through the application of research findings aimed at improving factors such as crop water use (Cairns 2009). Finally, demands from modern societies for sustainable production practices and pesticide-free produce will only be critically dependent on soundly-based research and development programmes. Ongoing investment in research and development of horticultural crops and production practices will be critical if these ongoing challenges are to be addressed in a meaningful and timely way.

Nowhere is this more important than in Asia and Africa (Rosegrant et al. 2007). Resource scarcity, particularly of water, will increasingly constrain growth in food production, and climatic stresses will likely reduce farmers' abilities to produce crops. Coincidentally, however, there will be a growing demand for high-value foods, such as livestock, fish, vegetables, and fruits. The consequences of these pressures will adversely affect food security and obstruct the goals for human wellbeing, slowing progress in reducing malnutrition, especially in children. Horticulture has a particularly important role as highlighted by the United Nations High Representative for the Alliance of Civilisations, J. Sampiao in his opening address to the 28th International Horticultural Congress (Janick et al. 2011). This echoed the views of Pretty et al. (2011) that horticulture has a substantial role in developing sustainable food supplies especially in under-developed areas such as Africa.

The axis between human health and welfare and horticulture is gaining momentum. The medical profession is now taking the concept that diet, recreation and health are interrelated very seriously. Possibly the outcomes of the United Kingdom's 1946 Cohort Studies which have dramatically shown that the health of children in their early stages, pre-five years old, set the mold for subsequent growth and eventual health failings have had an impact on medical thinking. Matching genetic profiles to disease susceptibility will be commonplace, and importantly for horticulture the genetic profiles of crop cultivars will be matched with the ability to suppress disease onset in very precise terms. Plant chemistry will be precisely tailored such that it produces medically valuable compounds and suppresses those which might be deleterious. Alongside this will be crops where their genetics have been so finely tuned that they produce highly specialised proteins which target the diseases of individual patients. These are the so-called 'Pharma-crops' which express specific characters capable of producing antigens which are so specialised that they can target a cancer in an individual patient. Obviously such crops are enormously valuable and need to be grown under specialised conditions and will continue to contribute to GDP in a number of developed countries.

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# Chapter 3
# Vegetable Crops: Linking Production, Breeding and Marketing

**Daniel I. Leskovar, Kevin M. Crosby, Marco A. Palma and Menahem Edelstein**

**Abstract** Vegetable production has been a major and dynamic activity devised by diverse human cultures to sustain their livelihood for centuries. Vegetables, being several times more productive per unit area than cereals, can play a vital role in facing food security and nutrition challenges in the coming decades. However, the predicted climate change and increased demand on limited land and water resources makes water conservation a key component of vegetable production systems. At the same time, there is an increased global demand for healthy and nutritious vegetables. Dramatic improvements have been achieved through breeding for important abiotic stresses and quality traits in many vegetables. Thus, successful emerging small or large commercial farmers now apply integrated strategies from farm to table, including planting, grafting, irrigation, use of modern cultivars and innovative marketing tools. In this chapter we highlight some technological advances in vegetable production, with emphasis on stand establishment and irrigation management for water-limited areas. We discuss the impact of breeding and genetics on the improvement of abiotic stress tolerance and provide evidences on the use of improved germplasm and cultivars to enhance the quality of vegetables. Finally, we discuss the critical role of marketing and consumer trends for vegetable products.

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**Keywords** Abiotic stress · Consumer trends · Deficit irrigation · Direct seeding · Drip irrigation · Drought · Genetics · Grafting · Irrigation management · QTL · Salinity · Trades · Traits · Transplanting · Water conservation · WUE

## Introduction

The next 50 years represent huge challenges for worldwide horticulture. This is due to a fast increase in population rates, rising bio-fuel demands and shrinking land and water resources. Current trends show an increase of 70 million people per year, and by 2050 the global population will rise to 9.5 billion, a 36 % increase (Silva and Ryder 2011). The productivity of major cereals is stagnating in certain regions of the world (Ray et al. 2012) while 868 million people are suffering from undernourishment and 2 billion are affected by micronutrient deficiencies (Anon 2012d). With strong urban and industrial land demands, there are limited possibilities to increase the use of fertile areas under crop production. Thus, farmers will have to adopt precise, resource-efficient and environment-friendly production technologies. To extend new production areas into marginal soils and marginal waters, varieties tolerant to region-specific abiotic and biotic stresses will have to be developed.

World vegetable production recorded 1.04 billion tons in 2010, a 33 % rise since 2000 (Fig. 3.1). About 75 % of the total global vegetable production is taking place in Asia, while China, India and USA are consuming 60 % of world vegetable production (Anon 2012f). Hundreds of diverse vegetable crops provide an efficient and economically viable means to deliver crucial, human-health related phytochemicals, minerals, vitamins, antioxidants, essential amino acids, fatty acids and carbohydrates (Galili et al. 2002) in which other foods are deficient. In spite of the increase in per capita availability of vegetables in the last decade, still 80 % of the low-medium income families consume less than the minimum recommended levels (Hall et al. 2009). Therefore, the future economic growth and increased health awareness are likely to cause an upsurge in global demand for vegetables (Silva and Ryder 2011).

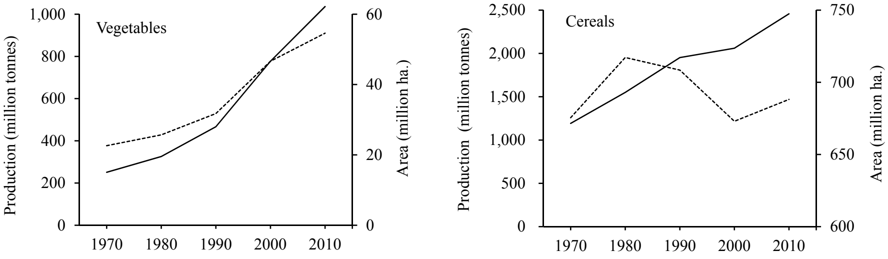

**Fig. 3.1** World vegetable and cereal production (—) and area cultivated (…) 1970–2010 (Anon 2010)

Based on 2010 FAO data, the worldwide gross value per ha for a major vegetable such as tomato was $ US 12,556 and much greater than cereals such as maize with $ US 331. Vegetables are adapted to a range of climatic conditions, offering a wide choice for farmers. A good example is the diversity of vegetable production in Middle Eastern countries located near the Mediterranean Sea, an area characterized by a cold and wet winter climate in the north, and a sub-desert climate in the south. Here, several vegetable crops can be harvested up to three times a year, such as in Turkey, Egypt, Syria and Israel. Major abiotic stresses which detract from sustainability in vegetable production systems are water limitations, high salinity, low fertility, and temperature extremes. Economic factors and competition for land and water resources often preclude solving the first three problems by cultural practices alone. The fourth factor is even more difficult to address in open-field production, as farmers are limited by their local production environments. In this chapter we highlight critical aspects that contribute to the success of intensive vegetable production systems. Those are: technological advances in stand establishment and irrigation management systems, breeding and genetics to improve abiotic stress tolerance and product quality, and marketing and consumer trends for vegetable products.

## Stand Establishment Systems

### *Seeding Technologies*

In 2012, the global vegetable seed market was estimated at US $ 4 billion with the distribution being solanaceous (39 %), cucurbit (18 %), root and bulbs (15 %), brassicas (14 %), leafy (7 %) and large seed vegetables (7 %) (Anon 2012f). Direct seeding has been the standard establishment system of vegetable production for centuries. This is in large part due to the use of cultivars developed by open pollination, which are much less costly than $F_1$ hybrid seeds. Direct seeding is the recommended method used for large-scale vegetable production aimed at machine harvesting such as tomato, sweet corn, snap bean, chili pepper, cucumber, leafy vegetables, roots and bulbs such as carrots, beets and onions. Farmers demand seeds that have rapid germination and seedling emergence, leading to uniform stands, particularly under stressful conditions of extreme temperatures, drought and high soil salinity.

Seed enhancement technologies such as seed coating (pelleting, encrusting, and filmcoating), hydration treatments (priming at low water potential) or gel mixtures with growth promoting compounds such as rhizobacteria or gibberellic acid have been developed to improve speed and synchrony of seedling emergence as well as seedling vigor in open fields of several vegetable crops, including tomato, pepper, and cucumber (Orzolek 1983; Watkins and Cantliffe 1983; Cantliffe et al. 1987; Bradford et al. 1990; Edelstein et al. 1995; Kloepper et al. 2004; Nowak et al. 2004; Halmer 2008; Cantliffe 2009).

**Fig. 3.2** Container grown onion transplants

**Fig. 3.3** Melon plug plant

## *Transplanting Technologies*

The development and adoption of polystyrene trays, known as Speedling®, for transplant production in nurseries was a "stepping stone" technological advancement in the vegetable industry during the early 1970s in Sun City, Florida. Now containerized transplants or plugs grown in trays with 72 to 800 cells have become prominent for small and large commercial vegetable farmers worldwide (Cantliffe 2009) (Figs. 3.2 and 3.3).

The use of grafting technology for vegetable transplants has also been increasing rapidly in Europe, Korea, Japan, Mediterranean Basin and the United States in the last decade, however its use is most common under protected rather than open field cultivation (Lee and Oda 2003; Davis et al. 2008) (Fig. 3.4).

Machine transplanting is the standard method of establishment for numerous commercial vegetable crops, including solanaceous (tomato, eggplant, pepper), cucurbits (melon, seedless and seeded watermelon), cruciferous (cauliflower, cabbage and broccoli), asparagus, celery, leek, and artichokes. This is mostly due to the high cost of hybrid seeds and the minimum root disturbance during transplanting. The importance of improving root development during the nursery period and to enhance seedling performance in the field has been reviewed by Leskovar and Stoffella (1995). Transplanting allows precise spacing, ensures the production of early crops and permits timing harvests for specific markets. Weed control may be

**Fig. 3.4** Grafted watermelon plant

**Fig. 3.5** Placing pepper transplants through plastic mulch

improved with transplants, without additional thinning costs as required for direct seeding. Furthermore, substantially less irrigation input is required to establish the transplanted crop under a plasticulture system as compared to direct-seeding, which is critical when growing vegetables in water restricted areas of semi-arid regions (Fig. 3.5).

Improved techniques aimed at modifying transplant root and shoot morphology, and physiology, have been developed in the nursery to suppress plant height, enhance plant compactness and condition or 'harden' transplants to better withstand post-transplanting stress. Many of these techniques have beneficial post-transplanting responses on early vegetative growth (e.g. tomato, pepper), but few provide long-term effects influencing reproductive development and yield potential. Numerous variables affecting growth and development of vegetable transplants in the nursery have been researched and several have been implemented in commercial nurseries. These include nitrogen, phosphorous and potassium management (Edelstein and Nerson 2001; Dufault 1998; Soundy et al. 2001), supplemental light (Boivin et al. 1987; Fierro et al. 1994), irrigation management and systems (Leskovar and Heineman 1994), selection of cell volume in the tray (Bar-Tal et al. 1990) and physiological conditioning with abscisic acid (Goreta et al. 2007; Agehara and Leskovar 2012).

**Fig. 3.6** Lysimeter and center pivot irrigation rig

# Irrigation Management

## The Problem of Water Scarcity and Resources

Irrigated agriculture is a major consumer of water, accounting for about two thirds of the total fresh water diverted to human uses (Fereres and Evans 2006) (Fig. 3.6).

The predicted climate change coupled with increasing number of drought events for many areas of the world is exacerbating the problem of water scarcity (Petit et al. 1999; Anon 2001; Luterbacher et al. 2006). The rising demands on water resources and limited availability makes water an increasingly valuable commodity. This is true for several southern regions of the U.S., such as Texas, which is heavily dependent on underground water resources. In Egypt, where farming is confined to less than 3 % of the total land area near the Delta, irrigation is mainly based on pumping of the Nile water from Lake Nasser and mixing it with underground water (Mason 2003). A much more complex scenario occurs in central and southern-desert areas of Israel, where the main water source for vegetable irrigation comes from a combination of water reservoirs, saline water, recycled sewage water and more recently, desalinated water.

## Water Conservation and Deficit Irrigation

Water conservation and crop water-use efficiency (WUE) is a matter of great concern among researchers, vegetable growers and government agencies. The WUE in the agricultural sector has been improving by the use of drought tolerant cultivars and by the utilization of efficient cultivation and irrigation practices (Chaves et al. 2003; Condon et al. 2004). The development of drip or "trickle" irrigation in Israel during the 1960's together with the adoption of the plasticulture technology on raised beds have been two major technological "milestones" for vegetable production. These systems are now widely used for fresh market vegetable production in open fields around the world (Goldberg et al. 1971; Hanson et al. 1997; Lamont 2005). Drip irrigation alone or in combination with plasticulture has significantly contributed to water savings and in many cases improved WUE by reducing runoff and evapotranspiration losses (Stanghellini et al. 2003; Jones 2004; Kirnak and Demirtas 2006) (Table 3.1) For large-scale production, water savings can be achieved with center pivot systems using drops converted to low-energy precision application (LEPA) heads placed at about 30 cm above the ground (Piccinni et al. 2009). Deficit irrigation implies that water is supplied to the crop at levels below crop evapotransiration (ET) levels, deliberately allowing crops to sustain some degree of water deficit without significant yield reduction but with important savings in irrigation water. Deficit irrigation strategies applied through drip systems have been shown to optimize water savings and productivity in several vegetable crops (Table 3.1). One environmentally-friendly approach to increase the use of marginal water (saline water) is grafting of salt-sensitive plants onto salt-tolerant rootstocks (Colla et al. 2010; Edelstein et al. 2011).

## *Application of Crop Coefficients*

Irrigation can be improved by the application of on-site microclimatological data and crop coefficients ($K_C$), which are calculated as the ratio of the crop evapotranspiration ($ET_C$) to a reference crop ($ET_O$) (Allen et al. 1998). $ET_O$ may be measured directly from a reference crop such as a perennial grass (Watson and Burnett 1995) or computed from weather data using either temperature models (Thornthwate 1948; Doorenbos and Pruitt 1977), radiation models (Doorenbos and Pruitt 1977; Hargreaves and Samani 1985), or combination models (Allen et al. 1998). Weighing lysimeters are employed to measure $ET_O$ and $ET_C$ directly by detecting simultaneous changes in the weight of the soil/crop unit (Schneider et al. 1998; Marek et al. 2006). Once $K_C$ values are determined, growers can calculate real time irrigation recommendations ($ET_C$) which can be obtained by local weather stations that determine $ET_O$ and therefore solve the equation: $ET_C = K_C \times ET_O$. Current $K_C$ values published for vegetable crops are given based on three growth stages: initial, $K_{Ci}$; middle $K_{Cm}$; and late development $K_{Ce}$ (Allen et al. 1998). Some examples include cabbage ($0.7_i$, $1.05_m$ and $0.95_e$), tomato ($0.6_i$, $1.15_m$ and $0.7–0.9_e$), cantaloupe ($0.5_i$, $0.85_m$ and $0.6_e$), potato ($0.5_i$, $1.10_m$ and $0.65_e$), peas (fresh) ($0.5_i$, $1.15_m$ and $0.30_e$), artichoke ($0.5_i$, $1.0_m$ and $0.95_e$), spinach ($0.7_i$, $1.00_m$ and $0.95_e$) and onions ($0.7_i$, $1.05_m$ and $0.75_e$). Recent studies have confirmed that $K_C$ recommendations need to be more precise both in terms of time and space. Piccinni et al. (2009) developed growth-stage specific $K_C$'s for onions and spinach based on leaf developmental stages in order to further assist growers in maximizing irrigation management. The values obtained for onion in the semi-arid Wintergarden region of Texas under silty-clay soils were: 0.40 (emergence), 0.55 (two leaf), 0.75 (3–4 leaf), 0.85 (5–6 leaves), 0.90 (7–9 leaves), 0.85 (fully developed bulb) and 0.70 (dry leaf). The application of newly-developed $K_C$'s for irrigation management has shown improvements in water use efficiency, yield and quality of short-day onions (Leskovar et al. 2011).

**Table 3.1** Impact of irrigation strategies on water saving, WUE, yield and/or quality of selective vegetable crops

| Crop | Water applied ($ET_c$, mm) |  | Water Saving (%) | WUE (± %) | Irrigation Strategies[z] | Yield and/or Quality Responses | Country | References |
|---|---|---|---|---|---|---|---|---|
|  | Full 100 % | Deficit <100% |  |  |  |  |  |  |
| Artichoke | 614 | 509 | 17 | 8 | DFI + mulch (SDI) | 75 % $ET_c$ decreased yield by 20 % | USA | Shinohara et al. (2011) |
| Tomato | 379 | 204 | 46 | 53 | DFI (DI) | 50 % $ET_c$ did not affect yield but improved fruit quality (TSS and ascorbic acid) | Italy | Patanè et al. (2011) |
| Pepper | 360 | 272 | 25 | 4 | DFI (DI) | 75 % $ET_c$ decreased yield by 23 %. DFI can be used cautiously in water limited regions | Ethiopia | Gadissa and Chemeda (2009) |
| Watermelon | 395 | 298 | 25 | −16 | DFI + mulch (SDI) | 75 % $ET_c$ decreased yield by 36 %, but increased fruit lycopene content by 7 % | USA | Leskovar et al. (2004) |
| Potato | 207 | 128 | 38 | 50 | PRD (SDI) | PRD increased N content, starch and antioxidant activity in tubers, without reducing yield | Serbia | Jovanovic et al. (2010) |
| Onion | 628 | 537 | 14 | −10 | DFI (SDI) | 75 % $ET_c$ caused modest reduction in bulb yield. Flavor and nutritional quality were maintained | USA | Leskovar et al. (2011) |
| Cabbage[y] | 400 | 240 | 40 | 156 | DFI (DI) | 60 % $ET_c$ increased yield by 54 % | India | Tiwari et al. (2003) |
| Cantaloupe[y] | 612 | 381 | 38 | 64 | Mulch (SDI) | Mulch (SDI) increased yield by 40 % | USA | Leskovar et al. (2001) |
| Lettuce[y] | 271 | 171 | 41 | 52 | (SDI) | SDI did not affect yield | USA | Hanson et al. (1997) |

[y] Furrow irrigation was used as control for cabbage, cantaloupe, and lettuce

[z] DFI = deficit irrigation (less than 100 % $ET_c$), SDI = subsurface drip irrigation, DI = drip irrigation, PRD = partial root drying

**Fig. 3.7** Cold tolerant pepper

## Genetic Improvement Targets

As with many crop plants, vegetables have received considerable attention from plant breeders and geneticists over the past 150 years. It was in fact a common vegetable, garden pea that served as the model for Mendel's remarkable experiments establishing the principles of trait inheritance and the foundation for the science of genetics. Dramatic improvements have been achieved for important traits in many vegetable species. Yield, quality and disease resistance have been the attributes of high priority for most vegetable breeders. Advances in molecular biology have been actively applied by plant geneticists in recent years to unravel the complex nature of important qualitative traits at the DNA level. At the same time, many complex traits which may contribute to sustainable production have yet to be characterized genotypically. In some instances this is due to a lack of phenotypic data or methods to generate such data. In other cases, there is not a consensus amongst plant scientists about which traits contribute most to sustainable productivity for a given vegetable crop. Here we will focus on some efforts to identify traits and specific genes which impact the resistance of specific vegetable crops to abiotic stresses (Fig. 3.7).

### *Breeding for Drought Stress Tolerance*

Because most vegetable crops have a relatively high water requirement, drought and water quality are factors which must be addressed to achieve sustainability in most production regions. Genetic improvement for both drought and salt tolerance is the key to sustaining productivity in many cropping systems around the world. The demand for high quality water by urban and industry groups, puts pressure on farmers to use less for irrigation. Natural and human induced salinity of irrigation supplies also limits crop selection and negatively impacts yield and quality.

Extensive research into mechanisms of drought and salinity tolerance has been conducted by plant physiologists for more than 60 years. Recently, geneticists and plant breeders have begun to screen for traits and genes conditioning resistance to these stress factors. Melon and watermelon are very important vegetable crops in warm climates, often produced in regions with both drought and salinity problems. Screening watermelon germplasm by breeders in Turkey, Japan and the USA has revealed genetic variation for drought stress resistance. Wild species of *Citrullus* demonstrated enhanced drought tolerance and produced elevated levels of citrulline. The investigators were able to identify a gene which codes for an enzyme of the deacetylase/carboxypeptidase family, involved in producing free citrulline (Kawasaki et al. 2000). Seedling drought stress screening revealed 25 *Citrullus lanatus* accessions from Africa with high tolerance amongst 1066 germplasm and breeding lines assayed (Zhang et al. 2011). Many of these accessions were from Zimbabwe, with an equal split between domestic (var lanatus) and wild (var citroides) types. These have potential for use as breeding parents to create both cultivars and rootstock lines with enhanced drought tolerance. The author has investigated root vigor and morphology in crosses between cultivated ('Crimson Sweet' and 'Dixie Lee') and wild (var. citroides) watermelon. Extreme heterosis for root length, area, diameter and lateral numbers was observed. Subsequent field trials revealed enhanced tolerance to both drought and vine decline due to *Monosporascus* root rot (Crosby 2000). These lines are currently the focus of rootstock trials in Texas. In Turkey, 85 watermelon accessions were screened for drought tolerance in field experiments with deficit irrigation. Over a third demonstrated drought tolerance based on 9 trait measurements, with one accession rating 99 on a scale of 100 (Karipcin et al. 2008). These drought tolerant genotypes are serving as the basis for development of new watermelon cultivars adapted to deficit irrigation and periodic drought conditions. The shift to smaller fruit size in commercial watermelon markets will complement enhanced drought tolerance traits due to reduced water demand at fruit maturity.

Onion is another major vegetable crop, produced and consumed on a year round basis. Resistance to drought in onion has been documented since ancient times. This crop evolved in semi-arid regions of central Asia. However, breeding has traditionally focused on increasing bulb size, and thus water content of the crop, under irrigated production systems. Survival of onions under deficit or dryland production systems has been demonstrated, but quality and yield are typically sacrificed. The shallow root system of onions suggests that the mechanism for drought tolerance may relate to leaf structure and transpiration more than root absorption capacity (Levy et al. 1981). Specific candidate genes involved in drought tolerance were isolated from leaf tissue of onions based on their homologies to *Arabidopsis* genes (Kutty et al. 2012). Protein candidates based on the sequences included Aquaporin and Calcium-dependant protein kinase. Thus, internal flow of water in onion leaf tissues and modulation of ABA activity may reduce water loss or limit oxidative stress under drought conditions. Selection of genotypes with enhanced expression of such genes could lead to more drought tolerant onion cultivars. Another approach would be to select onion genotypes with enhanced root area and vigor. This has been accomplished in Texas by introgression of resistance to the root destroying fungus *Phoma terrestris*, and selection in dry regions for large, vigorous root systems.

Cultivated tomato is probably the most important vegetable crop on a worldwide basis, and is often grown in arid regions to avoid serious foliar diseases. Breeding for drought tolerance in tomato (*Solanum lycopersicum*) has had limited success, possibly due to the extreme sensitivity of the large fruit to water stress. Investigations into leaf physiology have revealed differences in cell structure between genotypes with greater drought tolerance and more susceptible ones. Thicker leaves, longer palisade mesophyll cells and fewer, larger stomata were found in the more drought tolerant genotypes (Kulkarni and Deshpande 2006). They described a simple selection protocol for these leaf traits to breed tomato cultivars with enhanced drought tolerance. Another investigation of drought responses among different tomato species found no differences in stomatal conductance and leaf water potential, despite diversity in their natural habitats (Easlon and Richards 2009). Lack of shoot and leaf response variation, among the five species, for these traits suggests that other physiological attributes may contribute to drought tolerance. As in melon and onion, root physiology traits may contribute to differences in water uptake from native soil under stress conditions.

## *Breeding for Salt Stress Tolerance*

Salt stress is frequently associated with drought conditions, poor water quality and high pH soils in arid regions. Much progress has been made in breeding agronomic crops for tolerance to salt in soils and irrigation water. More recently, efforts to exploit salt tolerance traits in major vegetable crops have produced mixed results. Inherent salt tolerance is evident in some vegetable species such as asparagus, beets and melons. Efforts to screen germplasm for salt tolerance have yielded positive results for some major crops such as tomato, pepper, and cabbage, but not for onion, carrot and radish (Shannon and Grieve 1999).

Salt sensitivity varies among species depending on the environmental conditions, source of the salts and irrigation method. As many vegetable crops are being grown with drip or other limited irrigation systems, salt damage will likely increase. Flood irrigation helps leach detrimental salts from the soils, but is not sustainable in most regions where population growth is straining available water supplies. Generally, tolerance to sodium salts is more important for many vegetable crops, as calcium and potassium are important nutrients with high threshold levels before negative impacts occur. Screening germplasm and exploiting salt tolerance traits to develop novel cultivars has been successful in certain vegetable species. Variation for salt tolerance in lettuce revealed significant differences among germplasm accessions (Shannon and McCreight 1984), and Romaine types showed greater salinity tolerance than iceberg cultivars (Pasternak et al. 1986).

Salt tolerance in tomato has been investigated for at least 60 years. Wild species of tomato, including *Solanum pennellii. S. cheesmanii,* and *S. pimpinellifolium*, have been documented as salt tolerant by several investigators (Fredrickson and Epstein 1975; Cuartero et al. 1992). Several salt tolerant tomato lines have been developed through inter-specific hybridization and backcrossing between cultivated tomato and these species (Rush and Epstein 1981). Additionally, some salt-tolerant tomato lines have been selected from open-pollinated cultivars over multiple generations of production under saline conditions (Shannon 1997). Recently, candidate genes and QTL (quantitative trait loci) for salt tolerance traits at the seedling and vegetative stages have been discovered (Foolad 2004). Thus, DNA sequence data may be useful for marker-assisted selection to improve the efficiency of introgressing salt tolerance genes from wild species into cultivated tomato.

Peppers are frequently produced in arid regions to achieve optimum fruit quality with minimal pests and diseases. However, soils and irrigation water are frequently saline. Salt tolerance in cultivated pepper, *C. annuum*, is considered moderate, but variation for this trait exists within the germplasm. Aktas et al. (2006) screened 102 pepper germplasm accessions for salinity resistance and found 6 lines with only slight symptoms. Further tests revealed significantly less sodium accumulation in shoots of the 6 tolerant lines compared to 6 sensitive ones. In west Texas and New Mexico, salinity is a constant threat to pepper production, and tolerance is a valuable attribute within the germplasm. In another experiment, 20 diverse pepper lines of *C. annuum* and *C. chinense* were irrigated with a saline solution in pots for 4 weeks as a rapid screen for salt tolerance. Shoot dry weights were not significantly reduced compared to control plants for 6 of the 20 entries and final height was not significantly reduced for half of the entries (Niu et al. 2010). Total plant survival of several entries was also 100 %, while the most salt-sensitive entries had between 33 and 0 % survival. The most salt tolerant entry, 'AZ 20,' was selected in Arizona and New Mexico, under conditions of high salts in both irrigation water and field soils. In addition to breeding salinity problems can be overcome by different conventional ways as reviewed by Plaut et al. (2013).

## *Breeding for Cold Tolerance*

Open-field vegetable production is often subject to extreme temperatures which can inhibit growth, reduce quality and even destroy crops. Tolerance to low and high temperatures is determined by species adaptation, plant health and genetics. Breeding for cold and heat tolerance has been successful in both vegetable and agronomic crops to a limited extent. Tropical origin crops such as cucurbits, peppers, tomatoes and beans have almost no resistance to freezing or frost conditions. By contrast, onions, brassicas, spinach and carrots can withstand periods of exposure to sub 0 °C temperatures. Within species, progress has been made to select cultivars with greater degrees of cold tolerance, even for some tropical vegetables. In onions, Japanese germplasm has been utilized for its inherent cold tolerance, compared to other short day onions. Many of the European brassicas, such as cabbage and kale have greater tolerance to freezing conditions than East Asian brassicas. In tomato, cold tolerance from wild species *S. hirsutum* and *S. pimpinellifolium*, has been introgressed into cultivated tomato to develop some improved lines (Vallejos and Tanksley 1983;

Foolad et al. 1998). In both of these investigations, linkages between some molecular markers and cold tolerance QTL were confirmed in the interspecific populations. These may be useful for marker assisted selection to introgress cold tolerance traits. The emphasis was on seedling cold tolerance as this is an issue for early planting in many locations. Even within the *S. esculentum* germplasm, breeders have exploited cold tolerance traits to enhance flowering and fruit set at lower temperatures for short season regions. Cultivars such as ‘Siberia,’ ‘Sub-Arctic Plenty,’ and ‘Manitoba’ have these attributes.

Cold tolerance in melons has been achieved through traditional breeding as well. Hutton and Loy (1992) identified a cold temperature germination trait in melon and determined that both recessive genes and a cytoplasmic factor were involved. They successfully developed lines with this important trait for regions were direct seeding into sub-optimal soil temperatures is carried out. Edelstein and Kigel (1990) identified some melon accessions that are able to germinate at low (14 °C) temperature, and also have investigated the inheritance of these traits (Edelstein and Nerson 2009). Another investigation into mature melon plant cold tolerance demonstrated the positive impact of heterosis on performance traits under colder than normal conditions. Seven open-pollinated cultivars with above average cold tolerance were intercrossed and the F1 hybrids outperformed the parents under two cold temperature regimes. In cultivated pepper (*C. annuum*), very little cold tolerance exists in commercial types. The wild chile piquin (*C. annuum* var. aviculare) has some resistance to freezing temperatures and grows as a perennial in northern Mexico and south Texas. It may serve as a useful source of cold tolerance genes for breeders. The authors have conducted investigations into freezing tolerance within interspecific families derived from *C. annuum* x *C. baccatum* crosses. The latter species has a natural range that includes high elevations of the Andes in Bolivia and Peru. Preliminary results have demonstrated resistance to temperatures of −3 °C for 6 h in these lines. Backcross introgression and genetic studies of the cold tolerance genes is underway.

### *Breeding for Heat Tolerance*

Heat tolerance may be even more important for sustainable vegetable production, considering that many countries within the tropics struggle with food security issues. Though cucurbits, solanaceous crops and many other vegetables originated in tropical regions, not all are capable of yielding good crops in lowland areas or in the warmest growing periods. Adaptation to higher temperatures has occurred through human selection, but needs continued efforts. Quality of heat tolerant cultivars is often inferior to crops grown at optimum temperatures. Heat tolerance in tomato has been the focus of extensive breeding efforts in Texas, Florida and Taiwan. Heat tolerant, large fruited cultivars have been released by both Texas A&M and the University of Florida (Leeper and Cox 1986; Scott et al. 2006). High temperature pollen stability and fruit set are traits which permit these cultivars to yield even when day and night temperatures are high.

Heat tolerance also exists within pepper germplasm of cultivated species. The pepper breeding and physiology programs at Texas A&M University (TAMU) have investigated heat tolerance for the last 40 years. Thermo-stability of pollen and ability to develop flower buds at high temperatures are key traits present in heat-tolerant cultivars. Several cultivars, including bell, jalapeño, serrano, mild green chile, and habanero types have been released by TAMU for warm climates. Yields and plant growth are superior to many heat sensitive commercial cultivars in south Texas and other warm regions (Crosby and Villalon 2002; Crosby et al. 2010). Additional work on pepper heat tolerance has been conducted in other warm climate locations, such as Taiwan. Saha et al. (2010) investigated the response of different sweet peppers to high day/night temperatures and found clear differences in yield and fruit quality. Additionally, leaf proline content of heat-tolerant lines was found to be higher than in heat-sensitive ones. This could be a useful marker for breeding programs.

## Marketing

### *Defining Marketing*

Marketing is one of the most important factors in determining the success of any vegetable farming enterprise. However, vegetable growers and business managers usually tend to only associate marketing with either selling or advertising and promoting their products. Those two functions are an important part of a long and comprehensive decision making process called marketing. Marketing can be defined as the process of business activities designed to plan, price, promote and distribute products that satisfy the needs of current or potential customers while achieving the business objectives. The overall and main objective of any vegetable farming operation is to generate profits. While strategic marketing does not guarantee profitability it provides the necessary tools to gather information and make more informed decisions.

The decision making process starts before planting any vegetable seeds, by deciding which vegetables to grow, when to grow, and what quantities to produce to satisfy market requirements. In the traditional supply chain, marketing activities are viewed as the necessary steps to deliver the products from the farm to the consumer's plate. The modern marketing definition requires putting the consumer as the first and major emphasis in the marketing planning process. The process starts by identifying consumer trends and preferences for vegetable products, including varieties, sizes, colors, texture, labels, and packaging. Then, the manager plans the operations required to meet the consumer expectations for the products and services. It is important to keep in mind that it is always easier to sell consumers what they want to buy, rather than growing the products and then trying to find a buyer for it (Fig. 3.8).

**Fig. 3.8** High quality artichoke head

## *Vegetable Consumption Trends*

Total per capita consumption of vegetables in the USA increased from 336.8 pounds per year in 1970 to 424.6 pounds in 2000. This change represents a 26.06 % increase over that period. Since then, per capita vegetable consumption has decreased 7.94 % to 390.9 pounds in 2009 (Anon 2012b). Even with this decline the vegetable industry has been experiencing overall growth in the last decade. There are four main factors for this growth:

a. *Increase in population*. The USA population grew 8.89 % in the last decade from 282.4 million in 2000 to 307.5 million in 2009 (Anon 2012b).
b. *Increased consumer interest for non-traditional/exotic foods*. There has been an overall trend of increased consumption of non-traditional vegetables. This may be explained in part by the increasing demographic diversity in the USA and increasing demand for specialty niche products. One of the main obstacles why consumers are not willing to try new products is lack of knowledge about preparation and cooking of certain vegetables. During the last decade there have been several advances in food preparation mass education to consumers. There are currently several television networks devoting airtime to teach consumers how to prepare and mix non-traditional foods. As a result, there has been an increase in the demand for these products.
c. *Technological advances in the supply chain*. Advances in production, transportation and storage of the cold supply chain of vegetable products have allowed the industry to become more global. International trade of vegetable products has increased substantially in recent years. The share of US consumption derived from imports more than tripled from 8.3 % in 1980 to 25.0 % in 2010 (Anon 2012c).
d. *Year-round demand*. The global nature of the produce industry with movements of products, literally all over the world, has changed the consumer's view of seasonality of vegetable production. Consumers have become accustomed and expect to find most fruit and vegetable products available at supermarkets, retail stores and restaurants all year long.

## *Supply and Demand Macro-Trends*

At the beginning of the twentieth century, most vegetable products were sourced locally. Advances in infrastructure, transportation and the cold supply chain have converted the horticulture industry into a global activity. In spite of the perishable nature and weather conditions necessary to grow fruit and vegetables, technological advances have translated into increased efficiency of production, transportation and storage and a reduction in the cost of producing vegetables. Seasonality of production has allowed opportunities for certain regions to specialize in fruit and vegetable production for specific market windows where prices are usually higher due to a limited supply. Market window analysis helps match the demand for a product when the supply of that region is limited or restricted due to climatic differences that translate into significant increases in the cost of production.

There are certain factors in the vegetable industry that have the potential to make big structural changes and create considerable opportunities for growers all over the world. These factors are referred to here as produce macro-trends, due to the global nature and potential implications in changing the structure and paradigm of the produce industry.

a. *Demand for organic products*. The demand for organic foods has remained strong and continues to grow. According to Baginski (2011), total organic sales in the USA were estimated at $ US 23.4 billion in 2010. The produce industry was the top selling category and accounted for 37 % of total sales in 2008.
b. *Increased consumer interest in the origin of the products with an emphasis on local.* There is increasing consumer interest about the origin of fruit and vegetable production. Even though there is no generally accepted definition of local, and the term has different connotations to different people, locally grown products are becoming more important to consumers (McGarry et al. 2005). The number of farmers' markets in the USA has grown substantially from 340 in 1970 to 7,175 in 2011 (Anon 2012a). Total local food sales by farmers in the USA were estimated to be at $ US 4.8 billion, including $ US 887 million in direct-to-consumer sales, $ US 2.7 billion in intermediate marketing channels only, and $ US 1.2 billion through markets with both direct and intermediate channels (Anon 2008). The rapid increase in the number of farmers' markets is attributed not only to changes in consumer tastes and preferences and changes in the economics of agriculture, but also to the passage of the Farmer-to-Consumer Direct Marketing Act of 1976 by the USA Congress (Brown 2001).
c. *Food safety.* A proliferation in the number of food-borne illness outbreaks around the world has brought more attention to food safety in the produce industry. In the USA, the spinach outbreak of 2006 changed the consumer's view of food safety for the vegetable industry (Palma et al. 2010). As a result there have been many changes to both industry and government driven standards to ensure a safe food supply (Knutson and Josling 2009). The 111th Congress enacted the Food and Drug Administration (FDA) Food Safety Modernization Act (FSMA), which was signed into law by President Obama on January 4, 2011. This is the

first comprehensive reform of FDA food safety policy since the Federal Food, Drug, and Cosmetic Act was enacted in 1938. The most important policy change contained in the FSMA is that it authorizes and mandates that the FDA pursue a science-based and a risk-based food safety policy (Knutson and Ribera 2011).

d. *Functional foods for healthier lifestyles*. According to the American Dietetic Association, functional foods "include whole foods and fortified, enriched, or enhanced foods that have a potentially beneficial effect on health when consumed as part of a varied diet on a regular basis, at effective levels" (Hasler and Brown 2009). The functional food market was estimated at $ US 39 billion in 2010. There has been an overall change in the consumer's paradigm from using functional foods as medicine and disease-prevention, to a more comprehensive approach that views food as part of a healthy lifestyle in combination with exercise and other health promoting activities. Palma and Jetter (2012) found that the actual levels of consumption of fruits and vegetables were significantly lower than the recommended intake levels of the Dietary Guidelines for Americans (DGA) released in 2010. Ribera et al. (2012) point out that if consumers were to increase their consumption of fruits and vegetables in response to the DGA recommendations, the total supply of vegetables would have to increase 114 % to satisfy the increased demand. They projected the majority of the increase in supply would come from horticulture production areas domestically and overseas.
e. *International trade agreements.* There has been an increase in the number of trade agreements with several of them still pending negotiations. The worldwide volume of agricultural products traded has had an average annual increase of 3.8 % since 1990. The total value of agricultural products exported worldwide in 2010 was estimated at $ US 1.36 trillion (Anon 2011). The USA has trade agreements with Mexico and Canada (North American Free Trade Agreement), Central America (Central America Free Trade Agreement), Australia, Bahrain, Colombia, Chile, Israel, Jordan, Korea, Morocco, Oman, Peru, Singapore, and a pending agreement with Panama.

## Prospects

Large-scale vegetable production in open fields has evolved rapidly with improvements in technologies and use of resources. The diversity of production is highly dependent on weather conditions and crop input requirements. Commercial farmers now efficiently select, integrate and monitor environmental variables and preharvest production factors such as geographical location, weather conditions, soil and water resources, new cultivars, seed technologies, precision seeding, transplanting, grafting, irrigation systems, soil and canopy sensing technologies, fertilizer placement, mechanical harvests, crop protection strategies and food safety management. In fact more than 90,000 farmers in the world now follow standard field production practices as part of the voluntary Global Good Agricultural Practice or GlobalGAP program. The integration of new technologies has dramatically improved the quality of fresh produce with impressive yield gains per area of cultivation. High demand for more nutritious and healthier diets has also contributed to the vertical integration of large farmers. The future outlook for intensive open-field vegetable production is promising, as a 65 % increase in production was recorded between 1990 and 2009 (Anon 2012e). However, large scale production can be very cyclical and heavily dependent on global demands, trades, price structure and year-round availability.

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# Chapter 4
# Temperate Fruit Species

**Guglielmo Costa and Angelo Ramina**

**Abstract** Temperate fruit areas are located between 30° and 50° of latitude in the Northern and Southern Hemispheres. In addition, temperate fruit species may expand near the Equator using species and/or varieties with low chilling requirement or at high elevation to assure chilling requirement. The growing areas of the main temperate fruit species are listed and briefly characterized. The life cycle of a deciduous tree propagated from seed is classically divided into juvenility, maturity and senescence. In the fruit industry, juvenility is overcame by means of vegetative propagation based either on cutting and/or on grafting, using mature plant material. The reproductive cycle of a temperate fruit trees lasts 9–15 months and is peculiar since in the temperate areas it involves two subsequent growing seasons. In the deciduous species, reproduction starts with phase transition in the first growing season and ends up with the seed maturation and fruit ripening in the second one. Physiological and molecular aspects of flower differentiation, micro- and macrosporogenesis, bloom, pollination, mechanisms preventing self—fertilization, seed and fruit development and ripening are discussed.

**Keywords** Chilling · Dormancy · Juvenility · Maturity · Senescence

## Definition and Classification of the Temperate Fruits at World Level

The latitude between 30° and 50° includes, in the Northern Hemisphere, most of Europe, Northern Africa, most of Asia Minor, the Eastern States of the Russian Federation, the United States of America, Southern Canada, Japan, Central

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and Northern China, Manchuria and Mongolia, and, in the Southern Hemisphere, Southern South America, the tip of South Africa, Southern Australia, Tasmania and New Zealand. Temperate fruit culture in marginal areas (Tropics and Sub-Tropics regions) requires special horticultural practices and the use of specific genotypes (cultivars with low chilling requirement). The temperate deciduous trees or shrubs respond to seasonal changes in a number of ways depending on the extent to which their internal physiology is affected by external environment. If the plant is suited to a climate, each environmental change as light, temperature and gravity is perceived and transduced to morpho-physiological change. The plant response to environmental changes is mediated by internal signals such as the classical hormones (IAA; GGAA; CK; Ethylene, ABA), peptides hormones, small interfering peptides, small RNAs, sugars, etc.

The seasonal changes deeply affect deciduous trees behaviour determining a precise cycling of phases of intensive growth and rest. During the spring and the early summer, the phenology of the tree opens with the bud-break and the shoot elongation. Shoot length, strongly affected by day-length (LD = long day), is made up by pre-differentiated and newly formed phytomers. During the summertime, when a shortening of the photoperiod occurs, shoot growth rate decreases due to a progressive reduction of the internode length, while the morphogenetic activity of the meristem continues. The progressive shortening of the internode determines the formation of the terminal bud, which is a good indication that the meristem and, actually, the tree are entering in the rest phase, which is defined by reduced metabolic and morphogenetic activity of organs (buds, tissues and cells). It is also conveniently defined as a dormancy that from a functional point of view can be distinguished in endo-, eco- and para-dormancy.

The endo-dormancy is induced by a shortening of the photoperiod occurring during the middle-late summer. The shortening of the photoperiod is perceived by light receptors (phytochromes and cryptochromes) that through specific signalling pathways negatively affects GA biosynthesis and positively stimulates abscisic acid (ABA) production. GAs and ABA are the two main actors regulating the establishment of the endo-dormancy, although the role of other hormones cannot be ruled out. The establishment within the tree of the physiological syndrome relates to dramatic morphological changes, particularly evident in the aerial part of the tree and including formation of terminal buds, leaf senescence and abscission, structural cellular changes leading to a block of the symplastic network.

The overcame of endo-dormancy is determined by chilling. The chilling requirement of a variety is an important characteristic since it defines the cultivation areas of the temperate fruit species. It has been shown that it is a quantitative polygenic trait controlled by specific QTLs. This notion allowed the constitution of low chilling varieties and the introduction of some fruit species in marginal areas. When the chilling requirement has been coped, the trees shifts from endo-dormancy to eco-dormancy, a phase characterized by reduced metabolic and morpho-genetic activity due to a lack or reduced accumulation of heat. All the main phenological stages, such as bud-break, fruit bud development, and anthesis, are characterized by species/genotype-specific heat requirements. Heat accumulation might be quantitatively expressed as GDH (growing degree hours) and GDD (growing degree days). GDH is defined as 1 h at an actual temperature of 1 degree above a base threshold of 5 and 10 °C in early blooming species (all the *Rosaceae*) and in late blooming species (kiwifruit, grape, etc), respectively. GDD (growing degree days) is defined as the difference between the average daily temperature and the base threshold define above. GDH are conveniently used from bud-break up to anthesis, while GDD for fruit development up to ripening.

Climatological predictive models based on the dynamics of chill (chill unit-CU) and heat (growing degree hours-GDH) accumulation have been developed.

The para-dormancy is defined by the reduced metabolic and morphogenetic activity of one organ due to impediments external to the organ itself but within the tree. The apical dominance referring to apical and lateral meristems or apical and lateral buds relies on para-dormancy as all the correlative inhibitions existing within the tree.

The main temperate fruit species belong to the *Rosaceae* family and include pomefruit (apple, pear, quince), stonefruit (peach, nectarine, apricot, plum, almond, etc.) as well as other species belonging to different families as walnut, hazelnut, pecan, pistachio, chestnut, olive, fig, persimmon, grape, strawberry, raspberry, blackberry, blueberry, cranberry, currant and gooseberry, kiwifruit and some minor crop as pomegranate, jujube, juneberry and the northern papaya. In Fig. 4.1 the acreages and the yields of the main temperate fruit species are reported.

## Main Temperate Fruit Species

The general climatic requirements are given below for the main temperate fruit species.

*Apple* The domesticated apple (*Malus* × *domestica*) originated in the Caucasus region of South-Eastern Europe and possibly South-Western Siberia is one of the hardiest temperate zone fruits. The winter chilling requirement of the most commercial varieties is indicatively 1,700 h. The growing season can be as short as 140 days for some varieties, thus extending its growing areas to the higher latitudes.

*Pear* European cultivated pear (*Pyrus communis*) probably developed through selection of the wild pear (*Pyrus caucasica*) of South-East Europe, whereas Asian cultivated pear derived from *Pyrus pyrifolia* and *Pyrus ussuriensis*. Western pear varieties are somewhat less hardy than apple, so they cannot be grown at high latitudes. The chilling requirement for most pears is ranging from 500 up to 1,500 h. The *Pyrus pyrifoglia* varieties and its hybrids usually require less than1,000 h, thus are adapted to lower temperate latitudes. Pears perform well in a warm to hat arid summer. Low humidity helps in controlling fireblight, a bacterial disease caused by *Erwinia amylovora*, to which most pear and apple varieties are susceptible. The growing season varies from 100 to 180 days depending on the varieties.

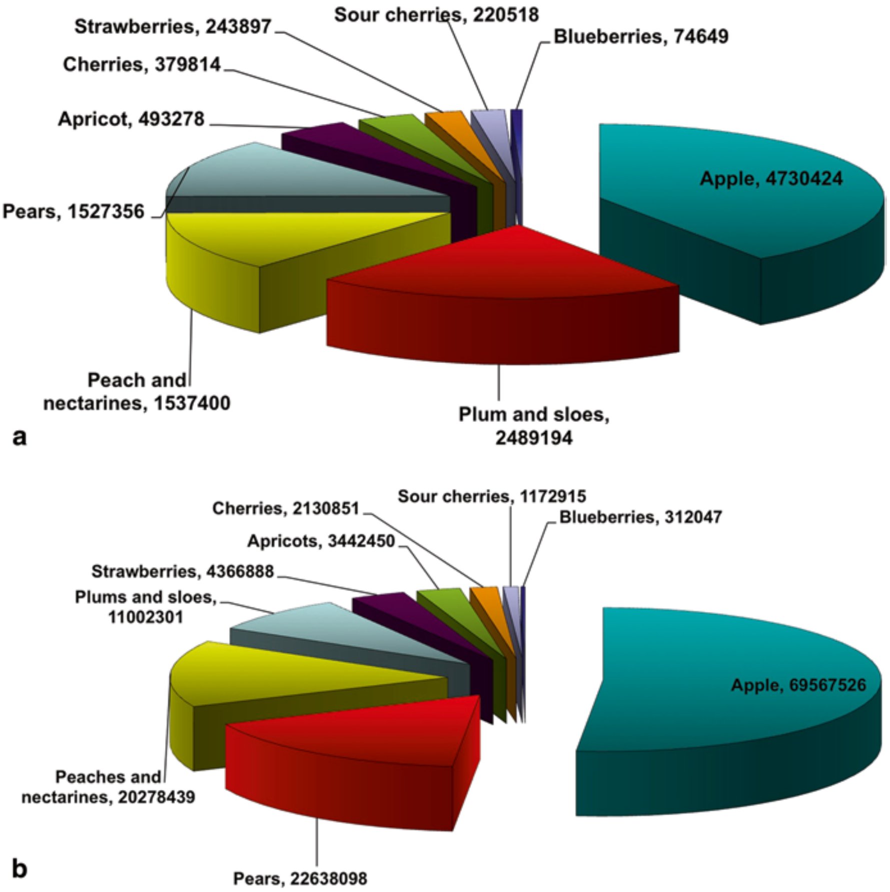


**Fig. 4.1** World acreage (**a**) and yield (**b**) of the main temperate fruit species

*Peach* The peach (*Prunus persica*) is native to the warmer areas of China, it thrives in hat summer climates and it is only moderately winter hardy. Flat peaches from Southern China are semi-evergreen and have a very low chilling requirement. They are used in some breeding program to obtain low chilling varieties for the subtropic. Peach varieties have a modest chilling requirement from about 400 to 800 h. They are less hardy than apple and pear and are grown mostly in lower temperate latitudes. Since peach blooms 20 days before apple, it should be planted in areas free of early spring frost.

*Cherry* The sweet cherry (*Prunus avium*) originated in the Caucasus between Black and Caspian seas. Sweet cherries are susceptible to brown-rot and should be grown where it is too cold or dry for the disease to develop. This fruit crop may grow in climates that are too cold for peach and apricot. Thus, areas with good winter moisture and dry cool summer are ideal. Cherry fruits ripe early, so irrigation is usually not needed in many areas. The firm cherries are more susceptible to fruit cracking than soft flesh varieties, so areas with low incidence of early summer rain are preferred. Sweet cherry trees are more hardy than peach but less than pear and plum. Cherry varieties have a chilling requirement ranging from 900 to 1,200 h.

The sour cherry (*Prunus cerasus*) originated from the same area, is mainly cultivated for processing industry, and is less susceptible to fruit cracking, so it can be cultivated in areas with a higher incidence of rainfall. In general, sour cherries are hardier than the sweet ones.

**Plum** At least 6 species of plum are commonly grown, but the most important are *Prunus domestica* and the Asian Plum, *Prunus salicina*. The *P. domestica* probably originated in South-Eastern Europe and is widely planted at middle latitudes. It is as hardy as common pear and requires 140–170 days to mature the fruits. It has a quite valuable chilling requirement ranging from 800 to 1,100 h. Asian plum is usually less hardy and requires less chilling than the European ones. Asian plum fruit mature earlier than the *Prunus domestica* ones, and orchard must be established on frost free sites, since it blooms very early. Other plum species from Europe and North America are about as hardy as apple, and they can grow at middle to high temperate latitudes.

*Apricot* Apricot (*Prunus armeniaca*) originated in China, Manchuria and Siberia. It requires less winter chilling than peach. Many varieties are hardy when grown at high latitudes, but are often injured by late winter freezes at lower-middle latitudes areas. Like most high latitude species with low to moderate chilling requirement, endo-dormancy is overcome by middle winter after which buds swell and deharden to early in middle latitude, and bloom is very early and subjected to spring frost. The crop mature in 100–120 days.

*Almond* Almond (*Prunus amygdalus*) originated from Western Asia. Almonds are among the first specie to bloom and area where moisture is high, fruit set can be negatively affected. In general, almond in hot Mediterranean areas 180–240 days are required to mature the nuts. Almond are less hardy than peach.

*Olive* Olive (*Olea europea*) is native to Mediterranean areas of Syria, Greece and North Africa. The tree needs considerable winter chilling and hot growing season to produce yields of high quality fruits. During bloom, however, extreme conditions such as high temperatures, dry winds and wet cool are undesirable. Frost killing occurs below about $-11\,^{\circ}\mathrm{C}$. Since ripening occurs at the middle/end of fall in Northern hemisphere, fruits can be injured by frost.

*Strawberry* Strawberry is derived mostly from the new world (*Fragaria virginiana and Fragaria chiloensis*). It is widely adapted because of its low chilling requirement and small plant size, which allow the cultivation under plastic tunnels to protect plants against winter freeze. In subtropical climates, strawberry can be grown as an annual and will crop from early spring until late fall. Because a fruit matures in 30–40 days, the strawberry can be grown at higher latitudes than those required by many other fruit species.

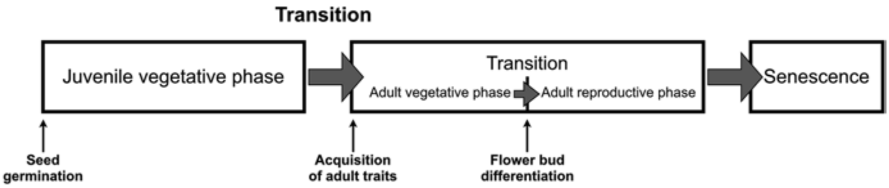


**Fig. 4.2** Diagram representing the different phase transitions occurring during the whole life cycle of the tree

## Life Cycle of a Deciduous Tree

The life cycle of a deciduous fruit tree propagated from seed is classically divided in three ontogenetic stages, named juvenility, maturity and senescence (Fig. 4.2). Each of these may last for several years.

### *Juvenility*

Juvenility starts with seed germination and ends when the physiological maturity of the shoot apical meristem is attained. The vegetative development of a juvenile tree is quite intense as far as the meristem activities are concerned. The tree displays a great sensitivity to gravity, a monopodial branching and a strong apical dominances, controlling lateral meristem development. This physiological behaviour leads to a basitonic development of laterals, to a cone shaped canopy and to a main root development controlling the lateral ones. The aerial part is made up by growth units characterized by a high growth rate and shoots are made up of preformed phytomers in the proximal part, and newly formed in the distal one. Laterals might be either of proleptic or proleptic and silleptic origin in case of strong or weak apical dominance, respectively. The morphology of leaf and lateral shoot might be quite divergent from that of adult tree. Multiple leaves characteristics of the juvenile phase might evolve to simple leaf at maturity, as well as the leaf margin in which indentation might change from the juvenile to the adult phase. Juvenile lateral shoot in the *Rosaceae* family might be thorn-like. Some of the juvenile features are of horticultural interest, for example the English ivy (*Edera helix*) is used as a ground covering plants because of its plagiotropic behaviour. An additional useful feature is represented by the higher rooting ability of the juvenile plants as compared to the adult ones, which is largely exploited in the nursery industry for rootstock production. The juvenile phase represents the complex physiological syndrome not yet characterized in which growth-controlling internal factors are involved. It is clear that the shoot apical meristem has the ability to measure the gaining of the ontogenetic experience accumulated throughout development. Practically, the ontogenetic experience may be evaluated by counting the number of phytomers progressively differentiated. The overcoming of the juvenile phase and the attainment of maturity occurs only after the differentiation of a critical number of phytomers, which is relatively low in the case of annual plants but much higher in woody species, where juvenile phase may last for several years. The juvenile phase length is a polygenic trait controlled by several QTLs, which appear unstable throughout development. Pioneer work in *Arabidopsis* demonstrated that the length of the juvenile phase is controlled by miRNA 156 and 172 targeting the transcription factors SPL and AP2-like, respectively (Bäurle and Dean 2006; Wu et al. 2009). These genes could be used to overcome juvenility. Recently, through the over-expression of the *FT* gene controlling phase transition, it was possible to shorten dramatically the juvenile phase in apple seedling (Tränkner et al. 2010).

It is clear that the presence of a long juvenile stage is a big constraint in breeding programs focused to improve fruit quality traits, since the progeny needs to be maintained up to the attainment of the physiological maturity. The cost reduction of such programs may be pursued by accelerating the seedling development by keeping them under continuous growth conditions. By means of this technique, it was possible to attain apple seedling maturity in 20–30 months. An additional system for reducing the costs would rely on the isolation and characterization of gene sets related to the traits of interest. These genes could be used as genetic markers in Marker Assisted Selection (MAS) programs allowing the evaluation of the progeny already at seed or early seedling level.

### *Maturity*

The gaining of the physiological maturity, related to the accumulation of a critical ontogenetic experience, allows the shoot meristem to become responsive to external and internal factors that may induce its transition from the vegetative to the reproductive phase (Poethig 2003). In case of monopodial branching, the apical meristem is the earliest to reach maturity. Within the canopy, maturation is established according to a hierarchy reflecting the age of the meristem and moving from external to inner shoots, according to a basipetal gradient. The attainment of the physiological maturity appears to be an irreversible process, maintained throughout development even though the meristem is grafted on a different rootstock. This behaviour is exploited in clone propagation through the grafting of mature buds on rootstocks which are usually in a juvenile phase. A regression of the shoot meristem from the adult phase to juvenility may occur as a consequence of traumatic events or chemical treatment. For example, thiazols sprayed at high concentrations may revert adult meristem to the juvenile phase, inducing the formation of juvenile leaves and modifying laterals in thorn-like structures.

The adult phase lasts for several years and is characterized by a balance between vegetative and reproductive activity. The latter consists of two overlapping independent reproductive cycles: one is related to the pending crop and the other one to the opening of the reproductive cycle that will be concluded in the following growing season. The concurrent presence of these reproductive cycles may generate problems since a balance between the two activities has to be achieved to avoid biannual bearing and to guarantee good yield quantity and fruit quality. The yield is strictly dependent upon the carbon source and the energy metabolism basically generated by the canopy, resulting from the vegetative activity of the tree. Since excessive shooting may negatively affect fruit bud differentiation and fruit development, the vegetation should be finely controlled to achieve the proper balance between vegetative and reproductive activities. On the contrary, an excessive fruit load may be detrimental for an inadequate canopy development, for current year fruit quality and for flower bud differentiation. The criteria to achieve a vegetative/reproductive balance are quite complex and depends primarily upon rootstocks and cultivars. For example, the use of standard or spur/compact type cultivars may require completely different management approaches to achieve best results in terms of cropping. The maturity is the longest phase of the tree life cycle and the most important for the economic return of the orchard.

### *Senescence*

Senescence is the last phase of the plant life cycle. It is a physiological syndrome that in monocarpic species becomes established in the plant very early during the transition phase, long before the differentiation of flower structures. In this case, the term used is "overall senescence" because all the plant body dies with the exception of the seeds which are in turn responsible of the species survival. In the case of polycarpic species, senescence is not related to transition phase but is regulated by different mechanisms changing according to the type of organ undergoing senescence. In the case of fruit trees species, the term "deciduous senescence" is adopted. The syndrome occurs at the end of each growing season and affects only leaves and fruits while the tree woody structure is maintained trough years. Organs undergoing shading are usually depleted of the plastic substances which are mobilized to and accumulated in storage parenchyma, and used to support the tree phenology in the following spring. The total senescence concludes the tree life cycle also in fruit trees, as a results of a process of aging that affect all the tree body. At the end of the adult phase, the tree slowly enters the senescence phase. The syndrome is established slowly and progressively manifested by reduction of meristem activity leading to a reduced number of phytomers, a slowdown of growth potential and an increase of the ratio between short and long shoots.

## The Biology of a Fruit Tree

### *The Adult Vegetative Phase*

Although orchards are made up of trees in adult phase, flower bud differentiation remains an alternative developmental path occurring only under proper external and internal conditions. If the flower bud differentiation does not occur, meristems follow the vegetative path differentiating vegetative phytomers, each made up of leaf primordia, axillary meristems and subtending internodes. In young orchards, the presence of an adult vegetative phase is essential in order to build in the shortest period the tree woody final structure and made the tree to fill up the assigned space. Only after this goal has been achieved, the reproductive development should be encouraged, keeping in mind that a certain degree of vegetative activity should be maintained throughout the orchard life, since a proper canopy development is necessary to provide energy for the fruit tree functions. As soon as the tree has reached the final structure, a balance between vegetative and reproductive activity should be maintained. In some cases, this could be difficult; in fact, in presence of vigorous rootstocks and cultivars, an excessive vegetative development could occur. In this case, the grower should depress vigour by means of growth retardants, shoot inclination and bending, canopy and root pruning, mineral nutrition, irrigation, etc. On the contrary, when the orchard is made up of dwarf rootstocks and/or spur or compact habitus varieties, the balance is in favour of the reproductive development with a limited vegetation. In this case, the vegetative activity should be stimulated by means of a proper pruning, avoiding the natural acceleration of senescence affecting these genotypes. In a modern fruit industry, high density planting is widely adopted in addition to the use of dwarfing rootstocks and spur or compact habitus varieties.

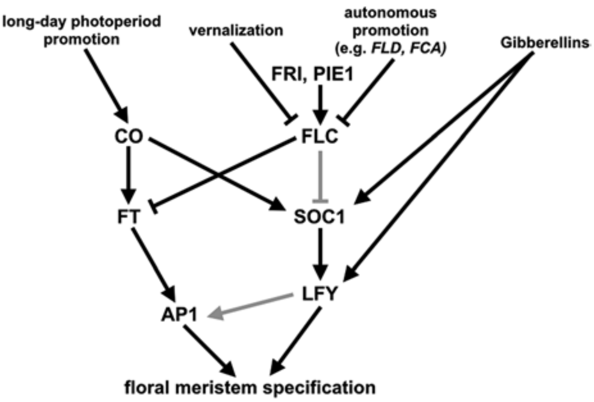
## *The Reproductive Phase*

### Transition Phase

In the deciduous species of temperate areas, reproduction starts with the transition phase and ends up with seed maturation and fruit ripening. This reproductive cycle involves two growing seasons. During the first one, transition phase of the meristem occurs, and inflorescence and flower differentiation proceed up to pollen mother cell formation. At this developmental stage, the flower differentiation stops concurrently with the establishment of endo-dormancy. During the second season, endo-dormancy is overcome, and reproductive structure differentiation is resumed up to anthesis. In evergreen species the reproductive cycle progresses continuously.

Transition phase implies a switch of the genetic program in the shoot meristem from vegetative to reproductive conditions. Several genetic studies carried out in model plant species allowed the identification of genes involved in transition phase leading to definition of LD, SD, autonomous and temperature dependent flowering pathways. GAs may interfere with LD and the temperature dependent pathways. The complex of the genetic studies led to the identification of *LEAFY* (*LFY*) and *APETALA1* (*AP1*) as flower meristem identity genes (Jack 2004). In plants, the transition phase appears to be related to the activation of the *FT* gene, whose

**Fig. 4.3** Major floral inductive pathways. Signals from the four major floral inductive pathways are integrated by FLC, SOC1, FT, and LFY. Interactions demonstrated to be direct are indicated in gray. (Jack 2004)



corresponding protein, produced at the level of leaf vascular system, moves up to the shoot apical meristem where it modulates the expression of *LFY* and *AP1* (Fig. 4.3) FT is a reminder of the elusive flowering hormone (florigen), whose presence was hypothesized more than 60 years ago.

## Flower Development

The temperate fruit species belonging to *Rosaceae* family share a unique flower structure characterized by a calyx, made up of 5 sepals, a corolla with 5 petals, several stamens, one monocarpellar or pentacarpellar pistil in the stone- and pome-fruit species, respectively. Within the *Rosaceae*, the peach has been assumed as a model taking into account that it has a diploid genome with a size similar to that of *Arabidopsis* (300 Mb). Moreover the two species belong to the same taxonomic subclass (rosids) and several genes, so far characterized, share similar structure and function. Based on this consideration, the flowering models elaborated in *Arabidopsis* may be applied to peach *in primis*, as well as to other rosids.

Flower organ development is controlled by genes that were originally related to the ABC model, further implemented to a ABCDE one. The 5 dominia include the homeotic genes *AP1*/2 (A), *AP3* and *PI* (B), *AG* and *SHP1/2* (C), *STK* (D) and *SEP* (E). All these genes encode transcription factors regulating the flower organ formation: *AP1*/2 control sepals, *AP1*/2 and AP3/*PI* control petals, *AP3*/*PI* and *AG*/*SHP1*/2 control stamens, *AG*/*SHP1*/*2* control ovary and *AG/SHP1/2* and *STK* control ovules. *SEP* genes interact with all the previous homeotic genes in the flower formation. All the previous proteins, except for AP2, act in association with each other forming tetramers (Fig. 4.4).

In the deciduous fruit species, phase transition occurs in the growing season preceding that of bloom. The time of transition may change according to the species

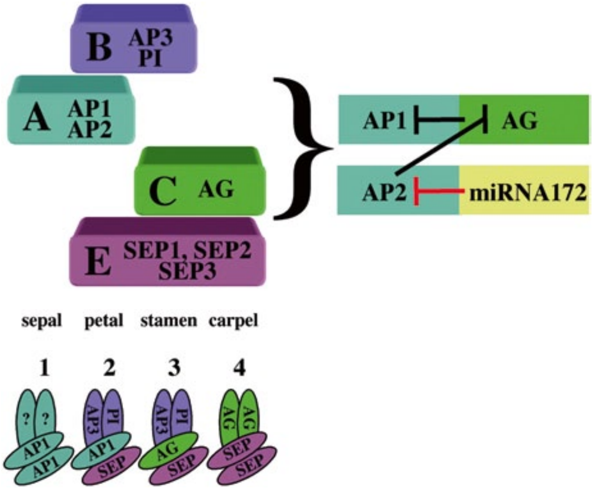


**Fig. 4.4** The revised *ABC* model of flower development. *A, B, C*, and E are four activities that are present in adjacent whorls of the flower. These four activities are postulated to function combinatorially to specify the identity of the four organs in the flower: sepals, petals, stamens, and carpels. A second major tenet of the *ABC* model is that *A* and *C* activities are mutually repressive. The specific molecular interactions between *A* and *C* class genes as well as their regulators are shown at *right*. The majority of *ABC* genes encode MADS domain transcription factors. Recent evidence suggests that MADS proteins function together in complexes larger than a dimer. The "quartet" model postulates that tetramers of MADS proteins specify floral organ identity (shown as colored ovals). Interactions demonstrated to be direct are indicated in *red*. (Jack 2004)

and to the type of shoot carrying reproductive structures. In species carrying inflorescences, differentiation leads primarily to the formation of inflorescence axis, which is controlled by *TFL* (*Terminal FLower*). The expression of *TFL* appears to be incompatible with that of *LFY* and *AP1*, which are flower meristem identity genes.

Flower organ differentiation proceeds rapidly after transition phase, so that all the flower parts are distinctly formed in many species by the time the tree enters into endo-dormancy. During the rest period, the differentiation process is blocked or proceeds very slowly up to the pollen mother cell formation, which is the most advanced stage of differentiation. When endo-dormancy is overcome, microsporogenesis occurs while, at the ovary level, differentiation is resumed and progressively continues up to ovule differentiation and embryo sac development, event that occurs in correspondence or immediately before anthesis. In the case of grape, the reproductive development is clearly time regulated. During the first growing season, the transition phase is followed by the differentiation of the inflorescence axis. Flower formation occurs only in the second growing season and starts when the endo-dormancy is overcome and the heat threshold achieved the critical level required for differentiation.

## Microsporogenesis and Pollen Differentiation

The anther hosts the microsporogenesis and male gametogenesis (McCormick 2004). The spore producing tissue is organized in four microsporangia evolving in four pollen sacs. Each of the microsporangia is surrounded by the tapetum, the tissue playing important functions in controlling pollen development and in releasing information essential for proper pollen/stigma interactions. In each microsporangium, the microspore mother cell differentiation occurs. Before meiosis this cells undergoes a cell wall callose deposition. Tetrads are formed after the meiosis and the spores will be released from the tetrads upon enzymatic digestion of the callose deposited on the external wall of the tetraspore. Each free microspore experiences an asymmetric mitosis forming the male gametophyte made up by two cells, one large and the other one small, named vegetative and generative cell, respectively. The generative cell is progressively surrounded by the vegetative cell and later on undergoes normal division forming the two sperm cells. This can happen at anther level or after pollination. Referring to the timing of this event, pollen of different species are usually classified as bi- or tri-nucleated, although at the end of differentiation the pollen of all angiosperms are tri-nucleated. The pollen cell wall is formed by an inner and outer layers, named intine and exine, respectively. The latter undergoes deep modifications throughout deposition, giving rise to pollen sculptures which are genotype specific and used as a taxonomic trait to recognize different species and varieties. The majority of the genes expressed in the pollen are shared by the sporophytic tissue. It has to be underlined that when the pollen leaves anthers, the complete transcriptome necessary for pollen germination and pollen tube development is already present in the vegetative cell.

## Macrosporogenesis and Ovule Formation

Female macrosporogenesis occurs in the ovule within the pistils (Yadegari and Drews 2004). The ovule originates from the carpellar leaf, in marginal or central position, from the placental tissue. It is made up by the nucellus surrounded by the inner and outer integuments, that develop toward the apical part of the nucellus defining the micropilar region. In opposite position to the micropyle, at the base of the nucellus, is located the chalaza. Within the nucellus, the megaspore mother cell after differentiation undergoes meiosis generating four megaspores. Three of these, located at the micropylar site, undergo degeneration, while the basal one, after three subsequent mitotic divisions, originates the embryosac (the female gametophyte). At the beginning, the embryosac is an 8 cell structure composed, moving from the micropylar to the chalazal region, as follow: in the upper part are the synergids and between them the egg cell. Below, in the central part are the upper and lower polar cells whose nuclei fuse shortly after division, and at the chalazal site, the three antipodal cells. The female gametophyte differentiation is controlled by specific genes, among which those involved in ovule and integuments development are the most characterized.

## Pollination, Pollen Germination and Fertilization

Pollination is the result of pollen transfer from anthers to the stigma. The event can occur within the same flower (self pollination) or between different flowers of the same or different trees. The terms pollinator and pollinizer are often confused. A pollinator is an agent of pollen transfer (e.g., bees, insects, people, wind, water, etc.). A pollinizer is the plant variety that produces the pollen. Pollination is a prerequisite to fruit set in most fruit crops. The presence of viable seeds in peaches, plums, cherries, almonds and apricots is necessary for normal fruit development, while in few apple and pear varieties seedless fruits can develop (partenocarpy). In some *Malus* and *Citrus* species, as well as in other plants, seed development can occur without fertilization (i.e., apomixis). Pathenocarpy can occur either naturally or be stimulated by growth bioregulators. Good fruit set and size in multiseeded species are usually related to the number of seeds per fruit underlying the role of fertilization in yield production.

The main systems of pollen transfer are wind and insects, depending on the species. Wind pollinated species bloom copiously and the pollen content per anthers may be higher than 20,000 grains, while in apple and pear, two insect pollinated species, the content ranges between 1,000 and 3,000. Chestnut, hazelnut, mulberry, olive, pistachio and walnut are wind pollinated. Nut species have male and female flowers. The pollen grains are very small and light, and can travel hundreds of meters. Stigmas are large, increasing the chance a pollen grain will land on the stigma and germinate. The number of pollen grains produced by male flowers is extremely high. For example, it is estimated that in hazelnut 250,000 pollen grains are produced by each egg cell.

Some species, such as strawberry, kiwifruit, pear and Italian prune, are pollinated both by wind and insects, the latter being dominant.

All plant species with showy flowers are insect pollinated. Pome fruits, stone fruits, and small fruits are all pollinated by insects, mostly bees. Honey bees do most of the pollination in commercial orchard. Most of the insect- pollinated temperate fruits have hermaphrodite flowers whose petals and odour attract insects. Anthers shed their pollen as the insect brush against them. The main factors affecting pollination are compatibility, pollen viability, pollinizer placement and pollinator activity.

Under normal conditions, a compatible pollen that has reached the stigma surface undergoes hydration and germination within 1 h (Edlund et al. 2004). These processes along with the pollen tube formation are carried out and controlled by the vegetative cell, are insensitive to transcription inhibitors but dramatically affected by protein synthesis inhibitors. Calcium plays a pivotal role in the pollen tube elongation. Besides other factors, pollen germination is positively related to the number of pollen grains present on the stigma, and the phenomenon is ascribed to the pollen density and named population effect. The pollen tube emerges from a germination pore and elongates within the stigma covered by exudates rich in stygmasterol, bore and phenolic compounds. Pollen tube grows inter-cellularly upon the production and extrusion of cell wall hydrolases (cutinases and pectinases) directed to the digestion of the cell wall middle lamella of the stylar cells. The pollen tube quickly overcomes the stigma barrier and reaches the central part of the style named transmitting tissue, which is rich in storages providing C and N sources necessary for pollen tube formation. The pollen tube growth through the transmitting tissue occurs very rapidly and is directed toward the ovules by a signal generated by the synergids. Upon reaching the base of the style, the pollen tube jumps into the ovule through the micropyle (porogamy). In some nut species the pollen tube penetration occurs through the chalaza at the base of the ovule (aporogamy). Upon ovule penetration the pollen tube approaches the embryosac at the synergid side and discharges the sperm cells through the synergids that undergo degeneration. Few minutes (4–7) after the discharge into the embryosac, one sperm cell fuses with the egg cell to generate the zygote, and the other fuses with the polar central cell to form the first endosperm cell. The double fertilization, which is typical of the Angiosperms, concludes the gametophytic phase of development. An efficient fertilization depends on external factors that strongly affect gametophyte viability and relies on long effective pollination period (EPP). EPP, expressed in hours or days, is the difference between the time required to pollen tube to reach the ovule after pollination and the lasting of the embryosac viability since bloom. Temperature plays a major effect on the two parameters. Low temperature regimes reduce pollen tube growth rate and extend the egg cell viability, while an opposite effect is produced by high temperature. The EPP is an extremely important parameter that should be taken into account in choosing the proper pollinizers for the varieties that are partially or completely self- sterile.

## Mechanisms Preventing Self—Fertilization

The diffuse presence of hermaphrodite flowers in higher plants is a condition that naturally favours self-fertilization, and progressively erodes the genetic biodiversity of the species and their ability to cope with environmental changes. To avoid this, species developed different sterility mechanisms preventing self-fertilization. In fruit tree species, three main mechanisms of sterility are present, namely: morphological (MS) and cytological (CS) sterility, and self-incompatibility (SI).

The MS relies on abnormalities targeting differentiation of flower organs that, at the end, may affect pollen and ovule viability, causing andro- and gyno-sterility, respectively. In most cases, andro-sterility is caused by disturbances in the tapetum differentiation leading to the formation of no- or non-functional- pollen. Andro-sterility is present in some old peach varieties (JH Hale, Alamar, Aurora, June Elberta), in almond (Rof), and in plum (Chabot and Flaming delicious). In chestnut, andro-sterility is caused by disturbances of stamen elongation and a lack of anther differentiation, while in some grape varieties (Picolit, Lambrusco di Sorbara, Laureiro) is due to the formation of abnormal pollen lacking of germination pores, thus incapable of germination.

The gyno-sterility relies on disturbances of ovary differentiation that may range from the absence of the organ to a normal ovary but no-viable ovules. The lack of ovary occurs in some ornamental *Prunus* species and in *Vitis vinifera sylvestris*. Ovule abortion has been reported in *Citrus lemon* and in *Olea oleracea*.

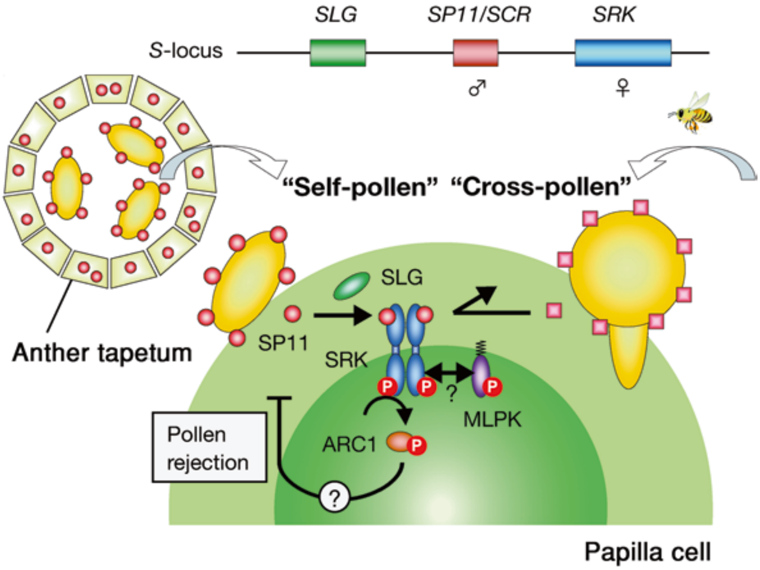


**Fig. 4.5** Molecular model of the self-incompatibility (SI) response in the Brassicaceae. The S-locus consists of three genes, SRK, SP11, and SLG. The SRK receptor kinase is the female determinant and spans the plasma membrane of the stigma papilla cell. SP11 is the male determinant and is predominantly expressed in the anther tapetum and accumulates in the pollen coat during pollen maturation. Upon pollination, SP11 penetrates the papilla cell wall and binds SRK in an S-haplotype-specific manner. This binding induces the autophosphorylation of SRK, triggering a signaling cascade that results in the rejection of self-pollen. SLG is not essential for the self-/nonself-recognition but localizes in the papilla cell wall and enhances the SI reaction in some S-haplotypes. The signaling cascade downstream of SRK has not yet been characterized, but the essential positive effectors include MLPK and ARC1. MLPK localizes papilla cell membrane and may form a signaling complex with SRK. ARC1, an E3 ubiquitin ligase, binds to the kinase domain of SRK in a phosphorylation-dependent manner and may target unknown substrates for ubiquitination. The proteasomal degradation of these substrates could result in pollen rejection. (Takayama and Isogai 2005)

The *CS*, present in triploid genotypes is due to irregularities occurring at micro- and mega-sporogenesis level leading to the formation of unviable pollen and embryosac. In fruit industry, triploidy might be a character of interest when associated to parthenocarpy, since it allows the production of seedless fruits. This type of sterility is present in some varieties of *Citrus*, apple and pear.

The *SI* is one of the most important systems to prevent inbreeding (Sanchez et al. 2004; Takayama and Isogai 2005). In many species, the self-/nonself-recognition of *SI* is controlled by a single polymorphic *locus*, the *S-locus*. Molecular dissection of the *S-locus* revealed that *SI* represents not one system, but a collection of divergent mechanisms. In the *Brassicaceae*, where a sporophytic type of *SI* is present, the determinant genes encode a pollen ligand and its stigmatic receptor kinase, whose interaction induces incompatible signalling(s) within the stigma papilla cells (Fig. 4.5). In the *Solanaceae*, where a gametophytic-type of *SI* is present, the determinants are a ribonuclease and an F-box protein, suggesting the involvement of RNA and protein degradation (Zhang et al. 2009) in the system. In the *Papaveraceae*, the only identified female determinant induces a $Ca^{2+}$ dependent signalling network that ultimately results in the death of incompatible pollen. In fruit species belonging to the *Rosaceae* family, a gametophytic-type of *SI* is present. All the old sweet cherry varieties are self-incompatible, along with many of the commercial apple cultivars. It is important to underline that *SI* may affect not only a specific variety, but also phylogenetically related genotypes.

## Seed and Fruit Development

### *Seed Development*

As previously described, upon the double fertilization, the zygote and the endosperm cells are formed. The endosperm cell is triploid (3n), as it derives from the fusion of the central cell (2n) with a sperm cell (n). The endosperm nucleus undergoes division very quickly, generating a cell-free structure that fills up the embryo sac and stimulates its enlargement. In peach, the final seed size is reached very early at pit hardening: at this developmental stage, most of the seed volume is occupied by the endosperm, while the embryo is still globular and made up by 32–64 cells. The endosperm cellularization (cytokinesis) starts from the periphery of the embryo sac and proceeds to the center, concurrently with endocarp lignification starting at the fruit stylar end. During cytokinesis, fruitlets display the greatest sensitivity to bioregulators promoting fruit growth and shedding. In the majority of the fruit tree species, the endosperm is not a seed storage tissue. In fact, after having reached its maximum expansion and undergone cellularization, endosperm is progressively re-adsorbed, along with a resumption of the embryo development. Embryo develops from the zygote that undergoes a first asymmetric cell division, forming a larger elongated cell at micropylar side, and a smaller one facing the embryo sac. The larger elongated cell undergoes divisions according to planes orthogonal to the cell main axis, while the smaller one divides according to subsequent orthogonal planes. After the resumption of growth, embryo moves from the globular through the hearth to the torpedo stage (Laux et al. 2004).

The integuments are of maternal origin and protect the mature seed. They may have a woody or a leather consistency. In some species (stone-fruit, nut, etc.), seeds are protected by a woody endocarp. The seeds of the different species differ in sizes and weights and their number/fruit can be quite variable within species (up to 10 or more in pome-fruit). Stone-fruit normally produce a single seed, despite the two ovules (one aborts very early): in some cultivars a certain percentage of fruit may have two seeds. This character can be considered positive if the seed is used for seedling production or negative for those species in which the seed is the edible part (nuts, etc). A certain percentage of aborted seeds is not a problem for the development of fruits provided with many seeds (apple). In early ripening cultivars (some stone-fruits), the rapid development of the fruit can cause apparently normal seeds not able to germinate. The causes of this phenomenon can be attributed to a discrepancy between the development of mesocarp and seed (Bonghi et al. 2011). The fruit is a metabolic sink stronger than the seed when the embryogenetic process has not been completed yet. In other cases (such as seedless grapes), competition between seed and fruit leads to an early abortion.

As previously reported, in some cases embryo development does not rely on fertilization. The process is called apomixis and the embryogenetic program is started in nucellar cells, different from the normal embryo sac (Bicknell and Koltunow 2004). There are three types of apomictic development, named “diplospory”, “apospory” and “adventitious embryony”. In the case of “diplospory”, the megaspore mother cell switches from sexual to an apomictic pathway to produce an unreduced embryosac. This can happens because of aberrant meiosis (“meiotic diplospory”) or from the failure of the megaspore mother cell to enter meiosis (“mitotic diplospory”). In both cases, the unreduced cell continues development similarly to a normal megaspore. In contrast to diplospory, aposporous embryo sacs form from additional cells that differentiate from the nucellus forming megaspore mother cell. Adventitious embryony develops from cells in tissue external to a sexual embryo sac. The nucellar form of adventitious embryony is the most common and is well described especially in *Citrus*. Somatic embryos originate from nucellar tissues within the same embryo sac. Apomixis is recognized as one of the most valuable biological process in improving agricultural important crops. In fruit species, apomixis is present in apple and, as above mentioned, in *Citrus* where the phenomenon is exploited in the nursery industry for rootstock propagation. Obviously, apomictic seeds cannot be used to propagate cultivars since they develop through a juvenile phase before reaching maturity. Thus, the orchard unproductive phase would last for several years, negatively affecting the economic return of the orchard.

## *Fruit Development and Ripening*

### Fruit Set and Physiological Drop

The fruit set defines the relationship between the number of fruit and the number of flowers initially present in the tree. The initial fruit set is determined by genetic characteristics of the species and by the climatic conditions occurring during anthesis; it can vary from 2 to 10 % in the case of pome-fruit and 15 to 30 % in stone-fruit, reaching the highest values (70–100 %) in species with little or no physiological fruit drop (e.g. kiwifruit).

These phenomena are depending upon correlative inhibitions between fruits and shoots and, subsequently, among fruits, allowing the tree to adjust the fruit load, in order to be able to properly support fruit growth and complete seed development. The fruit drop is therefore the most important strategy of self-regulation that the tree

**Fig. 4.6** Mechanical blossom thinning performer in an apple orchards in Germany. (Damerow and Blanke 2009)

activates for the survival of the species. The process, controlled primarily by auxin and ethylene, leads to activation of the fruit abscission zone. In the presence of an abundant flowering and optimal conditions during blooming, the physiological fruit drop may not be sufficient to ensure commercially-acceptable fruit sizes that can be achieved only with a further reduction of fruit load. This is achieved with flower or fruitlet chemical thinning depending upon the climatic characteristics of the growing areas. As a results of the inconsistency and the cost of some of the methods (chemical and manual) used in apple and peach, mechanical thinning was introduced in the practice.

In northern areas where frost damages frequently occur, fruitlet thinning is preferred and should be performed promptly because the persistence of an excessive load on the tree fruit can negatively affect flower bud differentiation. In apple, thinning must be performed within 30 days after full bloom, when the development of king fruitlet reach a diameter of maximum 15 mm (Dal Cin et al. 2005; Botton et al. 2011). When thinning is performed, aspects related to tree habitus, training system, light interception, leaf/fruit ratio, etc., should be taken into consideration.

The mechanical thinning can be performed either on flowers or fruitlets. As far as flower thinning is concerned, a machine called Darwin, consisting of a rotary body carrying whips that hit the flowers, was recently tested (Fig. 4.6). In order to optimize the intervention, it has been recommended to develop wall training system where the flowers are more uniformly exposed to the action of the rotating device. Fruitlet mechanical thinning is done by limb- (operating on branches) or trunk-shakers. The operation is cheaper than the manual one, although it requires specific adaptation of the training system. The chemical thinning in principle would be the less costly if properly performed and in presence of varieties which respond to the thinners. It is successfully performed on some apple varieties, while in stone-fruit, the lack of reliable chemical thinners is still one of the main problem.

### Fruit Development

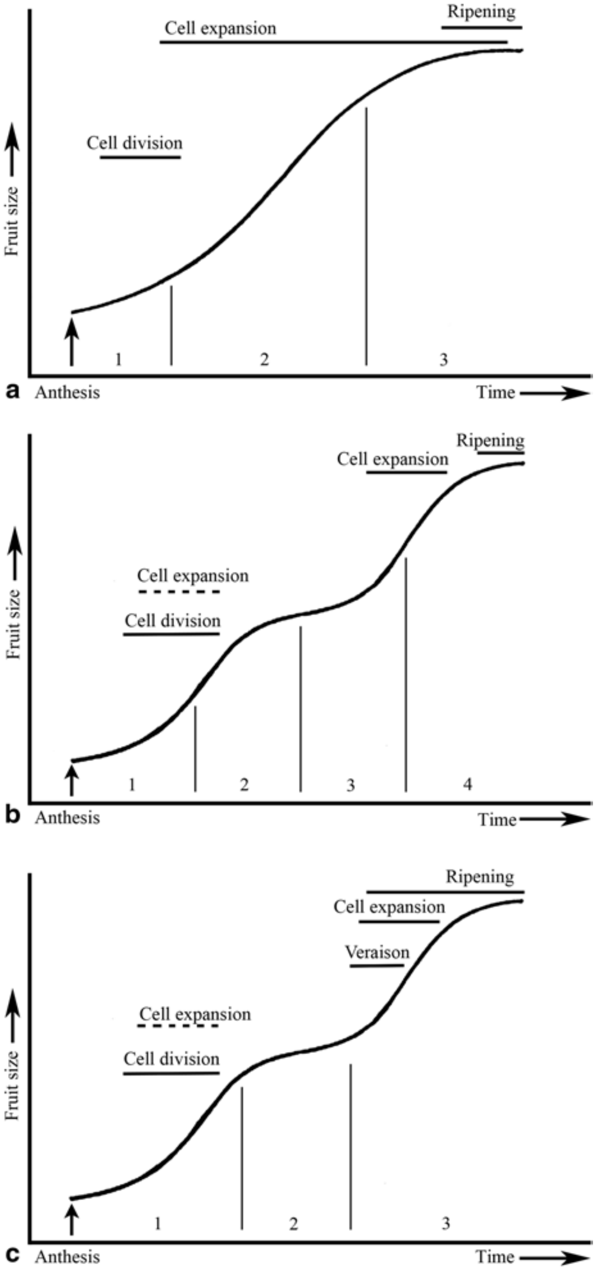
Fruits originate from ovary development (true fruit), as in stone-fruit and vines, or from the hypanthium (false fruits), as in pome-fruits. In general, fruit development is associated with seed fertilization and development, with the exception of parthenocarpic fruit species. Two main models for fruit growth can be found with a single or a double sigmoid dynamics (Fig. 4.7). The single sigmoid pattern is characteristic of pome-fruits, while the double sigmoid of stone-fruit and grape. Based on growth analysis, the peach fruit development cycle has been divided into 4 main phases called, S1, S2, S3 and S4 when the parameter used to monitor fruit development is the fruit cross diameter. The same 4 phases can be recognized when fresh weight (FW1, FW2, FW3 and FW4) or dry weight (DW1, DW2.DW3 and DW4) are used. The duration of the cycle of peach fruit development is genetically controlled and it may range from 60/70 (early ripening variety) up to 160/170 (late ripening variety) days after full bloom (DAFB). The length of the different phases varies according to the genotype: in general S1 is fairly constant (30 −35 DAFB) while S2 presents the greatest variability and can be very short in the early ripening varieties up to 60/70 DAFB in late ripening ones. The length of S3 and S4 is dependent upon the time of fruit ripening. S1 and S3 are the exponential growth phases, sustained by cell division (S1) and enlargement (S1 and S3). S1 is strictly dependent on environmental conditions affecting fruit density (number of cells/unit of fruit volume) at harvest as well as final fruit size.

In peach, the cell division may lasts from 7 up to 25 DAFB, depending upon the ripening period of the variety. The cell enlargement (S1 and S3), linked to increase in vacuolar volume and cell wall, is accompanied by a gradual increase in intercellular spaces. S2 is characterized by endocarp lignifications while S4 by the onset of ripening. Apples and pears, displaying a simple sigmoid pattern, show two phases of growth (S1 and S2), which can be represented by an expolinear model enabling to make predictions at an early stage (40–50 days before harvest) of the final fruit size. Parthenocarpy defines a situation in which the fruit is formed without a concurrent seed development (Fig. 4.8). Vegetative and stimulative parthenocarpy are recognized. In the first one, fruit development occurs naturally and is sustained by a continuous growth of the ovary and/or accompanying tissue (hypanthium) without any pollination. It is present in oriental persimmon and in some varieties of pear and fig. Stimulative parthenocarpy, dependent on pollination (but not fertilization), occurs in some grape varieties. The parthenocarpy behaviour is usually related to high levels of auxins, gibberellins and cytokinins. The same hormones sprayed at bloom time, may in some species, induced parthenocarpic fruit development.

### Fruit Ripening

Ripening is the final stage of fruit development and is a complex physiological syndrome, characterized by chemical and physical processes such as soluble solid content accumulation, starch hydrolysis, decrease in acidity, flesh softening and

**Fig. 4.7** Main models representing the possible fruit growth dynamics: simple sigmoid (typical of pome-fruit, **a**), double sigmoid (typical of stone-fruit, **b**, or grape, **c**)



color and flavor development, all changes devoted to increase fruit palatability. During ripening, the fruit acquires also negative traits such as an excessive flesh softening, a decrease of the nutritional value, an increase of allergenicity and a

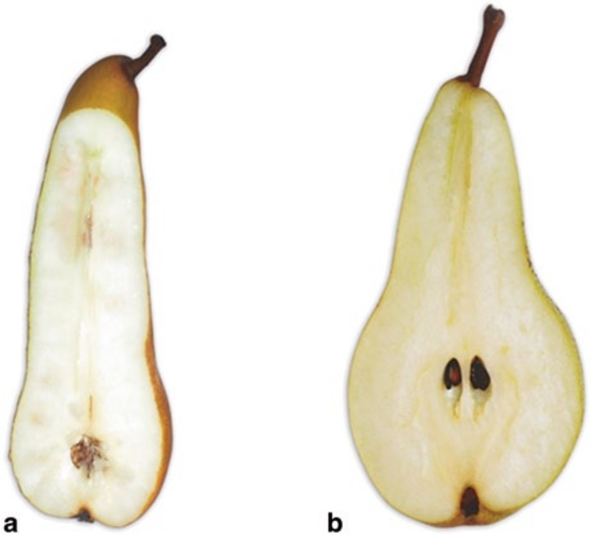
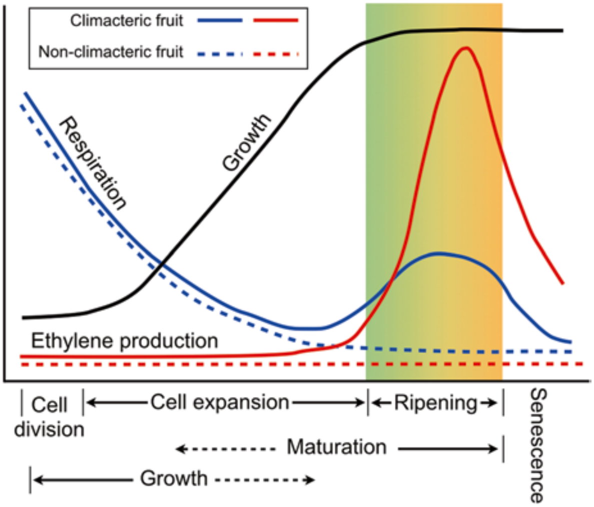


**Fig. 4.8** Parthenocarpic fruit (**a**) and normal fruit derived from fertilization (**b**) (Costa and Ramina 2012)

greater susceptibility to storage diseases. All these traits are genetically controlled and their elucidation will contribute to choose proper harvesting time and to develop new post-harvest strategies.

Temperate fruits are divided in climacteric or non-climacteric depending upon the increase in respiration and the biosynthesis of ethylene at the ripening stage (Fig. 4.9). In general, during fruit development, the respiration gradually decreases until it reaches the lowest values during senescence. However, this is true for the non-climacteric fruit in which the respiration rate can be higher than that of climacteric ones. Climacteric fruit show a different behaviour and show a respiration peak, which decreases in the post-climacteric phase representing the transition towards senescence. The rise of climacteric respiration is concurrent with the achievement of the maximum fruit size and with the main changes occurring during ripening. Ethylene biosynthesis follows the same trend of the climacteric respiration and controls most of the processes defining the ripening syndrome (Giovannoni 2004; Barry and Giovannoni 2007). The stimulation of ethylene evolution is the result of activation of two key biosynthetic enzymes, i.e. ACC synthase (ACS) and ACC oxidase (ACO), responsible for the hormone autocatalysis characteristic of the ripening phase. While the role of ethylene in climacteric fruit ripening has been sufficiently investigated, the auxin-ethylene interaction need further elucidation. In fact, exogenous applications of auxin may delay or stimulate ripening according to the stage of fruit development. In peach, it has been shown that an up-regulation of genes associated to IAA perception/action occurs at late S3, preceding the ethylene climacteric rise (Ramina et al. 2008). In addition, in tomato and peach, it has been shown that the expression of some members of the AUX/IAA family is stimulated by ethylene. The involvement of ethylene in grape, a non-climacteric fruit, has been assessed by means of

**Fig. 4.9** Ethylene biosynthesis in climacteric and non climacteric fruits, with respect to respiration and growth rates. The different phases of fruit development are also indicated



1-MCP, an inhibitor of ethylene action. Research pointed out that ethylene may be involved in the stimulation of ABA biosynthesis occurring at veraison and the subsequent sugar accumulation. Recently, it has been shown that an increase of brassinosteroids precedes the onset of ABA pointing out that other hormones may be involved in the regulation of the ripening syndrome.

The main biochemical and structural changes occurring during fruit ripening, are the depolymerization of cell wall components, the loss of cell turgor, the increase of mono and disaccharides, the biosynthesis of volatile compounds, degradation of organic acids and color development. Softening is related to juiciness and crunchiness. The fruits can be divided into two categories depending on the degree of softening: in the first group peaches, pears, plums and strawberries are characterized by an intense softening rate, while apple, quince and some pear varieties have a moderate softening rate and achieve a crunchy texture type. This different physiological behaviour affects storage and shelf life. The loss of cellular turgor is mainly due to the accumulation of solutes (carbohydrates, organic acids, ions, etc.) and by the loss of water by the fruit. In this sense, the structural characteristics and composition of the fruit cuticle play a fundamental role in regulating the loss of water through transpiration and, therefore, may affect the softening rate. The enzymes responsible for these modifications are cell wall hydrolases, among which are the endo-β-(1,4)-glucanases (EG), xyloglucan endotransglicosidases (Xet), pectin methyl-esterases (PME), pectate lyases (PL), polygalacturonases (PG) and β-galactosidases (ß-GAL). In addition the expansins (EXP) induce cell wall relaxation necessary to expose cell wall components to the action of cell wall hydrolases such as EG, ß-GAL, PME, PL, and PG, acting in a sequential manner. In the case of peach, it has been observed that an increase of PG activity is detectable only after the fruit has reached a firmness value of 20N, concurrently with the ethylene climacteric.

The most common change that occurs at fruit ripening is the loss of green color. This process also occurs in several non-climacteric fruits (grapes, citrus) at the acquisition of the best edible properties. The loss of the green color is caused by the degradation of chlorophyll due to both non-enzymatic processes (changes of pH) and to the action of specific enzymes which oxidizes the molecules of chlorophyll. The other major color change is related to the synthesis of carotenoids and anthocyanins. Carotenoids, responsible for the yellow-orange, are isoprenoids synthesized in chromoplasts from isopentenil diphosphate (IPP), the common precursor of all isoprenoids. The first synthesized molecule is the phytoene (C40) which is first converted to pro-lycopene and, subsequently, to lycopene. The introduction of oxygen molecules in the cyclic structure of the alpha-carotene determines the synthesis of xanthophylls (neoxantin, violaxanthin, cryptoxanthin), the pigments mostly responsible for yellow color in peaches and apricots. The accumulation of different carotenoids (lycopene, alpha-carotene, xanthophylls) in the mature fruit is genetically controlled and is the result of the selective adjustment of specific biosynthetic steps. In this context, the role played by ethylene in climacteric fruit is crucial. The biosynthesis of anthocyanins, responsible for the color ranging from pale-red to deep-blue/purple is genetically regulated, tissue specific and depends on the stage of development and environmental factors. Anthocyanins are water soluble phenolic compounds that accumulate in vacuoles and belong to the category of flavonoids, synthesized from phenylalanine by the action of phenylalanine ammonium lyase (PAL). The biosynthetic pathway, studied in details in grapes, proceeds through several steps leading sequentially to the formation of chalcones, dihydroflavonols, anthocyanidins and, finally, anthocyanins, responsible for the red color. This reaction is catalyzed by a structural gene (*UFGT*), whose expression is highly regulated both by endogenous factors (development) and exogenous ones (cultivation environment) (Castellarin et al. 2011). A genomic approach applied in grape and apple, established that anthocyanins biosynthesis is positively regulated by a MYB-type transcription factor.

The fruit taste and flavor are important sensory qualities defined primarily from the set of processes that regulate the metabolism of sugars and organic acids. Acidity is a key component of the flavor and develops during early fruit growth, following metabolic pathways shared by malate and citrate, the main organic acids in most of the fruits. The acidity decreases during ripening, mainly because of the use of organic acids as substrates for respiration (Cercós et al. 2006). The respiration rate, expressed as mole of $CO_2$ produced, related to $O_2$ consumption, tends to increase during ripening in both climacteric and non-climacteric fruits, and reflects the respiration substrate. The organic acids degradation is dependent upon both genetic factors and environmental conditions. As far as genetics, the low-acidity character is recessive in apple and citrus, while it is dominant in peach. The rate of respiration reflects the substrates type and is dependent upon environmental conditions (temperature) that may affect the activity of the malic enzyme and the availability of malate. Sugars, together with the organic acids, are among the most important compounds influencing fruit flavour. The main soluble solids are sucrose, glucose and fructose; the latter being present in all fruit, often in similar concentrations, while sucrose concentration may vary, being absent in cherries and berries. The fruit is an important metabolic sink capable of attracting carbohydrates from different sources as storage tissues and leaves. In stone fruit and grapes, the increase in reducing sugars occurs only when the fruit is still attached to the tree. In others (apple, pear, kiwi, banana), starch represents the main form of sugar accumulation. The maximum amount of starch varies from fruit to fruit in different species: in the case of apples and pears it may reach a concentrations ranging from 2–4 % of fresh weight. This occurs at the final stages of fruit development and, in apple, is associated to a starch synthase, whose expression levels peaks about 90 DAFB. The increase in hexoses in pome-fruit occurs during the post-harvest ripening and is the results of α and β amylase activity on starch. The concentration of starch decreases to values of 1–2 %, while that of hexoses increases from 1 up to 14–15 %. This process, in addition with softening, makes the fruit edible.

Fruit flavor develops during ripening and is responsible of the "bouquet", which is characteristic of each fruit type and variety. Volatile compounds are present as a ppm fraction, and belong to different classes of biochemical compounds, some of which still unidentified. In peaches and apples, aldehydes and alcohols, responsible of the herbaceous aroma, are the prevailing volatiles at preclimacteric stages, while esters and lactones are the most important at climacteric stage. Many volatile compounds are synthesized in a ripe fruit but only few are responsible for the characteristic aroma: in apple, for example, only a dozen of the several hundred volatile compounds identified are important for the aroma definition. The biosynthetic pathways and regulatory mechanisms that lead to the formation of individual volatile compounds, defining the "bouquet", are only partially known. In the case of grapes, the biosynthetic pathways leading to the formation of monoterpenes and sesquiterpenes, responsible of the floral note of the grape berry, have been elucidated. These biosynthetic pathways are generally present in all fruit species, although their activation and modulation occur differently in diverse species during fruit ripening.

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# Chapter 5
# Tropical and Subtropical Fruits

**Victor Galán Saúco, Maria Herrero and Jose I. Hormaza**

**Abstract** Production and commercialization of tropical and subtropical fruits have strongly increased in the last decade, particularly in countries with subtropical and Mediterranean climates, with important developmental advances due to significant research efforts, including control of flowering, intensive cultivation systems and use of growth regulators. This chapter covers general aspects such as the definition, classification and importance of tropical and subtropical fruits and their environmental requirements. Due to the different growth behaviour of monoaxial and polyaxial species different case studies covering some of the main tropical and subtropical fruits, i.e. bananas and papayas (monoaxials) and avocado, mango and cherimoya (polyaxials) are treated separately regarding their edaphoclimatic requirements for production and crop management, making special emphasis in reproductive biology, a key factor on the adaptation of tropical and subtropical fruits to different environments.

**Keywords** Origin · Reproductive biology · Crop requirements · Geographical distribution

## Introduction

Tropical and subtropical fruits, in contrast with temperate fruits crops, can be broadly defined by the following criteria (Galán Saúco 2003): they have their origin in the tropics or subtropics, are evergreen perennial crops, although some tropical

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species may be deprived of leaves under stressed conditions (i.e. severe drought or cool conditions or even during flowering), and others have a very limited degree of frost-resistance when grown below 10 °C, although variation can occur between species, varieties and age of plant or plant parts. Some citrus species, such as the lime (*Citrus aurantifolia* (L). Swingle), the pummelo (*Citrus grandis* (L.) Osbeck) or the grapefruit (*Citrus paradisii* Macfad.), could also fit into this definition, but citrus species are normally considered academically as a different area of research and will be covered separately in a different chapter in this book.

## *Area of Origin and Geographical Distribution*

Tropical and subtropical fruits originate in nearly all continents, except Europe, although most of the better-known tropical and subtropical fruits originated in the tropical and subtropical regions of America [e.g. papaya (*Carica papaya* Linn), avocado (*Persea americana* Mill., pineapple (*Ananas comosus* Merr.) or guava (*Psidium guajava* L.)] and Asia [e.g. mango (*Mangifera indica* L.), banana (*Musa* spp.), and litchi (*Litchi chinensis* Sonn.)]. Two commercially important fruits originated in Oceania; the macadamia (*Macadamia* spp.) in mainland Australia, and the coconut (*Cocos nucifera* L.) in the Pacific region, although in the latter case its origin may be more properly considered as pantropical (Martin et al. 1987). In addition, although many tropical fruits have originated in tropical Africa, none of them, except the date palm (*Phoenix dactylifera* L.), can be considered commercially important.

The spread of tropical fruits from their area of origin to other regions often came as a mean of providing shelter, clothing, wood or as medical supplies. Other fruits played an important part as a 'delicious' part of the human diet. The exchange of tropical and subtropical fruits between the Old and New World was especially active during the time of the great Spanish and Portuguese expeditions, which ranged from the end of the fifteenth until the middle of the seventeenth centuries, when these two countries dominated the tropical belt around the World. The Manila Galleon voyages that introduced the mango to Mexico from the Philippines is a clear example of these exchanges (Galán Saúco 2009; Galán Saúco and Cubero 2011).

## *Importance of Tropical and Subtropical Fruits*

Approximately 30 tropical and subtropical fruits (Table 5.1) are considered important production crops in the world and they can be divided into major, minor and wild tropical fruits, accordingly to their volumes of production and trade (Galán Saúco 1996).

Major tropical fruits are cultivated in most tropical and subtropical countries and are well-known in both the local and export markets. Strictly speaking they include mainly those covered by the Food and Agricultural Organisation (FAO) statistics and are based on the area planted, production, yield and trade trends (Table 5.2). Minor tropical fruits are less extensively cultivated and consumed and their trade tends

**Table 5.1** Important tropical and subtropical fruits and their botanical family

| Family | Fruit |
|---|---|
| Anacardiaceae | Mango, cashew nut (*Anacardium occidentale* L.) |
| Annonaceae | Cherimoya, sweet soap (*Annona squamosa* L.),<br>Soursop or guanabana (*Annona muricata* L.),<br>Custard apple (*Annona reticulata* L.),<br>Atemoya (*A. cherimola* x *A. squamosa*) |
| Bombacaceae | Durian |
| Bromeliaceae | Pineapple |
| Cactaceae | Pitaya or pitahaya (*Hylocereus* spp. and *Selenicereus megalanthus* |
| Caricaceae | Papaya |
| Guttifferae | Mangosteen |
| Lauraceae | Avocado |
| Malphigiaceae | Acerola *(Malpighia glabra* L.) |
| Meliaceae | Langsat or duku (*Lansium domesticum* Correa) |
| Moraceae | Bread fruit, Jack fruit (*Artocarpus heterophyllus* Lam.) |
| Musaceae | Bananas and plantains |
| Myrtaceae | Guava |
| Oxalidaceae | Carambola |
| Palmaceae | Coconut |
| Passifloraceae | Passion fruit, grenadille (*Passiflora ligularis* Juss) |
| Proteaceae | Macadamia |
| Sapindaceae | Litchi, longan, rambutan (*Nephelium lappaceum* L.) |
| Sapotaceae | Sapodilla, lucuma (*Pouteria obovata* Baehni) |
| Solanaceae | Sweet pepino (*Solanum muricatum* Alt.) |

to be more limited, both geographically and quantitatively, than those of the major category and several of them, together with wild tropical fruits, can be considered under the group of neglected and underutilised species (NUS). However some minor tropical fruits can be of significant economic importance in specific regional markets. Clear examples are the carambola or starfruit (*Averrhoa carambola* L.), durian (*Durio zibethinus* L.) and mangosteen (*Garcinia mangostana* L.), which are considered major fruits throughout south-eastern Asia. In the case of wild tropical fruits, the greatest effort should be devoted to germplasm conservation both *in situ*, including on farm, and *ex situ*, characterization, evaluation and appropriate use of genetic resources.

## *Nutritional Value and Other Uses*

With the exception of relative low caloric value fruits such as coconuts, bananas, macadamia and avocado, most tropical and subtropical fruits play an important role in the human diet due mainly to their high and diverse vitamin and mineral contents. This has been of significant importance in the tropics where people have been consuming them since ancient times either by collecting them directly from the wild or through cultivating these fruits in backyard gardens. The most important case is that of the banana and the plantains (*Musa* AAB, subgroup plantain), which have

**Table 5.2** World production and major producing countries of tropical and subtropical fruits in the first decade of the twenty-first century. (Source: Faostat 2013)

| Fruit | World production (x $10^3$ t) | | | Major producing countries |
|---|---|---|---|---|
| | 2000 | 2005 | 2010 | |
| Banana | 66,046 | 80,107 | 105,213 | India, China, Philippines, Ecuador, Brazil, Indonesia, Tanzania, Guatemala, Mexico, Angola, Colombia, Burundi Costa Rica, Thailand |
| Coconut | 51,194 | 57,574 | 59,882 | Indonesia, Philippines, India, Brazil, Sri Lanka, Thailand, Papua New Guinea, Vietnam, Mexico |
| Mango[a] | 24,852 | 31,671 | 37,284 | India, China, Thailand, Pakistan, Mexico, Indonesia, Brazil, Bangladesh, Philippines, Nigeria |
| Plantain | 30,453 | 33,471 | 36,299 | Uganda, Ghana, Cameroon, Colombia, Rwanda, Nigeria, Peru, Ivory Coast, Democratic Republic of Congo |
| Pineapple | 15,140 | 17,662 | 19,739 | Brazil, Philippines, Costa Rica, Thailand, China, Indonesia, India, Nigeria, Mexico, Vietnam |
| Papaya | 7,456 | 8,316 | 11,726 | India, Brazil, Dominican Republic, Nigeria, Indonesia, Mexico, Ethiopia, Colombia,Democratic Republic of Congo, Thailand, Guatemala |
| Avocado | 2,707 | 3,420 | 4,025 | Mexico, Chile, Dominican Republic, Indonesia, Kenya, Colombia, Peru, USA, Brazil, Rwanda, China |

[a] FAO includes here mangoes, mangosteeens and guavas

constituted a staple food in many underdeveloped and developing African countries (Robinson and Galán Saúco 2010). Tropical and subtropical fruits are becoming more important in the diet of the developed world and particularly important for people who show interest in a healthy diet and lifestyle. Many tropical fruits are a good source of carotene (provitamin A), outstanding examples being the mango and papaya in which the yellow colour of the flesh is an indicator of this vitamin. The guava and the mango are also well known for being a good source of ascorbic acid (vitamin C). Many tropical and subtropical fruits are also rich in pectin, fibre and cellulose, which stimulate intestinal activity, and they are also a good source of antioxidants, which stimulate appetite and facilitate digestion.

The prime form of consumption of most tropical and subtropical fruits is as fresh fruits (both as entrées or desserts), with the exception of the plantains (Musa AAB (subgroup plantain) and the breadfruit (*Artocarpus altilis* Fosb.), which are consumed cooked, and nuts which are often roasted or candied. Many fruits are also consumed in other ways such as jams, jellies, juices (made either from fresh fruits or concentrates or frozen pulp), ice cream, yoghurt, pickles and chutneys (the most famous being mango chutney, highly esteemed by gourmets). Tropical and subtropical fruits are also important components of baby food and different kinds of purees (aseptic, chilled aseptic or simply chilled) and flour can be prepared from the durian and the banana. Different dips can also be prepared from tropical and subtropical fruits, the most known being guacamole made from the avocado. Guava paste is generally consumed as part of the daily diet in many Latin-American countries as well as in the Canary Islands (Spain).

Beside the fruits, other plant parts such the stem, leaves, flowers, roots, seeds and even pollen have been described as useful for humans in different texts (Popenoe 1976; Chandler 1958; Singh 1960; Purseglove 1968; Ochse et al. 1972; Nagy and Shaw 1980; Coronel 1986; Morton 1987), but the potential of leaves or even flower extracts as biological products for use against pests and diseases is an open field of research. The leaves of banana and breadfruit, dried fruit and the seeds of dates and mango have also been found useful for animal feeding. The wood of different tropical and subtropical tree fruits, such as breadfruit, guava, longan (*Dimocarpous longan* Lourr.*)*, mango and mangosteen, has regularly been used mainly for interior partitioning or for furniture.

The potential of tropical fruits does not only rely on human consumption, but such plants have also been used in agroforestry and urban horticulture. Many tropical fruit trees are capable of improving air quality as well as contributing to ecological stability. They are easy to manage in gardens or in industrial or community building sites and are adequate for planting along country roads and may constitute new lines of research particularly when searching for cultivars which could be orientated towards wood (or flower) production. Lastly, some fruits can constitute an important part of the cultural and religious life of different countries with the mango in India and in many African countries being the most outstanding example (Galán Saúco 2009).

## Botanical and Horticultural Aspects

Although most tropical and subtropical fruits are woody plants, they also include herbaceous crops, like the banana, or vine crops, like the passion fruit (*Passiflora edulis* Sims). Different botanical types of fruits can be found ranging from single fruits such as berries (avocado), drupes (mango), capsules (durian), nutlets (litchi or longan), to compound fruits such as the typical syncarpium of the pineapple, or even a bunch of individual berries as in the banana. To differentiate such fruit crops from perennial vegetables eaten as a fruit it is necessary to keep in mind that in a horticultural sense a fruit is something eaten fresh, the exception being the plantains and the bread fruit which need to be cooked, and many nuts which need to be roasted or candied before consumption.

Tropical and subtropical fruits can be found in most botanical families of the plant kingdom. Martin et al. (1987) lists more than 1,000 tropical and subtropical fruits, all within 137 families. The better-known tropical and subtropical fruits are listed in Table 5.1.

When classifying tropical fruit crops, Verheij (1986) has grouped them into 2 main categories based on their branching habit and growth type:

A) Single-stemmed (monoaxial) species in which:
   1) Growth and floral development are concurrent (e.g. Papaya, Coconut).

  2) Continuous growth ending in flowering (e.g. Bananas and Plantains, Pineapple)

B) Branched (poliaxial) species in which:
  1) Floral development is concurrent in time and place with extension growth (e.g. Passion fruit).
  2) Floral development is separated from extension growth in:

    2.1 Different places:
      2.1.1 Cauliflory habit [e.g. Durian, Jaboticaba (*Mirciaria cauliflora* Berg)]
      2.1.2 Shoot dimorphism (e.g. Carambola, Avocado)

    2.2 Time:
      2.2.1 Asynchronous growth rhythm [e.g. Sapodilla (*Manilkara zapota* Van Boyen)]
      2.2.2 Synchronous growth rhythm (e.g. Mango, Litchi)

Further division can be undertaken in the last category (2.2.2) where the mango can be separated from the litchi and other similar plants due to the peculiar problems of erratic growth which occurs when mangoes are cultivated under tropical conditions and also due to the potential of mango to produce, under subtropical conditions, a second flowering in the same year after eliminating the first flowering wave.

Due to this different growth behaviour of monoaxial and polyaxial species, different case studies covering some of the main tropical and subtropical fruits, i.e. bananas and papayas (monoaxials) and avocado, cherimoya (*Annona cherimola* Mill.) and mango (polyaxials) are treated separately regarding their edaphoclimatic requirements for production and crop management, making special emphasis in reproductive biology, a key factor on the adaptation of tropical and subtropical fruits to different environmental conditions.

## Banana

Bananas (Fig. 5.1) belong to the genus *Musa* of the Musaceae family in the monocot order Zingiberales. The genus *Musa* is divided in 5 sections, one of which, the Eumusa Section, includes the two wild, seeded species, *Musa acuminata* Colla (A genome) and *Musa balbisiana* Colla (B genome), native to southeast Asia, which gave origin to most modern edible bananas. Plantains and other cooking bananas are hybrids with different degrees of ploidy of the two *Musa* species indicated above, although some hybrids gave rise to dessert bananas. Over many years, various inedible diploid subspecies of *M. acuminata* crossed naturally resulting in the production of numerous intraspecific hybrids that could be propagated vegetatively by suckers that were selected by local inhabitants. Commercial banana dessert cultivars are parthenocarpic and female sterile triploids (AAA) of *M. acuminata,* with 95 % of the total exports of bananas belonging to the *Cavendish* subgroup. Other speciality or exotic bananas, such as the red-coloured types as well as the ‘apple

**Fig. 5.1** Banana plant

(‘Manzano’), baby banana (‘Bocadillo’ or ‘Pisang Mas’) and ice cream (‘Lady Finger’) types are exported on a smaller scale to niche markets. A full description of banana and plantains cultivars can be found in Robinson and Galán Saúco (2010).

The early history of banana cultivation away from its centre of origin remains uncertain, but the possible dates and routes for the distribution of *Musa* outside Asia are discussed in detail by Simmonds (1962) and Purseglove (1968). An overview of the domestication and genomics aspects of bananas can be also found in Heslop-Harrison and Schwarzacher (2007).

## *Edaphoclimatic Requirements for Production*

### Soil Requirements

The most important soil factors for banana cultivation are porosity and mechanical impedance, aeration and natural drainage, water-holding capacity, and soil temperature (Delvaux 1995), from which drainage is essential for all banana soils (Simmonds 1966). The banana plant can be cultivated in different kind of soils from sandy light to clay soils that may require frequent irrigation or make use of mulching to the heavier soils where problems derived from lack of aeration and drainage can arise. Sandy-clay loam soils are best suited for banana cultivation with the optimum soil texture being around of 30:10:60 (clay:silt:sand) (Robinson and Galán Saúco 2010).

It is possible to cultivate bananas in soils of 40–60 cm in depth (vitro plants cultivated to a few -one or two- cycles, (Israeli and Nameri 1987), but the recommended soil depth for banana cultivation should be a minimum of 80 cm or, even better, 1.20 m.

Soto (1995) recommends that bananas are best cultivated within a soil pH range of 4.2–8.1. For optimum production, the soil pH, measured in water, should be between 5.8 and 6.5 (5.0 and 5.8 if measured in potassium chloride). The most important cations are potassium (K), calcium (Ca), magnesium (Mg) and phosphorus (P). In certain soils there may be a specific shortage of minor elements such as zinc (Zn) or boron (B). The banana crop is very demanding on K and large quantities of this element are removed from the soil. Potassium has been the most widely studied element in banana soils, and this crop is very sensitive to cation imbalances (Lahav 1995). In particular, the K/Mg and Ca + Mg/K ratios are very important. Potassium deficiency symptoms may be observed when soil Mg or Ca reserves are high, relative to K (Robinson and Galán Saúco 2010). Salinity is usually only a problem in dry mediterranean climates, such as Israel and the Canary Islands, often occurring in the absence of summer rain or poor quality irrigation water. The optimum ratio for soil K/Na is 2.5 with Na ideally less than 2 % of the total exchangeable cations on a mili-equivalent % basis. Values of electrical conductivity in the soil solution higher than 2.5 dS/m have been found detrimental for root development (Rodríguez and Lobo 2008).

## Climatic Requirements

Although the major banana growing areas of the world are geographically situated between the equator and latitudes 20 °N and 20 °S there are commercially profitable plantings in the subtropics at latitudes close or even slightly higher than 30 °N and 30 °S. Climatic conditions in the tropics are characterised by comparatively small day to night and summer to winter temperature fluctuations. In contrast, the main climatic characteristics occurring in the banana growing areas of the subtropics are: (a) wide day to night and summer to winter temperature fluctuations, (b) high and low temperature extremes in summer and winter respectively, and (c) poorly distributed, low annual rainfall.

Temperature is the main limiting factor of banana growth where enough water is available. Robinson and Galán Saúco (2010) indicate the cessation of new leaf emergence when the mean daily temperature threshold [(maximum + minimum) ÷ 2] falls below 16 °C. The net rate of growth (dry matter assimilation) ceases at temperatures below 14 °C, with 22 °C considered as the optimum temperature for both growth and flower initiation, and, approximately 31 °C as optimum for leaf emergence rate. In general, around 27 °C is considered as the best overall mean temperature for optimum balance between growth (assimilation) and development (leaf emergence rate). Temperatures below 13 °C, when plants are grown under field conditions in the subtropics or during banana fruit transport, may cause underpeel discoloration of fruit. Winter chill in leaves, which shows up as a progressive yellowing due to chlorophyll destruction, can also be seen in the subtropics when night temperatures fall to between 6 and 0 °C. Banana leaves die at 0 °C, although the plant may recover from rhizome buds if the frost is of both short duration and low intensity.

After temperature, rainfall is the main determinant climatic factor for banana cultivation. The banana has a high water demand, with 25 mm per week considered as the minimum for satisfactory growth. In some parts of the humid tropics, water requirements of bananas are supplied totally from rainfall, but in the dry tropics and subtropics, supplementary irrigation is essential to produce bananas of commercial quantity and quality.

## *Crop Management*

The cultivation of bananas was historically initiated as plants or mats in backyard gardens, either grown separately or associated with a range of other subsistence crops. Bananas were mainly planted to satisfy family consumption, with any surplus exchanged for other goods and services in nearby villages. Crop and animal residues and ashes were the only source of fertilisers and maintenance was minimal. Banana production progressively evolved towards a cultivation system where bananas were grown in association with other crops, mostly at low plant density, which acted to shade plants for shorter perennial crops or as a component of crop rotation systems within the natural bush. Banana production became a monoculture as soon as it became a more important source of income.

With the banana market increasing substantially in the twentieth century, producers looked to improved cultural practices in order to increase yields. However, throughout the 1990s the intensification of conventional banana cultivation not only resulted in an increase in production but also provoked increasing soil degradation problems and an increase in pests and diseases in many parts of the tropics. This has led to important changes in cultural practices, which include protected cultivation, to ensure sustainable profitable banana production.

The reader can find an updated description of the banana, as well as information on banana cultural practices that includes soil preparation, establishment, planting densities, choice of planting material, desuckering, fertilisation, irrigation and plant protection measures in the text book *Bananas and Plantains* written by Robinson and Galán Saúco (2010).

## *Reproductive Biology*

### Inflorescence and Bunch Development

After the early differentiation of some 25–50 leaves, the development of which is dependent on cultivar and environmental conditions, the apical growing point at the base of the pseudostem ceases to produce leaves and starts to develop an inflorescence. The transformation of this process is neither externally visible nor are there any other characteristic signs of flower initiation. The nature of the flowering stimulus is unknown and probably not related to temperature or photoperiod, although the latter factor may play some role (Turner and Fortescue 2012). The trigger for flower initiation could be hormonally induced with gibberellic acid ($GA_3$) involved in the process, but this hypothesis still has to be tested and verified. The anatomical and morphological changes occurring during flower initiation in banana, as well as other pertinent aspects related to the reproductive biology, have been summarised by Robinson and Galán Saúco (2010).

Flower initiation starts when the apical meristem rises into a dome that shows intense mitotic activity. This activity immediately ceases when the leaves are replaced by flower bracts; the first to emerge are the female bracts and later the male bracts. All bracts enclose axillary, crescent-shaped meristematic "cushion" from which the flowers differentiate. There is not clear morphological distinction between male and female flowers until the inflorescence is about 120 mm long and some 1.5 m from the base of the pseudostem. The inflorescence, a complex spike, consists of a stout peduncle on which the flowers are arranged in nodal clusters with each node comprising normally two rows of flowers set on transverse cushions, and subtended by a bract that protects the young flowers. The flowers are grouped in clusters with their bracts born spirally but do not completely encircle the peduncle. There may be from 5 to 18 basal (proximal) nodes bearing female flowers. By contrast the upper (distal) nodes contain male flowers and remain tightly enclosed in bracts that form a conical structure called the 'bell'. In between both flower types are some nodes containing hermaphrodite flowers with short ovaries that, as in the case of the male flowers, do not develop into edible fruits and, in most cultivars, abscise at an early stage after flower emergence.

The developing flower stalk (peduncle) rises inside the pseudostem until it forces the inflorescence to emerge through the top or 'neck' of the plant, the latter being formed by the petioles of the last few leaves to emerge. At the moment of flower initiation, 10–12 leaves are still inside the pseudostem and emerge progressively at the neck while the inflorescence moves upwards. At emergence the inflorescence is initially erect but quickly points downwards due to its own weight and the continued growth of the peduncle. After emergence, the bracts, that cover the double-layered female nodes (commonly called 'hands') and tightly packed fruit, rise and remain exposed. In banana (*Musa* AAA) cultivars the bracts roll back at their tips and progressively dry out and drop off during early bunch development. The bracts and flowers in their axils open in proximal to distal sequence while the peduncle continues elongating from the meristems ending in the male bell. Within a few weeks of inflorescence emergence the female fruits re-orientate themselves from pointing downwards to pointing upwards. This negatively geotropic response may possibly be auxin-mediated, and explains the curvature of the banana fruits (commercially called 'fingers'). Male flowers remain tightly packed in the bell together with their bracts for the entire bunch life, although in commercial practice the bell is usually broken off to prevent further meristem growth and elongation of the peduncle axis. Hermaphrodite flowers situated between female flowers and male bell, usually abscise at their base, leaving a callus scar on the peduncle axis but, in some cultivars, they remain attached to the peduncle until harvest.

The number of hands per bunch and fingers per hand is determined at flower initiation by the number of female flowers laid down on the transformed meristem. This in turn is controlled by: (a) genome group, (b) crop cycle, (c) temperature, (d) vigour of the plant and (e) the level of management. For AAA Cavendish bananas (which comprise 95% of all commercial bananas in the world) in the subtropics, flower initiation during cool temperatures can result in as few as 5–6 hands whereas flower initiation on ratoon plants in summer can produce 16 hands or more. Similarly, the number of individual fruits per hand, also determined at flower differentiation, can vary from as few as 10 under stress conditions, to over 30 under optimal growing conditions. The eventual size attained by each finger is a function of conditions prevailing after flower initiation, and this is determined by temperature, leaf number and leaf area during bunch development, soil fertility and water supply, as well as the stage of maturity at harvest. As a result of these variations, the mass of a mature Cavendish bunch can vary from 15 to 70 kg in weight.

## Fruit Development

The individual banana fruit, despite originating from an inferior ovary, can be botanically characterized as a berry with a pericarp. The exocarp is composed of the epidermis and an aerenchyma layer, the mesocarp forms the pulp and the endocarp is limited to the inner epithelium adjacent to the ovarian cavity. In contrast with wild seeded bananas, edible bananas are parthenocarpic developing a mass of edible pulp without pollination. Most of the pulp develops from the outer edge of the three locules (inner face of the peel where the vascular bundles are situated) present in the ovarian cavity. Pulp parenchyma also develops from the placental septa. Starch grains are deposited initially in these pulp cells that form in the vicinity of the vascular bundles, but thereafter starch deposition moves centripetally and continues until fruit maturity. Despite the early shrivelling of the ovules, they may be recognized in the mature fruit as minute brown flecks embedded in the edible pulp adjoining the central fruit axis.

The seedless nature of most banana fruits is attributed to specific female sterility genes and a lack of pollen due to triploidy, but differences between genetically close cultivars can be observed. Thus, while AAA Cavendish subgroup cultivars are highly female sterile, and cannot normally be pollinated successfully, the AAA 'Gros Michel' cultivar gives 1 or 2 seeds per bunch if pollinated with pollen from diploid genoytpes. It is, therefore, not completely female sterile but it is regarded as commercially sterile in the absence of pollen.

Development of the fruit can be divided into two phases, namely, that which occurs before inflorescence emergence, or the so called ’vegetative apparent phase’ and that occurring after, during the true reproductive phase. The pre-emergence phase is dominated by peel growth while the pulp does not start to develop until the fruit re-orientates itself upwards, after emergence. The most rapid development of the inflorescence occurs during 4–6 weeks prior to emergence. Around the time of inflorescence emergence the fruit increases rapidly in length. Lassoudiere (1978) has shown that, in the case of the tropical banana AAA (Cavendish subgroup) cv. ‘Poyo’, there is a rapid increase in finger length for 30 days, which progressively slows down and is completed in 40–80 days after emergence depending on location and climate. On the other hand, the increase in fruit diameter is much slower but continuous until harvest. In the case of cv. ‘Poyo’ during the first month after inflorescence emergence, the peel represents 80 % of total fruit fresh weight, but after this period of time, the pulp increases rapidly with the pulp:peel ratio increasing from 0.17 to 1.82 in 80 days.

At the cellular level, there are 3 main growth stages: (1) rapid cell division from 6 weeks before emergence to 4 weeks after emergence; (2) rapid cell expansion from 4 to 12 weeks after emergence, and (3) final fruit maturation from 12 to 15 weeks after emergence. These time intervals are only valid under tropical conditions in which the fruit can be harvested between 85 and 110 days after inflorescence emergence, but can take considerably longer in the cooler subtropics where fruit development can last up to 210 days before harvest. In the case of fruits harvested for commercial dessert purposes the fact that fruits are normally cut at ‘three-quarters round’ must be also taken in account, because at this stage, the fruit angles are still clearly visible, and the fruit has only reached about 75 % of its potential maximum size and mass. The final shape and size of a banana fruit (or finger) should be representative of the cultivar although there may be an environmental/genetic interaction that determines the eventual size reached at maturity. With the AAA Cavendish intermediate banana subgroup, the fruit size ranges from 60 to 400 mm, although larger fruit size differences within this subgroup with other cultivars, such as ‘Dwarf Cavendish’ and ‘Poyo’, can be observed. Genetic variability in fruit size also occurs within bunches of the same cultivar, with fruits from the distal (bottom) hand usually 30–40 % smaller than those from the proximal hand. In addition, fruits from the inner whorl of a hand can be 15 % smaller than those from the outer whorl. Cultural practices play a role on finger length and explains the reason why multinational companies normally remove the (distal) bottom two or three hands early in bunch development in order to maximise finger length on the larger proximal hands.

### Papaya

Papaya (Fig. 5.2) belongs to the small family *Caricaceae* in the Brassicales and is native to tropical America with the greatest diversity present in the Yucatan-San

**Fig. 5.2** Papaya fruit

Ignacio-Peter-RioMotagua area of Central America (Nakasone and Paull 1998). The long viability of the papaya seed explains the rapid spread of this crop throughout the tropics following the routes open by Spanish and Portuguese sailors soon after the discovery of America. It was already present in the sixteenth century in Brazil, West Africa, Madagascar, India and the Philippines (Lassoudiere 1968), but it was not introduced to Hawaii, where this crop later reached its most successful horticultural development, until the early 1800s by Don Francisco de Paula y Marin, an Spanish explorer and horticulturist (Yee 1970). Papaya is currently cultivated in most tropical countries and also in many subtropical areas of the world. The fruits show excellent taste and nutraceutical properties which make papaya production a great commercial opportunity.

## *Edaphoclimatic Requirements for Production*

### Soil Requirements

The most important soil physical factors for papaya cultivation are permeability and good drainage, since even short periods of flooding (>8 h) may cause root rot and plant death. Papayas prefer sandy deep, well drained soils, of pH 5.0–7.0 that contain large amounts of organic matter. Papayas have been also successfully cultivated in peat soils, with yields of more than 100 t/ha, but, as in acid soils, applications of high rates of lime (6–8 t/ha), peat and micronutrients, like boron (B) and copper (Cu), are required for best production. Papaya is moderately salt sensitive with seed germination and early seedling growth as the most critical stages (Chan 2009; Lopes de Siqueira and Botrel 1986).

### Climatic Requirements

Papaya is a tropical crop that requires high temperatures to produce good quality fruits all year round. After a brief juvenile phase, vegetative growth coincides with flower development and an inflorescence emerges in the axil of each leaf, provided climatic and cultural factors are adequate. Temperatures below 20 °C have negative effects that can cause, among other problems, carpeloidy, sex changes, reduced pollen viability and low sugar content of the fruit, the latter factor being of critical importance in marketing papayas. Furthermore, if the temperature falls below 12–14 °C for several hours, papaya production can be severely affected particularly in dioecious cultivars (Nakasone and Paull 1998). Temperatures higher than 35 °C favour sex reversal phenomena with hermaphrodite flowers changing to functional male flowers that do not produce fruits of commercial quality (Chan 2009).

Thus, in theory, the papaya can only thrive in a stable tropical climate, and, even then, cultural practices should be optimised to maintain a high constant growth rate throughout the entire life of the plant in order to achieve maximum yields. Modern protected cultivation is the solution of choice for the mild subtropics (Galán Saúco and Rodríguez Pastor 2007) such as in the Canary Islands, where over 250 ha of papaya (around 90 % of the total papaya plantings) are currently grown in greenhouses and additional plantings are planned for the near future. Commercial greenhouse cultivation is also carried out in Japan, with around 10 ha (about 30 % of total plantings) and Israel with 10 ha (100 % of total plantings). In addition to provide a suitable growing environment, greenhouse production of papaya also offers protection from the aphid vectors of Papaya Ringspot Virus (PRV), a most serious commercial threat against which only transgenic papaya cultivars have shown acceptable resistance. The fact that transgenic papayas are, at present, only approved for marketing in USA, Canada and Japan (Anon 2012) gives special relevance to greenhouse production of this crop. Papayas are very sensitive to wind damage and can be uprooted at wind speeds higher than 64 km/h but, even at lower wind speeds, partial defoliation can reduce both photosynthesis potential and total soluble solids (TSS) content of the fruits. Both problems can also be avoided by greenhouse cultivation. Papaya is a continuous fruit producing plant that responds to a regular, uniform watering and prefers an annual precipitation rate of around 1,200 mm. It has been reported that irrigation can increase yield by 20 % over naturally rain fed papayas in Malaysia, which can more than compensate for the cost of the irrigation system (Chan 2009).

## *Crop Management*

The cultivation of papaya as a backyard tree in home gardens has always been very popular in many tropical and subtropical countries but, more recently, in the twentieth century, papaya has become an important commercial crop in countries such as Hawaii in the US, Mexico, Malaysia and Brazil. Many attempts have been made to breed papayas to suit the subtropical conditions in places like Australia, Israel and

South Africa. The papayas can enter into production as early as 6–8 months after planting, and provide a high potential yield of 60–100 t/ha per year (Chan 2009). However, pollination, fruit set and production are closely related to sex expression that is highly dependent on genotype-environment interactions (Nakasone and Paull 1998). Hawaii has become the pioneer country for commercial cultivation both in providing modern commercial techniques (Yee 1970) and in developing commercial transgenic papayas with coat-protein mediated resistance to Papaya Ring Spot virus (PRV) (Gonsalves 1998). The key for successful cultivation under subtropical conditions not only lays in the possibility of obtaining high yields but also high content of soluble solids all year round and particularly during the coldest months.

## *Reproductive Biology*

*Carica papaya* is the only polygamous species of the genus *Carica* (Badillo 1971). Following a short juvenile period, in which only leaves are formed, papaya flowers are borne in modified cymose inflorescences located in the axil of these leaves. The type of inflorescence depends upon the sex of the tree and the type of flowers present. The structure of the flower allows for easy pollination by wind and insects.

### Inflorescence and Fruit Development

Three main flower types are produced in papaya: staminate or male (♂), hermaphrodite (H) and female, (♀) but numerous intermediate flower types can be observed, which have been summarised and simplified by Storey (1958) into eight categories, borne in three tree forms: male, hermaphrodite and female (Table 5.3).

In the tropical regions of the world, hermaphrodite trees are preferred for their higher productivity since every tree will produce commercial fruits. However, in subtropical regions, where cool winters are likely, female flower production is preferred for local markets because such flowers are stable at low temperatures. Hermaphrodite flowers tend to fuse their anthers with the carpels and produce deformed carpellodic fruits. Hermaphrodite flowers, which can give rise to the most preferred of commercial fruits, are largely cleistogamous with anthers dehiscing and releasing the pollen to effect self-pollination prior to anthesis (Rodríguez Pastor et al. 1990). Parthenocarpic seedless fruits are not commercially used due to their small adult tree size and the presence of bitter tiny underdeveloped embryos that sometimes occur in isolated female trees without any close pollen source (Chan 2009). This explains why commercial lines are usually gynodioecious presenting only female and hermaphrodite plants.

Commercial production usually requires the planting of 3–4 plants per hole to ensure the maximum number of gynodioecious plants. Undesirable plants are removed after the first flower is produced. According to the genetic makeup of papaya elucidated by Storey (1953), appropriate crossings (H × H) planted at 4 plants per

**Table 5.3** Types of papaya flowers and tree forms

| Types | Tree sex[a] | Flower sex[a] | Description |
|---|---|---|---|
| Staminate | ♂ | ♂ | Typical unisexual flower on long peduncles |
| Teratological staminate | ♂ | ♂ | Found on sex-reversing male trees, with some degree of carpel initiation and development. A number of hair-like structures—vestigial carpels—found at base |
| Reduced elongata | H | ♂ | Modified normal elongata flowers differ from staminate flowers in having a thicker and stiffer corolla tube, abortion of pistils and reduced ovary size and number of carpels. More frequent flower types produced during warm periods and late summer, and can last from 1–2 weeks to 6 months, depending upon cultivar and temperature |
| Elongata (normal type) | H | H | Elongata refers to the shape of the pistil terminating in fine lobes; these flowers develop into pyriform or cylindrical fruits, five laterally fused carpels. Petals fused two-thirds of length |
| Carpelloid elongate | H | ♀ | Transformation of the inner series of stamens into carpel-like structures. Numerous types with different number of stamens becoming carpelloid and degree of carpellody, from slight to developing locules with functional stigma. Fruit to varying degrees misshaped |
| Pentadria | H | ♀ | Normal hermaphrodite type, modified unisexual pistillate flower, through stepwise stamen transformation to carpels, with loss of the original carpels. Short corolla tube, only five stamens of the outer whorl on long filaments globose and furrowed pistil. From 5 to 10 carpels |
| Carpelloid pentandria | H | ♀ | The stamens of the outer whorl become carpelloid. Carpellodic forms in carious stage, especially under cool conditions. All 5 stamens fully carpelloid and fused laterally, with abortion of original carpels. Flowers resemble pistillate flowers—pseudo—pistillate |
| Pistillate | ♀ | ♀ | Unisexual flowers larger than H flower, lack stamens. Flowering form stable and unchanged by environment |

[a] Staminate or male (♂), hermaphrodite (H) and female, (♀)

hole can increase the probability of obtaining a hermaphrodite plant (Table 5.4). The probability when planting four plants per hole is 98.76% against 96.29% with 3 plants per hole. In the case of preferring a female plant, by crossing a female with a hermaphrodite plant the percentage may rise to 93.75% (four plants per hole) or 87.50% for 3 plants per hole.

**Table 5.4** Types of crosses and resultant progenies in papaya

| Pollen donor | Mother plant | Progenies |
|---|---|---|
| $M_1m$ | Mm | 1 mm:1$M_1m$ |
| $M_2m$ | Mm | 1 mm:1$M_2m$ |
| $M_1m$ | $M_1m$ | 1 mm: 2$M_1m$ |
| $M_2m$ | $M_2m$ | 1 mm: 2$M_2m$: |
| $M_1m$ | $M_2m$ | 1 mm: 1$M_1m$: 1$M_2m$ |
| $M_2m$ | $M_1m$ | 1 mm: 1$M_1m$: 1$M_2m$ |

M1M1, M2M2 and M1M2 are lethal combinations

$M_1m$ Male tree, $M_2m$ hermaphrodite tree, *mm* female tree

## Cherimoya

The cherimoya (Fig. 5.3) belongs to the early-divergent Annonaceae, the most diverse family within the order Magnoliales with more than 2,400 species (Couvreur et al. 2011), 900 of which are found in the neotropics (Chatrou et al. 2004). Currently, cherimoya is an underutilized fruit crop, although it has excellent organoleptic qualities providing it with a clear marketing niche for expansion into countries with subtropical climates. Since high cherimoya diversity has been found in the region of the inter-Andean valleys of Southern Ecuador and Northern Peru, this region has been proposed as the area of origin (Popenoe 1921; Van Damme et al. 2000). However, the centre of origin is still under discussion since closely related species are only found naturally in Mesoamerica (H. Rainer, personal communication). In addition, palaeobotanical evidence from Peru (Pozorski and Pozorski 1997) and recent molecular diversity studies in Central America (Hormaza et al. unpublished data) seem to corroborate a Mesoamerican origin of the species. In any case, cherimoya was domesticated in antiquity and the movement of plant material throughout the Americas took place in pre-Columbian times (Popenoe et al. 1989).

Commercial cherimoya production worldwide is small, with Spain being the main world producer, followed by Chile, Peru, Ecuador, Colombia, Portugal (mainly in Madeira), Bolivia, USA (mainly California), Argentina and Mexico. In Andean and Central American countries most of the cherimoyas are collected from small family orchards with very limited market involvement, with the exception of the cherimoya ‘Cumbe’ near Lima in Peru. A large proportion of the trees are found in a semi cultivated state, and have originated either as chance seedlings or planted by people who grow cherimoyas at the borders of paths or orchards in their villages.

Cherimoya is a fruit with excellent organoleptic and nutritive qualities (minerals, fibre, vitamin C, fructose and niacin). Moreover, the interest in cherimoya and other members of the Annonaceae have increased dramatically in recent years due to the presence of natural compounds called acetogenins. Acetogenins are found only in this family and have promising new cytotoxic, antitumor, antimalarial, and pesticidal properties (Alaly et al. 1999; Liaw et al. 2010) that could explain the use of cherimoya grinded seeds as an insecticide in various American countries as well as the utilization of different parts of this crop and others in the family in traditional medicinal applications (Morton 1987).

**Fig. 5.3** Cherimoya fruit

## *Edaphoclimatic Requirements for Production*

### Soil Requirements

Cherimoya and other species of agronomic interest in the genus *Annona*, such as the guanabana or soursop (*A. muricata*), the sugar apple or sweetsop (*A. squamosa*), the custard apple (*A. reticulata*), or the atemoya (a hybrid between *A. cherimola* and *A. squamosa*), can grow in a wide variety of soil types, from sandy to clay loams, although they perform better in a well-drained sandy loam soil with good drainage to avoid potential root rot problems. Cherimoya is able to tolerate some levels of alkalinity preferring a range of pH between 7.5 and 8.5 and carbonate contents up to 30 %, although, in the latter, additional applications of iron are needed (Guirado et al. 2003). Studies in Spain (Farré et al. 1999) indicate that a yield of 14 t/ha can extract 95 kg/ha of N, 4.6 kg/ha of P, 38 kg/ha of K, 9 kg/ha of Ca and 27.5 kg/ha of Mg from the soil. Usually there is a need to apply Fe (about 4–5 kg/ha/year) to cherimoya crops to avoid iron chlorosis.

### Climatic Requirements

Cherimoyas grow in the subtropical strata (1.300–2.300 m.a.s.l.) of the Neotropics, a region characterized by dry winters and wet summers. Optimum mean annual temperatures for *A. cherimola* range from 16 °C to 20 °C, although cherimoya is more tolerant to low temperatures than other species in the genus. Temperatures above 30 °C can result in pollination problems and can cause leaf and fruit burn as well as increase the drop of recently set fruits (Farré et al. 1999; Van Damme et al. 2000). Temperatures below −2 °C can produce damage to leaves, fruits and trunks (Farré et al. 1999).

## *Crop Management*

The cherimoya is a semi deciduous fruit tree with simple leaves arranged alternately that must abscise before bud development takes place, since axillary buds are enclosed inside the leaf petiole (Schroeder 1941). The leaves of the cherimoya abscise just before the blooming period. Flowers appear as single or small 2–4 flower clusters on a short peduncle on the current season's growth (Cautín and Agustí 2005). In Spain, the tree is pruned in an open vase system with 3 of 4 main branches. Before the new growth starts, fruit branches and the growing point of main branches are removed and, during the period of active growth, suckers are eliminated or removed from the tree (Farré et al. 1999). Commercial propagation is usually carried out by grafting onto seedling rootstocks (George and Nissen 1987) and no clonal rootstocks are commercially available.

## *Reproductive Biology*

### Flower Development

Cherimoya, like most species in the Magnoliales, has hermaphroditic flowers, with a pyramidal gynoecium and an androecium surrounded by two whorls of 3 petals; the internal whorl is small and scale-like whereas the external whorl is greenish and fleshy. Consequently, the flowers of *A. cherimola* are herkogamous with a spatial separation between the androecium and the gynoecium and a non-functional zone of carpels that lay above the anther rows that establish a clear boundary between the male and female organs of the flower (Lora et al. 2011a). The gynoecium is composed of up to 300 fused carpels (each containing a single ovule), forming a syncarp that occupies the centre of the conic receptacle. The androecium is located below the gynoecium and forms a helicoidal structure with up to 200 stamens. The cherimoya flowering cycle is characterised by a protogynous dichogamous system (Wester 1910), a common characteristic in Annonaceae (Gottsberger 1999) an in other early-divergent angiosperm lineages with hermaphrodite flowers (Endress 2010); in species showing protogynous dichogamy, the female function matures before the male function, generally preventing self-fertilization in the same flower. Moreover, flowers of the same genotype usually open synchronously and, consequently, transfer of pollen between different flowers of the same genotype is difficult (Lora et al. 2010).

## Pollination and Fruit Set

The cycle of the cherimoya flower is completed in two days. In the first day of the cycle the flower opens in the female stage about midday under the environmental conditions of southern Spain. This phase lasts for about 30 h with the flower switching to the male stage on the second day of the flower cycle, followed by anther dehiscence around 17:00–18:00 h, depending on environmental conditions, mainly temperature (Lora et al. 2009b). After anther dehiscence, the receptive stigma rapidly dries up losing receptivity. The length of the stigmatic receptive phase varies depending on environmental conditions with high humidity and low temperatures extending stigmatic receptivity whereas stigmatic receptivity is shortened with low humidity and high temperatures. Thus, under some conditions (mainly low temperatures and high humidity), the stigmas can be receptive even when the flowers have already switched to the male state (Lora et al. 2011a; George et al. 1989).

Recent studies on the final stages of pollen development in cherimoya have shown a rapid and active pollen development before pollen release, resulting in the production of both bi and tricellular pollen at anther dehiscence, a very uncommon fact in flowering plants. The ratio between these two different types of pollen is greatly influenced by temperature (Lora et al. 2009a) and the pollen is released in a partially hydrated stage (Lora et al. 2012). Individual pollen grains are released from the tetrads after contact to the stigmas or to an artificial germination medium. Similarly to other tricellular pollen (Brewbaker 1967), cherimoya pollen is difficult to germinate in vitro (Rosell et al. 1999). This is due to a short viability (Rosell et al. 2006) and high sensitivity to desiccation and, consequently, pollen storage is difficult (Lora et al. 2006). Recent work (Lora et al. 2012) has shown a significant influence of environmental conditions (mainly temperature and humidity) on different pollen characteristics during the final stages of pollen development modifying pollen behaviour and explaining the variability observed in pollen tube performance. Cherimoya shows a simple primitive pistil with a short style and a semi-open continuous secretory carpel that provides substrate for pollen tube growth (Lora et al. 2010). Pollen tube growth is fast and the pollen tubes arrive to the ovule 1 day after pollination and only a single tube is able to penetrate the ovule and achieve fertilization (Lora et al. 2010).

Nitidulid beetles that breed and feed in decaying fruits or sap flows are the main pollinators of most *Annona* species including cherimoya (Peña et al. 2002). Work in Spain has shown that hemiptera insects of the genus *Orius* could also be effective as pollinating vectors in cherimoya; in fact, the presence of high densities of *Orius* in flowers and leaves of maize have led to the planting maize plants among cherimoya trees to increase natural pollination (Guirado et al. 2001). However, natural pollination often results in the production of asymmetric fruits with low commercial value. In fact, inadequate pollination is one of the most important factors that limit commercial production of *Annona* species in most locations. Since the crop was propagated from its areas of origin without its natural pollinator agent, hand pollination with pollen and stamens together is a common practice for commercial production in all countries where the crop has been introduced (Schroeder 1971). Moreover, hand-pollinated flowers result in fruits that show better symmetry than those resulting from insect-pollinated flowers. Due to the short longevity of cherimoya pollen, growers have to collect pollen daily to perform hand pollination although recent results indicate that pollen can be stored at low temperatures for several months (Lora et al. 2006).

In order to increase the commercial value of cherimoya and other species in the genus, a common objective in most breeding programs is the reduction in the number of seeds in the fruit. The possibility of producing seedless cherimoya cultivars has been recently put forward thanks to molecular work that has allowed the identification of a key gene involved in ovule and seed development in the genus *Annona* (Lora et al. 2011b).

In Spain, the cherimoya blooming season commences in late May and lasts through July whereas the regular harvesting season extends from October to December. However, under appropriate cultural practices (that mainly involve pruning before the blooming period), it is possible to induce flowering in August through to early September; the fruits set by those late flowers overwinter in the tree and can be harvested over March–April. This same approach can be used in other regions with similar environmental conditions in order to extend the commercial harvesting season.

## Avocado

The avocado (Fig. 5.4) belongs to the Lauraceae, a family included in the order Laurales and, together with the orders Canellales, Magnoliales and Piperales, form the Magnoliid clade in the basal angiosperms (Soltis et al. 2005). More that 50 genera and a variable number of species (ranging from 2,500 to 3,000) distributed along tropical and subtropical regions of the world are included in the Lauraceae.

The center of origin of avocado can be placed in an area that ranges from the eastern and central highlands of Mexico through Guatemala and to the Pacific coast of Central America (Popenoe 1976). Archaeological records suggest that selection and use of this crop took place in Mexico at least 10,000 years ago (Knight 2002; Galindo-Tovar et al. 2008). *Persea americana* consists of at least 8 botanical varieties or subspecies of which three, also called horticultural races, have agronomic significance: West Indian (*P. americana* var. *americana*), Guatemalan (*P. americana* var. *guatemalensis*) and Mexican (*P. americana* var. *drymifolia*) (Scora et al. 2002) (Table 5.5). The three horticultural races show no inter-race sterility barriers and most currently cultivated commercial varieties, such as 'Hass' and 'Fuerte', are inter-race hybrids. The crop is currently widely distributed in regions with subtropical and tropical climates.

### Edaphoclimatic Requirements for Production

### *Soil Requirements*

Avocado can be cultivated in a wide range of soils from volcanic to sandy loam and calcareous soils. Optimum pH values range from 5 to 7 and pH values above 7.0

**Fig. 5.4** Avocado fruit

**Table 5.5** Comparison of some selected traits of the three horticultural races of avocado. (Modified from Lahav and Lavi 2002)

| Trait | Mexican | Guatemalan | West Indian |
|---|---|---|---|
| Native region | Mexican highlands | Guatemalan highlands | Tropical lowlands |
| Climate | Subtropical | Subtropical | Tropical |
| Cold tolerance | High | Intermediate | Low |
| Salt tolerance | Low | Intermediate | High |
| Leaf anise scent | Present | Absent | Absent |
| Flowering season | Early | Late | Early-intermediate |
| Time from bloom to maturity | 5–7 months | 10–18 months | 6–8 months |
| Fruit size | Small-medium | Small-large | Medium-very large |
| Oil content in fruit | Very high | High | Low |
| Skin thickness | Thin | Thick | Medium |

require adapted rootstocks (Wolstenholme 2002). Due to the susceptibility of most avocado genotypes to soil root rots, such as those caused by *Phythophthora cinnamomi* or *Rossellinia necatrix*, good drainage with a low water table is essential. Although avocado is sensitive to soil salinity conditions, the West Indian genotypes show higher salt tolerance. Salinity problems are more common in semi-arid or arid regions due to the lack of leaching rain (Wolstenholme 2002). Since avocado is originated in areas where soils are usually rich in organic litter, mulching with organic substances is a recommended practice to improve overall tree health and performance (Whiley 2002).

### Climatic Requirements

The climatic requirements of avocado reflect the conditions present in the areas of origin of the species in Central America. Avocado has a shallow root system and, consequently, prolonged dry periods can seriously affect flowering and production. A moderate rainfall between 1,250 and 1,750 mm is desirable and, in most avocado growing regions, irrigation is needed during the dry periods.

Avocados can be grown under a wide range of temperatures, although the three avocado ecological races show different temperature requirements. Thus, both the Mexican and Guatemalan genotypes originate in the tropical highlands of Central America and, consequently, they can also be cultivated in areas with subtropical climates, although the Mexican race seems to be more adapted to low temperatures. The West Indian genotypes, originated from lowlands in the Pacific Central American coast are more adapted to warmer conditions with optimum temperatures between 25 °C and 28 °C and they are highly sensitive to frost. In spite of the different climatic adaptations, avocado, in general, has shown adaptation to very different edaphoclimatic conditions and current cultivation regions range from the tropics to higher than 35° N (Southern Spain) or 35° S (New Zealand). Differences also occur in the tolerance to temperature among cultivars from the same botanical race. A careful site selection should be made in areas prone to low winter temperatures in order to reduce the risk of frost damage. Nevertheless, freezes can sometimes take place even in important avocado growing regions in subtropical climates; in those cases, it is recommended that pruning of dead wood is postponed for several weeks or months to evaluate damaged branches.

## *Crop Management*

Traditionally, commercial propagation of avocado has been performed by grafting on seedling rootstocks. However, more recently, clonal rootstocks are increasingly been used especially due to the development of new selections, such as Duke 7 or Dusa, with tolerance to *Phythopthora* root rot. For a thorough review on avocado propagation see Bender and Whiley (2002).

Alternate or biennial bearing is common in avocado and different crop management practices such as the use of appropriate rootstocks, harvesting most of the crop as soon as commercial maturity has been reached, especially in 'on' years, and selective heavy pruning before blooming can help to reduce alternate bearing. See Whiley (2002) for a review.

## *Reproductive Biology*

One of the main limitations in avocado production worldwide is the massive abscission of flowers and developing fruitlets that results in a fruit set that ranges between 0.001 and 0.23 % (Sedgley 1980). Inadequate pollination itself cannot explain these low yields and, consequently, several additional factors are also implicated.

### **Inflorescence and Flower Development**

Reproductive growth usually occurs once per year in most cultivars following a rest period (Davenport 1986). Floral primordial are usually found in terminal and subterminal buds of spring and summer growth flushes (Scora et al. 2002).

Although the avocado flower is bisexual with functional male and female organs, outcrossing is promoted through a synchronous protogynous dichogamous breeding system also present in other early-divergent angiosperm species, such as cherimoya. In the case of avocado, each flower opens twice, the first as a female flower with a white receptive stigma; the flowers close overnight and the following day the flowers reopen functionally as male flowers, the anthers dehisce and the stigmas loose receptivity (Davenport 1986). Based on their flowering cycle, the different avocado cultivars are classified in two groups (A or B) (Nirody 1922). In type A cultivars, the flowers open in the female stage in the morning, close at midday and reopen the afternoon of the following day at the male stage. In the type B cultivars, the flowers open in the afternoon at the female stage, close in the evening and reopen the following morning in the male stage (Stout 1923). However, this floral behavior is only observed under optimum climatic conditions because the cycle can vary depending on environmental conditions, particularly cold temperatures being especially the case for B types (Sedgley 1977; Sedgley and Annells 1981; Sedgley and Grant 1983; Alcaraz and Hormaza 2009a).

### Pollination and Fruit Set

The avocado is mainly pollinated by insects. Different species (mainly Hymenoptera) act as natural pollinating vectors in Central America but in most avocado producing countries the European honeybee (*Apis mellifera*) is the main pollinator of avocado (Ish-Am and Eisikowitch 1993; Gazit and Degani 2002) even if avocado speciation took place before honey bees were present on earth. As a consequence, the avocado flower is not well-adapted to honey bee pollination and honey bees prefer flowers of other species that coevolved with them (Ish-Am and Eisikowitch 1998). The success of a good pollination in avocado requires the presence of a sufficient amount of beehives just before flowering.

Three different pollination systems can be observed in avocado (Gazit and Degani 2002): (1) autogamy, when the pollination takes place in the same flower; (2) geitonogamy or close pollination, when the pollen of one flower is deposited on the stigma of another flower of the same tree or of a different tree of the same cultivar; or (3) allogamy, when the pollen belongs to a different cultivar. Although several works have reported that stigmas are no longer receptive in flowers in the male stage, other results suggest that pollination and fertilization can occur in this stage allowing autogamy (Davenport 1986). The differences are probably due to the temperature and humidity conditions at flowering with an extended receptivity under lower temperatures and higher humidity situations that can prevent the stigma from desiccation during the male stage allowing pollen germination (Alcaraz and Hormaza 2009b). Geitonogamy is possible because there is a variable time of overlap between closing female flowers and opening male flowers that can allow transfer of pollen between flowers of the same cultivar in different developmental stages (Alcaraz and Hormaza 2009a).

In spite of the high flower drop rate, no morphological differences are apparent in avocado between the flowers that drop and those that will be retained in the trees (Sedgley 1980). Early fruit abscission has been attributed to low carbohydrate reserves in the trees (Davie et al. 1995) and the presence of starch in the ovary has been reported at anthesis (Sedgley 1979). Recent results show that, whereas no external differences are apparent among flowers at anthesis, a wide variability exits in starch content at flower opening supporting the idea that flowers with the highest starch content at anthesis could present some advantage to develop into fruits (Alcaraz et al. 2010, 2013).

Traditionally, in order to ensure an appropriate pollination process and optimize production, the interplanting of A and B flowering type cultivars has been recommended (Goldring et al. 1987; Garner et al. 2008), although this is still a subject of discussion since the results are variable depending on the cultivars and environmental conditions (Kobayashi et al. 2000; Alcaraz and Hormaza 2011).

### Fruit Development

Fruit development in avocado can last from six to more than 12 months depending on the cultivar and the environmental conditions. Fruit growth in avocado is sigmoidal and most cell division takes place at the initial phases of fruit development, followed by cell enlargement, although cell division continues at a slow rate while the fruit is on the tree (Schroeder 1953). The differences in fruit size are, thus, mainly due to the number of cells rather than by cell size (Scora et al. 2002). During fruit development there is an increase in oil concentration; in fact, percentage of dry matter, which is related to oil concentration, is the main parameter used to assess the maturity index and determine optimal harvesting time in avocado.

## Mango

The Mango (Fig. 5.5) is the most important species of the family Anacardiaceae in the Sapindales, both for its economic importance and world distribution. The genus *Mangifera*, one of the 73 genera belonging to the family Anacardiaceae, comprises 69 species, of which 12 are at least of local commercial importance. The area of origin of the mango may extend between Assam (India) and Myanmar where wild populations still exist, but it may also be native from the low slopes of Himalaya or areas close to Nepal or Bhutan (Kosterman and Bompard 1993). Two other well known fruit species belong to the same family, the cashew nut, also of tropical requirements, and the pistachio (*Pistacia vera* L.) of temperate origin.

Some botanists estimate that the mango was domesticated around 6,000 years ago (Hill 1952). Mango dispersal through the Indian subcontinent and the Malay Archipelago was very rapid being this species present around the fourth—fifth Century through all tropical and subtropical countries of Southeast Asia

**Fig. 5.5** Mango fruit

(Singh 1960). The Phoenicians first and later the Arabs seem to have been responsible for mango distribution through East Africa arriving to Madagascar through migration from the Indian subcontinent and surrounding areas around the tenth Century (De Laroussilhe 1980). Dispersal to other tropical zones was rather slow and had to wait till the arrival of Spanish and Portuguese sailors who, as in the case of the papaya, distributed it around the world after the sixteenth century (Galán Saúco and Cubero 2011).

## *Edaphoclimatic Requirements for Production*

### Soil Requirements

Mango can be considered as the hardiest tropical fruit tree withstanding a wide range of a sandy-lime or sandy-clay soil types. The mango has been successfully planted in soils as shallow as 40 cm in the rocky and calcareous soils of southern Florida, in the USA, to terraces with only 80 cm of soil depth in the Canary Islands (Galán Saúco 2009). The mango is also cultivated in Israel in calcareous (>38 % $CaCO_3$) and very sandy soils, with scarce organic content (0.3 %), and a low cation exchange capacity (CEC 7–13 mmol/100 g soil) with low water holding capacity (Whiley and Schaffers 1997). Whereas the soil pH of these soils are as high as 8.7, the mango prefers soil pH of between 5.5 and 7.0.

Values of electrical conductivity (EC) higher than 1.4 dS/m may cause salinity problems for mango, although there are some rootstocks like 13–1 that can withstand salinity levels as high as 3.1 dS/m in the irrigation water when under drip irrigation and with an appropriate water leaching program (Kadman et al. 1976).

### Climatic Requirements

The mango is well adapted to hot tropical conditions, but the ideal temperature conditions for its sustainable growth and cultivation include the following (Galán

Saúco 2009): a relatively cold winter (minimum temperatures around 10–15 °C) to induce flowering, a relatively warm spring (minimum temperatures above 15 °C) to favour good fruit set, warm summer and autumn seasons to get good fruit development and good vegetative growth after harvesting and a climate with small differences between night and day temperatures.

The incidence of frost is a limiting factor for mango cultivation. Young mango trees can die when exposed for several hours to temperatures below −4 °C with death of adult trees occurring at −6 °C and young shoots being burnt at temperatures below 0 °C (Campbell et al. 1977). Leaf chlorosis may occur both at temperatures below 10 °C or above 40 °C. However the mango tree can tolerate temperatures above 48–50 °C during the fruit development and ripening phases provided adequate irrigation is given (Donadio 1980; Majunder and Sharma 1985). This indicates the potential of mango to survive stressful conditions since most plants die when exposed to temperatures between 40 and 44 °C (Salisbury and Ross 1985).

Temperatures below 15.6 °C during flowering may give rise to poor pollen tube growth and embryo abortion (Young and Sauls 1979). Temperatures lower than 10 °C may impair pollen development because of the sensibility of the microspores originating during the meiosis process occurring inside the anthers (Robbertse et al. 1998). Lower temperatures (7–10 °C) can also increase the typical problem of poor ovary formation occurring in mango, where under normal conditions only 5–10 % of the hermaphroditic flowers are viable (Singh 1960). Despite the beneficial effect of low temperatures to induce flowering, when these temperatures fall close to 5 °C the ratio male/hermaphrodite flowers may increase (Chaikiattiyos et al. 1997).

Most authors indicate a minimum of 700 mm (annual rainfall or irrigation) as appropriate for mango cultivation, but the distribution of water is considered more important than the total amount of rainfall. In the absence of cold winter temperatures the mango needs a dry season to induce flowering in the tropics. The presence of rainfall during flowering, fruit set and harvesting can be detrimental for mango, since it can reduce pollination as well as favour the incidence of several fungal diseases (De Laroussilhe 1980), particularly anthracnose (Malo 1972). Mango is well adapted to wide variations in relative humidity, from 40 to 85 % (Whiley et al. 1988) and can withstand prolonged dry conditions, particularly due to its deep root system, as well as the presence of laticiferous channels in the leaf that can avoid an internal water deficit (Schaffers et al. 1994). Mango is also well adapted to varied rainfall conditions that can range from 250 mm, with regular irrigation during the period of fruit development (Majunder and Sharma 1985), until 5,000 mm (Donadio 1980). However as with many other tropical fruit crops, water stress at or during fruit set or early fruit growth can result in an excessive fruit drop and reduced fruit size that will have a negative effect on yield.

## *Crop Management*

Until recent times mango was considered a very rustic crop with cultivation techniques kept to a minimum and reduced in most cases to weeding, pest and disease control and minimum pruning, limited to removal of dead, badly conformed or broken branches. It was not until the onset of cultivation of this crop in subtropical areas that special attention was given to mango cultural techniques. Israel was the place in which control of irrigation, nutrition and flowering (see reproductive biology below) was developed and practiced, while in South Africa work was focused on pruning techniques and control of orchard density to the point of making successful high density plantings. Due to the strong stimulus of low winter temperatures there is practically not juvenile phase for the mango tree in subtropical climates being mandatory to avoid or remove all flowers produced during the training period, which can last between 2 and 4 years depending on cultivars and climatic conditions. The control of the erratic flowering of mango is one of the main objectives of mango cultivation. Since the age of the last flush is a critical factor for regulating floral induction (see reproductive biology) it is of importance that cultural techniques like irrigation and nutrition be orientated towards avoiding shoot initiation before the resting terminals are mature enough to induce flowering.

The management of the mango crop has been discussed in some of the literature mentioned already above but specific references are provided for nutrition and irrigation (Crane et al. 2009; Bally 2009), pruning (Fivaz and Grové 1998) and management of high density plantings (Oosthuyse 2005, 2009). It is also important to mention that with the application of all these techniques, mango production has steadily increased from less than the 10 t/ha, which is common in most producing countries, to average yields in the range of 22.5 t/ha in Israel (Homsky 1997) or even to exceptional yields of 35 t/ha in high density commercial orchards (Oosthuyse 2009).

## *Reproductive Biology*

Although most mango books and publications refer to the inflorescence as a panicle, the mango terminal inflorescence is a composed thirsoid (Coetzer et al. 1995) formed by a primary axis that ramifies either in the secondary and tertiary flower bud, but seldom in the quaternary, axis or directly in 3 flower buds. The mango is a monoic plant but presents in the same thyrsoid both hermaphrodite and male flowers. The number of flowers and the ratio of hermaphrodite to-male flowers changes in relation to temperature and cultivar, climatic conditions, location on the tree, and the level of tree productivity (Singh 1963; Galán Saúco et al. 1984).

The mango is a branching species in which the vegetative and reproductive phases are separated in time for each terminal, but not necessarily so for the whole tree. Although flowering in mango is mainly terminal, profuse cauliflory flowering has been reported in the older buds of mango following 'window pruning' of mature trees (Galán Saúco 2009). The mechanisms that control the morphogenic development of mango meristems, which ultimately express flowering, are largely determined by temperature and to a minor extent by water stress. Whereas the role of low temperatures in inducing flowers has been well established, the action of water stress in mango flowering is not clear. According to

Albrigo and Galán Saúco (2004) there is some evidence that, in the absence of low temperatures, the initiation of floral differentiation will usually occur after a long period of water stress. It is also clear that such a dry period can increase the intensity and synchrony of flowering, both in tropical and subtropical climates, although the response can vary with cultivar. In addition, the age of the wood is important for mango flowering: the older the wood, the more readily it will flower after any form of stress.

The mango is not a continuous growing tree, but has flushes of shoots developing from apical or lateral buds that occur at discontinuous, intermittent intervals (Nakasone et al. 1955; Davenport 2009 *et passim*). Flowering also stops the vegetative growth of mango terminals. The typical growth pattern of mango development consists of vegetative flushes ending with the formation of determinate inflorescences. After fruiting and harvesting, the terminal growth usually produces one or several growth flushes (intercalary units), depending mainly on temperature and cultivar but will eventually reach a resting stage. The apical resting bud of each intercalary unit is surrounded by a densely packed whorl of around 12 leaves with short internodes and has several preformed nodes containing a leaf bract or leaf primordial and a lateral meristem contained within. Depending on the inductive conditions, these apical buds may develop into vegetative or into reproductive shoots on which the lateral meristems, such as the bracts and primordia, do not fully develop. By contrast, the lateral meristem then starts to elongate and alters after several transformations that give rise to the inflorescence. The behaviour of the terminal meristems of the mango is more complex. In reality, six different shoot types, i.e. totally vegetative, totally flowering, mixed panicle, 2 transition stages (vegetative-to-flower and flower-to-vegetative) and chimeral (flowers on one side and leaves on the other) may develop mainly depending on the duration of low temperature at the time (Davenport 2009), with the interval between differentiation and flower emergence being as short as 29 days (Goguey 1995). This condition may explain why some flower shoots undergo a reversal from vegetative to floral shoot or vice versa as well as changes the frequency of mixed shoots when temperature conditions change sharply. However, according to Kulkarny (2004), the emergence of the different types of shoots is a consequence of the interaction between the floral promoter and the floral inhibitor that controls flowering in mangoes. As in many other tree crops, flowering can be suppressed or considerably delayed by the application of giberellic acid ($GA_3$). There are also indications that moderate applications of $GA_3$ can increase the proportion of missed shoots (Vázquez–Valdivia et al. 2009).

As a consequence of its peculiar flowering behaviour, flowering can be manipulated out of season. If the terminal flowering is destroyed, either by climatic or phytopathological reasons, the use of chemical sprays or pruning, or delaying the flowering by $GA_3$ sprays, the relatively low environmental temperatures occurring under subtropical conditions allow the emergence of a second flowering mainly from buds located at the base of either the terminal node, or axillary buds (Galán Saúco 2009). Stressed conditions provide for a second flowering, unlike the first flowering produced before the end of the winter, and in response to spring temperature which are high enough to ensure good fruit set. A similar phenomenon may also occur under more tropical conditions in Mexico where occasional cold air currents called “nortes” (Norths) have been reported to induce flowering (Mosqueda et al. 1996). Under subtropical climates and with night winter temperatures below 15 °C, most mango terminals will flower and produce after harvesting, when temperatures are higher, vegetative shoots conferring the mango tree a synchronous aspect. Perfect synchronic growth indicates the presence of a severe stress in the period of flower differentiation that may force 100 % of flowering or provide for an excessive amount of vegetative growth, both of which may compromise yield.

The manipulation of flowering can also be done under tropical conditions, in absence of low temperatures, with potassium nitrate stimulating out of season flowering although this treatment does not always produce dependable results. In fact, flowering only occurs in the tropics after the release of long periods of non-lethal stresses (Davenport 2009) which gives rise to asynchronic flower or vegetative shoot emissions on different terminal growth (Verheij 1986). This explains the differential habit of growth in the mango where part of the tree can be in the vegetative phase (both young and old shoots) and other part with flowers or fruits at a different stage of development. Despite this erratic behavior the tree keeps a well-structured canopy in equilibrium as the advance taken by a sector of the tree during one season is balanced by the other side in the following season.

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# Chapter 6
# Citrus Production

**Manuel Agustí, Carlos Mesejo, Carmina Reig and Amparo Martínez-Fuentes**

**Abstract** Currently, citrus is the main fruit tree crop in the world (104 million t, 7.1 × $10^6$ ha) with production largely cultivated in Brazil, China, India, USA, México, and Spain as well as many other tropical and subtropical regions of the world. There are six citrus groups of economic interest: sweet orange [*C. sinensis* (L.) Osb.], common mandarin (*C. reticulata* Blanco), Satsuma mandarin (*C. unshiu* Marc.), grapefruit (*C. paradisi* Macf.), lemon (*C. limon* Burm. f.) and lime (*C. aurantifolia* L.) with an additional group of hybrids under consideration. This chapter discusses the main exogenous and endogenous factors that determine citrus fruit production and quality (edaphoclimatic requirements, fruit and tree physiology, plant nutrition, and physiological fruit disorders) when in cultivation.

**Keywords** Citrus spp. · Taxonomy · Flowering · Fruit development · Ripening · Cultural practices

## Introduction

### *Origin and Distribution*

*Citrus* originated in eastern Asia, in an area that extends from the Himalayan southern slope to southern China, Indochina, Thailand, Malaysia and Indonesia. The oldest reference known comes from China and belongs to the *Book of History*

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written in the fifth century BC. It explains how the Emperor Ta-Yu (twenty-third century BC) included among the taxes to deliver two types of oranges, large and small, which indicates the high value of these fruits through the ages. Theophrastus (372–288 BC), the disciple of Aristotle, stated in his *History of Plants* extensive information on over 500 plants, among them the citron (*Citrus medica* L.), brought by Alexander the Great (356–323 BC) from Asia. He referred to the citron, a species known in Media and Persia (now Iran), as the medical apple (*Malus medica*), and describes the flower morphology and aromatic and medicinal properties of this fruit. Virgil (70–19 BC) was the first Latin writer who mentioned citron in his *Georgics*, a poem in four books, that highlights its characteristics as anti-rheumatic antidote. Surprisingly, in the Bible, which recognizes more than 200 fruit tree species, there is no clear reference to citrus and only *Citrus medica* has been described from around 200 BC.

Nevertheless, the French archaeologist Victor Loret (1859–1946) found paintings in the temple of Karnak in Egypt, with Killerman in his *Die Zitronen und Orangen in Geschichte und Kunst* (1916) identified seeds of citrus in his excavations at the south of Babylon. It is concluded that the origin of *Citrus* established as part of the ancient culture of Mesopotamina, Egypt and Greece around 4000 BC.

During the Roman Empire agriculture progressed remarkably, however it is not easy to find references to *Citrus*. Pliny the Elder (23–79 AD) in his *Natural History* and, later, Palladio (4th century AD) in his *Treaty of Agriculture*, refer to the characteristics and properties of the citrus crop. Greek culture, at the beginning of the Modern Era, also refers to *Citrus*. Disocórides of Anarzaba (60–70 AD) in his *Medical Matter* described the medicinal properties of *Citrus* fruits and seeds.

The Arabs spread the growing of *Citrus* in the Mediterranean basin. Ali al-Masudi (896–956 AD), historian and geographer of Baghdad, published in 943 AD his work *Al-Dhahab Moruj* (*Golden Fields*) and describes the importance of weather conditions on the characteristics and properties of sour orange trees (*Citrus aurantium* L.) as well as the citron (*Citrus medica* L.), in what might be called first study on the ecological adaptation of *Citrus* species. Ibn Wahsiya, Iraqi farmer, in his book *The Nabatean Agriculture* refers for the first time to lemon trees [*Citrus limon* (L.) Burm.f.]. The Spanish-Arab Abu Zaccaria (Ibn al-Awan) (twelfth century), in his *The Book of Agriculture*, devotes a chapter to describe citrus and study's separately, the citron, sour orange, azamboa or bastanbon (probably pummelo) and the lemon, mentioning some of their varieties, unrecognizable today. He also describes several cultural practices such as transplanting, irrigation, organic fertilization, pruning, thinning, and the propping up of branches, and even refers to some physiological disorders such as chlorosis. There are no references of when and how the sweet orange [*Citrus sinensis* (L.) Osb.] was introduced to the Mediterranean basin, the first one being referred to at the commencement of the sixteenth century.

The Spanish conquerors introduced citrus cultivation in America in the 16th century onwards. Franco Calabrese (2004) provides an excellent study on *The Fascinating History of the Citrus Fruit* from his native Italy.

## Geographic Distribution and Production

Citrus are grown in most of the tropical and subtropical regions of the world between the latitudes 40 °N to 40 °S. However, the large-scale, commercial plantations of citrus have developed almost exclusively in subtropical regions where temperatures are moderated by sea winds. These occur in two fringes around the world that extend roughly between 20 ° and 40 °N and S of the equator.

Currently, citrus is the main fruit tree crop in the world. By 2010 world citrus fruit production was about 104 million t, with a crop area exceeding $7.1 \times 10^6$ ha. Brazil ($20.2 \times 10^6$ t) and China ($16.2 \times 10^6$ t) continue to be the main producing countries, followed by India ($8.6 \times 10^6$ t), USA ($7.5 \times 10^6$ t), México ($5.9 \times 10^6$ t), Spain ($5.0 \times 10^6$ t) and others (FAO 2012).

# Taxonomy

*Citrus* species and related genera belong to the order Geraniales, suborder Geraniineae, and family Rutaceae. The family is subdivided into six subfamilies; the subfamily Aurantioideae includes true citrus and related genera. See the review by Swingle and Reece (1967) for further information. Within the Aurantioideae there are many tribes, subtribes, genera and species. The tribe Citreae, subtribe Citrinae, contains six genera including *Citrus*, *Poncirus*, *Eremocitrus*, *Microcitrus*, *Fortunella* and *Clymenia*. Primitive citrus relatives and the true citrus group are included in these genera, but only *Fortunella*, *Poncirus* and, above all, *Citrus*, have commercial interest.

The genus *Fortunella* (kumquat) includes four species of small trees, leaves and fruits. Leaves are unifoliate, flowers are borne singly or in clusters in the leaf axils, and fruits ranging in shape from ovate to round.

The genus *Poncirus* has two species, *P. trifoliate* and *P. polyandra*. The trees are small in size with trifoliate, deciduous leaves. Bud scales are pronounced and produce long thorns in the leaf axils. Flowers are globular and fruits are small and pubescent, and have a very bitter taste. *Poncirus* trees, and its intergeneric hybrids, are used as rootstocks.

The genus *Citrus* consists of several species of evergreen trees ranging in size from moderate to large. Branches are angular with numerous thorns when young and cylindrical with less prominent thorns when mature. Leaves are unifoliate, and vary in size depending on the species. Flowers are borne single or in clusters. Flowers generally have 5 sepals, 5 petals, 20–40 stamens and a single ovary with 8–12 fused carpels (segments) containing 4–8 ovules each. The style is long and has one stigma. The fruit varies in shape and size depending on the species and varieties and has a peel containing numerous oil glands and two tissues. The external part of the peel is called the flavedo; the internal one is called the albedo. Flavedo is a leathery tissue that varies in colour from orange and reddish orange (oranges) to deep orange (mandarins) or green-yellow (lemons, limes and grapefruit). Albedo is a white and spongy tissue, which separates flavedo from the segments. Juice is located into vesicles attached to the segment dorsal walls. Seeds are ovate to roundish in shape, mono- or poly-embryonic, with cotyledons colour ranging from white (oranges and grapefruit) to green (mandarins).

Although some taxonomists have combined all *Citrus* into a single citrus species, recent studies suggest that there are only three major affinity groups within *Citrus*, the *C. medica* group (*C. medica*, *C. aurantifolia* and *C. limon*), the *C. reticulata* group (*C. reticulata*, *C. sinensis*, *C. paradisi*, *C. aurantium* and *C. jambhiri*), and the *C. maxima* group (*C. maxima*). There is a fourth group with no commercial importance (*C. halimii* group).

There are six citrus groups of economic interest: sweet orange [*C. sinensis* (L.) Osb.], common mandarin (*C. reticulata* Blanco), Satsuma mandarin (*C. unshiu* Marc.), grapefruit (*C. paradisi* Macf.), lemon (*C. limon* Burm. f.) and lime (*C. aurantifolia* L.). An additional group of hybrids is under consideredation. For detailed information on these citrus groups see the reviews by Agustí (2003), Donadio et al. (1995), Hodgson (1967), Jackson (1991), Saunt (2000), and Vacante and Calabrese (2009).

## *Sweet Oranges*

Sweet orange may be separated into three groups: (1) the common oranges, (2) the navel oranges, and (3) the pigmented (blood) oranges. The common oranges (Fig. 6.1a) are more important commercially and are mainly processed for juice production. Navel oranges (Fig. 6.1b) are the second most widely planted group and are mainly marketable for fresh consumption. The third group, blood oranges (Fig. 6.1c), is a very much less important group and plantings are limited to areas with Mediterranean-type climates. Sweet oranges ripen from early in autumn to late in spring. The most important sweet orange cultivars are described below.

### Common Oranges

‘Valencia’ is most likely of Chinese origin, but is so named because it resembles a similar cultivar growing in Valencia, Spain. It is the most important late-season sweet orange. Fruit usually matures from March to May in the northern hemisphere (NH) and from September to November in the southern hemisphere (SH). Fruit remain on the tree without important loss of internal quality, but may regreen on the tree and can reduce flowering the following spring inducing the tree to alternate bearing. Fruits are of medium size, spherical to oblong, orange-yellowish and commercially seedless (fewer than nine per fruit). Juice is of excellent quality because of its high concentration of total soluble solids (TSS) and is keenly sought for processing into juice. There are several cultivars of ‘Valencia’, such as ‘Frost’, ‘Midknight’ and ‘Delta’ that differ in fruit shape, peel thickness and date of maturty.

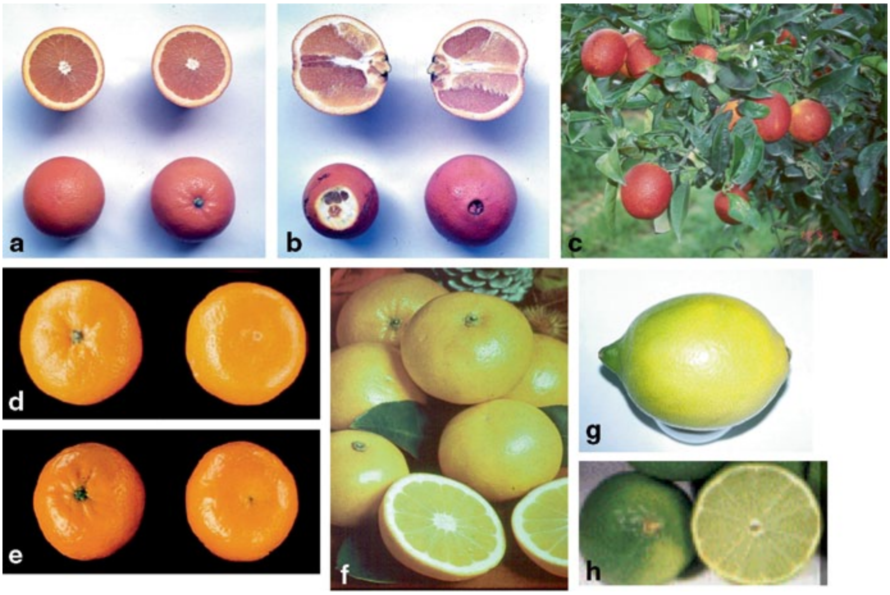

**Fig. 6.1** Commercial cultivars of *Citrus* spp. **a** 'Salustina' common sweet orange. **b** 'Washington' navel sweet orange. **c** 'Sanguinelli' blood sweet orange. **d** 'Owari' Satsuma mandarin. **e** 'Clemenules' Clementine mandarin. **f** 'Marsh' grapefruit. **g** 'Eureka' lemon. **h** 'Tahiti' lime

'Hamlin' is widely planted in Florida, in the USA, and Brazil and used mainly for processing into juice. Trees grow upright and fruit mature in September-December in the NH. Although this cultivar is very prone to drop when mature, fruit hold on the tree well until February to March in the NH. Fruit are spherical, smaller than other common oranges and seedy (6–8 seeds). Juice is of poor quality, with low TSS concentration. The peel is thin and susceptible to *puffing,* a serious physiological disorder in which the pericarp and flesh separate from each other (see Section "Edaphoclimatic requirements for production and improved fruit quality").

'Pera' is a very important cultivar grown for the processing and fresh markets in Brazil. Trees are vigorous, densely foliated, and grow upright. They produce multiple blooms and crops a year, which make for a difficult harvest at the best maturity stage for processing into juice. Fruit are of medium size, ovate, seedy (5–10 seeds) and of medium quality because it's low TSS content.

'Salustiana' is a mid-season sweet orange, which originated in Valencia, Spain, as a bud mutation from the 'Comuna' sweet orange. It is grown in Spain and Morocco and, to a lesser extent in South Africa. Trees are vigorous, well developed and very productive, although they are prone to alternate bearing. The fruit is medium to large in size, with a finely pebbled and medium thick peel, spherical, with a very good colour, and seedless. The fruit matures in December-January (NH) and hangs well on the tree until late April.

## Navel Oranges

Navel oranges have a small secondary fruit embedded in the stylar end of the primary fruit, which is distinctive of the group. Navels are the earliest maturing of oranges varieties, producing seedless fruit of large size, spherical in sharp, with deep orange colour, and a rich, sweet and pleasant flavour and are marketed for fresh consumption. Navel group cultivars represent a significant proportion of the citrus production of Australia, Argentina, California, Morocco, Spain, South Africa, Turkey and Uruguay.

'Washington' navel is by far the widely planted and commercially important navel orange cultivar. Trees are of medium size, vigorous, and flower profusely. Fruit is round in shape with a rind slightly rough, moderately thick and intensely ripened. The flesh is firm, tender, juicy and of sweet flavour and adequate acidity. The fruit drops easily at physiological maturity. Several 'Washington' navel bud mutations have been developed, some earlier varieties, such as 'Leng', 'Navelina', 'Fisher' and 'Newhall', and some later maturing varieties, such as 'Lane Late' and 'Navelate'. The harvesting of Navel oranges lasts from November to May (NH).

The 'Leng' navel sweet orange originated in Australia, where is extensively planted. Tree vigour and size are very similar to 'Washington' navel, but leaves are narrower in shape. Fruit is smaller and earlier maturing, and holds well on the tree without decaying in quality. Rind texture is smoother and thinner, and has good colour, developing into a deep reddish-orange intensity. The flesh is very juicy with good flavour.

'Navelina' sweet orange originated in California, USA. It is a smaller tree than 'Washington' navel, with dark green leaves; fruit is earlier maturing and tends to drop after colour break. Fruit size is smaller than 'Washington' navel, rind texture is very slightly smoother, develops a very intense colour, and flesh has an excellent flavour. Two lines of this cultivar have been identified depending on shape, round or oblong fruit.

Tree and fruit characteristics of 'Newhall' are almost indistinguishable from 'Navelina' apart from fruit maturity, which is advanced due to deeper rind colour and low acidity.

'Summerfield' navel is widely grown in Florida, USA, because it is well adapted to the humid tropical-type climate. Trees are productive and fruit matures earlier than 'Washington' navel.

'Baianinha' is the most important navel sweet orange planted in Brazil, originated as a bud mutation of 'Bahia' navel sweet orange. It is less vigorous and has a smaller secondary fruit than the 'Washington' navel. Fruit size is medium to large, slightly oblong in shape, and of good and sweet flavour; the navel is small and almost concealed. It is well adapted to hot arid growing conditions.

The 'Lane Late' was discovered in Australia, and it is grown to some extent in Australia, South Africa and Spain. It is late maturing, moderately productive and the fruit hold well on the tree up to mid-spring without deteriorating in quality. Trees are very similar to 'Washington' navel in vigour and size. Fruit rind texture is smooth, and orange-yellowish pale in colour; the navel is small and protruding. The flesh is tender, juicy and of sweet flavour and with a low limonin content of its juice.

‘Navelate’ sweet orange is a late maturing navel orange originated in Spain. The trees are vigorous and similar to ‘Washington’ navel, but branches are thorny and are moderately productive. Fruit of medium size, with small and almost concealed navel; rind is thin and of yellowish-orange colour; flesh is very tender and juicy, and of extraordinary quality. Fruit can be left to hang on the tree up to mid-spring without loss of quality.

### Pigment (Blood) Oranges

Blood oranges are of some commercial importance in some Mediterranean countries, mainly in Italy. This group of varieties develops deep red flesh colour due to the anthocyanin pigments, which can also develop in the rind. It is related with hot days and, above all cold nights. Fruit of medium size, oval to oblong in shape, and thin peel. Flesh is very juicy and of excellent quality. Trees are usually small, of dense canopy and pale leaves.

The most important cultivars include early maturing (January–February; NH) cultivars ‘Tarocco’ and ‘Gallo’, medium (February–March) ‘Tarocco Ippolito’ and ‘Sciara’, and late maturing (April–May) cultivars ‘Sanguinello’ and ‘Moro’, the latter being the most important variety for juice processing.

## *Satsuma Mandarin*

Satsuma mandarin probably originated in China and exported to Japan (sixteenth century AD). The Satsuma mandarin market is growing in Japan and Spain and to a lesser extent to Korea, Turkey, Georgia, California (USA), Argentina, Uruguay and South Africa. In Japan and Spain, production has been declining in the last decades.

This species is well adapted to cool sub-tropical regions and has low heat unit requirements for fruit maturation, however rainfall and relative humidity changes colour and makes the fruit prone to *puffing*.

Satsuma mandarins are mainly grown for fresh consumption, but are suited to processing for juice and for canning segments in syrup or juice.

The Satsuma tree is vigorous and very productive, and exhibits a spreading habit with long dropping branches. Leaf is large, slightly leathery, dark dull green, and has a prominent midvein. Fruit is moderate large compared to other mandarins, slightly flattened in shape, smooth peel, yellowish, of acceptable flavour, and seedless. Size, shape, colour and flavour mainly depends on the growing area, fruit produced under cooler conditions being usually small, flattened and of deep orange peel colour.

Satsuma cultivars are commonly divided into two groups on the basis of their maturation date. The early to mid-season cultivars mature from October to December in the NH, and the earlier maturing ones are marketable from September onwards. The early to mid-season cultivars include ‘Owari’ (Fig. 6.1d), widely grown in Japan and Spain, and ‘Wenzhou’, in China. The earlier maturing varieties include ‘Miyagawa’ wase (*wase* means early maturing in Japanese), which is the most widely grown Satsuma in Japan, 'Okitsu' wase, which originated as a nucellar seedling by controlled pollination from 'Miyagawa' fruit, widely grown in Japan and Spain, and 'Clausellina', an 'Owari' bud mutation originated in Almassora, Spain.

## *Common Mandarin*

Common mandarin has many cultivars with similar characteristics. Tree has upright growth habit. Leaf size is medium to small, bright green and petiole size is reduced. Fruit size is medium to small, with firm and adherent rind, and easy to peel. Cultivars Clementine and Dancy belong to this group.

The origin of Clementine mandarin is uncertain, but is believed to originate in China and selected in Algeria. In Spain and Morocco 'Clementine' has become the fastest expanding citrus variety over the past five decades. 'Clementine' mandarin also extends to Argentina, Uruguay, South Africa and Peru. The tree is densely foliated, small to large size depending on the cultivar and has regular high yields. Leaves are lanceolate. Fruit is medium to small in size, easy to peel, with excellent flavour, and seedless, although cross-pollination with common oranges, grapefruit and hybrids, can develop several seeds per tree. The 'Clementine' mandarin fruit is sensitive to rainfall and relative humidity (RH), developing a very fast senescence period that reduces external fruit quality. Several cultivars of 'Clementine' have been obtained by spontaneous bud mutation in Spain differing in time of maturation, tree size, fruit size and yield.

One of the better mutations derived from Clementine is 'Fina'. This was first introduced to Spain in 1925, probably from Algeria. Fruit of 'Fina' is of excellent quality, deep orange-reddish and has very good organoleptic characteristics: pleasant aroma, tender, sweet and high juice content; however it is very small. The rind is smooth and easy to peel. The fruit must be collected no later than mid- to the end of December (NH). 'Clemenules' mandarin (Fig. 6.1e) is, nowadays, the most extended Clementine mandarin in Spain and Morocco. Similar to 'Fina', it has larger fruit, and is a little more resistance to environmental conditions. Of the other mutations 'Oroval', 'Oronules' and 'Marisol' mature two to four weeks earlier, and 'Hernandina' one month later. Clementine mandarins produce weakly parthenocarpic fruit, requiring gibberellic acid ($GA_3$) sprays to achieve adequate fruit set and yields.

The 'Dancy' mandarin originated in Florida, USA, where it is the most widely planted mandarin. This cultivar has high heat requirements. Fruit develops an acceptable orange peel colour but is too small for fresh consumption, and tends to dry when hold on the tree. 'Dancy' is susceptible to *Alternaria* brown spot and tends toward alternate bearing.

## *Mandarin Hybrids*

There are several like-mandarin natural and man-made hybrids. Among the former group are 'Murcott', 'Temple', 'Ellendale', and 'Ortanique' are the most important natural like-mandarin whereas ‘Nova’, ‘Kara’, ‘Fortune’, and ‘Minneola’ and ‘Orlando’ tangelo [mandarin (tangerine) x pomelo (grapefruit)] are man-made hybrids.

‘Murcott’ is probably a tangor (tangerine x sweet orange), a vigorous tree of upright growth habit. The fruit is medium sized, seedy and oblate. The rind is firm and not as easy peeled as true mandarins. Internal fruit quality is excellent, but juice is high in limonin and some bitter flavour components; fruit is harvested for fresh consumption. Fruit reaches commercial maturity from January to March in the NH. A new seedless mid-season irradiated selection of ‘Murcott’, called ‘Tango’ mandarin, has been developed in California, USA.

The ‘Temple’ mandarin is of unknown origin. The trees are of medium vigour, thorny, and have lanceolate leaves. Fruit is of medium-large size, slightly flattened, very seedy, and of good flavour. Rind highly coloured, fairly thin and easy to peel. Much of the production is processed.

The tangor ‘Ellendale’ has fruit of medium-large size, flattened, of good deep orange colour rind, of smooth texture and easy to peel. The pulp is tender and juicy and has a good, sweet and rich flavour. Fruit tends to *split* at the stylar-end, especially after a dry period and if followed by rainfall, causing the fruit to drop. ‘Ellendale’ also develops *granulation*, (a physiological disorder characterised by enlarged, hardened juice vesicles) especially under dry conditions, and *creasing* (see Section “Flowering”). It is a self-incompatible cultivar, but can set many seeds when planted near pollinating varieties. Fruit matures from November to mid-December in the NH depending on the growing area.

The tangor ‘Ortanique’ originated in Jamaica. Trees are vigorous, with spreading branches and very productive. The leaves are large, lanceolate, and dark green in colour. Fruit is of medium size and round. The rind is of deep orange in colour, rough and very difficult to peel. Fruit matures late in the season (March, NH).

‘Nova’ is a hybrid between ‘Fina’ Clementine and ‘Orlando’ tangelo. The trees are vigorous, moderately thorny, and productive. Leaves are undistinguishable from Clementine trees. The fruit is of medium size and the rind colour is reddish-orange and easy to peel. Internal quality is very high, very juicy and tender, with a very fine flavour, and seedless, but is cross-pollinated with pollinating varieties such as ‘Clementine’, or ‘Orlando’ tangelo,

‘Kara’ mandarin is an ‘Owari’ Satsuma x ‘King’ mandarin (*C. nobilis*) hybrid. The tree has moderate vigour, spreading habit like the Satsuma, productive, and tending to alternate bearing. The leaves are similar to Satsuma. The fruit is of medium-large size and slightly necked. The rind is rough, of deep orange colour, easy to peel and susceptible to *creasing*. Internal fruit quality is moderately acceptable. Juice has very high sugar levels, but the acidity remains very high and has several seeds.

‘Fortune’ mandarin is a hybrid of ‘Clementine’ x ‘Dancy’ mandarin. The trees are vigorous, of medium size and productive. The fruit is medium to small size, round in shape. Leaves are short, broad, slightly cupped and dark green. The peel texture is very thin, fairly tightly adhering, and easy to peel, but sensitive to *peel pitting* disorder caused by cold winds (see Section “Taxonomy”). The pulp is juicy, very sweet, but its acid content is high. It is a seedless cultivar, however fruit can develop many seeds when planting close to suitable pollinating cultivars. Fruit reach commercial colour in December (NH), but due to the acidity harvest is usually delayed to February-March.

‘Minneola’ tangelo trees are very vigorous, large, spreading, and productive in temperate areas. The fruit is large and round, with a pronounced neck at the stem-end. The peel is deep reddish orange, moderately adherent and finely pebbled. When grown in a solid block develops seedless fruit, but when grown close to pollinating cultivars fruit sets several seeds depending on the degree of cross-pollination; nevertheless, to achieve optimum yields and adequate fruit size requires cross-pollination or gibberellic acid sprays. Fruit reach commercial maturity in January–March in the NH.

‘Orlando’ tangelo has large vigorous trees. The leaves are large, broad and cupped laminae. The fruit is medium to large in size, round, slightly oblate, and slightly necked at the stem-end. The rind is light orange, very thin and moderately tightly adhering, not easy to peel. The pulp is tender, juicy, very sweet, but rather insipid flavour with low acidity. Both ‘Minneola’ and “Orlando”, require cross-pollination to obtain adequate yields and fruit size. Fruit reach maturity in December–January in the NH.

‘Afourer’, also named ‘Nadorcott’, is of unknown origin, but originated from seed from the ‘Murcott’ tree in Morocco. It might be a nucellar selection, a bud mutation of ‘Murcott’ or, most probably, a ‘Murcott’ x Clementine natural hybrid. The trees are very vigorous, of upright growth habit, tending to alternate bearing. It is widely propagated in Morocco and, in a lesser extends, in California (USA), Uruguay, and Spain where law limits the number of trees planted. Fruit is medium size and slightly flattened. Seedless when isolated from pollinators, but is sensitive to cross-pollination with ‘Clementine’, ‘Nova’, and ‘Fortune’ mandarin, and also with lemon, grapefruit and common sweet orange. The rind is deep orange-coloured, fairly fine and thin, easy to peel, and with the albedo characteristically coloured. The flesh is very juicy and sweet, with high sugar content and good acidity level. Fruit reaches commercial maturity in mid to late February in the NH.

## *Grapefruit*

The origin of grapefruit (pomelo, toronja) is uncertain, but there are some evidences that seeds were introduced to Barbados by the early settlers and introduced into Florida (USA) at the beginning of nineteenth century from Cuba, Jamaica or Bahamas. Grapefruit distribution is more limited than sweet oranges and mandarins.

Grapefruit trees are very vigorous and have a spreading-type growth. Leaves are very large, ovate, with serrated margins, with a large and winged petiole. Fruit is the largest of any commercial citrus cultivars. The sweetest, juiciest and most bitter-free fruit is grown in semi-tropical summer rainfall regions. In the cooler drier areas fruit has thicker rind, lower sugar and high acid level in the juice and to have some bitterness. Fruit quality improves and juice acid content decrease as the fruit remains on the tree.

Grapefruit cultivars are divided into two groups according to peel and flesh colour. The white or common cultivars of which only ‘Marsh’ (Fig. 6.1f) is of any significance, and the pigmented cultivars of which ‘Rio Red’, ‘Star Ruby’ and ‘Redblush’ are of commercial importance. Other cultivars such as ‘Duncan’ (white grapefruit), ‘Henderson’, ‘Hudson’, ‘Ray Ruby’, ‘Flame’ and ‘Burgundy’ are of a great lesser importance.

The ‘Marsh’ grapefruit has an unknown origin. This cultivar still predominates in all citrus producing countries. The tree is vigorous and very productive. The fruit is large, with yellow and thick rind. The flesh has a high juice content of sweet flavour of rather high acidity. ‘Marsh’ grapefruit has typically just two or three seeds per fruit, but is rarely seedless. The fruit matures in November in the NH, but can remain on the tree for several months without noticeable quality deterioration.

‘Rio Red’ originated as a selection of a seedling of ‘Ruby Red’ grapefruit. Budwood of this selection was irradiated and propagated and a mutation selected for its deep red colouration. ‘Rio Red’ trees are vigorous with an open growth habit. The rind is thick, with deeply blushed areas. Flesh is light red in colour, soft, and with an excellent juice content. Seed content is low, usually one to three per fruit.

Irradiating seed from the ‘Hudson’ cultivar produced ‘Star Ruby’. ‘Star Ruby’ trees are less vigorous than most cultivars and, in general, are less productive and bear smaller fruit. Pruning is of great importance to increase the yield, fruit size and internal fruit quality of this cultivar. The rind is thin, smooth and fine, and appropriately pigmented. Flesh has high juice content, is very sweet, and deeply pigmented. ‘Star Ruby’ is almost seedless, rarely having more than one or two seeds in a minority of fruit. However, it is the most problematic of all grapefruit trees to grow well. This cultivar is susceptible to root rot (*Phytophthora* spp.), sunburn, chlorosis and micronutrient deficiency and is quite cold sensitive. Fruit matures from mid-October to early November (NH) but can hang on the tree up to March without appreciable quality deterioration.

‘Redblush’ originated as a bud mutation of ‘Thompson’, which, in turn, is a pink mutation of ‘Marsh’. It is also named ‘Ruby Red’, and ‘Henninger’. This cultivar is widely grown worldwide. Good internal and rind pigmentation. Apart from the colour, ‘Redblush’ is virtually identical to ‘Marsh’ and has few seeds.

## *Lemons*

The Mediterranean lemon we know today is very likely to be a hybrid of citron. Lemon cultivars are grouped in three types: Sicilian, Verna, and *Femminello*. Lemon trees are very sensitive to low temperatures and to fungal and algal diseases, thus it is not well adapted to humid subtropical or tropical regions. However they do grow well under the Mediterranean climate. Lemon trees tend to grow, flower, and produce fruit continuously throughout the year, but in Mediterranean climate trees have two major flowering periods, in spring and summer. Depending on several factors, the fruit is harvested either in autumn, winter or summer. The principal, *invernale* or *limoni* crop is harvested from December to May (NH), the *verdelli* or *maiolini* crop from June to September, and the *primofiore* from September to November; an extra-crop, *bianchetti*, from April to June, exists for Femminello type.

Lemon trees are very vigorous and thorny, having an upright habit that becomes more spreading when the tree matures. Leaf morphology is variable depending on the tree vigour, generally being large, ovate, with serrated margins. Newly developing leaves and flowers are purple but as they develop become green and white, respectively. Petiole is reduced and even non-existent. Fruit shape varies from spherical to elliptical, has a characteristic apical nipple at the stylar end, variable in size, and even nearly non-existent, depending on the cultivar, and develops a necked stem-end also cultivar-dependent in size. Lemon fruit are high in acidity (5–7 %) and low in total soluble solids (7–8 %), and is moderately seeded or seedless. Fruit can be storage for long periods under controlled temperature and humidity conditions.

'Eureka' (Fig. 6.1g) is the most important cultivar in the Sicilian group. It is of great importance in California (USA) and Australia, and is also grown in Israel, South Africa and Spain. Trees have a less densely foliated spreading canopy and are less frost-hardy than other cultivars. Fruit are moderate to small-sized, ovate with a moderate apical nipple, and has high juice content with a high acid level. The rind is smooth to coarse in texture, thin, and, sometimes, develops *puffing*. Seeds are few, less than five, and often the fruit is seedless. 'Lisbon' is important in Argentina, Australia, California (USA) and Uruguay. Trees are densely foliated. Fruit is of excellent quality, has a pronounced nipple, and fewer than nine seeds. 'Lisbon' produces superior yields than 'Eureka' and has denser foliage that protects the tree from wind and frost damage to the fruit. Fruit harvest periods occur over winter and spring.

'Verna' is the major cultivar of Spain (50 % of crop). Its origin is unknown. The trees flower twice and can also produce a third crop; however, only the first one (February–July; NH) is of commercial quality. It is of medium to large fruit with a pronounced nipple and a well-developed neck. The rind is medium thick and rough. The pulp is tender, and the juice content is lower than other cultivars but of good acidity; fruit have few seeds.

*Femminello* comprises a group of selections, 'Comune' ('Ovale'), 'Santa Teresa', and 'Siracusano' being the most important ones. It is the most extended type of lemon grown in Italy, accounting for about 75 % of total crop. Collectively, this group is harvested all throughout the year. *Femminello* selections are productive; produce fruit of medium size, moderate thick rind, and lower juice content than other cultivars but with higher acidity. Seeds number varies upon the crop, probably because the bees' habit, from 2 to 12, *primofire* and *limoni* having the larger. *Femminello* selections are very susceptible to *mal secco* disease (*Phoma tracheiphila*), a severe tracheomycotic disease of citrus.

## Limes

Lime trees probably originated in the tropical Malay Archipelago. They are the most freeze-sensitive of all commercial citrus species and, thus, its grown is limited to the tropics and warm, humid subtropical regions of the world.

There are two groups of limes: ‘Tahiti’ and ‘Mexican’ limes. The former includes the ‘Persian’ and ‘Bearss’ limes, the latter includes the ‘West Indian’ and ‘Key’ limes.

Lime trees are very vigorous, thorny, with upright and spreading growth habit. Leaf lamina of ‘Tahiti’ lime is large and elliptical, whereas that of ‘Mexican’ lime is small and nearly round. Margin is serrated and petiole almost non-existent for both types. Flowering occurs in two major peaks, but may occur continuously producing several crops a year. Petals of ‘Tahiti’ lime are purple, whereas those of ‘Mexican’ lime are white. Fruits are spherical to elliptical. ‘Tahiti’ lime does not produce seeds since it is a triploid and produces no viable pollen; ‘Mexican’ lime has 10–15 seeds per fruit.

The fruit of ‘Tahiti’ lime (Fig. 6.1h) is greenish-yellow or pale yellow when fully mature, very juicy and extremely acidic. The rind is very thin with distinctive rind oil aroma.

The fruit of ‘Mexican’ lime is greenish-yellow or yellow when mature, but it is often harvested earlier while still dark green in colour. The flesh is tender, greenish-yellow, very juicy and highly acidic.

## *Citrus Rootstocks*

With citrus seedlings, the trees have an extended juvenile period, in which trees are unable to flower and, thus, are non-productive and excessively vigorous. Seedlings are also susceptible to many soil-related problems, such as calcium, salinity, drought, nematodes and some root rot diseases mainly *Phtophthora* spp. To overcome these problems, most citrus trees consist of two parts: the cultivar that is budded on a rootstock. The combination integrates favourable attributes of both of them, and, although there is not perfect rootstock even for a specific situation, rootstock selection is a major consideration to the success of the plantation.

Today the range of rootstocks is ample. Some are natural species, but man-made hybrids are increasingly being used. The most important rootstocks are listed above, together with their main agronomical characteristics (Table 6.1) and tolerance to disease (Table 6.2). For additional information refer to reviews by Agustí (2003), Castle (1987) and Saunt (2000).

Sour orange (*C. aurantium* L.), sweet orange, and rough lemon (*C. jambhiri* Lush.) rootstocks were widely used but they are now in decline because of the susceptibility to citrus Tristeza virus (CTV) and to *Phytophthora* root rot. Nevertheless, sour orange is an excellent rootstock that has been and will probably continue to be the main rootstock used worldwide. Sweet orange is a good rootstock tolerant to many virus diseases including CTV, but has been replaced by other high quality-inducing rootstocks.

Cleopatra mandarin (*C. reshni* Hort. ex Tan.) is of minor importance worldwide. However, increasing interest is being shown in some citrus producing countries because its high calcium, salinity and CTV tolerance.

Table 6.1 Agronomical characteristics of the major citrus rootstocks. (Agustí 2003)

| | Calcium tolerance | Salinity tolerance | Drought tolerance | Tree vigour | Yield | Fruit quality |
|---|---|---|---|---|---|---|
| Sour orange | H | I | I | I | I | I |
| Sweet orange | L | L | L | H | I | I |
| Cleopatra mandarin | H | H | I | I | I | I |
| *Poncirus trifoliata* | L | L | L | I | I | H |
| Citranges | L | L | L | H | H | H |
| *Citrus volkameriana* | H | I | – | H | H | L |
| Citrumelos | L | I | H | H | I | I |
| *Citrus macrophylla* | H | H | – | H | H | L |

*H* high, *L* low, *I* intermediate

Table 6.2 Behaviour of the major citrus rootstocks against virus diseases and root rot. (Agustí 2003)

| | CTV | Exocortis | Psoriasis | Blight | Root rot |
|---|---|---|---|---|---|
| Sour orange | S | T | T | T | R |
| Sweet orange | T | T | S | T | S |
| Cleopatra mandarin | T | T | T | T | T |
| *Poncirus trifoliata* | R | S | T | S | R |
| Citranges | T | S | T | S | T |
| *Citrus volkameriana* | T | T | – | S | T |
| Citrumelos | T | T | T | – | R |
| *Citrus macrophylla* | S | T | – | S | R |

*S* susceptible, *T* tolerant, *R* resistant

Trifoliate orange (*Poncirus trifoliata* [L.] Raf.) is widely used in Argentina, Australia, China, Japan and Uruguay. Trees budded onto trifoliate orange are not well adapted to high calcium soils and high salinity, but are not affected by CTV and produce fruit of high quality.

Citranges are hybrids of *C. sinensis* x *P. trifoliata*. Several of them have been tested as rootstocks, but only two of them arose from ‘Washington’ navel orange as seed parent, ‘Troyer’ and ‘Carrizo’, are extensively used. They are very similar in nematode tolerance, the latter ‘Carrizo’ being more tolerant. ‘Carrizo’ is widely used in Florida (USA) and Spain, and ‘Troyer’ in California (USA).

Volkamer lemon (*Citrus volkameriana* Pasq.) is adaptable to a range of soils and produces vigorous and productive trees. It is not susceptible to CTV although it is affected by nematodes and citrus blight, caused by the bacterium *Xanthomonas axonopodis*.

Citrumelos are hybrids of *C. paradisi* x *P. trifoliata*. ‘Swingle’ citrumelo is the most propagated rootstock, having a semi-dwarfing effect on sweet orange. They are tolerant to nematodes, *Phytophthora* root rot, CTV and other virus diseases, and to citrus blight. In the Mediterranean area, increasing interest is being shown in Citrumelo CPB4475 selection.

*Citrus macrophylla* Wester, also named ‘Alemow’, produces vigorous and productive trees, but has some serious limitations, such as sensitivity to nematodes, and CTV and other virus diseases, and to blight. With the exception of lemons, the internal quality of most varieties is poor on macrophylla. Since lemon/macrophylla trees do not developed CTV disease, ‘Alemow’ is recommended for lemons in some citrus producing areas.

## Edaphoclimatic Requirements for Production and Improved Fruit Quality

Environmental factors include climate (temperature, wind, rainfall, hail), gas exchanges, soil quality, orchard location (altitude and latitude) and pollution. Others, such as drought, salinity, brightness of light, are consequences of the former factors. Some of these factors are necessary for production and quality, but sometimes become damaging and reduce yield and fruit quality. Climate is the major factor determining crop load and internal and external fruit quality. For further information see reviews by Agustí (1999; 2003), Davies and Albrigo (1994), Jones and Embleton (1973), and Reuther (1973).

### *Soil Requirements*

Citrus trees can be grown satisfactorily on a wide range of soils. They only need soil as physical support and as source of essential elements, oxygen and water. Both physical and chemical soil characteristics determine the ability of the soil to supply these materials.

Clay soils reduce root development. Roots are shorter and less developed than those developed in sandy soils. Comparing clay and sandy soils, the former develop smaller sized fruits of thicker and rougher peel, lesser juicy, but of higher TSS and vitamin C content.

Citrus trees need soils of good drainage. Accumulation of free water in the root zone results in poor aeration and root injury. Soil permeability between 10–30 cm $h^{-1}$ is considered optimum for citrus growth; values higher than 40 cm $h^{-1}$ and lower than 5 cm $h^{-1}$make the soil unprofitable.

Satisfactory soil depth for the growth of citrus roots may be limited by the presence of parent rock in residual soils, or the cemented stratum or a tight clay layer in old alluvial ones. Because the physical and chemical make-up of the soil varies markedly with depth, one portion of the root system may be in well-aerated topsoil and another in poorly aerated subsoil. Thus roots are under decreasing oxygen supply and both direct and inverse mineral-nutrient gradients with increasing depth.

Lack of drainage can result in accumulation of salts, which, in turn, can reduce tree development, leaf size, which can dehydrate and cause abscission of the fruit, resulting in reduced fruit size and yield. Citrus are very susceptible to salinity where the conductivity of soil to a depth of 1.25 cm is higher than 3.2 dS $m^{-1}$ is considered dangerous for the growth of citrus.

The physical characteristics of citrus soils are more important than the native fertility. Soil analysis for diagnosing the nutritional status of a tree has serious limitations. In fact, there is a lack of a general correlation between tree behaviour and soil composition fertility. Thus, nitrogen analysis is of limited value for diagnostic purposes. For example, less than 5 ppm nitrogen as nitrate does not necessarily indicate a deficiency, but rather that the nitrogen level must be verified by leaf analysis. Phosphorus analyses are of value only in the evaluation of accumulation, movement, and redistribution of soil phosphorus, since its loss by removal with the fruit amounts to only about 2 % of the total phosphorus in the 0–1 m soil depth. Soil analysis for potassium is also of limited interest. Although there is a significant correlation between leaf potassium content and exchangeable potassium in the soil, in orchards where there is a need for potassium it is difficult to obtain an adequate increase in leaf potassium content from soil-applied potassium.

In general, a soil of low fertility with good drainage and other physical characteristics is superior to a soil of high fertility with poor physical characteristics. The deep, well-drained sandy loam soils are considered better for citrus production.

## *Climatic Conditions*

Probably the most important climatic variable determining fruit set and quality is temperature. In citrus trees growing in tropical-type climates, vegetative growth competes with fruit growth and such a competition may be reflected in the intensity of fruitlet abscission, fruit size, carbohydrate reserves and even in fruit colour. It, together with the relative low rates of photosynthate production, emphasizes the limitations of carbon for citrus tree growth that may result in alternate bearing and reduction of fruit quality.

In seeded cultivars, temperatures ranging from 15 °C to 20 °C improve pollen germination and pollen tube growth. In parthenocarpic cultivars, temperatures between 20 to 22 °C/11to 13 °C (day/night) contribute to increased fruit set, whereas those between 30 to 34 °C/21 to 25 °C (day/night) fruitlet abscission is promoted in ‘Valencia’ sweet orange.

Fruit size is generally associated with air temperature. Night temperatures rather than day temperatures largely control fruit growth rate. Fruit growth tends to be greater in the 20–25 °C temperature range regardless of the day/night combination, with the final fruit size of ‘Ruby Red’ grapefruit positively correlated with spring temperatures and negatively correlated with summer temperatures.

Low air temperatures, below 13 °C, cause colour-break of citrus fruits, while high air temperatures influence regreening. However, temperature effects upon fruit colour are dependent upon peel pigment composition. In fruits growing under constant high temperatures, chlorophyll levels remain high for oranges and mandarins and the fruit peel remains green. But when temperature is as low as 15 °C, chlorophyll is degraded and carotenoids synthesized. Carotenoid synthesis is reduced above 15 °C but still occurs at temperatures conducive to chlorophyll degradation.

The ratio of TSS:TA (total soluble solid:total acidity; Brix: g/100 cc) is the most widely used criterion for internal fruit maturity. Fruit from warm regions usually have higher percentages of TSS and TA, and a higher TSS:TA ratio than those from cooler regions. In tropical climates, TSS and TA are reduced in mandarin, orange, grapefruit, tangelo and tangor, but not in lemon and lime. Advanced maturity of the navel orange has been related to high heat summation (over 13 °C) in the spring, mainly affecting TA. Furthermore, the higher the day/night temperature, the lower the percentage of TA in Satsuma mandarins. This inverse relationship between temperature and acid content was found in oranges, grapefruit, mandarin and pummelos under orchard conditions. This decrease in TA, due to high temperatures, has been attributed to rapid respiration of organic acids at these temperatures. Unlike TA, there is no clear relationship between TSS and temperature. Grapefruit and pummelo cultivars, unlike most orange and mandarin cultivars, develop as high a TSS concentration in juice in tropical as in subtropical climates, and temperature regimes have little influence on TSS concentration.

Freeze-damage greatly reduces citrus fruit quality. Severely damaged fruit is useless for fresh consumption and slightly damaged fruit gradually becomes partially dry. The extent of damage depends on the cultivar, temperature, duration of low temperatures and the TSS concentration in juice. Mandarins, lemons and limes are more susceptible than oranges. Grapefruits and pummelos are moderately susceptible. Citrus fruits suffer irreversible damage at temperatures of −2.5 °C or lower. Recovery from freeze damage is cultivar dependent, but if fruits are damaged they have lower concentrations of TSS and TA in the juice. The peel of externally injured fruit contains parts of completely desiccated tissue, typically around the calyx. Damage to leaves and branches can also affect fruit quality and yield of new crops. Low temperatures are also involved in the development of some physiological disorders, which will be discussed in a later section.

Relative humidity (RH), together with the prevailing temperature regime, determines fruit set. Moderate temperatures contribute to improved fruit set, and low or higher temperatures followed by sharp changes, promote fruitlet abscission during cell division at the fruit growth stage.

Relative humidity also affects fruit size. Consistent low values through the night reduce the growth rate of ‘Valencia’ oranges, of which 37 % RH is considered the critical level. Relative humidity can reduce fruit quality dramatically, especially that of mandarins.

Fruit shape is also affected by RH with grapefruit grown in humid subtropical or tropical regions developing an oblate shape, while those grown in arid regions becoming spherical. Grapefruits and mandarins attain better colour under high atmospheric conditions of RH.

An inverse relationship between average annual precipitation and TA in grapefruit juice has been reported. Similarly, heavy rainfall in the 2 months prior to harvest can significantly reduce TA and TSS content in Clementine mandarins and 'Valencia' orange juice. Rainfall also affects fruit shape and peel thickness. Sometimes, and on an irregular basis, hail damage occurs in citrus-growing areas. The extent of the damage depends on the size of the hailstones, but the peel may get slightly pitted, deeply sunken or even dramatically broken.

Citrus trees have high shade tolerance, but maximum yields are produced under high light intensity. There is a correlation between smaller fruit sizes and the high percentage of cloudy days through the spring. Total soluble solids concentration increases with higher light intensity, and the vitamin C content in the juice can vary with exposure of the fruit to light, with the outside fruit having the highest content. However, juice content of the fruit can decrease with exposure to increasing light intensity. Peel colour is also affected by light, which is necessary for carotenoid and anthocyanin synthesis, with exposed fruits more coloured than those exposed to shade.

Citrus fruits are highly resistant to insolation (sunburn) injury. Temperature as high as 44.4 °C is necessary to cause sunburn injury in 'Valencia' whereas the 'Murcott' tangerines and some early maturing Clementine mandarins are peculiarly susceptible to sunburn.

Wind can have a definitive limiting effect on citrus production and quality. Wind injuries have been recognized as the major abiotic factor contributing to peel damage worldwide. Wind speeds above 24 km $h^{-1}$ have been considered potentially damaging. Wind injuries take the form of an irregular brown spots, which normally affect only the flavedo or the outer colored layer of the mesocarp of a citrus fruit. Intensity of the injury depends on wind speed, varietal sensitiveness, the presence and size of thorns, the leaf roughness, and the size of fruit.

## Flowering

In subtropical regions, *Citrus* has three flushes of shoot development, early in spring, after physiological fruitlet drop, and later in summer, with bloom occurring during the spring flush (Fig. 6.2). In tropical climates, however, bud sprouting and flowering take place throughout the year, although the main bloom also occurs in spring.

*Citrus* species produce leafy and leafless flowered shoots, the number of both flowers and leaves varying among them. Thus, there are single-flowered and multi-flowered leafy and leafless shoots, and vegetative shoots (Fig. 6.3).

The proportion of each type of shoots depends on the species and varieties. For example the Satsuma mandarin group produce only single flowered shoots and vegetative shoots.

Citrus species have 2–5 years period of juvenility in which trees are unable to flower. Afterwards, citrus trees usually produce larger number of flowers than they need to achieve optimum yields. However, in some cases, competition among developing

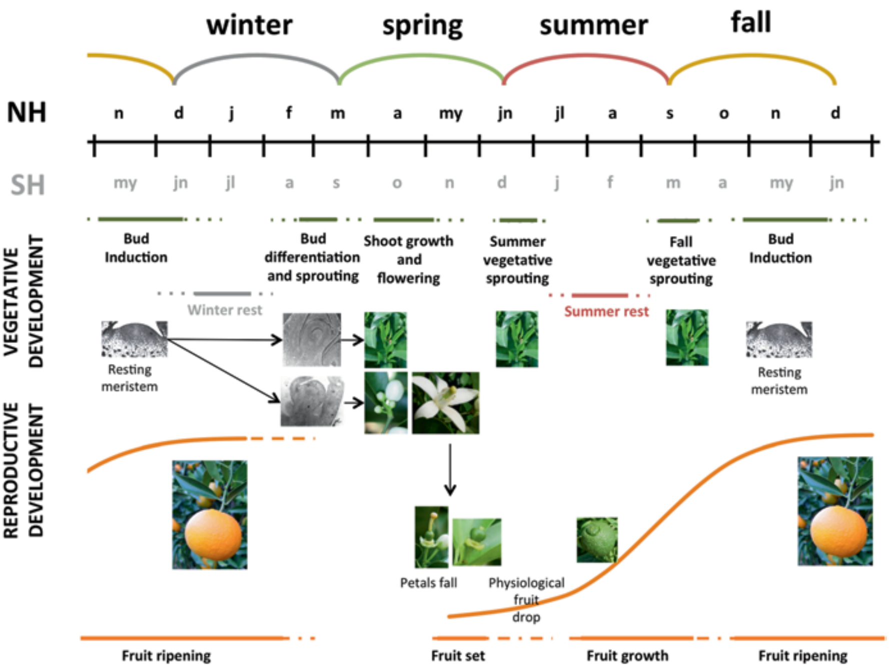

**Fig. 6.2** Schematic representation of phenological events occurring during a 1-year developmental period in *Citrus* growing under Mediterranean-type Climate. *NH* northern hemisphere, *SH* southern hemisphere

flowers and fruitlets gives rise to a massive drop of fruitlets, named physiological fruit drop, which results in a reduced yield. Some other cultivars follow a year of heavy fruit load (*on* year) with reduced flower production and yield (*off* year) the effect of which depends on the length of time the fruit remains on the tree. This phenomenon is termed *alternate bearing* and represents an important problem worldwide.

Gibberellic acid, applied at the floral bud inductive period, November–December in the NH (Fig. 6.2), reduces excessive bloom problems. A concentration of 25 mg $l^{-1}$ active material at 7–8 l $tree^{-1}$ for a regular tree (sprayed by hand-gun; 25–30 atm) is recommended. Increased flowering is often very difficult to achieve. It has been reported that paclobutrazol, an inhibitor of gibberellin biosynthesis, applied at the floral bud inductive period to the soil, at an amount of 1–10 g $tree^{-1}$, or as a foliar spray, at a concentration of 1,000 mg $l^{-1}$, promotes flowering in *Citrus*. However, its effectiveness depends on the tree crop load, and under heavy crop load conditions fruit nullifies its effect.

Although a minimal amount of carbohydrates is required for bud sprouting and flower initiation, neither soluble sugar content nor the accumulation of reserve carbohydrates seems to fulfil an inductive function; some kind of imbalance in the nitrate-reducing mechanism in leaves has been observed in trees which are prone to flower scarcely.

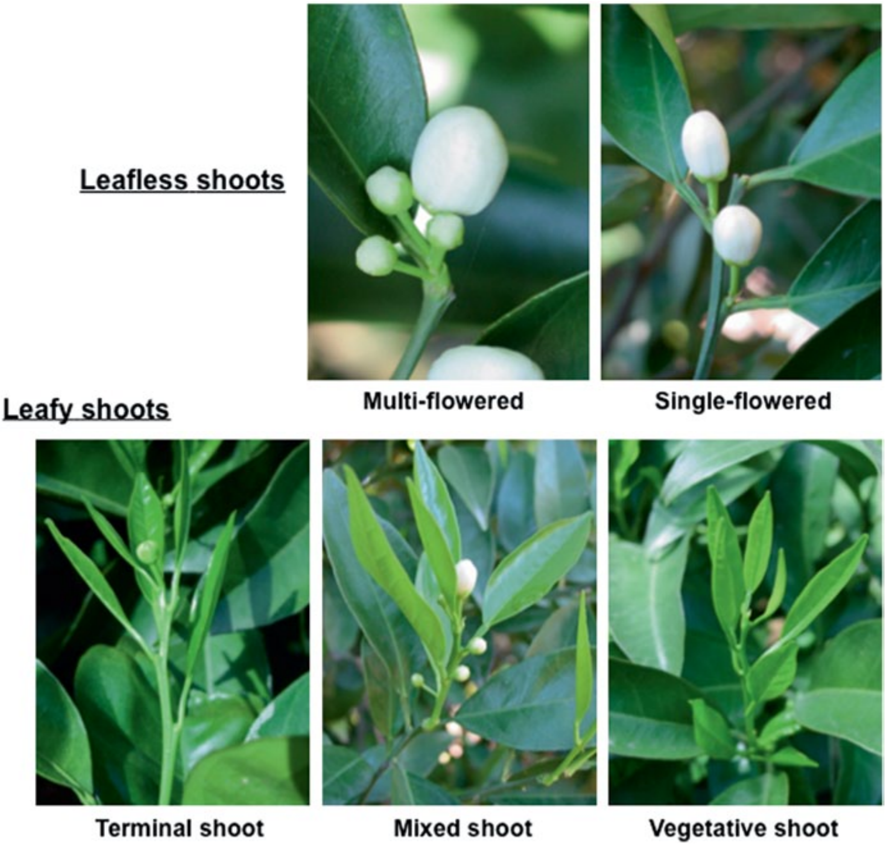

**Fig. 6.3** Different type of shoots in *Citrus* according to the number of leaves and flowers

In *Citrus*, flower induction has been reported to occur late in autumn, whereas differentiation occurs afterwards (Fig. 6.3). Recent molecular approaches support this scheme, distinguishing between genes that regulate flowering induction and those that regulate the floral differentiation processes. As for other species, it has been shown for *Citrus* that flowering ability is influenced by the integration of environmental signals from the photoperiod and vernalization pathway, mainly modulated by two floral integrators, the *FLOWERING LOCUS T* (*CiFT*) and the *SUPRESSOR OF OVEREXPRESSION OF CONSTANS 1* (*SOC1*) genes. Accordingly, an increased FT protein constitutes a signal *per se* that is exported from leaf to the shoot apical meristem, where floral differentiation takes place. Once the bud is induced, the increased *CiFT* expression found in both buds and leaves is responsible for a continuous flux of FT protein to the developing meristems up until the floral morphogenetic phase is initiated. *SOC1* induces early flowering and delays senescence of floral organ.

*FLOWERIN LOCUS C* (*FLC*) gene encodes a domain protein that represses flowering. Elevated levels of *FLC* expression may be responsible for reductions in *FT* activity. It has been hypothesized that floral repressors ensure the correct reproductive timing by controlling promoters, and, in some cases, reducing its expression to facilitate the action of promoters, thereby contributing to flowering induction.

The determination of floral identity, i.e. bud differentiation, is linked to *APETALA1* (*CsAP1*) and *LEAFY* (*CsLFY*) genes.

*FLOWERING LOCUS D* (*FD*) encodes a protein required for *FT* function, and takes part in the specific signalling pathways that occur at the shoot apex. In *Citrus*, *FD* expression in buds was markedly higher than in leaves in both November and February (NH). As for other species, this observation reinforces the hypothesis that its role in *Citrus* is decisive at the apical level, possibly because the transition from vegetative to floral meristem mainly occurs there. In fact, this gene has been described as a strong modulator of *FT* action specifically in the meristem. Hence, promoter genes, such as *FT* and/or *FD*, together with the reduction in the suppressive action of inhibitor genes (*FLC*), and with the expression of *CsAP1* and *CsLFY* identity genes, probably contribute to the development of floral morphogenesis in *Citrus*. Fruit, low temperature and water stress have been related to floral bud induction.

See Agustí (2003), Agustí and Almela (1991), Chica and Albrigo (2013), El-Otmani (2006), El-Otmani et al. (2000), Muñoz-Fambuena et al. (2011; 2012), Nishikawa et al. (2007), Spiegel-Roy and Goldschmidt (1996) for further information.

## Fruit Development and Ripening

### *Fruit Set*

Fruit set is defined as the transition of the quiescent ovary of the flower to developing fruit. The process requires the reactivation of cell division in the ovary, and it is regulated by external and, mainly, internal factors. If ovary growth is not reactivated or if it is arrested during early fruitlet development the abscission process is triggered and fruit set is not accomplished. For further information see reviews by Agustí (2003), El-Otmani (2006), El-Otmani et al. (2000), and Spiegel-Roy and Goldschmidt (1996).

In *Citrus* seeded varieties, in which pollination and fertilization are absolutely necessary for fruit set, ovary growth of un-pollinated flowers is observed in the first 2 weeks following anthesis; thereafter, a rapid 100 % ovary abscission is produced. But the anatomical changes in the ovary occur in the same way, and at the same time, in un-pollinated or cross-pollinated flowers during the first days following anthesis, which reflects an uncoupling of the fertilization and fruiting time processes. Thus, ovary growth at the onset of the cell division stage is independent of pollination, and the ability to set fruits in seeded varieties should be inevitably associated with the stimuli produced by gibberellins in developing seeds. This is the case of some sweet orange cultivars.

However, in *Citrus* there are a lot of seedless cultivars; therefore, other major regulating factors, aside from seed derived stimuli, must also be implicated. In seedless cultivars, fruit set appears to be developmentally regulated, probably operating also through the synthesis and action of gibberellins in ovary walls.

In *Citrus*, gametic sterility and homogenetic sterility are the main genetic mechanisms that produce parthenocarpy, or the natural or artificially induced production of fruit without fertilization of ovules. Navel orange and Satsuma mandarin are species of gametic sterility, Clementine mandarin, hybrids-like mandarins (i.e. 'tangors', 'tangelos', etc.) and pummelo are species of homogenetic sterility.

*Natural* parthenocarpy can be *obligate* or *facultative*, depending on the fertility of the flower. When the flower is sterile, obligate parthenocarpy takes place without any external stimulation. Navel orange and Satsuma mandarin are species of obligate parthenocarpy. When the flower is fertile, facultative seedless fruit is produced if fertilization does not occur. Clementine mandarin presents facultative parthenocarpy.

## *Factors Determining Fruit Set*

### Environmental Control

As mentioned above, temperature and relative humidity determine *Citrus* pollination. Their effect may be either indirect, through modifying bees (*Apis mellifera*) activity, or direct, inducing pollen sterility or modifying pollen tube growth.

Under Mediterranean conditions, the effective pollination period of a flower varies between 8–9 days for sweet oranges and Clementine mandarin and 2–3 days for Satsuma mandarin. High temperatures during flowering accelerate pollen tube growth, and stigma and ovule maturation, and low temperatures slow pollen tube growth and extend ovule viability.

Fruit set also shows a significant and negative correlation with daily mean leaf-temperature during the physiological fruit drop.

Relative humidity may influence pollination in *Citrus* through its effect on stigma longevity. The *Citrus* flower has a wet-type stigma with unicellular and pluricellular papillae covered with a conspicuous secretion that plays a part in stigma receptivity to pollination. Low relative humidity, together with high temperatures, increase tree transpiration, which may increase the physiological fruitlet drop, especially when soil moisture and tree water status are low.

### Nutritional Control

In *Citrus* trees, many flowers and fruits abscise during flowering or during the physiological fruitlet drop period. It is of great importance in some sweet orange cultivars in which the higher the flowering intensity the earlier and heavier the abscission process is, and the number of fruitlets remaining correlates negatively with fruit growth rate. This is attributed to the high demand for carbohydrate by the developing organs.

Several sources scoring demonstrate the positive relationship between carbohydrates and fruit set: (1) leafy shoots set fruits in a higher proportion than leafless shoots; (2) full or partial tree defoliation reduces carbohydrate concentration in fruitlets and increases fruitlet abscission; (3) experiments involving translocation of $^{14}$C-metabolites and a $CO_2$-enriched atmosphere show positive effects of carbon availability on fruit development; and (4) girdling decreases fruitlet abscission by increasing carbohydrate availability for the growing fruitlets. However the latter effect is mostly observed in leafy shoots through an increase in leaf $\Phi$PSII. Girdling also increases GA content in the ovary.

Girdling or scoring, which are the complete removal of a strip of bark from the secondary branches of the tree or the performance of a cut around the complete circumference of these branches, respectively, improves yield irrespective of the parthenocarpic ability of a given cultivar. Its effectiveness increasing fruit set depends on the date of treatment (35 days after anthesis being the optimum) and is negatively related to flowering intensity.

### Hormonal Control

Auxin concentration in the ovary is not a limiting factor controlling early fruit development in citrus whereas there is strong evidence supporting the role of GA inducing fruit set. Thus, in seeded sweet orange cultivars, pollination increases ovary $GA_1$ concentration compared with un-pollination, which parallels a higher fruit set of seeded fruits. When comparing a number of parthenocarpic mandarin cultivars differing in their ability to set, the higher GA content at anthesis correlates with the higher parthenocarpic ability. On the other hand abscisic acid (ABA) content is higher in the ovaries of weaker parthenocarpic genotypes.

*Citrus* seedless cultivars of weak parthenocarpic ability (mostly Clementine mandarin cultivars and some hybrid-like mandarins) need $GA_3$ sprays to obtain a commercial yield. The effectiveness depends on the date of treatment (petals fall) (Fig. 6.2) and concentration applied (5–10 mg $l^{-1}$), and is negatively related to flowering intensity.

## *Fruit Growth*

Citrus fruit development follows a characteristic sigmoid growth curve and is divided into three major stages: cell division, cell enlargement, and fruit maturation (Bain 1958; Fig. 6.2). Stage I comprises the period of fruit set and extends from anthesis to the end of the physiological fruit drop, and the increase in fruit size is mainly due to peel growth. Juice vesicles are formed during this stage, and seed primordial growth is characterized by a curvature in the micropylar end, and by expansion in the chalazal end.

Stage II is a rapid growth period of fruit development due to cell enlargement and water accumulation. During this period the increase in fruit size is mainly due to pulp growth, juice vesicles reach their maximum size storing water, sugars and acids, and zygotic embryo matures. This stage comprises from the end of the physiological fruit drop until the onset of fruit colour change, its duration depending on the cultivar.

In stage III, growth is mostly arrested and fruits undergo a non-climacteric ripening process. During this stage fruit metabolism changes occur that determine the final external and internal fruit quality. The process of external fruit ripening mainly involves the progressive loss of chlorophyll and the gain of carotenoids, thus changing peel colour from green to orange. The process of internal fruit ripening involves a decline in acidity, mostly due to the catabolism of citric acid, and an increase in sugars, both determining the maturity index. External and internal ripening not always coincides in time.

## Factors Determining Fruit Growth

### Environmental Control

Fruit growth depends on the tree water status and carbohydrate partitioning. In fact, the fruit serves as a storage organ of water and its final size depends directly on the availability of water. Drought provokes biochemical inhibition of citrus photosynthesis that reduces fruit carbohydrate supply and can stop fruit growth. But fruit continue to be a strong carbohydrate sink and apparently continues to accumulate and is available for fruit growth after the drought is relieved. This decline in fruit development is almost irreversible and fruit become smaller. Drought also reduces peel turgidity and consistency and, consequently, there is resistance to handling and consumer acceptance.

### Nutritional Control

Final fruit size is closely linked to the number of developing fruits. Competition for photosynthate among fruit is the hypothesis that has prevailed for many years to explain the relationship between fruit size and fruit number. Accordingly, fruit thinning is widely used to increase the final size of the remaining fruit on the tree. This effect, based on a reduction of competition among developing fruit, has been explained as being due to a modification of source-sink relationship. In *Citrus*, synthetic auxins have been widely used as thinner agents. Auxins temporarily induce photosynthetic disorder that leads to reduction in photosynthate production and fruitlet uptake that temporarily slows its growth, triggering ethylene production and fruitlet abscission. Afterward, the remaining treated fruit overcomes this effect, increases growth rate, and reaches a larger size than untreated fruit. According to the non-linear relationship between fruit size and fruit number, a significant increase in fruit size occurs only if fruit thinning is higher than 50–60 % of total fruit number, and if it is performed early in fruit development.

### Hormonal Control

The application of synthetic auxins at the beginning of the cell enlargement stage increases final fruit size without fruit thinning. The 2-ethylexyl ester of 2,4-dichlorophenoxipropionic acid (2,4-DP) or 3,5,6-trichloro −2-pyridyloxiacetic acid (3,5,6-TPA), as free acid, at a concentration of 25 mg $l^{-1}$or 15 mg $l^{-1}$, respectively, applied at the onset of cell enlargement stage, is recommended for Clementine and Satsuma mandarins and for hybrid-like mandarins. It has been suggested that their effect is related to an increase of fruit sink strength since fruit dry weight is generally increased. Accordingly, auxin treatment significantly increases carbohydrate contents in the fruit; in fact, the direct increase in fruit size due to auxin treatment is associated with an enhancement of cell enlargement, rather than cell division, which, in turn, produces an increase in absolute juice content and also in pulp and rind content, i.e. dry matter. Cell enlargement consists of two interrelated processes: the osmotic uptake of water, driven by a water potential gradient across the plasma membrane, and extension of the existing cell wall, driven by the turgor generated stress within the wall. Auxins are related to both processes by: 1) increasing carbohydrate content that may reduce osmotic potential, and 2) the use of the *acid growth hypothesis* that proposes protons ($H^+$) as a mediator between auxin and expansins, the latter of which are induced plant cell wall loosening proteins. But auxin treatment also increases fruit peduncle cross-sectional area; this effect is partially due to the increase of fruit size promoted by the auxin, as well as the direct effect of the auxin promoting the development of peduncle vascular tissues, thus allowing for a larger water uptake into the fruit.

Agustí and Almela (1991), Agustí et al. (2002), El-Otmani (2006), and El-Otmani et al. (2000) are recommended reviews for further knowledge.

## *Fruit ripening*

*Citrus* fruit colour development is under the regulation of several factors, including environment, nutritional factors and plant hormones.

Rind colour-break and colour intensity are markedly affected by both air and soil temperature (see Section “Edaphoclimatic requirements for production and improved fruit quality”). Based on these observations and his experiments conducted *in vitro*, Huff (1983; 1984) hypothesised that *Citrus* may degreen in response to a reduced nitrogen flow into the fruit accompanied by an increased concentration of photosynthate to the epicarp. Under field conditions, soil temperatures below 20–22 °C reduce citrus root activity and nitrogen uptake and translocation to the fruit, which, nevertheless, remains as a strong sink for photosynthate that both reduces nitrogen uptake and increases sugar uptake in fruit colour development. Under Mediterranean climates, fruit colour-break does not take place at a certain soil temperature, but after several hours at 20–23 °C soil temperatures. Thus, reducing soil temperature during the 2 months before harvest using reflective-mulch advances external ripening and harvest date in the Clementine mandarin.

On the other hand, fruit colour-break can be also advanced by means of ethylene releasing compounds. Although *Citrus* fruit is classified as non-climacteric fruit, exogenous ethylene stimulates changes in fruit colour by increasing chlorophyllase *de novo* synthesis and enhancing carotenoid biosynthesis pathway genes. Spraying 100–200 mg $l^{-1}$ ethephon (an ethylene releasing compound) accelerates colouration and thus the harvest of mandarins by 1–3 weeks. Its effectiveness depends on the date of treatment, the best results obtained for 20–25 days before the usual date of colour-break. An important leaf and fruit abscission may occur, with these negative effects closely related to temperature. The ethephon treatment does not change internal fruit quality.

In *Citrus*, GA-like activity has been detected up to the onset of chlorophyll loss, the lowest one reached at ripening. In sweet orange, fruit changes colour by reducing active gibberellin concentrations ($GA_1$ and $GA_4$) in the flavedo, which are involved in regulating sugars and ABA accumulation and in reducing N fraction concentration as rind colour develops. Besides, exogenous $GA_3$ applied prior to colour-break delays chlorophyll degradation and reduces carotenoid concentration in the peel. About 10–20 mg $l^{-1}$ $GA_3$ retards fruit colouring in 30–45 days, and nitrogen compound such as calcium nitrate (2 %) or ammonium phosphate (1.5 %) reinforces the effect.

## Physiological Fruit Disorders

Physiological disorders are a group of disorders affecting fruit quality, sometimes also fruit crop, which are directly related to malfunctions of fruit development induced by environmental factors. See Agustí (2003), Agustí and Almela (1991), Agustí et al. (2002; 2004), El-Otmani (2006), and Petracek et al. (2006) for an extensive knowledge.

### *Splitting*

*Splitting* is a physiological fruit disorder manifested as a fissure of the peel, usually developing from the stylar end and reaching, or even extending beyond, the equatorial zone (Fig. 6.4a). *Splitting* is a frequent problem in oranges and mandarins all over the world.

The causes of fruit *splitting* are not well understood, although seasonal water deficits followed by rains during cell enlargement stage have been closely related with the number of 'Nova' mandarin affected fruits, although in some varieties, such as 'Ellendale' mandarin, this correlation did not apply.

*Splitting* develops as a consequence of a disruption between peel and pulp growth. During cell enlargement stage, if the peel does not re-start its growth when

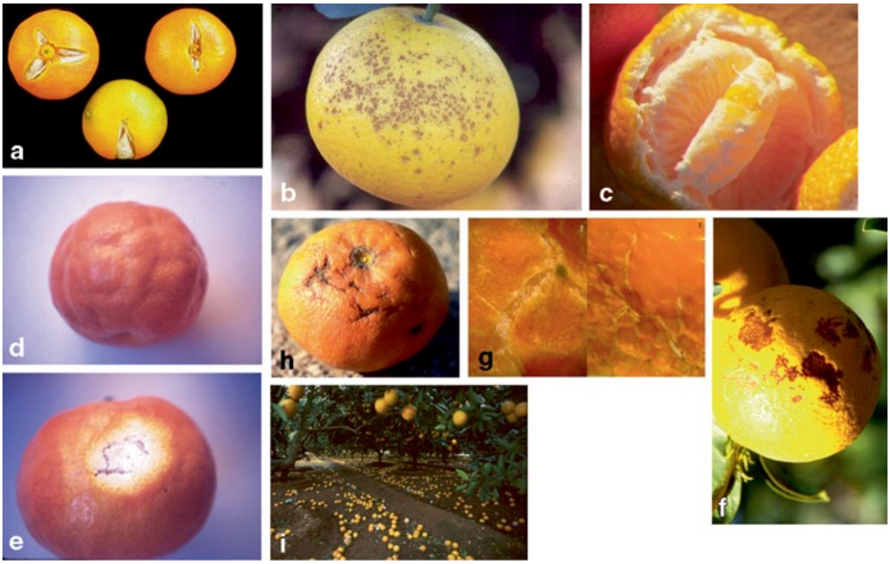

**Fig. 6.4** Physiological citrus fruit disorders. **a** *splitting* in 'Nova' mandarin. **b** *peel pitting* in 'Marsh' grapefruit. **c** *Puffing* in Satsuma fruit. **d** *Creasing* in Clementine mandarin. **e** Albedo breakdown in a Clementine fruit showing *creasing*. **f** Navel rind stain. **g** and **h** peel senescence in Clementine mandarin. **i** Navel fruit abscission

pulp expansion takes place, the fruit splits. Although the albedo may alleviate pulp pressure because of its sponginess, the flavedo tissues are more rigid and will eventually crack. This appears to be the reason for the negative correlation found between peel thickness or peel resistance to puncturing and the number of fruits affected by *splitting*.

The application of calcium nitrate sprays at the beginning of the cell enlargement stage significantly reduces the proportion of fruit affected by *splitting*, but the response is often erratic. Best results are obtained with the application of a mixture of $GA_3$ and 2,4-dichlorophenoxyacetic acid; the treatment significantly reduces fruit *splitting* and the repetition of the treatment improves the response. Treatments do not increase peel thickness but significantly increase peel resistance to puncturing.

## Cold Pitting (Peel Pitting)

*Cold pitting* or *peel pitting* is a physiological disorder usually related to post-harvest storage conditions, but in some cases, as for 'Fortune' mandarin and 'Marsh' grapefruit (Fig. 6.4b), *peel pitting* appears before harvesting.

Pre-harvest *peel pitting* starts on fruit as discrete areas forming sunken reddish-brown to black lesions that tend to coalesce producing larger depressions of affected areas. The incidence of this disorder varies among the years.

The cause of pre-harvest *peel pitting* is not well known, although cold and dry winds, low temperature and relative humidity have been suggested as responsible for pitting. These climatic conditions change the physiological properties of membranes and cuticles and modify the water balance of injured areas.

The breakdown of epidermal cells is the first event of *peel pitting*. The shape of the injured epidermal and hypodermal cells are responsible for undulating and depressed appearance of the rind in affected fruit, with no observable disruption of the cuticle. These depressed areas are devoid of crystalline wax structures and have crushed epidermal and hypodermic cells with unfolded walls. These cells are either empty or filled with reduced cytoplasm amount that is located in central position of the cell.

Some antitranspirants, such as pinolene, a polyterpen film former, replaces the loss of crystalline waxes and, in this way, can substitute for their action, reducing the water loss of fruit.

The application of calcium nitrate just before or at fruit colour-break has been shown to be effective in controlling pre-harvest *peel pitting* of 'Fortune' mandarin. There are evidence of a relationship between the reduction of *peel pitting* and the decrease of water permeability associated with the use of calcium nitrate.

## *Puffing*

*Puffing* is a physiological disorder characterized by separation between peel and pulp (Fig. 6.4c). It is related to the disintegration of the deepest cell layers of the albedo tissue that gives rise to aerial spaces. The development of these spaces results in a cracked and low resistant albedo in mature fruits. The symptoms increase as peel grows just after the pulp has completed its development. This belated peel growth takes place only in a few mandarin varieties, such as 'Satsuma' mandarin or 'Oroval' clementine mandarin, which are susceptible to *puffing*.

The cause of *puffing* has been related to the water exchange regulation through the peel. Accordingly, high values of RH together with high temperatures at fruit colour-break increase the appearance and intensity of *puffing*, particularly after a period of drought.

The application of 10 mg $l^{-1}$ of $GA_3$ before fruit colour-break reduces the occurrence of *puffing* in Satsuma mandarin. The $GA_3$ treatment prevents the late growth of the peel and increases the compactness of the albedo. The addition of nitrogen compounds reinforces the effect of $GA_3$. The main internal fruit characteristics are not modified by such treatments.

## *Creasing*

*Creasing* is a physiological disorder of fruits causing cracks in the cell layers of albedo tissue of peel. It corresponds with depressions on the flavedo that alternate with healthy areas that turn bulky (Fig. 6.4d, e). Albedo cells are tubular in shape and those lining the cracks separate at the middle lamella leaving like-protruding stumps. This separation sometimes takes place with no damage to the cells so that cells retain their turgor, but many cells are irreparable damaged, lose their turgor and wall collapses.

The cause of *creasing* is not yet clearly understood. Climatic factors, cultural practices and endogenous factors have been related with this physiological disorder. A number of mineral elements have been also related to *creasing*, with molybdenum (Mo) being of critical importance.

*Creasing* has been connected with pectin degradation, loosening the connection among the cells of the albedo tissue. Promotion of pectinmethylesterase activity of albedo tissue of creased fruit has been demonstrated and also a significant increase on the amount of water-soluble pectins. It is suggested that molybdenum acts as a co-factor in ureide synthesis, required in the formation of galacturonic acid, a major component of pectins.

The application of $GA_3$ (10–20 mg $l^{-1}$) at early stages of fruit development or just prior to fruit colour-break reduce considerably the incidence of *creasing*. As for *puffiness*, the addition of nitrogen compounds reinforces its effect. It had a strong inhibition effect on colour development when applied close to colour-break.

## Navel Rind Stain

Fruits of Navel oranges are very susceptible to rind breakdown. Initially, injured fruits show small depressions on the rind with no changes in colour and retain their intact oil glands. The disorder begins at the flavedo-albedo union area, where the cells become dehydrated and flattened, and finally die (Fig. 6.4f). Despite of it, the cuticle did not show any sign of disruption or damage. When damage riches up the flavedo and epidermis, the cells die as well and develop brown to black lesions of necrotic depressed areas.

The cause of this physiological disorder has been related to nutritional imbalances, drought and rainy periods in alternation with cold periods. The incidence of navel rind stain varies in intensity from year to year, among orchards and even among varieties, affecting up to 50 % of mature fruits in some cases, such as 'Navelate' in Spain. Fruit position on the tree has shown as important factor in developing rind breakdown, fruits outside of canopy being most sensitive fruits and the outside face of fruit being more sensitive than the inside face. In 'Navelate' oranges stored at 20ºC, transference of fruit from low (45 %) to high (95 %) RH starts or aggravates the incidence of this disorder.

Nowadays we have not effective treatments to control it. However, rootstock plays an important influence in the development of the disorder. Carrizo citrange is more susceptible than Cleopatra mandarin, and it, in turn, more than sour orange. This dependence has been related to rootstock influence on water transpiration capacity, supported by the histological study of fruit peduncle.

### *Peel Disorders Linked to Fruit Senescence*

In the marketing of citrus for fresh consumption an oversupply often occurs, with a consequent fall in price. It is the case of Clementine mandarins, for which it is of the utmost importance to extend the picking season and so the market. But the on-tree storage of fruit up to its plain maturity leads to the appearance of physiological disorders linked to peel senescence, such as discoloration, stains and blemishes that diminish fruit quality (Fig. 6.4g, h). After plain maturation high temperature and high relative humidity accelerate the process.

Some of these disorders can be partially controlled by applying gibberellins. The application of 5 mg $l^{-1}$ of $GA_3$ prior to fruit colour-break is enough to delay the peel senescence for more than 30 days with a consequent delay on the appearance of peel disorders linked to the process. As for other physiological disorders related to peel tissue nitrogen compounds are known to enhance the effectiveness of $GA_3$. Such treatments do not affect internal fruit characteristics, which is particularly important for Clementine mandarins; however this group of mandarins loses the juice progressively after fruit colour-break, and $GA_3$ treatment does not stop it; consequently, 30–50 days after treatment it is possible to pick fruits of high external quality but with very low juice content

### *Fruit Abscission*

Fruit of navel oranges and of some hybrids are prone to abscission as soon as they overcome the maturation process (Fig. 6.4i). Applying synthetic auxins can efficiently control this process. The application of 2,4 DP (15 mg $l^{-1}$) delays significantly fruit abscission of navel oranges. Treatments must be carried out prior to the abscission process. Those applied 1 month before colour-break have shown efficacious retarding fruit abscission of 'Navelate' sweet orange for more than 5 months. Repetition of such treatment 2 months later has no additional effect except if more than 5 months of on tree storage is requested.

Internal fruit characteristics are not altered by these treatments; however, since treatments are applied to delay harvesting, rind disorders associated to senescence must be prevented by $GA_3$. The delay of harvest time reduces the intensity of the next flowering and that must be taken into account, especially in the case of alternate bearing varieties.

## Plant Nutrition and Fertilization

Mineral nutrition of citrus has been extensively studied. This subject, actually, involves five macronutrients (N, P, K, Ca and Mg), and some micronutrients that influence and often limit fruit production. See reviews by Agustí (2003), Davies and

Albrigo (1994), Spiegel-Roy and Goldschmidt (1996), and Vacante and Calabrese (2009) for a more extensive information.

## Mineral Elements

Citrus varieties respond readily to nitrogen and potassium applications, however their effectiveness depends on the type of soil and the nutritional status of the plant. Phosphorus has very seldom been found lacking in soils planted to citrus, with the exception of some countries in South America. The minor elements seem to have no detectable effects on fruit production and quality in absence of gross visible deficiencies. Nitrogen is the most important element regarding fruit production and quality.

Nitrogen fertilizer is generally required in greater amounts by citrus than any other fertilizer. With an N deficiency, yield reduces markedly and fruit tend to be smooth, smaller and of somewhat lower acid content. High N levels are particularly detrimental to orange peel colour, thus an increase in N rate increases the percent of green fruit. Moreover, in addition to temperature, the degreening and regreening of citrus fruit are affected by N fertilization. Most citrus fruit degreens in response to reduced flow of N to the fruit accompanied by increased concentrations of sugar in the epicarp, both usually induced by cool temperatures; regreening of late-season citrus fruit in the spring and summer can be attributed to renewed N flux and a reduction in sugar concentrations induced by warming temperatures. Volatile peel oil yield increases with increased N rates in sweet oranges and lemons. In orange juice, (1) increased N rates increase both the red and yellow pigments, and (2) varying N levels on TSS and TA content has been small and inconsistent. A similar trend has been observed in the concentration of ascorbic acid. Nitrogen level generally has no effect on lemon fruit quality.

High levels of N in orange trees are associated with thicker peel, a lower juice percentage and coarser peel texture. In Satsuma mandarins, high N fertilizations may increase fruit size, but they produce poor quality fruit with rough peel, low sugar and high acid content.

Nevertheless, nitrogen applications are essentially ineffective on a wide range of N-rich soils ranging from fine sand to moderately heavy loamy clay soils. Moreover, withholding N from previously well-fertilized soils had no effect on fruit composition.

The timing of N application and the form in which it is applied influence fruit quality of oranges, mandarins and grapefruits.

Regarding phosphorus, neither yield nor fruit size of oranges and lemons increased with an increase in phosphorus rate. Only for grapefruit an increased yield and fruit size paralleled P content in leaves. In solution-culture experiments, it has been shown that fruit symptoms of P deficiency include coarse, thick but well-coloured rind, hollow cores, and high total acidity (TA) in the juice, and that the correction of the deficiency generally reversed these characteristics. An important negative effect of excess P in the soil reduces copper, zinc, boron, iron and other micronutrient availability. Phosphate also may affect nitrogen nutrition unfavourably. In spite of this, P seems to have some effect in reducing the acid content.

Levels of K above the yield-limiting level are of only moderate importance to fruit production and quality. Field evidence indicates that an increase in potassium supply increases fruit size of sweet oranges, grapefruits, limes, and lemons. High level of K delays fruit colour development in sweet oranges, Satsuma, and 'Temple' tangor, remaining partially green up to harvest. Potassium applications frequently result in an increase in ascorbic acid in the juice. High K rates reduce the incidence of *creasing*, and *splitting* can also be reduced or almost completely avoided by raising the level of K in affected trees.

High levels of K often, but not always, increase peel thickness and reduce juice percentage in oranges and grapefruit. Increasing K strongly increases TA in juice and hence reduces the TSS:TA ratio, thus delaying maturity. In contrast, K applications to lemon trees reduce peel thickness and increase the percentage of juice in the fruit, and also increase TA and the concentration of ascorbic acid in juice. Increased K rates reduce the yield of peel oil in orange and lemon and tend to decrease yellow pigments in juice of the sweet orange.

In Citriculture, concern for calcium (Ca) is due to its indirect effect of modifying soil fertility and not on its direct effects as a nutrient. However, there are some known effects of Ca that can improve citrus fruit quality. As mentioned above calcium nitrate sprays have beneficial effects on fruit *splitting*, although the response appears to be erratic. The application of calcium salts prior to or during maturation has been shown to be effective in reducing chilling injuries by reducing cuticular permeability. Calcium carbonate applied just at the beginning of colouring reduces the occurrence of puffing by reducing rind water content. Calcium also delays mandarin peel ripening and senescence.

The low native level of Mg in soil causes magnesium deficiency, and it is particularly acute on the light sandy soil from which Mg readily leaches. The deficiency results in substantially smaller fruit that is lower in TSS, TA and vitamin C. In oranges, there is a quite marked paleness of colour of both pulp and peel.

Among micronutrients, boron, copper, zinc and manganese deficiencies may be of some importance. Boron (B) deficiency produces gum pockets and greyish to brownish discoloration in albedo of young and mature fruits, and reduces TSS and juice content. Copper (Cu) deficiency causes dark excrescences of gum on the rind of fruit, which may be associated with small cracks; at maturity, fruits are often misshapen, with coarse rinds, and have a low content of TA and vitamin C. Zinc (Zn) and manganese (Mn) deficiencies influence fruit set and size of some cultivars, such as Clementine mandarins, which are quite sensitive.

Excessive fertilizer applications to the soil or by spraying, inappropriate pH solution, the presence of relatively high quantities of biuret as an impurity in urea, or perchlorates as impurities of potassium nitrate, can produce symptoms of toxicity in the leaves that indirectly affects fruit quality.

The timing of foliar application of certain nutrients has a great impact on the nature of their effects on the tree and may solve certain fruit quality problems. On the other hand, it appears that in certain cases nutrients may function partly or even entirely in place of certain growth regulator substances. Moreover, there are several examples of some additive and even synergetic effects of nutrients and plant growth regulators (PGRs) on fruit quality. This is the case of gibberellic acid and nitrogen compounds in reducing *creasing*, controlling *puffing* and delaying peel senescence, as mentioned, and of synthetic auxins and potassium nitrate in increasing fruit size. In fact, it has been suggested that growth regulators may act by directing the flow of nutrients in plants to sites where they are required for protein synthesis, and even that foliar application of $K^+$and $NH_4^+$ ions may have a promoting effect on gibberellin synthesis in tissues.

## *Organic Matter*

There is little information about the effect of organic matter on fruit quality in citrus, apart from changes it produces on soil structure. The most important beneficial effect found is a higher resistance to freeze of fruits from orchards whose soils are rich in organic matter. Improvement of soil structure, with some improvement in aeration and its consequence on fruit quality, can be made through the use of organic matter. On the other hand, it is known that owing to the ameliorating effects of organic matter on soil structure, potassium penetrates into dense citrus root areas more rapidly. Organic matter seems to aid in the rate of phosphorus movement, as heavily manured soils show deeper penetration than those not receiving organic matter. Winter cover crops turned under in the spring and organic manures usually decrease the severity of Zn deficiency.

## *Fertilization Guide*

The aim of fertilization is to complement the supply of mineral elements in the soil to obtain commercially acceptable growth and yields. There are several ways to determine fertilizer needs, however leaf analysis provides a common method for making comparisons from soil, field cultures, localities, years and climates. Leaf analysis is useful primarily in determining the tree's current nutritional status. Ranges for levels of nutrients in leaves for maximum production and fruit quality are established as *deficient*, *low*, *optimum*, *high* and *excess*. These ranges, however, may be different from those for producing the maximum amount of vegetative growth or largest fruit size.

Legaz et al. (1995) lists a range of elements in six-months old spring-flush leaves from nonfruiting twigs for Spanish conditions (Tables 6.3 and 6.4).

The type of nutrients required and the amounts depend on the soil type, growing region, cultivar, tree age, and crop load. Thus, soils with a low cation exchange capacity (CEC) need supplementary amounts of all the major macro and micronutrients; that suit regions that differ on rainfall and temperature, and to replace those

**Table 6.3** Leaves analysis guide for diagnosing micronutrient status of citrus adult trees. (Legaz et al. 1995)

Ranges (dry matter basis; ppm)

| | Deficient | Low | Optimum | High | Excess |
|---|---|---|---|---|---|
| Fe | <35 | 3560 | 61–100 | 101–200 | >200 |
| Zn | <14 | 14–25 | 26–70 | 71–300 | >300 |
| Mn | <12 | 12–25 | 26–60 | 61–250 | >250 |
| B | <21 | 21–30 | 31–100 | 101–260 | >260 |
| Cu | <3 | 3–5 | 6–14 | 15–25 | >25 |
| Mo | <0.06 | 0.06–0.09 | 0.10–3.0 | 3.1–100 | >100 |

**Table 6.4** Leaves analysis guide for diagnosing macronutrient status of citrus adult trees. (Legaz et al. 1995)

Ranges (dry matter basis; %)

| | | Deficient | Low | Optimum | High | Excess |
|---|---|---|---|---|---|---|
| Sweet orange | N | <230 | 2.30–2.50 | 2.51–2.80 | 2.81–3.00 | >3.00 |
| | P | <0.10 | 0.10–0.12 | 0.13–0.16 | 0.17–0.20 | >0.20 |
| | K | <0.50 | 0.50–0.70 | 0.71–1.00 | 1.01–1.30 | >1.30 |
| Clementine Mandarin | N | <2.20 | 2.21–2.40 | 2.41–2.70 | 2.71–2.90 | >2.90 |
| | P | <0.09 | 0.09–0.11 | 0.12–0.15 | 0.16–0.19 | >0.19 |
| | K | <0.50 | 0.50–0.70 | 0.71–1.00 | 1.01–1.30 | >1.30 |
| Satsuma Mandarin | N | <2.40 | 2.40–2.60 | 2.61–2.90 | 2.91–3.10 | >3.10 |
| | P | <0.10 | 0.10–0.12 | 0.13–0.16 | 0.17–0.20 | >0.20 |
| | K | <0.40 | 0.40–0.60 | 0.61–0.90 | 0.91–1.15 | >1.15 |
| All species | Ca | <1.60 | 1.60–2.90 | 3.00–5.00 | 5.10–6.50 | >6.50 |
| | Mg | <0.15 | 0.15–0.24 | 0.25–0.45 | 0.46–0.90 | >0.90 |
| | S | <0.14 | 0.14–0.19 | 0.20–0.30 | 0.31–0.50 | >0.51 |

lost from the soil. Clementine mandarins are very prone to Zn and Mn deficiencies, whereas Navel oranges demand high amounts of N. Accordingly, a number of studies regarding fertilization programmes have been carried out (Embleton et al. 1973; Legaz and Primo-Millo 1988). We present a fertilizer programme by Legaz and Primo-Millo (1988) (Table 6.5), and a yearly distribution of a macronutrients fertigation programme for the Spanish Mediterranean Area (Table 6.6).

## Cultural Practices

In most citrus producing countries, grafting is a common practice and is performed by placing a number of buds on suitable scaffold branches with the purpose that the foliage renewal occurs as soon as possible. It is an expensive cultural practice because it involves about two crops and around 4 years until the tree reaches its former size. During the changing process care must be taken with pruning, irrigation and

**Table 6.5** Average yearly amounts of N, P, K recommended for citrus according to tree age. (Legaz and Primo-Millo 1988)

| Tree age (years) | Nitrogen | | Phosphorus ($P_2O_5$) | | Potassium ($K_2O$) | |
|---|---|---|---|---|---|---|
| | g/tree | Kg/ha | g/tree | Kg/ha | g/tree | Kg/ha |
| 1–2 | 40–80 | 16–32 | 0–20 | 0–8 | 0–30 | 0–12 |
| 3–4 | 120–160 | 48–64 | 30–40 | 12–16 | 40–80 | 16–32 |
| 5–6 | 240–320 | 96–128 | 50–60 | 20–24 | 100–120 | 40–48 |
| 7–8 | 410–500 | 164–200 | 80–100 | 32–40 | 160–200 | 64–80 |
| 9–10 | 550–600 | 220–240 | 120–150 | 48–60 | 250–300 | 100–120 |
| >10 | 600–800 | 240–320 | 150–200 | 60–80 | 300–400 | 120–160 |

**Table 6.6** Monthly distribution of a macronutrients fertigation programme for Spanish Mediterranean citrus growing area. Values expressed as percent of annual amount. (Legaz and Primo-Millo 1988)

| Fertilizer | | March | April | May | June | July | Aug | Sep | Oct |
|---|---|---|---|---|---|---|---|---|---|
| Young trees | | | | | | | | | |
| Ammonium nitrate | N | 5 | 10 | 10 | 15 | 20 | 20 | 15 | 5 |
| Phosphoric acid | $P_2O_5$ | 10 | 15 | 15 | 15 | 15 | 10 | 10 | 10 |
| Potassium nitrate | $K_2O$ | 5 | 8 | 10 | 10 | 20 | 25 | 15 | 7 |
| Magnesium nitrate | MgO | 5 | 10 | 12 | 15 | 20 | 20 | 10 | 8 |
| Mature trees | | | | | | | | | |
| Ammonium nitrate | N | 5 | 12 | 15 | 18 | 25 | 15 | 10 | |
| Phosphoric acid | $P_2O_5$ | 10 | 20 | 15 | 15 | 15 | 15 | 10 | |
| Potassium nitrate | $K_2O$ | 7 | 10 | 13 | 15 | 25 | 20 | 10 | |
| Magnesium nitrate | MgO | 10 | 12 | 15 | 18 | 20 | 15 | 10 | |

fertilization, in order to not unbalance the plant. Special caution is required in using disease-free vegetative material that can be transmitted by budding.

Pruning is a very important practice that usually is performed by hand, although mechanical pruning is increasingly used. Young plants are shaped with two to three arms during the initial years. Mature mandarin trees are usually pruned once a year. Oranges, grapefruit and lemons are often pruned every 2 or 3 years because of high cost.

Fertilization is done either by conventional procedures or by fertigation (see Table 6.6), providing elements according to particular soils and climatic conditions. In most citrus producing areas, conventional nitrogen fertilization is done by using ammonia sulphate, ammonia nitro sulphate, ammonia nitrate, or urea, at annual rates of 0.6–0.8 kg N per adult tree, with distribution two or three times a year depending on the soil's characteristics and type. Phosphorus and potassium fertilization is basically made in the spring, using calcium superphosphate and potassium phosphate at rates depending on their content in the soil; average annual maintenance rates range from 0.2 kg $P_2O_5$ and 0.3 kg $K_2O$ per adult tree. The use of soluble or liquid fertilizers is increasing due to increasing trickle irrigation. Foliar applications are usually made in the spring and summer for correcting Mg, Zn and Mn deficiencies by using Mg nitrate, Zn sulphate, Mn sulphate at a concentration of 0.5 %, 0.15 % and 0.22 %, respectively.

In some producing countries, Citriculture is absolutely dependent on irrigation due to poor or erratic rainfall. In general, flood irrigation is still widespread, but trickle irrigation is used in the main citrus producing countries and increases every year. Amounts of water, irrigation dosage and the modules are variable, depending on the soil and the year, but general figures range from 6,000–7,000 $m^3$ $ha^{-1}$ $year^{-1}$.

Sometimes the structure of ownership, and narrow spacing make mechanization difficult. Sprays need sophisticated machinery and soil is tilled several times a year by using small machinery or medium size tractors. Many orchards are treated with residual, contact, or translocation herbicides, but the semi-non-tillage method quite widespread, with plant cover in winter, and bare soil in summer.

The use of PGRs contributes to improve production and fruit quality. PGRs improve fruit set of some Clementine varieties, and increase fruit size of Clementine and Satsuma mandarins and hybrids (see Sections "Fruit set" and "Fruit growth", respectively), promote fruit colouring by using ethylene in degreening chambers, and delay peel senescence of Clementine mandarin. PGRs also control several physiological fruit disorders (see Section "Physiological fruit disorders").

Harvesting of citrus fruit is done manually by carefully cutting the peduncle with special clippers.

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# Chapter 7
# Viticulture and Wine Science

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**Abstract** The grape and wine industry is commercially attractive because it includes a significant value adding chain. Its structure, size and competitiveness however make it a complex industry. The skills required to produce wine usually distinguish between those associated with the production of the fruit and those associated with processing it. This chapter first looks at the history of wine as well as the global wine industry. The basic botany of grapevines is then reviewed and the more important aspects of viticulture and vineyard management are explored. The production of wine is presented before exploring the microbiological and chemical nature of this agro transformation.

**Keywords** Viticulture · Vineyard management · Winemaking · Wine science · Wine chemistry · Wine microbiology

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## Introduction

Grapes are an important global crop. The Food and Agriculture Organisation (FAO) reports that 93 countries produced grapes in 2011, ranging from the large Chinese production (9.1 million t) to the modest 12 t produced in Quatar, making grapes the third largest of 37 major crops behind Bananas and Apples with almost 70 million t produced. It is however the most important crop by area of production (7 million ha). Only 16 countries produced in excess of 1 million t of grapes in 2011 and average yield ranged from 21.5 t/ha in Albania to 0.4 t/ha in the Philippines. Most countries had an average national yields ranging from 5 to 12 t/ha. The value of the commodity to the producer varied greatly, ranging from US $ 7550/t in Japan to US $ 54/t in Chile (in 2011).

Grapes are grown for three main purposes: eating as fresh products (table grapes), dried and for winemaking. This chapter focuses on the production of grapes for winemaking, but many sections will be relevant to professionals in the dried and fresh industries.

## The History of Wine

The earliest evidence of intentional winemaking practices dates from 4500 BC in Georgia (Berkowitz 1996). Additional evidence was found in the Zagros Mountains in nearby Iran (dated 4500 BC) and Armenia (dated 4100 BC). Furthermore, evidence of a winery was also found in Armenia in the Areni-1 cave complex (dated 3000 BC). In northern Greece, charred grape pips and grape skins were discovered at the Neolithic site of Dikili Tash, and dated 4500 BC (Valamoti et al. 2007). The process may have included the addition of figs and honey pre or post fermentation, and support the hypothesis that the wine originated from wild grapes as they often have a bitter taste.

The exact period of vine domestication is still unclear but archaeological evidence supports that Near East (current region north of the Zagros Mountains) and Sumer (current Iraq) are the original sites of wild grape domestication approximately 3000 BC. Vines were cultivated in Egypt around 3000 BC (where there were no wild grape cultivars) and spread through northern Europe during the Greek and Roman civilisations where it was an important component of ceremonial life. Under Roman influence, the practice of viticulture and winemaking dramatically improved, particularly for storing and transporting wine. Extensive spread of vines by the Romans in Europe led to an edict in 97 BC for a ‘vine pull scheme’ in an early attempt at protectionism for Italian wines, but this edict was revoked in 200 AD.

Comparative and morphological genetic studies have identified with certainty the wild progenitor of modern grape variety. *Vitis sylvestris* was regarded as a separate species but is now considered the wild race (subspecies) of the cultivated grape

**Fig. 7.1** Wild grapevines using trees to support their growth towards the sun in North Carolina (USA)

and is called *V. vinifera* ssp *sylvestris*. These wild races are widely distributed over southern Europe and western Asia from Spain to France to Tajikistan. They inhabit the evergreen vegetation belt along the Mediterranean and thrive as climbers along the Caspian and Black Seas.

*Vitis vinifera* is one of the oldest cultivated plants for which living progenitors still exist. Within the genus *Vitis*, there are three natural groups based on geography. They include the North American group (25–30 species), the European group (1 species) and the Eastern Asian group (25–30 species). The exact number of grapevine cultivars used commercially varies in the literature between 1,200 and 1,500 globally. The single European species, *Vitis vinifera*, has contributed most to viticulture around the world, particularly for the production of winegrapes.

The movement of grapes from areas of domestication to the various western Europeans countries led to the establishment of "Old World" countries such as Spain, Portugal, Italy, France, Germany, and various Balkan and North Africaxn countries. These countries are still today the leading wine exporters. Colonisation movements (1500–1800 AD) introduced winegrapes to what is now called the "New World" countries such as the USA, Chile, Peru, Argentina, South Africa, Australia and New Zealand. These industries are still vibrant today (Fig. 7.1).

In addition, winegrapes were introduced to China in 128 BC by General Zhang Qian, but remained unpopular until recently. Nevertheless, the low adoption is compensated by the large population and China is now firmly established as a wine producer. More importantly, China is seen as an important trade partner (for wine and services) by most countries. Similar to other new wine countries, the consolidation of a domestic industry in a developing market involved early bulk import of wine and winemaking skills until the country is able to manage and maintain its production using local facilities and skills. China will be no exception but represent a modern market opportunity.

## The Global Wine Industry

Following the sustainable establishment of their domestic industries, most countries have adopted protection strategies. Some for commercial reasons (such as regional branding), but often to preserve quality and style within a region. The concept of "appellation" is now adopted in most wine countries, but the basis of the definition of the regional zoning varies greatly from rather simple in the New World to complex integration of biophysical, social, historical and political influences in the Old World. Traditionally, Old World countries have designed systems of productions that are highly regulated, including the legislation of grape varieties within an appellation, pruning and training practices, specific planting densities, nominated harvest periods and yields as well as specific winemaking techniques. By contrast, New World countries are highly sensitive to market liberalism and have traditionally legislated far fewer constrains. As a result, the concept of "terroir" in France represents the unique relationship between the location of production (including the soil and climate) of a product, its traditional production practice and its raw ingredients. This concept is present in many Old World countries and is now protected under international trade law. The global wine industry uses the concept of regionality as an important marketing tool to stimulate demand.

The FAO evaluates the global world wine production at 28.7 million t in 2011, produced by 70 countries (note that FAO uses tons as a standard measure of production output). The top ten larger producers accounted for 84 % of the global production. France accounted for 23 % of the global production, Italy 16 %, Spain 12 %, the United States of America 8 %, China 6 %, Argentina 5 %, Australia and Chile 4 % each and South Africa and Germany 3 % each (Fig. 7.1). Of the top five large producers, Italy Spain and The United States of America display a clear decrease in production in the past 6 years, in line with a global wine crisis. By contrast, France reviewed its approach to wine marketing and increased production. Similar, China displayed a steady growth, albeit from a lower base (Fig. 7.1). Markets such as France, Italy and Spain were very strong net exporters of wine, while developing markets such as the USA and China export very little when compared to the volume of total wine traded (Fig. 7.1).

The statistics presented in Fig. 7.1 clearly demonstrates the importance of the Old World traders such as France, Italy and Spain. Not only do they produce a lot of wine but they also export large volumes, hence consolidating their marketing strategies.

On the other hand, China has displayed a steady gowth in wine production since 2005 and a 3.3 fold in wine imports between 2005 and 2010, clearly indicating a rise in demand by Chinese consumers. However, due to the very large population, consumption per capita seemed unchanged over the same period, unlike trends in Europe, where alcohol education has reduced wine consumption (Fig. 7.1). Indeed, it would only take an increase of 0.82 L per Chinese capita (just over one bottle per person) to equal the total domestic consumtion of France (using current population data). Clearly, in view of a rise of the Chinese middle class, China is an emerging market with enormous potential (Fig. 7.2).

## Botany

The grapevine is a perennial species that carries out a number of integrated processes as it progresses from dormancy through budburst, canopy development, root growth, flowering, berry ripening, leaf senescence and then back into dormancy. These processes include nutrient and water uptake, leaf gas exchange, and translocation. Berries contain seeds, and carry out the reproductive function of the vine, maintaining and spreading the species geographically.

### *Roots*

The roots of a grapevine can spread over extensive distances and depths, especially in unirrigated situations. Because grapevines can live for over 100 years the amount of biomass invested into the root system can be enormous. Older roots are covered in a corky layer and anchor the vine in the soil. These roots also hold a critical source of carbohydrate reserves that supports early shoot growth shortly after budburst in spring. The fine roots, however, are covered in numerous root hairs to increase surface area and facilitate absorption of water and minerals. These root hairs are an extension of the epidermal cell and are very short-lived. Soil moisture and temperature have an impact on new root growth in early spring and this impacts nutrient and water uptake. Aside from slowing new root growth, cool soils also hamper starch metabolism and can delay canopy and reproductive growth such that flowering and veraison dates are delayed (Rogiers and Clarke 2013). Because roots are in direct contact with the soil they are able to relay information from the below-ground environment to the above ground vine components by sending signals through the vascular system. For instance, abscisic acid is produced in the roots in response to water deficits and sent to the leaves to initiate stomatal closure.

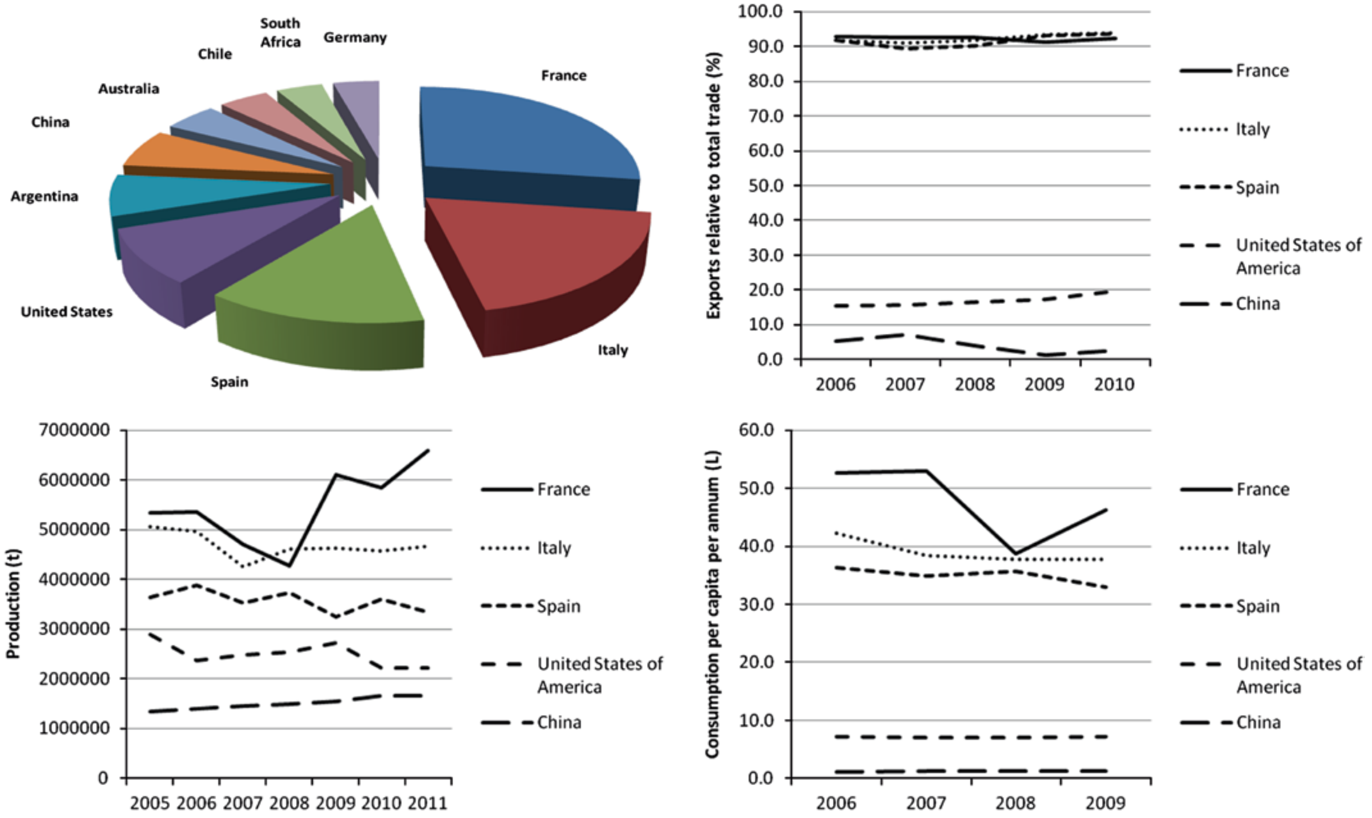


**Fig. 7.2** Ten largest wine producers in 2011 (*top left*); production trends of the five largest producers (in 2011) between 2005 and 2011(*bottom left*); exports relative to the total amount of wine traded (exports + imports) by the five largest wine producers (*top right*) and domestic wine consumption per capita and per year of these producers (*bottom right*). (Source: http://faostat3.fao.org/home/index.html#DOWNLOAD)

## *Trunk and Cordons*

The trunk and cordons carry the vascular tissues that provide structural support and transport water as well as essential nutrients through the vine. The trunk and cordons may also store some carbohydrate and mineral reserves.

## *The Canopy*

The shoots of the grapevine consists of nodes and internodes and a growing shoot tip. After leaf abscission in autumn the shoots are referred to as canes. At each node, a bud is located just above the leaf petiole and these contain the partially developed shoots and inflorescences for the following season. Inflorescences (usually two per shoot) form at the third to sixth nodes from the base of the shoot. Tendrils have the same ontogenetic origin as inflorescences but their role is to attach shoots to stable structures so that the growing shoot tip is able to grow toward the light. In their natural state, grapevines are vigorous climbing lianas that can climb up trees to enormous heights.

The leaves of grapevines most often have a palmate shape with five main vascular bundles. The edges of the leaves are usually serrated with variety differences in the degree of their sharpness. The leaves follow an alternating pattern on the shoot with a single leaf at each node on the two opposing sides of the shoot (Mullins et al. 1992). The leaves carry out the critical process of photosynthesis where light energy is converted to chemical energy. When young, leaves import carbon to support expansion and development but as they mature the leaves become net carbon exporters. Young, fully expanded leaves will undergo maximal photosynthesis for several weeks, but as they age photosynthesis begins to decline (Fig. 7.3).

Grapevine leaves have stomata, or pores, scattered on the bottom epidermal layer through which gas exchange occurs (Fig. 7.3). Stomata are responsible for $CO_2$ entry and water vapour loss in the process called transpiration. Grapevine stomatal density (the number of stomata per unit of leaf area) is responsive to environmental factors such as light, atmospheric $CO_2$ concentration as well as root-zone temperature (Rogiers et al. 2011a).

## *Source-Sink Interactions*

A carbon source may be a photosynthetically active leaf or a root full of stored starch while a sink is an area where the carbon is used for respiration and the maintenance of existing biomass, or for growth such as in developing shoot tips. The grape bunches are another strong sink, especially after veraison, while the roots become a strong sink during the periods of active root growth and carbohydrate reserve replenishment. Sink feed-back mechanisms exist to co-ordinate the supply and demand of carbohydrates (Wardlaw 1990). For instance, the removal of berries

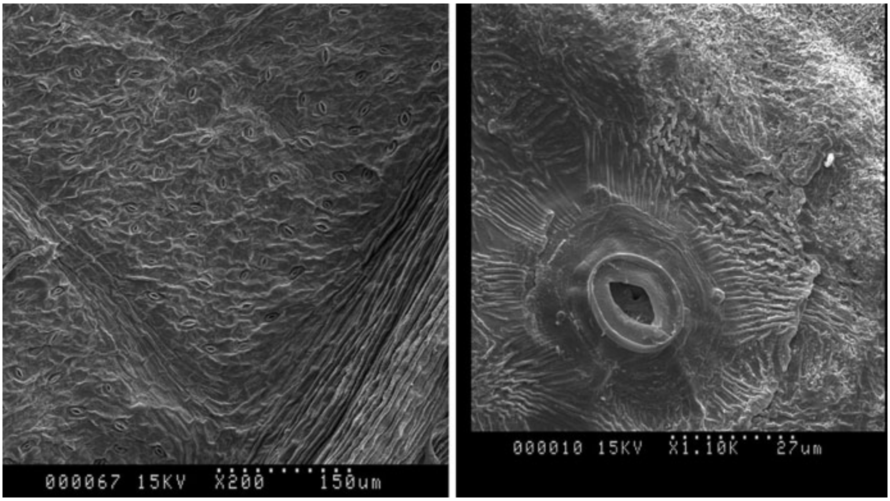


**Fig. 7.3** Opened stomata on the underside of young and expanded grapevine leaf (*Left*). An opened stomate on a berry at fruitset (*Right*)

can lead to lowered rates of photosynthesis (Candolfi-Vasconcelos and Koblet 1990) and under severe defoliation post-veraison berries are able to source carbohydrates from the woody storage tissues (Kliewer and Antcliff 1970). The intricate balance between photosynthetic capacity and the allocation of resources to vegetative versus reproductive components ensures that the vine maintains enough capacity for both survival and reproduction in a resource-limited environment.

## *Inflorescence*

The shape and size of the inflorescence is variety dependent but it is referred to as a panicle and often includes several branches which can be further ramified. Usually between two to five flowers are found at the terminal branch. The hypoclade is the portion of the main stem that is located between the shoot and the first branch and encloses the vascular bundles that carry water and nutrients from the shoot to the flowers and berries. The main axis below this point is referred to as the rachis and often carries a lateral wing or a tendril. The bunchstem elongates rapidly early in the season with thickening occurring until mid-flowering. Lignification begins at veraison and continues until berry maturity.

## *Reproductive Cycle and Yield Components*

Reproductive development and yield formation in grapevines is a process that spans two seasons. Inflorescence primordia are initiated in the buds that form in the axil

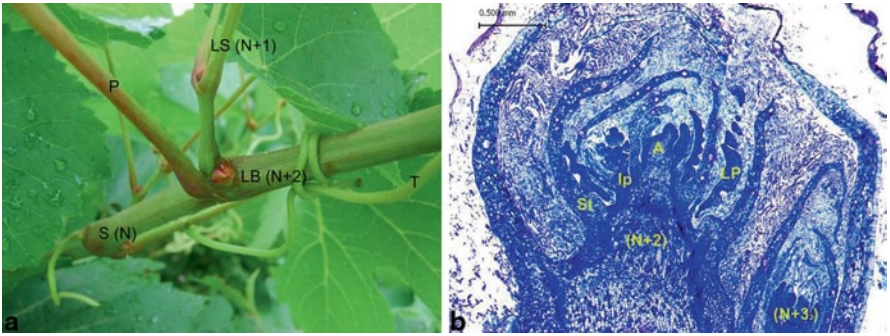


**Fig. 7.4** Shiraz shoot (**a**) and latent bud section at flowering (**b**). Labels indicate main shoot axis (*S*), petiole (*P*), lateral shoot (*LS*), latent bud (*LB*), stipule (*St*), inflorescence primordia (*Ip*), and bud apex (*A*). Shoot generations indicated by N, N+1, N+2, N+

of each leaf during the spring of the first season, and then undergo several orders of branching before entering the winter dormancy period. Inflorescence development resumes at bud break with the growth of the shoot primordia and the development of individual flowers, and continues through from flowering to berry maturation and harvest in mid-summer to mid-autumn.

Fruit yield at harvest in the following season is a function of bunch weights and the number of bunches per vine, and both parameters can be influenced by genotype, environmental conditions and viticultural management practice during the reproductive cycle. Bunch weights are determined by berry weight and berry number per bunch, and in turn by inflorescence flower numbers, the proportion of flowers that are successfully fertilized at anthesis, and by the growth and final weight of berries at harvest. Bunch numbers per vine are determined by shoot numbers and the fruitfulness of those shoots, with the number of buds retained at pruning and percentage bud-break determining shoot numbers, and the number of inflorescence primordia initiated by these buds in the previous season determining shoot fruitfulness.

## *The Grapevine Bud*

Grapevine buds consist of a prompt bud that usually bursts through late spring and summer to form a small lateral shoot, and a latent or compound bud that forms in the axis of the first bract of these summer laterals (Fig. 7.4).

The latent bud typically develops six to twelve leaf primordia and initiates between one and three inflorescence primordia before entering the winter dormancy period (May 2004). The fruitfulness of these buds, together with the number buds retained at pruning, are one of the key yield determinants for the followed season. Within the latent bud, second order buds are also formed in the axis of the basal bracts. These buds are generally smaller and less fruitful than the primary shoot meristem, but if the primary bud is damaged or dies during the season, one of more of the secondary buds can develop further and replace it in the following spring. In susceptible cultivars such as Shiraz, a physiological disorder called primary bud necrosis (PBN) can lead to the death of up to 60 % of primary buds, and a significant loss of yield potential in the following season. Other causes of bud loss include mechanical damage, mites, fungal pathogens and severe winter freeze events.

### *Formation of Inflorescence Primordia*

Inflorescence development in grapevines commences with the separation of an anlage or uncommitted primordium from bud apex when three to seven leaf primordia have been produced (Srinivasan and Mullins 1981). The exact timing varies according to cultivar and climate, but may range between 2 and 6 weeks after budbreak (Vasconcelos et al. 2009). Anlagen at this point can develop into a tendril, inflorescence or sometimes an intermediate form, with commitment of the anlage to a pathway of inflorescence development promoted by cytokinins and inhibited by gibberellins (Boss and Thomas 2002; Srinivasan and Mullins 1981). In hot climates, inflorescence primordia may be initiated up to 3 weeks before flowering at the basal node positions, and this process continues in an acropetal direction along the shoot through spring and early summer (Swanepoel and Archer 1988). The development of the inflorescence primordia continues through the season, and at the onset of dormancy several orders of branch and subtending bract primordia can be observed. Individual flowers are not formed until bud-break in the following spring, but variation observed between inflorescence differentiation in cool and warm climates suggests that yield may be influenced by the extent of inflorescence development in the season of initiation (Watt et al. 2008).

The number of inflorescences initiated per bud can range between one and three, although for most cultivars two is more common. Environmental factors that favour the formation of inflorescence primordia over tendrils include temperatures above 20 °C and less than 35 °C in the weeks leading up to flowering, and well exposed shoots that ensure a good supply of assimilates for the developing buds (Buttrose 1969; Sanchez and Dokoozlian 2005). Carbohydrate reserves, or at least carbohydrate reserve mediated effects on canopy development may also influence bud-fruitfulness (Smith and Holzapfel 2009), and the perennial nature of stored carbohydrates potentially extends the influence of management practice and climatic conditions on yield to a 3 year cycle or beyond. Varying the number of buds retained after pruning offers one of the main avenues for yield regulation in grapevines, and where bud dissections are undertaken to assess bud fruitfulness during winter, pruning may be adjusted to target a specific number of bunches in the following season.

## *Flowering and Fruit Set*

The development of individual flowers commences at bud-break, and by anthesis the total number of flowers per inflorescence typically ranges between about 100 and 400. However, this may extend to over a 1,000 for some cultivars, or to just a few flowers for intermediate tendril and inflorescence forms. Air and soil temperature treatments applied at the time of bud-break can induce a 10–25 % variation in the number of flowers formed on an inflorescence, and demonstrate a mechanism through which weather conditions in early spring can have a direct influence on yield formation (Petrie and Clingeleffer 2005; Field et al. 2009; Rogiers et al. 2011b). Other factors that can influence the number of flowers per inflorescence include rootstock, position of the inflorescence on the shoot and pruning system. Vine carbohydrate reserve status can also alter inflorescence flower numbers (Bennett et al. 2005), although for all of these factors it may be difficult to separate effects on inflorescence primordia branching in the season of initiation from effects on flowering formation in the subsequent spring (Dunn and Martin 2007).

Anthesis commences with the shedding of the first flower caps or calyptra some 6–10 weeks after bud-break depending on climatic conditions and cultivar, and will continue for approximately a week until all of the flowers on the inflorescence have opened. Typically 20–30 % of flowers will develop into normal berries, but this figure can be as low as 15 % or as high as 60 % and vary according to cultivar, cultural practice and weather conditions during flowering (May 2004). The optimum temperatures for cap-fall and pollination occur between 20 and 30 °C, while temperatures above 35 °C are detrimental. At temperatures below 15–17 °C flower caps do not open at all, and through extended periods of cold and wet weather, the number of successfully fertilized berries can be substantially reduced. Fruit set is also highly dependent on an adequate supply of carbohydrates, and can be reduced by competition with excessively vigorous shoots, from other flowers on large inflorescences, or even concurrent storage of carbohydrate reserves in perennial tissues (Rogiers et al. 2011b).

## *Berry Morphology*

The grape berry develops from the fertilised ovary and is composed of the seeds, flesh and skin. The flesh is comprised of cells containing large water-filled vacuoles that accumulate fructose and glucose, and small quantities of malic and tartaric acids. The skin is referred to as the exocarp and consists of an inner hypodermis and outer epidermis and this is covered in a waxy cuticle which prevents desiccation and offers resistance against pathogens (Possingham et al. 1967). Stomata are present on the surface of the berry but they become occluded with wax and are non-functional shortly after flowering (Blanke and Leyhe 1987). The pedicel of the berry (berry stalk) connects the berry to the bunch stalk (rachis) and contains six vascular bundles (Mullins et al. 1992). The vascular bundles entering the berry branch out into a network supplying the seeds and the pericarp. The torus (receptacle) is the structure at the base of the pedicel.

Grape berries carry up to four seeds. These seeds contain an embryo, endosperm (a nutrient supply) and the seed coat. Greater seed number and larger seeds are often associated with larger berries and this is thought to be due to the stimulation of cell mitosis in response to the release of hormonal signals from the seeds (Ojeda et al. 1999). The demand for seedless but large table grapes by consumers can be addressed by the application of gibberellin at flowering or fruit set which increases the sink strength of the berries. Seed development is influenced by climatic conditions, vine water status and management practices such as pruning.

## *Berry Growth*

The grape berry is classified as a non-climacteric fruit as it does not show an increase in respiration with ripening. Complex interactions of hormones appear to be involved in berry ripening including declines of indole acetic acid and increases in abscisic acid, the brassinosteroid castasterone and ethylene (Chervin et al. 2004; Davies et al. 1997). Berry growth follows a double sigmoidal pattern (Coombe 1992) entailing two stages of rapid growth (Mullins et al. 1992). During late ripening a third stage characterised by berry shrinkage is evident in some varieties. The first 10 days after fertilization, are characterised by rapid cell division and this is followed by cell enlargement which lasts 40–60 days (Harris et al. 1968) depending on temperature and other environmental parameters. Organic acids, tannins and hydroxycinnamates accumulate and seed enlargement also occurs during this stage (Pratt 1971). Following the first stage of rapid growth is a lag period that can last anywhere from 7 to 40 days. During the second phase of growth berries begin to soften, lose chlorophyll and, in red varieties, will undergo a colour change. Veraison is the term referred to as ‘berry softening’. This rapid stage of growth can last anywhere from 35 to 55 days and is accompanied by cell wall metabolism that encourages cell expansion (Ojeda et al. 1999). Maximum berry weight is obtained approximately 95 days after flowering, and depending on irrigation practice and variety can range between 0.5 and 2.5 g on a fresh weight basis at harvest. Sugars and volatile aromas accumulate during this stage and acid concentrations decrease. During the final stage of development, berry weight may plateau or decline (McCarthy 1999) and further changes in flavours and aromas occur.

## *Determinants of Berry Volume*

Irrigation and vine water status can have a significant impact on berry size. Water stress between flowering and veraison can decrease berry size and this is often irreversible (van Zyl 1984; Matthews et al. 1987) possibly because this is when cell division occurs and cell number per berry is determined. Nutritional deficiencies and heat stress early during berry development may result in a similar decrease in berry size. Berry volume is also highly dependent on cell expansion both early and late in development (Ojeda et al. 1999).

During the pre-veraison stage water flow into the berry is primarily through the xylem but after veraison water inflow is chiefly through the phloem and this is accompanied with a switch from symplastic to apoplastic unloading (Zhang et al. 2006). The decline of water flow through the xylem may be the result of a reduction in the hydrostatic gradient between the pedicel and the xylem (Tilbrook and Tyerman 2009). Under certain conditions, the xylem, can however, continue to contribute up until late ripening (Rogiers et al. 2001; Rogiers et al. 2006c). The volume of the berry is a function of water inflow through the xylem and phloem and the water lost through transpiration or backflow. Diurnal cycling in berry volume is the result of these opposing influences (Greenspan et al. 1994; Rogiers et al. 2006a). Berries expand during the night when vine water status is high and when berry transpiration is low. Conversely, berries will shrink during the day when high evaporative demand drives transpirational water loss from the berry's surface. Vine water status is therefore one prime determinant of berry volume and this is dependent on environmental factors such as readily available water in the soil and evaporative demand. Water loss through transpiration from the berry's surface is also dependent on the position of the berry in the bunch and the degree of bunch compactness. Berry age is another determinant since transpiration rate on a surface area basis decreases rapidly after veraison (Poni et al. 2001; Rogiers et al. 2004), possibly as a result of changes in the physical structure of the epicuticular wax layer.

Some varieties such as Shiraz are prone to shrinkage during late ripening, affecting composition and overall yield per hectare. It is thought that exposed berries have higher transpiration rates and this contributes to shrinkage since water flow into the berry is often reduced at this later stage. There is also some evidence of water movement out of the berry and back to the shoot through the xylem in the process called backflow (Lang and Thorpe 1989; Tyerman et al. 2004; Keller et al. 2006). This can potentially occur when the water status of the vine is more negative than that of the berry. On the opposite extreme, splitting of the berry skin can occur after a rain event or on humid days. In Shiraz, susceptibility to splitting is highest shortly after the onset of ripening and remains high for about 1 month. After this stage, the susceptibility to splitting declines due to a loss in cell vitality and the turgor generating capacity of these cells (Clarke et al. 2010). There are currently few management options to control splitting but bunch zone aeration to increase transpiration and cultivar choice upon vineyard establishment are important considerations.

## *Berry Composition*

During grape berry ripening the flesh accumulates carbohydrates, organic acids and amino acids while the skin and seeds are sites of colour and tannin accumulation. Glucose and fructose are the predominant sugars accrued within the berry. Tartaric and malic acid are the main organic acids while proline and arginine are the predominant amino acids. The distribution of these compounds through the berry is not homogenous and varies with developmental stage. The purpose of these changes in composition is to aid seed dispersal by appealing to a bird's sense of sight, smell and taste.

Berry composition is sensitive to the environment and can be manipulated to some extent with management practises. For instance, leaf removal from the fruiting zone between flowering and veraison can increase light penetration and can improve flavour and aroma development in the fruit, however excessive exposure can decrease sugar accumulation, malic acid and titratable acidity (Zoecklein et al. 1992) and increase fruit susceptibility to sunburn, especially in warm climates. Leaf removal can also result in an increase in fruit phenolic concentrations (Poni et al. 2004) and depending on variety may lead to more bitter and astringent wines (Jackson and Jackson 2009). The severity of the treatment and the methods employed to remove the leaves (ie hand vs mechanised) contributes to the types of compounds produced in the berry. This exemplifies that practises such as leaf removal need to take into consideration the climate, the variety and the style of wine that is targeted.

## *Sugar Accumulation*

While Brix is a measure of soluble solid concentrations it is not necessarily a good indicator of sugar loading kinetics since berry volume can increase after rain or shrink during later stages of ripening. Sugar loading into berries is dependent on photosynthesis rates and the strength of competing sinks. Phloem derived sucrose is unloaded via an apoplastic route requiring sucrose or hexose transporters (Fillion et al. 1999; Terrier et al. 2005; Robinson and Davies 2000) but the precise location of these transporters is yet to be determined. After entering the cell, glucose and fructose are stored in the vacuole. Rates of sugar accumulation are strongly dependent on seasonal temperatures with global warming over recent years resulting in more rapid ripening, leading to wines with higher alcohol content. Vine water status is also crucial to berry sugar content since it controls stomatal conductance and this has a direct effect on photosynthesis rates. Crop load is critical to berry ripening since an insufficient leaf area results in a source limitation. Canopy architecture will also have an influence on sugar accumulation since both leaf and berry temperatures are influenced by exposure to the sun and wind.

## *Mineral Accumulation*

Berries accumulate minerals in the skin, flesh and seeds. Potassium is the predominant mineral (approx 70 %), but phosphorus, calcium, sulphur and magnesium accumulation is also significant (Rogiers et al. 2006b). The xylem mobile minerals calcium, manganese and zinc accumulate prior to veraison while the phloem mobile minerals potassium, phosphorus, sulphur, boron, iron and copper accumulate throughout development. Minerals act as catalysts in biochemical reactions and they are also components of structural molecules such as proteins and nucleic acids. Cell walls, for instance, contain calcium and potassium is an osmotically active cation involved in sugar transport. Potassium has a strong influence on berry pH because it can substitute for protons. High juice calcium and potassium levels can result in undesirable precipitation of tartrate in wines while high manganese can promote acetaldehyde production (Cacho et al. 1995). The micronutrient, iron, can alter the tint of a wine towards the blue spectrum while copper can prevent oxidation of the phenolics.

## Acid Depletion

Berry titratable acidity is dependent on variety and climate. Both tartrate and malate accumulate early in berry development and decrease during ripening. Tartrate concentrations are higher near the skin while malate concentrations are higher towards the interior of the berry. Other organic acids, such as citrate, are present in the berry but these are in much lower concentrations. In warm to hot regions berry titratable acidity is often less than desired and this is due to the rapid degradation of malic acid (Kliewer 1971). As a result, tartrate is often added in the winery to adjust the pH of the juice and wine. Malic acid can undergo transformation to sugars under conditions when berry metabolism is slow but the proportion relative to sugar import is very small.

### *Nitrogenous Compounds*

The amino acids serve as precursors of aroma molecules and are an important source of nitrogen for yeast during the fermentation process. Nitrogen enters the berry through the xylem and phloem mostly as glutamine and concentrations are dependent on variety, nitrogen fertilisation, weather and soil type (Huang and Ough 1991). Most of the nitrogen that enters the berry is transferred to the seeds and skin with approximately 20 % allocated to the flesh. While proteins take up only a small portion of the nitrogen fraction within the berry they are important for stress management and defence against pathogens. The amino acids proline and arginine account for approx. 70 % of the amino acids in the berry. Proline concentrations increase before harvest while in some cultivars arginine remains relatively stable after veraison (Kliewer 1968). Therefore the proline to arginine ratio can be a good indicator of berry maturity. Shading can, however, decrease the proline to arginine ratio (Pereira et al. 2006).

## Phenolics

Phenolics are a diverse group of compounds with a six-carbon aromatic ring and hydroxyl group. Colour in red varieties is a function of anthocyanin accumulation. In most varieties anthocyanins are located in the skin and the immediately subtending cell layers and its production depends on the availability of phenylalanine, which is synthetised from sugars. The pH of the juice or wine will influence its red or blue tint. Grape berry anthocyanin development is mainly driven by light and air temperature (Kliewer and Antcliff 1970; Buttrose et al. 1971; Dokoozlian and Kliewer 1996) but, in Shiraz, can also be negatively correlated to high crop load (Wolf et al. 2003). Excess nitrogen can impair anthocyanin accumulation in the berry due to slowed ripening as a result of competition with shoot growth (Keller et al. 1999).

Astringency is a function of the berry tannin content. Seed tannins become fixed to the seed coat as they mature and therefore tannin extractability declines with ripening. These tannins also become less bitter with ripening due to polymerization. Skin tannins can decline or increase with ripening (Bindon et al. 2013). To date, however, there has not been a clear link between berry tannin and the wine tannin concentrations (Fournand et al. 2006).

## Aroma Development

A characteristic sequence of aromas develops as a berry of a particular variety ripens (Suklje et al. 2012). Environmental parameters, however, have a strong influence on the intensity of particular aromas so that some compounds are masked by other more dominating ones. Aromas arise from volatile compounds, such as terpenes, norisoprenoids, and thiols stored as sugar or amino acid conjugates in the cell vacuoles of the skin and flesh (Lund and Bohlmann 2006). Some key flavour precursors have been identified in particular varieties. Isobutyl methoxypyrazine is responsible for the green bell pepper attribute in Cabernet Sauvignon. The floral and citrus characters of white varieties, however, can be attributed to a class of compounds called terpenoids. Both light and temperature have been found to influence the degradation and synthesis of aroma compounds in berries (Reynolds and Wardle 1989; Marais et al. 2001; Suklje et al. 2012).

## Yield

At the upper levels of normal production systems in hot climate irrigated vineyards, grapevines may produce over 35 kg of fruit per vine, or around 40 t on a per hectare basis. At the other extreme, fruit yields may be restricted to only a few kilograms per vine were limited by water availability, soil fertility or deliberate regulation of cropping level.

## Vineyard Management

### Nutrition

Grapevine nutrition is an important part of grape production with implications on vine growth and berry composition. The acquisition of nutrient is influenced by the soil environment, particularly soil moisture and temperature. The uptake of nutrients from the soil solution requires energy from stored or recently assimilated carbohydrates for further root growth to explore more soil volume and for the active nutrient uptake necessary for several nutrients. The inorganic macro and micro nutrients (based on concentration in plant material) are essential for plant growth. Nutrients are important as structural components, and are involved in energy transfer reactions, activation of enzymes or metabolic processes. Nutrients can also be taken up by the leaves via the cuticula by diffusion, allowing for foliar fertiliser application often used for some micro nutrients in grape production.

Nitrogen (N) is part of number of organic compounds and is taken up in the form of a cation as ammonium ($NH^{4+}$) or an anion as nitrate ($NO^{3-}$). The uptake depends mostly on the presence of the ions in the soil solution. In grapevines, $NO^{3-}$ is the primary source of N due to the high nitrification rates in vineyard soils. The vine xylem contains $NO^{3-}$ and glutamine is the dominating amino acid. The amino-N can be translocated via the phloem to growing organs or to the storage tissue to be available when nutrient uptake is low.

Based on the concentration in plant tissue the elements N, P, K, Mg, Ca and S generally defined as macro nutrients (Marschner 2012). N, Mg and S form part of the chlorophyll molecule and are for the production of sugars by the photosynthetic process. The elements N and S are also components of proteins, while Ca is part of cellular structural components and P of cell membranes. The later is also important for high energy bonds required for the transfer of energy within cells and between organs of the grapevine. K has an important role in carbohydrate metabolism and transport as well stomatal functioning, regulating the movement of water in grapevines (Keller 2010). Other essential elements Fe, Mn, Zn, B, Mo and Cu, and are classified as micro nutrients and are generally present in lower concentrations than the macro nutrients. Fe, Mn, Zn and Cu are involved more or less in the assimilation process, by either involvement in the chlorophyll synthesis (Fe and Cu), chloroplast development (Zn) or involvement in the light reaction (Mn). In addition, Fe and Mn activates enzymes and Cu is present in enzymes. Zn and Mo have a role in the N metabolism, in either synthesis of proteins (Zn) or the conversion of nitrate N taken up by the roots to useable forms (Mo), while B has an important role in carbohydrate metabolism.

The phloem mobility of nutrient varies and is an indication to what extent these nutrients can be remobilised from reserve tissue or from older tissues into developing organs. Differences in nutrient mobility are observed when deficiencies are present. The classification of phloem nutrient mobility has been determined by assessing the concentrations in the phloem or by using labelled elements (radioactive or stable isotopes and the long distance transport is followed (eg. tip of a leaf blade). The phloem mobility is high for most macro nutrients except Ca, while the intermediate mobility is present for the micro elements except Mn (Marschner 2012). The mobility determines the effectiveness of foliar applied fertiliser, with the movement of a particular nutrient into the required tissues of the grapevine.

The vine demand for nutrient depends on the developmental stage and the level of productivity and is generally met by nutrient acquisition and/or remobilisation in stored parts of the vine. Because of limited mobility of some nutrients in the phloem, uptake of some nutrients by roots becomes critical and can impact on the development of the roots (Mengel and Kirkby 2001). Nutrient uptake varies during the growing season concurrent with changes in root growth activity. Generally, this is high when the growth demands from other parts of the vine, such as shoots and grapes, are low. Before flowering, shoot growth is strongly dependant on N mobilised and transported from reserves stored during the previous season (Zapata et al. 2004). The leaves, shoots and bunches are strong sinks for N assimilated during the period from flowering to veraison. Between veraison and harvest, when N uptake might slow or stop, redistribution from roots, shoots and leaves to bunches takes place,. The redistribution of N is, however, dependent on N availability during the berry ripening period. Therefore, the two most efficacious periods of N uptake by grapevine roots are during periods of excess carbon supply available to the roots. The first being after rapid shoot elongation ceases and the second after harvest, this leads to further uptake of N and other nutrients during the post-harvest period (Wermelinger 1991). The stored N is important because early demand in spring cannot be guaranteed by root uptake. Nutrient reserves in the permanent structure are highest in winter but can be influenced by cropping levels, vineyard management and environmental conditions.

Adequate nutrient supply to grapevines ensures sustained yield levels and is important for grape composition. A deficiency of any nutrient reduces yields, although the reserves in the perennial structure of some nutrients in grapevines are important during times of insufficient uptake. These occur in early spring, when root activity is relatively low and demand by the developing canopy is high, also the uptake and demand might not be matched during the berry ripening period. In both times the demand for carbohydrates is high in relation to production, restricting the supply of assimilates to the roots and therefore the energy for uptake. The supply of nutrients can alter the grape composition directly, by moving them into the berry, or indirectly by influencing vine development and yield level. N is the most dominant nutrient affecting must composition, with impact on the wine making process and the wine.

The relationship between nutrient content in grapevine tissue and vine performance (growth and yield) is important to develop nutrient standards. The adequate (or optimal) range for a particular nutrient is greater than the deficient values and less than the luxury upper values which can lead to undesired growth. Excess of nutrients causes toxicity and nutrient imbalance results in the decline of growth and productivity (Smith and Loneragan 1997). The increase of a nutrient in a deficient range will lead to improved growth and to a dilution effect and lead to a greater deficiency of another nutrient which was also lacking. The critical deficiency range also leads to poor plant performance. Both the effect of toxicity and deficiency only becomes visible with severity; the micro nutrients generally have a much smaller range between the two extremes than macro nutrients. A number of nutrients impact on reproductive development of grapevines if deficient, while high N supply can lead to poor fruit set and increase the sensitivity to botrytis (Keller 2010). The insufficient supply of the macro nutrient P leads to poor fruitfulness and fruit set, while a lack of K can reduce bunch weight and uneven ripening. Localised Ca deficiency is seen as the cause of the physiological disorder of the grape bunch bunchstem necrosis (BSN); with the symptoms appearing after veraison and increasing during the ripening period. A deficiency of the macro nutrients Zn, B and Mo negatively impact on fruit set, B leads abnormal fruit set (millerandage), and Zn to poor fruit set (coloure), while a lack of Mo has also been related to poor fruit set on acid soils (fixation).

The composition of grapes influences the winemaking process and the wine produced from these grapes and all nutrients effect crop quality directly. However, the supply of the macro nutrients N, P and K alter must composition, excessive K results in high juice pH and low colour in the ferment and wine. The amounts nitrogenous compounds present in the must as amino acid and ammonium ($NH^{4+}$) have a critical role in the fermentation process and the final wine composition (Bell and Henschke 2005). Yeast assimilable Nitrogen (YAN) consists of $NH^{4+}$ and free assimilable amino N (FAN), while the amino acid proline is classified as non assimilable amino-N (YNAN). The uptake of nitrogen from the must is ordered, $NH^{4+}$ is taken up first, followed by argenine and then the other amino acids present in the must. The level of YAN impact on fermentation kinetics and desired/undesired compounds produced during the fermentation and present in the wine. As indicated before juice N content and composition impact on the wine making process, the amount of N present in form of YAN which includes all assimilable amino and $NH^{4+}$ is critical. Low must YAN lead to a slow fermentation, high amounts of thiols (eg. $H_2S$) and undesired higher alcohols and low levels of desired esters and long chain fatty acids. A fast fermentation is present when YAN levels are high and ethyl acetate, acetic acid, volatile acidity is produced during the wine making process, the final wine contains high levels of undesired ethyl carbamate and biogenic amines (Bell and Henschke 2005). This indicates appropriate level of YAN is required for the must, the vineyard N application should be designed to produce the optimal YAN content in the grapes, while further fine tuning can be conducted in the winery with the addition of N supplements such as di-ammonium phosphate (DAP).

Assessing grapevine nutrient status is important to verify the requirements for fertiliser application in a vineyard. The general appearance of grapevines in relation to vine vigour and leaf symptoms is a first observation of how well a vineyard is supplied with nutrients. However, visual deficiency (or toxicity) symptoms become apparent after the productivity declines, some nutrients specifically reduce the yield levels at key stages of reproductive development as mentioned previously. Determining the annual grapevine nutrient status with supporting information on soil nutrient levels is an important to ensure optimal vineyard productivity and grape composition. The appearance of visual deficiency symptoms vary between nutrients and the severity of the lack of supply (Nicholas 2004), in general most macro symptoms appear first on the older leaves (except N and S), while most micro nutrients deficiencies appear on the younger leaves (except Mn). The difference between the occurrences of deficiencies (from leaves of different age) relates remobilisation and the phloem mobility of the nutrients. However, more severe deficiencies appear on the leaves of various ages. The symptoms include general leaf yellowing (N and S), leaf curling (K) or interveinal chlorosis (Fe, Mn and Zn). A further impact of deficiency is observed with growth reduction (N and P) or stunted growth induced by number of marco nutrients due to low supply. Toxicity symptoms show also on the older leaves (Na, Cl and B); more severe B oversupply induces leaf symptoms on all leaves on a shoot (symptom of initial B toxicity on picture).

The most common assessment of grapevine nutrient status is determined in the petioles collected at flowering (Robinson 1992). Shoot vigour and leaf health are also important information at flowering, while fruit nutrient concentration indicates the amount of nutrients removed. Petiole sap concentration has been utilised, but the information for standard ranges is limited. Another possibility is to monitor winter wood reserves, since it provides a useful information on grapevine reserves and early information on the nutrient status than the petiole levels assessed in spring. Assessing nutrient levels in the vineyard soil before planting and during full production of vineyards is an additional tool to determine fertiliser requirements. Soil sampling is usually not taken annually and is most appropriately conducted during the dormant period of grapevines. The vineyard nutrient cycle is complex; commonly the main movements of nutrients in a vineyard system are the removal by the crop, the recycling of organic material and the input of fertiliser (Bauer 2002). Nutrients are removed by the soil by the grapevines and the covercrop, the later can be important for bringing nutrients from deeper soil levels (nutrient mining). The removal by the crop is less if part of the grape material is brought back to the vineyard via pressings. The nutrients present in the green and root mass of the covercrop, together with the prunings can also be recycled. The application of organic and mineral fertiliser fills the gap of nutrients brought about by the removal of grapes and losses from the soil by leaching.

Vine nutrition is important for grape production, with nutrients have several crucial functions in vine development and vary in mobility and winter storage. Both yield and grape composition is influenced by nutrient supply (mobilisation and uptake). The information on vine and (soil nutrient) status is essential for vineyard fertiliser management, with the application of fertiliser needs to consider the vineyard nutrient cycle and root dynamics.

## *Irrigation*

In many grape growing regions of the world, irrigation is not permitted. Growers nevertheless are astutely aware of the plant water requirements as a yield limiting component and monitor soil or plant based signs of water stress. Where it is permitted, irrigation is an important component of vineyard management, particularly

**Table 7.1** The relationship between soil and vine water status

| Soil water tension (kPa) | Soil status | Vine status | Vine condition |
|---|---|---|---|
| 0 | Saturation | Anaerobic root environment | Unfavourable in prolonged situations |
| 10 | Field capacity | Transpiration is not restricted by water availability | Transpiration under stomatal control |
| 10–60 | Readily available water | Transpiration is not restricted by water availability | Transpiration under stomatal control |
| 60–200 | Stress available water | Transpiration is restricted by water availability | Transpiration under stomatal and non stomatal control |
| 200–1500 | Deficit available water | Prolonged drought conditions | Transpiration under non stomatal control |

when water is managed through a complex blend of water entitlement and complementary water purchase. As the cost of water increases as a result of scarcity, management of this resource further influence the net profit of this enterprise.

Irrigation has traditionally been managed using soil based methodologies, sometimes coupled with atmospheric demand and/or indicators of plant response to soil water. In these methods, the soil is perceived as a water reservoir that is depleted daily via soil evaporation and plant transpiration. Sandy soils hold less water than clay soils and the ratio of sand silt and clay is often used as a predictor of the water holding capacity of a soil.

A soil is called at Field Capacity (FC) or Drained Upper Limit (DUL) when totally filled with water and subsequently allowed to drain under the influence of gravity. By contrast, when water can no longer be extracted from the soil and plants wilt, the soil is called at Permanent Wilting Point (PWP) or Lower Limit (LL). The amount of water help by a soil between FC and PWP is directly related to its texture and organic matter content and is called the Plant Available Water (PAW). The fraction of PAW easily extracted by plants is called the Readily Available Water (RAW) and will not lead to yield reduction. It is followed by the Stress Available Water (SAW), associated with the onset of yield loss and the Deficit Available Water (DAW) associated with a significant loss of yield and plants. The tension required to extract water from the soil is often used to assess vine water status, but other instruments measure water fractions in volumetric terms (Table 7.1).

Evaporative demand is evaluated using one of two common methods. The Pan Evaporation method is a physical method where a change in water level is monitored physically of electronically. The integrated impact of wind speed, ambient temperature, relative humidity and solar radiation (collectively called the "evaporative demand") is observed regularly. Alternatively, weather stations recording the environmental components listed above can be used to compute the reference evapotranspiration. Reference Evapotransiptation is the evapotranspiration of an unstressed lucerne crop (alfalfa in the US) mowed and maintained at 10 cm. A range of computational methods exist, mostly based on the work of Penman (Penman

**Table 7.2** Minimum water allocation as a percentage of total water available to the manager

| Growth stage (Lorenz et al. 1995) | Minimum percentage allocation | Recommended soil water potential Ψ (kPa) for the implementation of RDI |
|---|---|---|
| Budburst to flowering | 9% | >−30 |
| Flowering to fruit set | 6% | >−10 |
| Fruit Set to veraison | 35% | −80 |
| Veraison to harvest | 36% | −80>Ψ>−200 |
| Harvest to leaf fall | 14% | >−200 |
| Dormancy | N/A | >−30 |

1948). The reader is directed towards the seminal work of the FAO (Allen et al. 1998), the ASCE (ASCE 2002) and the ITRC (Burt et al. 2002). In these methods, a reference (or the pan evaporation) is related to the grapevine water demand using crop based coefficients throughout the growing season. The difficulty in using these methods is the need to adjust the coefficients for site specific conditions such as the use of mid row swards, the density of planting or the ratio of exposed undervine bare soil. Typically, these methods are used for the creation of a water budget in order to evaluate soil water depletion, and therefore identify what fraction of the soil water reservoir the plant is extracting (Table 7.1). Water budgets can be "truthed" using a range of commonly available soil moisture monitoring equipment over the depth of the grapevine rootzone. Alternatively, irrigation can be driven directly using soil moisture sensors and the definition of thresholds based of the various soil fractions (Table 7.1) for a given soil texture. Of particular interest of growers operating in regions where irrigation water is scarce yet necessary, is water budgeting on the basis of the available water (such as water allocated via a commercial irrigation scheme and dam water) rather than that required in order to ripen the crop. The minimum water allocations are summarised in Table 7.2 (Beckingham et al. 2004).

Deficit irrigation strategies were developed to manage the growth of the canopy, based on the hypothesis that smaller canopies intercept more light, leading to better quality fruit with no or little impact on fruit yield (Kriedemann and Goodwin 2004; Smart and Robinson 1998).

Two irrigation strategies are currently the subject of much research, namely Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD). More strategies have been suggested in the literature, such as Stress Deficit Irrigation (SDI) but are not yet widely adopted.

## *Regulated Deficit Irrigation*

Applying deficit irrigation after berry set and until veraison limits shoot growth without limiting the number of berries per bunch, as this is determined at berry set (Hardie and Considine 1976). Berry size at harvest is however reduced as berries undergo a phase of cell expansion both before and after veraison (Coombe 1973).

The reduction in berry size is often beneficial for wine styles requiring a high skin/pulp ratio as is the case for some red wines (and to a much lesser extent for some white wines) when high colour and tannin levels are preferred. For most white cultivars as well as table grape cultivars, a reduction in berry size is however unwanted. Hardie and Martin (1989) recommended soil based water potentials for the implementation of RDI (Table 7.2).

Goodwin & Jerie (1992) added the following recommendations to accommodate the responses of different soils to the wetting/drying cycle in cool and warm climates for the veraison to harvest growth stage:

- In coarse textured soils, water should be withheld in the mid-zone of the grapevine root system until the soil water potential (measured using Gypsum blocks) reaches −100 kPa.
- Fine textured soils should permit drying of the mid-zone of the grapevine root system until soil water potential reaches −200 kPa.
- In either case, water is added to replace 25 % of the computed pan evaporation for the period of deficit irrigation. It was recommended that care should be taken to rewet a similar volume of soil each time irrigation is carried out to ensure that the wetting/drying cycle is applied to the same population of roots. Vineyard water savings were approximately 30 %.

## *Partial Rootzone Drying*

Partial Rootzone Drying (PRD) is a recent advance in irrigation management based upon the physiological response of grapevines to drought (Dry et al. 2000a). In PRD the root system is water fed using two independent delivery networks, virtually splitting the root system in two zones. Each zone is watered alternatively thus creating wet/dry cycles, thought to induce drought like response from the plant. Several authors reported a lower juice pH, an increase in berry anthocyanins, an increase in berry phenolics, a reduction in shoot growth, increased water use efficiency, equivalent yields to fully irrigated or RDI irrigation strategies (Dry et al. 2000a, b; Kriedemann and Goodwin 2004; Loveys 2000; dos Santos et al. 2003), even in very high yield situations (37 t $ha^{-1}$, Riesling) (Kriedemann and Goodwin 2004).

PRD vines are able to maintain a pre dawn leaf water potential similar to that of fully hydrated vines combined with stomatal behaviour similar to that of droughted vines. Under PRD, shoot growth and water loss are restrained by hormonal signals from the droughted roots while photoassimilation capacity remains relatively unimpaired. This physiological response was found to be temporary and cultivar dependent. After partial droughting of the roots for between 5 and 14 days, stomatal control returns to normal, i.e. stomatal conductance of water increases (Kriedemann and Goodwin 2004). The determination of the most appropriate wet/dry cycle length, perhaps as a function of evaporative demand, the ability to induce sufficient dryness, and the high cost of establishment therefore seem critical issues in regard to broader uptake of PRD by the grape and wine industry, both in Australia and abroad.

## Plant Based Indicators of Water Stress

There is an array of indicators available to commercial grape growers wishing to understand the water status of their vines for irrigation scheduling purposes. In most cases, these indicators are used in complement of soil based methods. Where soil based methods are excellent for coarse irrigation management, the nature of RDI and PRD clearly requires a fine tuning of the understanding of plant water status and response to irrigation.

## Leaf Water Potential

Leaf water potential $\Psi_{\mathrm{leaf}}$ is by far the most reported plant based water stress indicator reported in the literature and is usually measured using a pressure chamber (Waring and Cleary 1967; Scholander et al. 1965), although automated continuous data acquisition is also possible using thermocouple psychrometers (Loveys 2005).

A considerable amount of literature reports studies using the leaf as the preferred hydraulic component for determining plant water status. In grapevine studies, most of the work has used $\Psi_{\mathrm{leaf}}$ to characterise the degree of water stress and/or identify a threshold value for the onset of irrigation. The diurnal course of leaf water potential however typically displays a large variability (Loveys 2005) in particular, due to the rapid response by leaf water potential to environmental changes in low stress situations.

## Pre-Dawn Leaf Water Potential

This measure is now commonly accepted as an indicator of water stress (Carbonneau 2004 a, b; Yuste et al. 2004, 1999; Quereix et al. 2001; Medrano et al. 2002). During the night, hydraulic gradients at the soil/root interface decrease and stabilise at a value related to the soil water content. The vine's hydraulic system equilibrates and pre dawn leaf water potential can be used as a surrogate indicator of rootzone water status (Lebon et al. 2003; Riou and Lebon 2000) although not all authors are in agreement. Furthermore, the relationship between $\Psi_{\mathrm{PD}}$ and the soil water fraction is not linear, and its strength varies as a function of $\Psi_{\mathrm{PD}}$ (being weaker at values closer to 0).

## Xylem (Stem) Water Potential

Estimates of water potential in shoot xylem $\Psi_{\mathrm{xylem}}$ are achieved from leaf petioles after the leaves have been covered and bagged for at least one hour. This allows the xylem water potential of the leaf petiole to equalise with that of the shoot (Chone 2001). The use of xylem water potential (also termed stem water potential) over leaf

**Table 7.3** Summary of thresholds for various energy status measured using Pre Dawn water potential ($\Psi_{PD}$), midday leaf water potential ($\Psi_{leaf}$) and midday xylem water potential ($\Psi_{xylem}$). Modified from Ojeda (2007), Williams and Araujo (2002) and Carbonneau (2002)

| Stress intensity | $\Psi_{PD}$ (MPa) | $\Psi_{leaf}$ (MPa) | $\Psi_{xylem}$ (MPa) |
|---|---|---|---|
| Mild | −0.4 | −0.8 | −1.1 |
| High | −0.6 | −1.1 | −1.4 |
| Severe | −0.8 | −1.4 | −1.6 |

water potential is based on a stronger correlation with transpiration in cases of mild water stress. Such estimates are also less variable than those of $\Psi_{leaf}$ (Lopes 1999; Lopes et al. 1999; Silvestre et al. 1999; Sipiora and Lissarrague 1999; Flexas et al. 1998; Chone et al. 2000; Chone et al. 2001; Naor et al. 1997).

By contrast, Carbonneau et al. (2004) reported that $\Psi_{leaf}$ represented stomatal behaviour better than $\Psi_{PD}$ at lower values of $\Psi_{leaf}$. Both authors reported a gradient in measured xylem water potential along the shoot.

Table 7.3 compares the threshold values of the various expressions of energy status ($\Psi_{PD}$, $\Psi_{leaf}$ and $\Psi_{xylem}$) as reported in the literature. One must note that the relationship between $\Psi_{PD}$ and

## *Vapour Pressure Deficit*

Although not a plant based indicator, the measurement of VPD represents an alternative to estimating water use directly from stomatal conductance. The relationship between VPD and stomatal conductance reported in the grapevine literature may be linear (Williams and Baeza 2007) or curvilinear (Lu et al. 2003). The range of reported correlative equations suggests that these results are cultivar and site specific even in non limiting situations. A global relationship to reflect the degree of feed forward and feedback stomatal control should therefore be normalised for water stress level using $\Psi_{leaf}$ as an intermediate variable.

Various studies have used VPD as a predictor variable for the computation of the Crop Water Stress Index in grapevines with various degree of success (Riou and Lebon 2000; Anconelli and Battilani 2000).

## *Canopy Temperature*

A side effect of the necessary plant transpiration is the moderation of temperature in the canopy microclimate. Indeed, the state of the stomata can be derived mathematically when the canopy temperature and environmental parameters are known. Measuring leaf temperature became more convenient with the development of portable field radiometers. Reasons for the poor uptake of this technology have not yet been reported but this methodology suffers from the fact that errors can be introduced when measuring a surface's temperature including non transpiring tissue (soil, sky or wood) within the field of view of the device. Such errors are common when using a device with a small field of view. The principal advantage of the use of plant canopy temperature to estimate stomatal conductance is that an increase in leaf surface temperature reflects a physical change in stomatal opening regardless of the cause of the change (Cifre et al. 2005), which is not the case in the leaf water potential-stomatal conductance relationship. Canopy temperature can relatively easily differentiate between well irrigated grapevines and vines submitted to deficit irrigation. Clawson et al. (Clawson and Blad 1982) showed that leaf temperature variability within the field of view may be a more sensitive indicator of water stress than leaf temperature itself.

## *Micromorphometry*

Diurnal variation in water movement through the vine induces a temporary, reversible change in shoot and trunk diameter (Goldhamer et al. 2000). Measurement of such changes is termed micromorphometry, dendometry or phytomonitoring. The differential between the maximum and minimum trunk (or shoot) diameter is termed Daily Contraction Amplitude (DCA) or Maximum Daily Shrinkage (MDS). Although micromorphometry is reported as appropriate for irrigation scheduling in vineyards, Loveys (2005) noted the need for further improvements if growers are to take up the technology.

## *Leaf Area*

Grape leaf area was measured daily by Bindi et al. (2005), who found a close relationship between leaf area growth rate and soil water depletion, thus demonstrating the potential use of leaf area measurements for irrigation scheduling. Several researchers have found measurement of leaf area in the field, using allometric relationships, easy to carry out (Guisard 2004; Carbonneau 1976; Sepulveda and Kliewer 1983). This method is however limited to the phenological stages associated with leaf growth and could not be applied after veraison. Gómez del Campo et al. (1999) proposed that crop coefficients used in irrigation scheduling from evapotranspiration be formulated using measures of leaf area through the growing season. Long term studies would provide a methodology to engineer leaf area targets to match site specific evaporative constraints.

## *Carbon Isotope Discrimination ($\delta^{13}C$)*

Atmospheric $CO_2$ is mostly composed of $^{12}C$ (about 99 %) and $^{13}C$ (about 1 %) stable isotopes. The lighter and more mobile isotope $^{12}C$ is most abundant in opened stomatal cavities and is preferentially assimilated in the photosynthetic pathway.

When stomata close, $^{12}C$ is gradually depleted and $^{13}C$ is then assimilated. After veraison, sugars accumulate in the grape berry therefore providing a reservoir of $^{13}C$ representative of the level of stress-induced stomatal closure that occurred between veraison and harvest. When the $^{13}C$ to $^{12}C$ ratio is compared to a standard, the delta $^{13}C$ ($\delta\,^{13}C$) index can be computed from the work of Farquhar et al. (1989). Measurements are laboratory based and lack of automation. It is therefore difficult to envisage that this methodology will be used for irrigation scheduling without further technological development. The method is however highly correlated to water stress measured over long periods (Gaudillere et al. 2002) and is applicable to within vineyard discrimination of stress prone zones, precision vineyard management and the determination of vineyard hydrological "history" (Gaudillere et al. 2004; Gaudillere et al. 2002).

## *Canopy Management*

Grapevines have traditionally been cultivated using a self standing strategy and still are in many regions of the world. The move towards higher yields and lower planting densities resulted in the newly termed "big vine", requiring physical support via trellising. A debate is omnipresent in the industry over the relationship between yield and quality. It is believed that high quality fruit can only be produced from low yielding vines, although there is ample evidence that high yielding vines are able, when managed appropriately, to produce high quality fruit. The reality for vineyard managers however, is that vineyards produce fruit with respect to a set of standards and for specific wine markets. Even fruit for controlled appellations are required to display a range of specific characteristics. The role of vineyard managers is therefore to produce as much as possible of the fruit required and permitted by local regulations in order to maximise (and in some cases simply to generate) profit.

### Training, Trellising and Pruning

There is a very large range of trellis designs available to growers and the reader is directed towards the voluminous literature on this matter (Fig. 7.5). In particular, the work of Carbonneau in France (Carbonneau et al. 2007) and Smart in Australia (Smart and Robinson 1998). Of particular interest to vineyard managers is the relationship between the trellis system and the overall architecture of growing vines. The manipulation of the architecture of vines for the purpose of fruitfulness, fruit quality and foliage management is called canopy management.

Trellis design fall under three categories:

- Undivided with no foliage support
- Undivided with foliage support
- Divided with foliage support

**Fig. 7.5** Illustration of a range of training and pruning systems (**a**) Spur pruned bush vines (gobelet) in the Barossa Valley (Australia), (**b**) Bi lateral cane pruned in (cordon de Guyot) Bordeaux (France), (**c**) Lyre in California (USA), (**d**) Head trained, spur pruned in Asti (Italy), (**e**) Cordon trained, spur pruned, with minimum foliage support (Ozzie Sprawl) in Australia, (**f**) Vertical Shoot positioned in New Zealand

The division of foliage is required where vines display vigorous growth. Vigour may be induced by one or a combination of factors including genetics, rootstock, rainfall distribution, soil fertility or management practices. Large and vigorous vines require canopy division as well as foliage support for the purpose of appropriate light

**Fig. 7.6** Cordon trained 10 years old Riesling vine in the process of spur pruning to two bud spurs. Spurs are numbered to help visualise the process. From left to right, spurs 3, 4 and 5 were reduced from two canes to one cane, itself reduced to 2 buds. The lower cane is retained in order to control the excessive growth of the permanent spur over time

distribution within the canopy (in order to optimise carbohydrate production; promote colour development and promote fruitfulness) as well as air flow within the canopy to reduce the severity of diseases and facilitate spray deposits. The desired overall canopy shape, and in particular the permanent parts of the architecture is referred to as “training”. In mechanised areas, the shape of the canopy is limited by its compatibility with machine operations, and in particular (but not limited to) machine harvest.

Pruning is required annually for most training systems and is greatly reduced in vines grown in a mature “minimum pruning” system. Pruning is the action of removing unwanted woody material to prepare the vine for the onset of the vegetative growth of the subsequent year (Fig. 7.5). Pruning activities may range from hand pruning to totally mechanised hedge pruning. It is an important component cost in vineyard budgets and can occur over several months on large vineyards (Fig. 7.6).

Clearly, pruning is an important aspect of yield control. The number of buds left behind after pruning represents a permanent constrain on yield formation in a given year. For example, a 3 m row spaced vineyard, pruned at 15 buds per metres, with a historical fruitfulness of 1.8 bunch per shoot and historical fruit weight at 120 g per bunch will theoretically yield a maximum of 10.8 t per ha. Interestingly, yield components such as bunch and berry characteristics will have adaptive behaviour if the canopy architecture is modified from 1 year to another or even during a given season. As a result a change in bunch weight in the example above (after a particularly heavy or light pruning) may lead to a different yield. Similar, a change in bunch primordia initiation due to a departure from a canopy management practice may lead to a change in bud fruitfulness 2 years later.

## The Ideal Canopy

Smart (Smart and Robinson 1998) characterised canopies to create the “Winegrape canopy ideotype”. The score card clearly demonstrates the need to grow enough leaves to ripen a crop, but not in excess such that the fruit will be excessively shaded. Of particular importance to vineyard managers are vegetative characteristics such as recommended 12 $cm^2$ of leaf surface area per gram of fruit. This photosynthetic capacity is controlled by a recommended maximum leaf layer of 1–1.5 and a ratio of Leaf Area to Canopy Surface Area of 1.5. This clearly demonstrates that canopies increase in sizes as yield targets increase, but within limits. Similar, an ideal shoot would display an internode length of 6–8 cm, a shoot length of 90 cm with 10–15 nodes and displaying self termination at veraison. Shoots should be spaced at approximately 15 shoots per metre (equivalent to 13 cm spur spacing when training vines at two bud spurs). Most importantly, canes should weight 20–40 g and the ratio Yield to Pruning Weight should be maintained between 5 and 10.

The definition of this ideal canopy is contested by some managers and some components may require site definition or adjustment. Nevertheless, the creation of guidelines grounded in vine physiology have led to a generation of vineyard managers capable of describing canopies using a standardised approach and therefore benchmark against other regions, countries or competitors.

## *Diseases*

The main diseases of grapevines are caused by fungal organisms. Fungi are distinct from green plants in that they lack chlorophyll and are heterotrophic obtaining nutrients by absorption. We will discuss each of these diseases in turn. Many fungi are saprophytes (obtains nutrients from dead plant material) while a smaller number are pathogens (cause disease).

## *Grey Mould*

### Symptoms and Infection

Grey mould or Botrytis bunch rot is caused by the fungus *Botrytis cinerea*. As well as infecting grapevines, *B. cinerea* can attack a range of other horticultural crops and it can also grow well as a saprophyte on dead tissues (Elmer and Michailides 2004). So the fungus can be a pathogen or a saprophyte depending upon the conditions (Fig. 7.6) and (Fig. 7.7).

*B. cinerea* is normally associated with diseases of mature grapes where it causes grey mould in the post-veraison berry. It can however attack the vegetative parts of the vine and over-winter on dormant canes (Nair and Nadtotchei 1987). It also attacks grapevine flowers and management of grey mould in a vineyard includes spraying fungicides at flowering to prevent a build-up of the diseases that will cause problems at harvest. So this disease can cause a loss of yield by both infecting flowers and mature berries.

**Fig. 7.7** *Botrytis cinerea* (or grey mold) on a Chardonnay bunch. Note the various stages of infection along the bunch

Infection of grape berries by Botrytis frequently occurs when berries split in the bunch. Berry splitting can occur following heavy rain periods when there is a sudden uptake of water and also following other weather events, such as hail damage. Bird damage can also be a problem, in fact anything that breaks the skin of the berry can lead to bunch rot development. The skin of the berry is thus a natural barrier to infection, and once this is broken then berries are susceptible to disease. Berry splitting is common in grape varieties that have a tight bunch structure, Pinot noir is such an example, while bunches with a looser structure, e.g. Shiraz tends to get less Botrytis simply because berry splitting is less likely to occur. Another way in which this disease is spread is via the activities of an insect, larvae of the Light Brown Apple Moth (LBAM) which feed on the interior of the bunches. Aside from damaging tissue which allows for infection, it has been shown that the LBAM larvae can also carry fungal spores on their bodies, leading to disease spread.

Grey mould frequently occurs in regions of the globe where summers are cool and wet, moisture is important for growth of the fungus and the fungus tends to grow best around 25 °C.

### Impact on Wine

Aside from a loss of yield, the fungus produces an enzyme, called laccase and this can be a problem in red wine production, since laccase is an oxidative enzyme that can reduce the colour content of red wine. The fungus also converts the berry sugar (glucose and fructose) in to glycerol and produces a range of polysaccharides called glucans. Glucans are large molecular weight compounds that can cause problems when wine is filtered, causing blockages in the filtration process. As with most moulds the disease often imparts musty, mouldy characters on the wine (Steel et al. 2013).

### Control

Control of Botrytis is based on canopy management and chemical sprays. Closed canopies where the fruit is shaded and does not dry after rain is more susceptible than fruit in open canopies. Canopy management is thus a major tool used in the control of this disease (English et al. 1993). Use of chemical sprays is widespread, but this particular fungus is very adaptable to its environment and so resistance to many of the fungicides used to control Botrytis has developed (Latorre and Torres 2012; Leroch et al. 2011; Rosslenbroich and Stuebler 2000).

### Noble Rot

In some circumstances incidence of Botrytis on grapes is desirable (Thibon et al. 2009). If the fungus colonises the bunch at the end of the growing season in autumn, and if conditions are dry, then a type of rot occurs that is termed noble rot. Typically noble rot occurs in temperate climates where damp conditions occur early in the morning followed by warm afternoon sunshine. In this situation the fungus grows very slowly on the surface of the fruit without invading the tissue. The fungus dehydrates the fruit, concentrating the sugar and forms glycerol. Glycerol is a simple molecule that is viscous and enhances the sweet sticky characters of the fruit. Dehydration of the fruit can further be enhanced by wind. Typical varieties of grapes that are used for noble rot include Riesling, Semillon and Sauvignon Blanc.

## *Powdery Mildew*

### Symptoms and Infection

Symptoms of powdery mildew include a white fungal growth on the upper surface of vine leaves (Gadoury et al. 2001). Aside from affecting the leaves, powdery mildew can also occur on pre-veraison berries. As the berries mature post–veraison, earlier powdery mildew infections can result in scarring of the fruit (brown web-like markings). The disease is caused by the fungus *Uncinula necator* and is sometimes referred to as Oidium. The disease begins around bud burst on developing foliage, and if unchecked can result in a serious loss in photosynthetic function of the vine. Infected berries have a white covering of powdery growth. At the end of the growing season the disease over winters as specialised structures called *cleistothecia* in woody tissues such as the bark and dormant buds. These infected buds then give rise to more disease the following season after bud burst. The disease can develop under a range of environmental conditions. As with botrytis, the disease results in wine with mouldy fungal characters (Stummer et al. 2003). Powdery mildew is an obligate parasite, growing only on grapevine material.

### Control

Monitoring the vineyard is a key to the success of powdery mildew management. After budburst the vineyard manager should check flag shoots (young shoots with only one or two leaves expanded) for signs of powdery mildew infection. Fungicides for the control of powdery include chemicals that inhibit the synthesis of sterols, which are components of the fungal cell membrane. Without these sterols, the fungus is unable to function and dies. There are also a number of other chemical groups that are registered for powdery mildew control. These include the strobilurins (e.g. Cabrio) that interfere with fungal respiration. Sulphur based sprays are also effective and these have been used in viticulture for over a century. A strategy termed the '2:4:6 strategy' has been employed for powdery mildew control, where fungicides are applied at two, four and six weeks after budburst. Once powdery mildew is established in the spring, it can be difficult to eradicate.

## *Downy Mildew*

### Symptoms and Infection

Like powdery mildew, downy mildew also infects the leaves, but the symptoms are different. Downy mildew manifests itself initially as yellow oil-like spots on the upper surface of the leaf. Surrounding the oil spot there is often a darker halo, these spots will enlarge until they may eventually merge to cover the whole leaf. On the underside of the leaf there will be a white mildew of growth. Pre-veraison berries are also susceptible, infection results in an arrest in berry development.

Berries then stop growing and develop a purple colouration before dropping from the bunch. Downy mildew was first introduced to Australia in 1917 in Victoria, and then quickly spread to other areas. The disease is indigenous to North America and was probably introduced to Europe on phylloxera-resistant rootstocks. Like powdery mildew, downy mildew is an obligate parasite; it cannot be cultured in the laboratory on artificial media. Downy mildew is caused by *Plasmopara viticola* (Gindro et al. 2012) and strictly speaking this organism is not a fungus, it belongs to a group of organisms that are in the kingdom Chromista.

### Control

Monitoring the vineyard is important in downy mildew control. Infection is favoured when there is at least 10 mm of rain while the temperature is 10 °C or more over a 24 h period. This observation led to the development of a model known as the '10:10:24 model' to predict disease outbreaks. Many vineyards in downy mildew prone areas monitor the weather in order to predict likely disease outbreaks.

## *Phomopsis cane and leaf blight*

### Symptoms

Phomopsis cane and leaf blight was formerly known as dead arm, however there are a number of other diseases of vines that cause similar symptoms. The disease is caused by the fungus *Phomopsis viticola*, and it was thought that there were two types or strains of this fungus in vineyards, type 1 and type 3, which differ slightly in spore size. Recently type 1 has been renamed as *Diaporthe perjuncta*. *D.perjuncta* is now regarded as non–pathogen to grape vines and is present on vine material as an endophyte.

All green parts of the vine can be affected by Phomopsis, on leaves the fungus causes spots while on canes black lesions or scars form. These can become large, and in fact may girdle the shoot, which leads to death of the shoot. Alternatively as the shoot matures into a cane, it may snap-off in wind. The fungus over-winters on canes and spurs, which become bleached (have a white appearance). Eventually black speckles appear on the surface of the cane. These are fruiting bodies, termed pycnidia. The pycnidia contain fungal spores which are spread in rain splash and result in spread of the disease to new shoots in the spring.

### Control

For many years sodium arsenite was used to control phomopsis. Dormant canes used to be treated during the winter period, but these sprays are now no longer encouraged. One method of control is to ensure that planting material is free of disease, and vineyard hygiene during pruning is also important in preventing the spread of this and other wood diseases. Some common fungicides used to control Phomopsis include Captan, Dithianon and Mancozeb.

## *Other Vine Diseases*

### Fruit Rots

There are a range of other bunch rotting organisms that can occasionally attack the fruit (Table 7.4). Many of these are opportunistic pathogens, i.e. infect fruit that has been damaged or infected first by a primary invader, and some are important post-harvest rots. Post-harvest rots are of concern in table grape production, where the fruit might be in storage and transport for extended periods of time. Some examples of these rots are shown in the table below. All of these rots attack the post-veraison berry. In most cases little is known about these diseases.

**Table 7.4** Summary of Bunch rots relevant to grape growing

| Bunch Rot | Appearance/comments |
|---|---|
| Alternaria | Black. Frequent as a post-harvest rot |
| Aspergillus | Black. Some strains produce a toxin, ochratoxin. Ochratoxin is important because it is carcinogenic |
| Colletotrichum | Orange sporulation. Occurs mainly in sub-tropical vineyards. Common name—ripe rot |
| Greeneria | Black sporulation in rings around the circumference of the berry. Widespread in sub-tropical vineyards. Common name—bitter rot |
| Penicillium | Bluish/green mould. Frequently a secondary invader, occurring in split berries |
| Rhizopus | Dark black. Frequently a secondary invader, occurring in split berries and within the bunch |
| Sour Rot | Generally this bunch rot syndrome is caused by a mixture of yeasts, fungal saprophytes and growth of acetic acid bacteria. Watery berries smell of vinegar, with a dirty white to brown appearance. Sour rot generally occurs in ripe fruit (particularly white varieties) that has been damaged |

## *Other Diseases of the Vegetative Structures*

We have covered the principal diseases of grapevine foliage; however, there is one other disease of grapevine leaves that is worth mentioning. Black spot (anthracnose) is caused by *Elsinoe ampelina*. Use of the fungicide Ziram largely controls this disease in most vineyards. As the name suggests this fungus produces black spots on the leaves and also on fruit (Magarey et al. 1993).

There are a number of fungal diseases of the trunk and cane that can lead to a serious decline in the productivity of the vine. Often the only management option for these diseases is removal of the affected wood which should be subsequently burned, and possible re-grafting. Vineyard hygiene during pruning is important in preventing the spread of these diseases since they are transmitted through wounds. Some of the more important diseases include Eutypa die back and Botryosphaeria. Eutypa die back is caused by *Eutypa lata*, a fungus that produces a toxin eutypine, implicated in the disease. Symptoms of die back include stunted shoot growth and dead wood tissue extending back towards the crown of the vine. Symptoms of Botryosphaeria are similar to those produced by *E. lata* and it is difficult to distinguish the two diseases in the field. Botryosphaeria infection of grapevines is commonly referred to as Bot canker (Savocchia et al. 2007). There are a number of fungi that can also attack grapevine roots. Some of the more common ones are *Phytophthora cinnamomi* and *Amillaria* spp.

## *Diseases Caused by Bacteria and Viruses*

Microscopically bacteria and viruses are much smaller than fungi and their cell biology is very different. Crown gall is caused by the bacterium *Agrobacterium* *tumefaciens*. The trunks and other woody parts of infected vines have growths or galls at the site of infection. Pierce's disease (*Xylella fastidiosa*) is another bacterial disease worthy of mention, since it is not present in Australia but widespread in the USA. The disease is spread by various insect vectors and there is concern that this disease may be introduced into Australia in the future.

There are a number of viruses that will also attack grapevines; generally they result in distorted and discoloured leaves. The most common one is Grapevine Leaf Roll Virus (GLRV). There are five types, types 3 and 5 are the most prevalent in Australia. Typing is based upon the outer structure (protein coat) of the virus. The leaves of vines infected with GLRV have a bronzed appearance which may just be present around the edge of the leaf and generally does not extend the veined area. This leaf discolouration only occurs in the autumn; throughout the spring and summer leaves appear unaffected. Essentially leaves appear to senesce prematurely. GLRV reduces yields and can delay fruit maturity.

## *Pests*

### Light Brown Apple Moth

This moth attacks a wide range of fruit crops, damage to grapevines is caused by the larvae which feed on shoots and developing bunches. Larvae feeding on bunches facilitates bunch rot diseases, primarily *Botrytis cinerea* or grey mould (see above). The insect tends to feed on protected locations, e.g. with a compact bunch, which as discussed previously, will be more susceptible to fungal attack.

### Phylloxera

Phylloxera or *Daktulosphaira vitifolii* is a very destructive pest of grapevines, which nearly led to the collapse of grape growing in Europe after its introduction from North America. Phylloxera is an aphid that feeds on the roots of the grapevine. Despite the fact that this insect has been present in Australia since 1877, it is still confined to a relatively small number of viticulture regions. This has largely been due to quarantine practices that limit the movement of vine material between regions and also good vineyard hygiene.

### Nematodes

Nematodes are microscopic worm-like organisms that live in the soil and are sometimes referred to as eel worms. Many nematodes are saprophytes, feeding on dead tissue in the soil, while others feed on soil bacteria and even on other nematodes. A small minority of nematodes are parasitic for plant roots. There are three types that are important in viticulture, rootknot nematodes, the citrus nematode, lesion nematodes and Dagger nematodes. Nematode infestation can result in a slow decline in the productivity of the vineyard, vines can be stunted, unproductive and lacking in vigour. Control measures largely involve using rootstocks that are tolerant to nematode attack, although considerable research has been carried out on the use of cover crops (companion crops) in the inter row area. A number of plants belonging to the Cruciferaceae family (e.g. mustard, radish, canola etc) produce compounds in their roots that can inhibit the growth of nematodes. These natural nematicides are volatile, and so they may not remain in the soil. The technique is referred to as biofumigation.

Rootknot nematodes include four species of *Meloidogyne*, the most important being *M. javanica*. This nematode causes galls on grapevine roots which then become stunted which impacts on root function.

## Challenges and Opportunities in Viticulture

A range of challenges, but also opportunities are facing vineyard managers. Long term climate change has the capacity to modify the fabric of an industry built on traditions, perceptions and local education. On the other hand, the increasing mechanisation of vineyards and the use of precision viticulture management practices are likely to offer further control over the component costs associated with the production of grapes and wines for specific markets.

### *Climate Change*

Recent global climate monitoring and modelling (AR4) indicates that anthropogenic climate change has the potential to increase global average temperature by 1.5–6° (IPCC 2007) by 2100, with significant changes in the frequency and intensity of temperature extremes. Suitable sites for viticulture would therefore shift pole ward and in elevation (Hannah et al. 2013; Hall and Jones 2009; White et al. 2006). Global precipitation changes are less certain, although in general higher ocean and atmospheric temperatures are likely to encourage more intense rainfall events, and shift the distribution of rainfall. For example, strengthening of the mid-latitude high pressure belt, linked to anthropogenic climate change, has caused reductions in rainfall across much of southern Australian viticultural regions in recent decades (Steffen et al. 2013).

Significant atmospheric $CO_2$ enrichment should enhance biomass production although this response varies between species and C3 and C4 photosynthetic pathways. Experimentation on the impacts of combined temperature/$CO_2$ increases is still required to elucidate grapevine responses (Schultz and Stoll 2010). For improved modelling of grapevine responses to change, Global Climate Models (GCMs) need to be dynamically downscaled to resolutions more relevant to viticultural operations. For example, enhanced skill-selection of AR4 GCMs has produced more refined 2050 modelling for south eastern Australia (Pitman and Perkins 2008).

Some changes in viticultural phenological indicators have already been observed in response to recent climate changes. These include shifts in harvest dates in France (Schultz and Jones 2010), and in ripening profiles in Australia (Webb et al. 2011).

## *Summary of Potential Impacts*

Many of the general impacts of climate change would be common across all agricultural industries, including possible water deficits, heat stress, changed growing seasons and extreme effects such as hail, flooding and extended drought. The specific requirements of viticulture and the production of wine make it likely that wine quality will be influenced greatly by climate change (Jones et al. 2005), and include:

- changes in wine styles due to hotter conditions
- in extreme cases some varieties may become commercial unviable due to mismatching of variety and environmental conditions (terroir).
- direct heat stress, including increased leaf temperature, respiration shutdown, loss of crop
- impacts on grapevine phenology, eg. timing of bud burst, flowering, veraison, harvest.
- shortened growing seasons and earlier maturity (potential stylistic impacts)
- undesirable sensory characters in the grapes
- increased fire risk
- smoke taint from nearby fires
- changes in water availability
- increased need for irrigation inputs, hence increased cost of production
- increased risk of new suite of pests, diseases and weeds

## *Adaptation Solutions*

Viticulture is perennial and based around significant infrastructure such as trellising and irrigation. These restrictions govern long term climate change adaptation, and future vineyard establishment must now factor in projected changes in climate over the lifetime of the business. Current viticultural operations are usually well attuned to dealing with climatic variability (vintage conditions). Therefore adaptation to normal climate variability is a good indicator of how future vineyards will fare, although ultimately some critical threshold will likely be exceeded, which in the wine industry could be viticultural (eg. heat stress, water restrictions, pests and disease, reduced yields etc.), or oenological (eg. Shorter, hotter growing season leading to undesirable stylistic changes).

The first climate-induced impacts will affect wine styles, which can be manipulated in the winery to some extent. Viticultural practice can also be modified to buffer climate changes, including mulching to maintain soil moisture, introducing water use efficiencies by regular monitoring of soil water balance and irrigating accordingly, modifying trellising for better airflow. Eventually some threshold will be reached whereby it becomes too difficult to maintain a consistent product. At this point a grower may opt to change varieties to ones that are better adapted to hotter conditions. This would require a change in marketing strategy as well. The next threshold would be a wholesale change of location of the vineyard to a cooler site.

## *Summary of Potential Adaptation Options to Climate Change (With Increasing Level of Adaptation)*

- Canopy management to manipulate shading or exposure
- Cover crops, mulches or grassy swards to reduce soil and canopy temperature and improve soil structure
- Increase soil organic matter (nutrient buffering, soil water retention)
- Sprays to reduce heat stress
- Grafting new more resilient varieties or replacing with new varieties or wine styles
- Modified row orientation and spacing
- New vineyard establishment in (cooler) areas

## *Future Opportunities in Vineyard Management*

The most important opportunities in vineyard management relate to those attempting to reduce production costs, in particular using vineyard mechanisation. Indeed, there is now an increased reliance on mechanisation in countries where the cost of labour is high. Areas of current adoption and/or consideration for mechanisation include pre pruning, pruning, cane removal, de suckering, leaf removal, shoot positioning, wire lifting, netting, spraying, harvesting and weed control. It is possible to conceive that most operations in vineyard can be carried out using mechanical tools or at least, pre operation can be mechanised and only finished by hand. The design of "smart" mechanical tools is likely to benefit from rapid advances in robotics. Tools can now see, feel and make rapid decision, as evidenced in the Citrus and Apple industries. Some challenges still exist when handling complex and divided canopies as well as when carrying out delicate operations.

Another important opportunity for vineyard managers will be the capacity to carry out precision viticulture. This technology already allows for the selective management of vineyards (a common occurrence). It is of particular interest in variable vineyards in order to produce fruit of consistent quality. Irrigated vineyards were seldom designed such that irrigation blocks followed soil variability, resulting in vigour variability within blocks. As a result, precision vineyard management allows for the moderation of canopy variability via differential fertilisation, differential spray volumes and in some case differential irrigation. Multispectral imagery is also important for precision vineyard management as it permits the capture of large amount of data using land based or aerial (manned or unmanned) equipment. In particular, the specific surface properties of foliage and fruits allows for the rapid capture of plant based information (such as canopy volumes, canopy health, canopy temperature and fruit quality) allowing the manager to respond to changes in growing conditions.

Vineyard mechanisation and precision vineyard management suffer from the traditional problems associated with new technologies. They are relatively expensive, require new skills and may not carry out a task as accurately as a trained worker. Nevertheless, in line with much of current technologies and practices, those that will demonstrate a sustained positive contribution towards the triple bottom line of businesses or increase the resilience of vineyards against climatic challenges will be adopted.

## Wine Making

Figure 7.3 shows the normal production steps in red and white winemaking. There are obviously similarities between red and white winemaking, particularly in the early and later stages, but the major difference is that red wine production requires the extraction of red pigments (anthocyanins) and phenolic materials from the skins. This generally necessitates fermentation to be carried out “on skins”. In many white wine styles, extraction of phenolic material is often regarded as undesirable (eg crisp, aromatic wines such as Sauvignon Blanc or Riesling), however winemakers aiming to produce wine with a complex, textural mouthfeel may ferment with high amounts of solid material to obtain the desired phenolic level (Fig. 7.8).

### *Grape Receival*

Generally grape receival bins take the form of a V-shaped, stainless steel or epoxy-coated steel bin, with an augur in the bottom to deliver the grapes to the crusher. In larger wineries they are often constructed with the top of the bin at ground level to accommodate tip-trucks whilst smaller wineries typically utilise forklifts to empty individual fruit bins into a smaller receival or ‘hopper’ bin.

Wine styles that require low phenolic extraction (eg sparkling wine production) can be loaded directly into the press (discussed below) without being crushed or destemmed. Quality conscious wineries may also use grape sorting tables or automated sorting machines to help prevent diseased, unripe or matter other than grapes (MOG)

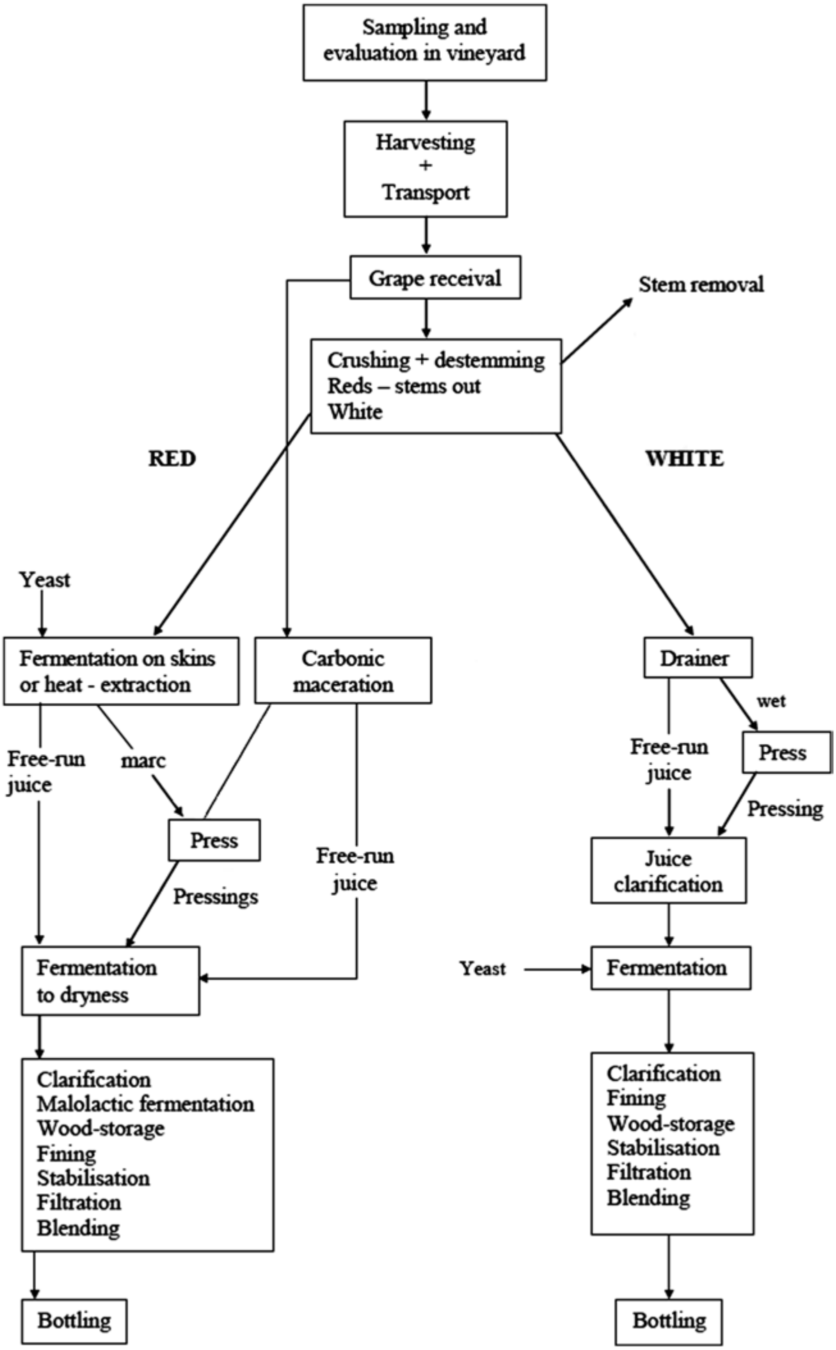


**Fig. 7.8** Summary of the winemaking process

## Crushing and Destemming

Destemmers consist of spirally-arranged, radial fingers which rotate in a holed cylinder and remove the rachis with remarkable effectiveness. Typically the stems to be discarded are collected in a bin or removed from the receival area using a conveyor system. The crusher is often incorporated directly under the destemmer and should break the berry skins with little pulping or other damage using a wringer or mangle action. After crushing, the must (a term used to describe crushed grapes), is pumped to the press (for white grapes) or directly to the fermentation vessel for red wine fermentation. Some red wines are produced using a whole bunch component (ie no destemming and crushing) to impart a stem and carbonic maceration character (see below) in the wine.

## Red Wine Fermentation

Some wine styles/varieties benefit from a "cold soak", where the must is usually chilled to a temperature whereby fermentation is inhibited. An addition of sulfur dioxide ($SO_2$) also helps limit microbial spoilage and oxidation. The majority of red wines produced in the new-world are inoculated with commercially prepared yeast, however indigenous yeast are often utilised to help provide a diversity of both flavours and textures. Other possible additions at the beginning or during fermentation include nutrient supplements, the most important being nitrogen and vitamins. These are added depending on the nutritional status of the juice and help prevent stuck/sluggish fermentation and prevent off aromas such as hydrogen sulphide production by yeast.

During red fermentation the skins form a dense 'cap' at the top of the vessel and most fermenter designs incorporate features to facilitate colour extraction from the cap and to separate the juice/wine and cap when sufficient colour has been extracted in the later stages of the fermentation. Specifically, the requirements for a red fermenter are as follows:

- for maximal colour extraction the cap should be kept submerged or percolated by the fermenting juice. Depending on fermenter type (open, closed, roto or red), heading down boards, manual or automatic plunging or punch downs, automatic or manual pump-overs or a technique referred to as rack and return can be employed.
- the fermentation temperature needs to be controlled, and in Australia this generally involves refrigeration to maintain the ferment at approximately 28–30 °C
- the juice should be easily run off at the end of the 'on skins' part of the fermentation;
- the wet marc (seeds and skins) should be easily removed for pressing.

## *Other Methods of Red Wine Production*

Fermentation on skins is the most traditional and still the most widely-used method for making red wines in most areas. However there are two other methods also worthy of mention.

## *Carbonic Maceration*

The most notable usage of carbonic maceration is in the Beaujolais area of Southern France where all red wines are made using this process. For true carbonic maceration, sound uncrushed clusters of grapes are loaded into a closed vessel (best results are obtained if the vessel has been pre-filled with carbon dioxide gas), and then left for 1–2 weeks during which the grapes respire any remaining oxygen and eventually 'drown' in carbon dioxide. The colour then permeates from the skin cells into the grape flesh, and there is also some alcohol production, loss of acidity and flavour production characteristic of the technique. The grapes are then removed from the tank and pressed, and the resulting red, partly-fermented juice is treated as any other juice/wine after pressing.

## *Heat Extraction*

The pigmented skin cells of red grapes release their colour into the juice of the grape when heated. A number of methods are used industrially to heat freshly-crushed red must and then to drain and cool the coloured juice which is then treated as a white juice.

## *Pressing of Whites and Reds*

In red winemaking, colour extraction is largely complete after 3–4 days of fermentation. After this period, extraction of phenolic material (which provide astringency and bitterness) is the most important reason to continue post ferment maceration. The winemaker must decide on the desirable amount of phenolic extraction and then the ferment is drained off as the 'free run' component. The remaining wet skins and seeds are transferred to the press, generally manually or directly into the press by gravity.

Basket presses. These are the oldest and simplest form of press still used, and consist of a basket of wooden slats seated in a steel juice-collecting tray. The wet marc is loaded into the basket and then compressed by a large plate which is forced hydraulically or by screw into the basket.

Horizontal screw presses. These presses work on the same principle as the screw-operated basket press except they are horizontal and more commonly manufactured from slotted stainless steel, with revolution of the basket the cake to be loosened between pressure applications.

Air bag presses. Marc is loaded through doors in the side of the basket, distributed evenly by rotating the basket and then pressed by inflating the bag. Because of the relatively short distance the juice has to travel to the basket only low pressures are required and the pressing action is gentler with less extraction of hard, bitter phenolics and oxidation can also be limited. Therefore these presses are excellent for white juice pressing, but are also quite suitable for reds.

Continuous screw presses. Marc is fed in at one end of a rotating screw which forces it through a slotted stainless cylinder against a weighted door. Continuous screw presses are mainly used in large, high throughput wineries for producing relatively low-priced wine.

## *Clarification of White Juice*

It is common practice to partially or completely clarify white juice prior to fermentation. The benefits of juice clarification include a more pure fruit flavour expression that is free from cardboard-like, 'solids' character. However highly clarified juice may cause slow and/or incomplete fermentation due to removal of certain yeast nutrients with the solids fraction. Thus, the desirable degree of clarification depends on the required balance of these factors. Often, full-bodied wines are made from less-clarified juice (e.g. Chardonnay, as its full flavour is not as easily dominated by 'solids' character), while highly-clarified juice is used to make light, clean, aromatic wines.

Following are brief descriptions of the main methods of juice clarification:

Settling. Over a period of approximately 24–72 h, the majority of grape solids will fall out of suspension due to gravity. The clarified juice can then be taken (or 'racked') from the above the settled solids, Juice is held in normal closed tanks at low temperature (desirably, less than 10 °C), with an addition of sulphur dioxide, to minimise wild yeast growth and the effects of oxidation. Pectolytic enzymes are also often used to degrade natural grape pectins that delay settling.

Centrifugation. Continuous centrifuges are often used in large wineries where their main advantage is continuous running with low labour requirements. Juice or wine is fed into the outside of a rapidly-spinning rotor and then 'up' the gravity gradient to the centre of the rotor. Because of their greater density relative to the juice, the solids 'settle' to the outside of the rotor and discharged.

Flotation. Flotation utilises the injection of gas bubbles (nitrogen is most commonly used) to the bottom of a tank containing juice. The bubbles carry suspended solids to the top of the tank where a foamy layer of suspended solids is formed. A gelatin fining agent is also usually used to facilitate this process. The clarified juice underneath is then be pumped into fermentation tanks.

Filtration. The most common form of filtration is the use of rotary drum vacuum (RDV) using diatomaceous earth. In general, filter pads do not have sufficient capacity for solids retention without clogging and so are seldom used. Recent developments include the use of cross flow filtration, a form of tangential flow membrane filtration, for clarification of juice in addition to final wine filtration.

## *Fermentation of White Juice*

Once the juice is clarified, it is fermented, often with a selected yeast culture, generally in a simple closed stainless steel tank. Most premium quality whites are generally fermented at low temperatures (10–15 °C) as high temperature may cause loss of desirable fruit flavour. Therefore under warm conditions refrigeration needs to be available either as in-place cooling plates or external heat-exchangers. In cool areas or with late season fermentations, the opposite problem may occur and fermentations may need to be warmed using the same types of heat exchangers and heated water. Fermentation in oak barrels is also carried out when oak influence is a desired part of the wine style. Fermentation can be stopped before completion in order to make sweet wines, by chilling the wine to the point where the yeast ceases to ferment and falls out of suspension

In many cases, after primary alcoholic fermentation has finished, the wine is racked of the yeast lees to prevent the uptake of flavours and aromas derived from the breakdown of the yeast cell wall. In other wines, the wine is deliberately left on the yeast cells and the breakdown of the yeast encourage by yeast lees stirring (or batonage).

## *Post Fermentation (Red and White Wine)*

Following primary alcoholic fermentation in nearly all red wine and many white wines, the process of malolactic fermentation (MLF) is either encouraged or discouraged. It is also possible to perform MLF during alcoholic fermentation, a process known as co-inoculation.

## *Malolactic Fermentation (MLF)*

Malolactic fermentation converts malic acid (derived from grapes) to lactic acid and is conducted by lactic acid bacteria.

- MLF improves the stability of the wine, because when all the malic acid is consumed, the wine will not undergo a further MLF in the bottle.
- MLF reduces the acidity, which can be an advantage in countries with wines of natural high acidity.

- MLF also contributes to increased flavour complexity.

In white wines where the fruit aromas are the most important aspect of the desired style, MLF can be inhibited by initially chilling the wine and maintaining a free $SO_2$ level of approximately 20–30 ppm to achieve a molecular $SO_2$ level of 0.5–0.8 ppm.

### *Storage and Maturation of Wine*

The main types of storage vessel are stainless steel tanks or a variety of different sized oak barrels. Oak barrels are used to import oak characters through lactones. Different oak characters may be delivered with the use of different toasting levels, sizes and types (eg French or American) of barrels. Stainless steel tanks are inert and help minimise oxidation to maintain the wine's fruit aromas. They also allow the following steps to be performed as necessary;

- Potassium bitartrate stability
- Protein stability.
- Other fining including the use of protein fining agents and copper sulphate.

These steps are outlined in "Wine Chemistry" (see below).

Bottling When the wine is ready for bottling it is fine-filtered, generally sterile grade using pads and/or membrane filters, and immediately filled into bottles or bag in box containers. A number of different types of fillers are in use for different applications. The most basic form is a simple syphon filler while more sophisticated machines fill under vacuum or under an overpressure of inert gas. Important aspects in bottling are the prevention of oxidation and the prevention of microbiological contamination by careful sterilisation of equipment and sterile filtration.

## Wine Microbiology

The production of wine from grape juice or must is fundamentally a microbial process. Grape juice and wine are largely inhibitory to the growth of most organisms due to the low pH and high osmotic pressures in juice and must, and high concentrations of ethanol in finished wine. Arising from these selective pressures, it is only highly adapted organisms that are capable of growth in grape juice, must or wine. Numerous microorganisms participate in the production process and may contribute in a positive or negative manner to the overall sensorial qualities of the end product. The impact of microorganisms upon the wine making process is summarised in Table 7.5. Unquestionably the most important microbial process in wine production is the bioconversion by yeast of fermentable carbohydrates glucose and fructose into ethanol. Yeast growth and metabolism also contribute significantly to the overall sensory properties of the wine. Yeasts are responsible for the conversion of certain aroma precursors to volatile compounds; metabolism of organic

**Table 7.5** The diversity of microorganisms in winemaking

| Microbial roup | | Representative organism | Significance |
|---|---|---|---|
| Fungi | Yeasts | Saccharomyces cerevisiae, Saccharomyces bayanus, Pichia anomala, Dekkera/Brettanomyces, Hanseniaspora uvarrum | Alcoholic fermentation; autolysis; sensorial modification to aroma and mouth feel. Production of spoilage caharacters |
| | Moulds | Botrytis cinerea | Contribute to the production of dessert style wines, imparting viscosity, sweetness and complexity. Spoilage of grapes by bunch rots |
| Bacteria | Lactic acid bacteria | Oenococcus oeni, Pediococcus spp. | Preferred organism for malolactic fermentation, contributes to improved sensorial attributes, deacidification, spoilage |
| | Acetic acid bacteria | Acetobacter aceti, Gluconobacter spp. | Production of off flavour and taint compounds |
| | Miscellaneous | Bacillus, Actinomyces, Streptomyces spp. | Production of taint compounds such as triichloroanisole |
| Viruses | | Bacteriophage | Inhibition of malolactic fermentation |

acids and formation of glycerol that elicits specific mouth feel qualities. Bacteria are also important micro organisms associated with wine production and contribute to the development of positive and deleterious aroma and mouth feel properties of wine. Yeast and bacteria may also contribute to wine spoilage and many facets of wine production are aimed directly at controlling unwanted growth of spoilage organisms (Schmidtke 2003; Iland et al. 2007). This section will present a brief synopsis of the production aspects of wine microbiology; for a discussion on wine spoilage by yeasts the reader is directed to the review by Malfeito-Ferreria (Malfeito-Ferreira 2011), and bacterial spoilage is presented in the paper by Bartowsky (Bartowsky 2009).

### *Yeast Growth*

Assuming grapes are of sound quality the growth of organisms within juice and must commences at harvest and the contribution of indigenous berry organisms to the sensory properties of wine is considerable. A plethora of organisms exists upon the berry surface and the reader is directed to recent reviews for further in-depth discussion (Barata et al. 2012). The yeasts involved in winemaking are limited by the environmental conditions associated with the product. Thus, while some species can be found on the grape, their presence in wine is dictated by their ability to survive the relatively harsh conditions of fermentation. Whilst fermentation commences with the indigenous yeast species, it is *Saccharomycecs cerevisiae* that completes the transformation of carbohydrate to ethanol. The evolution of yeast species during fermentation occurs in a reasonably predictable manner. Initial fermentative activity is mainly due to yeasts belonging to the genera *Candida*, *Pichia*, and *Kloeckera Hanseniapora* (particularly *Kloeckera apiculata*, or its perfect form *Hanseniaspora uvarum*) which may grow to levels of around 106–107 cfu/mL. However, as fermentation proceeds and the alcohol content of the wine increases, these yeasts begin to die and are replaced by strains of *Saccharomyces cerevisiae* which possess greater ethanol tolerance with cell concentrations for this organisms typically over 108 cfu/mL (Fleet 2003) during fermentation.

The growth of non-*Saccharomyces* yeasts will affect the chemical composition of the juice, and thus influence the final sensory quality of the wine. Firstly, these yeasts produce flavour and aroma compounds as a direct result of their metabolic activity. Secondly, the changes to the chemical composition of the juice as a result of their growth will influence the growth and metabolism of the succeeding generations of *S. cerevisiae*. For example, strains of *Kloeckera apiculata* can produce large quantities of acetic acid and ethyl acetate which impact the sensorial qualities of the wine and inhibit growth of *Saccharomyces*. Additionally, the growth of the non-*Saccharomyces* yeasts will reduce the amount of nutrients (carbohydrates, vitamins, trace elements etc) available for growth of Saccharomyces thereby adversely impacting growth of the desirable species.

## *Temperature Requirements for Growth and Fermentation Management*

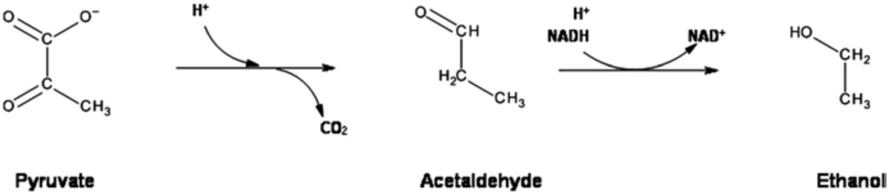
The growth and biomass production of yeasts during the initial stages of alcoholic fermentation is reliant upon the typical parameters that beset growth of any microorganism, i.e. adequate nutrient supply, suitable pH and optimum temperature. Frequently deficiencies of nutrients can be overcome somewhat by the addition of fermentation aids such as diammonium phosphate, yeast derived cell membranes and vitamins where specific food regulations permit the use of these supplements. In regards to winemaking decisions, the most easily controlled parameter that exerts a significant impact upon the growth and outcomes of fermentation is the regulation of temperature. *Saccharomyces cerevisiae* has a wide range of temperature in which it actively metabolises thus the manipulation of temperature during fermentation is important to enhance the final sensory qualities of the finished wine. Low temperatures of 10–15 °C support good growth on the non-Saccharomyces yeasts and growth of these organisms will increase the amounts of aroma-active compounds such as esters, higher alcohols and acetic acid. Temperature fermentations around 15 to 18 °C are favoured for the fermentation of white juices to preserve the more delicate varietal characters in these wines. During the fermentation of red grapes, increased temperature profiles of 25–30 °C during fermentation may be encouraged as this expedites the fermentation process and enhances extraction of phenolic compounds, including pigmented anthocyanins from the berry skin mass thereby producing wines with more intense colour. A most important consideration regarding temperature profiles of red ferments is to ensure that the maximum temperature achieved during fermentation does not exceed the threshold for cell membrane damage as this will lead to the potential loss of cytoplasmic constituents, which along with ethanol toxicity may lead to sluggish or stuck fermentations. Most red ferments are managed to ensure temperature do not exceed 30 °C (Fugelsang and Edwards 2007).

## *Ethanol Production*

The outcome of carbohydrate metabolism by yeasts during fermentation is principally ethanol. The conversation of fermentable carbohydrate proceeds by the glycolytic pathway common to all eukaryotic cells such that two molecules of pyruvate are formed from each molecule of glucose or fructose. During fermentation conditions rapidly become anaerobic and the production of ethanol by yeast is the fundamental driver for the continued production of energy from the glycolytic pathway. It is the production of ethanol concomitant with the regeneration of the electron transporting molecules NAD + from NADH that enables further energy to be produced to drive the cellular demands for biomass production. The net reaction of the glycolytic pathway is summarised below:

$$\text{Glucose} + 2\text{ADP} + 2\text{Pi} + 2\text{NAD}^+ \rightarrow 2\text{Pyruvate} + 2\text{ATP} + 2\text{NADH} + 2\text{H}^+ + 2\text{H}_2\text{O}$$

Conversion of pyruvate to ethanol proceeds via acetaldehyde with loss of a carbon moiety thereby producing carbon dioxide. This is shown in the following reaction:

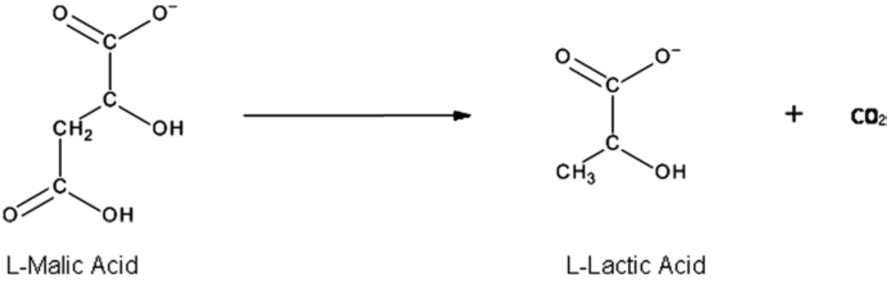


Thus Overall the conversion of glucose (or fructose) by yeasts to ethanol during alcoholic fermentation can be summarised as:

$$\underset{\textbf{Glucose}}{\mathbf{C_6H_{12}O_6}} \rightarrow \underset{\textbf{Ethanol}}{\mathbf{2C_2H_5OH}} + \underset{\textbf{Carbon dioxide}}{\mathbf{2CO_2}} + \underset{\textbf{Adenosine triphosphate}}{\mathbf{2ATP}}$$

## *Malolactic Fermentation*

The conversion of malic acid to lactic acid by *Oenococcus oeni* is often referred to as a secondary fermentation or malolactic fermentation (MLF), although in the strictest sense this is simply a microbial transformation as there are no direct energy production. Generation of a proton motive force across the bacterial cell wall does lead to energy formation and thus improved growth rates of lactic acid bacteria capable of conducting MLF in wine. The evolution of carbon dioxide during this process is likely to have been the catalyst for the misuse of the term fermentation as this mimics the evolution of gas during the alcoholic fermentation process. MLF is important in wines for several reasons; firstly it minimise the opportunity for microbial growth in wines post packaging as a substrate capable of use as a carbon source is removed; secondly the conversion of the diprotic malic acid to monoprotic lactic acid softens the acidity and enhances the textural mouthfeel aspects of wine; finally specific sensory notes such as buttery aromas may be imparted into the wine by the formation of diacetyl. This reaction is shown below:



Wine is an extremely harsh environment for bacterial growth and it is the highly adapted species of lactic acid bacteria with tolerance to low pH, low nutrient concentrations and high ethanol concentrations that manage to grow successfully in wine that complete the MLF. Whilst several species of *Lactobacillus, Pediococcus* and *Leuconostoc* have been reported to occur in wine, the preferred species for MLF is *Oenococcus oeni* due principally to the ability of many strains of this organism to grow without the production of off flavours in the wine. Numerous reviews on starter culture selection, conducting and the impact of malolactic fermentation and in wine are published and the reader is directed to these more comprehensive publications (Powell et al. 2005; Bauer and Dicks 2004; Zhang and Lovitt 2006; du Toit et al. 2011) to supplement information present here.

Traditionally MLF is encouraged in red and some white wines such as chardonnay and like alcoholic fermentation, winemakers may choose to use specific starter cultures to induce MLF in their wines. Starter cultures have advantages in that the organisms have well characterised attributes that confer tolerance to conditions prevalent in wine (low pH, nutrients, etc), nutrient requirements and impact on the sensory properties of the wine and these are traditionally added following the completion of alcoholic fermentation. However, even with the use of commercial starter cultures, delayed or stuck MLF can arise from poor or inappropriate nutrient management, the production of inhibitory compounds from yeast, or the extremely harsh physicochemical properties of the wine matrix. Timely completion of MLF enables more efficient winemaking practices and blending decisions to take place.

Problems may arise from late inoculation of starter cultures into wine for MLF. An unexpected temperature drop combined with nutrient depletion and high ethanol concentration can make the management of MLF challenging. It is not uncommon for wineries to have some wines that have not completed MLF prior to winter, and these must be left with low concentrations of sulfur dioxide until seasonal temperatures rise, which allow bacterial growth and metabolism to resume, or have expensive temperature control to ensure appropriate conditions conducive for growth of the MLF organisms. The cellaring of wines without adequate sulfur dioxide to prevent oxidation and limit growth of micro-organisms can be deleterious to wine composition, as spoilage organisms can commence growth along with *O. oeni* when warmer temperatures permit (Alexandre et al. 2004).

On the other hand, the growth of certain LAB, including *O. oeni*, early in the winemaking process is considered by some to be undesirable for wine composition. Increased acetic acid and D-lactic acid levels may arise from heterofermentative degradation of fermentable carbohydrates (Lonvaud-Funel 1999), hence the reluctance by some winemakers to use MLF starter cultures early in the winemaking process. Inhibition of bacterial growth by nutrient depletion arising from yeast metabolism may be augmented by the production of inhibitory excretory products of yeast growth, the most obvious being ethanol, sulfur dioxide, low molecular proteins and medium chain fatty acids (Comitini et al. 2005; Capucho and San Romão 1994). Several reports have recently described the microbial interactions of concurrent growth of *S. cerevisiae* and *O. oeni* in either model wines—wine made from white grape varieties or bench top vinifications (Jussier et al. 2006; Alexandre et al. 2004).

Loss of bacterial viability when MLF cultures are added during alcoholic fermentations has been reported, although successful MLF is still possible (Rosi et al. 2003). Yeast metabolic activity will be highest during fermentation, and it can be reasonably expected that production of inhibitory compounds such as ethanol and sulfur dioxide will be greatest at this time (Larsen et al. 2003). Ethanol has an inhibitory impact upon the growth of *O. oeni* at concentrations greater than 6 % v/v, although the effect is strain dependant (Henick-Kling 1995), hence an advantage of early inoculation with MLF starter cultures is the gradual acclimatisation of the bacteria to rising alcohol levels (Silveira et al. 2004), along with greater levels of organic acids, which improve ethanol tolerance (Zhang and Lovitt 2006). Medium chain fatty acids derived from yeast autolysis are generally higher in concentration if yeast lees are allowed to accumulate (Powell et al. 2005). Therefore, expeditious inoculation for MLF following completion of alcoholic fermentation is also warranted if winemaking practices prevent early inoculation.

The simultaneous inoculation of yeast and bacterial starter cultures for winemaking may not be a universally acceptable or a practical approach in the production

**Table 7.6** Concentration ranges of the major chemical constituents of dry wine

| Constituent group | Example | Concentration range |
|---|---|---|
| Major alcohols | Ethanol | 8–15 % (v/v) |
| | Glycerol | 0.3–1.4 % (v/v) |
| Organic acids | Tartaric acid | 1–6 g/L |
| | Malic acid | tr—8 g/L |
| | Lactic acid | tr—5 g/L |
| | Succinic acid | tr—1.5 g/L |
| | Acetic acid | tr—1.5 g/L |
| Sugars | Glucose | tr—5 g/L |
| | Fructose | tr—5 g/L |
| Phenolic compounds | Flavonoids | tr—4 g/L |
| | Anthocyanins[a] | 0–0.5 g/L |
| | Non-flavonoids | 0.1–0.5 g/L |
| Cations | Potassium | 0.5–2 g/L |

*tr* trace

[a] Anthocyanins are a sub-group of flavonoids

of all wine styles. Early completion of microbial wine fermentations is particularly advantageous in wineries located in cooler climates, in those wineries with limited facilities for temperature control of fermentation, and when the demands of winemaking require early blending decisions to be made, such as in the preparation of sparkling wine bases. Concurrent inoculation of MLF and yeast starter cultures or inoculation prior to the completion of alcoholic fermentation is now a common industry practise (Schmidtke et al. 2010)

## Wine Chemistry

The major components of dry table wines can be broadly categorised by the general groups outlined in Table 7.6. Of course the exact composition of wine will depend on a multitude of factors such as grape variety, vintage conditions, wine production techniques and wine age. Furthermore, the less concentrated components of wine that are at mg/L concentrations and below, can have a dramatic impact on the sensory appeal and hence commercial success of the wine. This is particularly the case for certain aroma compounds in red and white wines. This section will provide a broad description of the types and sources of compounds contributing to wine aroma, mouth-feel and red wine colour. This section will also outline the methods utilised to ensure that a wine will remain fault free for a suitable period of aging in the bottle, without the formation of colloidal material, precipitates or detrimental oxidation characters.

The aroma of a wine is an important feature of the finished commercial product. Certain wine styles have pronounced aromas associated with the grape variety and are commonly termed ‘varietal’ styles (such as Sauvignon Blanc), whilst others are more dominated by wine production aromas (i.e., yeast-derived and/or oak-derived)

**Table 7.7** The stages of aroma compound synthesis during wine production

| Stage of synthesis | Example[a] | Chemical class of example |
|---|---|---|
| Grape | Linaloo (fruity/floral) | Terpene |
| | Isobutyl-methoxypyrazine (capsicum) | Pyrazine |
| Crushing of grape | *trans*-2-hexenal (grassy) | Aldehyde |
| Yeast fermentation | ethyl octanoate (fruit) | Ethyl ester |
| | 3-methyl-1-butanol (banana) | Higher alcohol |
| | 3-mercaptohexanol (passion fruit) | Thiol |
| | 3-mercaptohexyl acetate (boxwood) | Acetate |
| Oak maturation | Furfural (almond) | Furfural |
| | Vanillin (vanilla) | Volatile phenol/aldehyde |
| Wine aging | TDN (kerosene) | $C_{13}$ compound |
| | Sotolon (maple-syrup) | Furanone |

[a] Typical aroma note parenthesis

and are termed 'non-varietal' styles (Chardonnay). The compounds contributing to the aroma of wine may be sourced from a variety of stages throughout the wine production and aging process. This includes compounds generated biosynthetically in the grape, during grape processing, during primary and secondary fermentation (MLF), and then those compounds extracted into the wine during maturation in oak, and chemically evolving during the aging of the wine in bottle (Table 7.7). There is commonly overlap between these sources, for example, precursors to aroma compounds may be formed in the grape and converted to active aroma compounds after a later wine production step. An example is the passionfruit aroma in Sauvignon Blanc that arises predominantly due to 3-mercaptohexanol. This compound in its free aroma active from is largely absent in the grape but instead exists bound either to an amino acid (cysteine) or a tripeptide (glutathione). During yeast fermentation a portion of the bound form can be biosynthetically released into the free aroma active form (Ribéreau-Gayon et al. 2006).

For many aroma active compounds in wine, flavour thresholds have been determined that indicate the concentration above which the compound is generally detected in a wine. However, certain compounds exhibit synergistic influences on wine aroma when in combination with other aroma compounds despite being below there specified aroma thresholds. Furthermore, at high concentration the aroma note (or flavour) of the compound may change and become undesirable or simply overpowering. Methoxypyrazines are biosynthetically generated in the grape, accumulating in the pre-ripe phase of the grape development, and impart a capsicum/bell pepper aroma to wine. While this character may be desirable in certain wine styles, consumers generally do not appreciate wines high in this character, especially with the related unripe aroma characters that accumulate in the pre-ripe grapes.

The phenolic compounds extracted from grapes contribute to the sensations of bitterness and astringency of wine and also contribute to the colour of wine. The phenolic compound will contain at least one chemical phenolic group ($C_6H_5OH$)

consisting of a benzene ring ($C_6H_6$) with a hydroxyl group (-OH) substituted for one hydrogen atom. A compound with more than one phenolic group is termed a polyphenolic compound.

As indicated in Table 7.6, and described in the Wine Production Section, the concentration of phenolic compounds is typically higher in red wines compared to due to the extended extraction from skins in red wine production. The phenolic compounds in wine are often classified as flavonoids or non-flavonoids. Given that non-flavonoids are mainly located in the pulp of the grape, white wines contain mainly this component of phenolic compounds and only minor amounts of flavonoids (Table 7.6). Alternatively, red wines will contain similar non-flavonoid levels as white wines, but g/L levels of flavonoids extracted from the skin and seeds of the grape. The non-flavonoid concentration of the wine may be supplemented by extraction of phenolic compounds from oak, and both flavonoids and non-flavonoids may be supplemented by endogenous additions during wine production. Within the group of flavonoid compounds are anthocyanins and tannins (i.e., flavonoid polymers) that impart the colour of red wine and contribute to the astringency of wine, respectively. The monomeric and lower molecular weight flavonoid polymers are suggested to be important contributors to bitterness sensation in wines, and tannins of 'medium' length contributors towards astringency, however much debate still occurs on the type, range of sizes and confirmation of tannin that are most important for astringency (Scollary et al. 2012). Current research is focused on better understanding astringency mechanisms and linking wine tannin structure to viticultural parameters.

To modulate the perception of bitterness and astringency, soluble or insoluble proteins are added to wines and are termed 'protein fining' agents. The proteins are able to interact with phenolic material and ultimately lead to the aggregation and precipitation of a fraction of the phenolic material which is then removed by settling and/or filtration. This alteration of the phenolic composition of the wine leads to dramatic changes in the astringent/bitterness profile of the wine. Due to the variable composition of both the wine and the protein fining agents, the action of the fining agent is difficult to predict and small scale trials are usually conducted to ascertain the most suitable fining agent and the addition rate. Over addition of protein can cause a detrimental loss of aroma compounds and result in an unbalanced wine. The source of the protein material added to the wine is mainly animal-based (gelatine, isinglass, egg white, milk/casein). Insoluble synthetic polymers (polyvinylpolypyrrolidone, PVPP) have been developed that allow also modification of the phenolic profile of a wine (Sims et al. 1995).

Red wines typically have only trace levels of residual proteins present due to their high concentration of phenolic compounds, which induces the precipitation of grape-derived proteins after crushing and during fermentation. However, white wines with lower phenolic concentrations can have significant concentrations of protein remain in the wine. This protein may stem from fining additions or derive from the native protein of the grape. During storage of the wine in the bottle, a fraction of the protein can aggregate and form a haze in the white wine, which is considered a fault by consumers. To avoid this haze formation, white wines are commonly treated with a volcanic clay mineral (bentonite) that is efficient in exchanging cations such as sodium and calcium ions for the positively charged sites of proteins. Once attached to the bentonite mineral the suspended bentonite settles and the wine is decanted from the bentonite/protein sediment. Alternatives to bentonite have been sought, as high rates of benonite can be of detriment to sensory features of the wine, and the use of bentonite requires a variety of processing steps for the removal of the deposited sediment. One recent approach has been the use of a specific enzyme for the degradation of targeted proteins that have been identified as key instigators in the haze formation (Waters et al. 1995).

Another detrimental phenomenon that may occur during the bottle aging of wine is the precipitation of salt crystals. The most common precipitate in this regard is due to potassium hydrogen tartrate crystals. The formation of such crystals does not tend to impact the organoleptic qualities of the wine but they are considered highly undesirably by consumers. To prevent the crystal formation during bottle aging, the crystal formation is induced during the wine production process. The most common approach is the chilling of wine to 0–4 °C or lower, with the addition of potassium hydrogen tartrate crystals to aid crystal growth, for extended periods and then removal of the resulting precipitate from the wines. Such a chilling step can contribute significantly to the energy costs of wine production and consequently alternative treatments have been proposed, including techniques such as electrodialysis, ion exchange and reverse osmosis (Low et al. 2008). Although these alternate techniques can significantly reduce energy costs, it ultimately comes at a cost of some other production parameter (i.e., additional processing steps, increased labour costs, elevated water usage and/or excessive wine losses (refer to Low et al. (2008) for further comparisons)).

Stability against oxygen during wine storage is of crucial importance to red and white wines. The dissolved oxygen in wine reacts with phenolic compounds to generate products capable of changing the colour and flavour of wine. Sulfur dioxide is the key preservative to prevent the detrimental reaction induced by oxygen, as well as its ability to inhibit microbial growth. Sulfur dioxide, equilibrates between molecular sulfur dioxide ($SO_2$), hydrogen sulfite ($HSO_3^-$), and sulfite ($SO_3^{2-}$) at wine pH, with the hydrogen sulfite form dominating (i.e., 80–90 %). All these forms of sulfur dioxide in wine are termed 'free sulfur dioxide', whilst the component that reversibly binds to aldehyde and ketone compounds present in wine is termed 'bound sulfur dioxide'. The free sulfur dioxide in wine can efficiently scavenge the oxidation products formed by molecular oxygen and phenolic compounds before any significant impact occurs to wine. The ability of sulfur dioxide to perform this role in red wine is complicated by the ability of the anthocyanins in red wine, responsible for the red colour of grapes and young red wines, to reversibly bind to sulfur dioxide. Consequently the concentration of sulfur dioxide in red wines cannot be maintained at concentrations as high as in white wines without the removal of significant colour in red wines. During time the anthocyanins in red wine become incorporated into polymeric phenolic compounds (i.e., via reactions with other phenolic compounds) and as a result they become less reactive to sulfur dioxide.

After the bottling of wine the concentration of sulfur dioxide typically decreases as oxygen trapped in the bottle (termed 'total packaged oxygen' is consumed). Recent advances now allow the measurement of the total packaged oxygen which consists of oxygen dissolved in the wine after bottling as well as oxygen trapped in the headspace of the wine bottle (i.e., between the surface of the wine and the bottle closure). After the total packaged oxygen is consumed by the bottled wine, it is oxygen permeating through the bottle closure that leads to a decrease in sulfur dioxide, and this oxygen permeation rate will depend on the bottle closure utilised. Such closure include traditional cork closures, synthetic closures, technical closures (i.e., re-amalgamated cork), and screw cap closures. The latter two closures tend to have more global reproducible oxygen permeation rates, which are also often lower than that for the former two closures. Current research is investigating optimum oxygen permeation rates through closures for given styles and/or varieties of red and white wines (Dimkoou et al. 2011; Lopes et al. 2009).

## Conclusions

The grape and wine industry is grounded in interdisciplinary science. This chapter is a broad overview of the skills required for the production of high quality fruit and wine for specific markets. For deeper knowledge, the reader is directed towards the voluminous literature on viticulture and wine science in English, French, German and Spanish.

The production of wine is paved with challenges, but the industry has a long history of applied research and innovative solutions. The depth and breadth of research, extension and corporate knowledge is the scaffold for a successful transition towards a new industry. China will be an important market for export for some time but will acquire the structural and intellectual winemaking capacities in due time. In the meantime, the global and competitive nature of this value added agro industry will continue to drive pressure on the production costs for what is essentially a luxury product. As a result, viticulturists and winemakers will continue to require advanced training and skills in order to remain competitive.

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# Chapter 8
# Plantation Crops

Yan Diczbalis, Jeff Daniells, Smilja Lambert and Chris Searle

**Abstract** Plantation horticulture is an important part of the economic landscape of many tropical countries. Plantations were developed in association with colonial expansion and the original models were based on the production of monocrops which had a ready export market, using cheap or slave labour. Plantations in the twenty first Century are less likely environments for exploitation of human and environmental capital. They are however, linked to crop production on a large scale for produce to be sold, at profit, for export to distant markets rather than local sale. A range of crops can be broadly categorized into plantation crops. Plantations continue to be effective models for efficient agricultural production and will evolve in response to the continued demand for food, fruit, fibre, oil crops and timber from a growing population.

**Keywords** Plantation · Crop categories · Cocoa · Banana · Macadamia

## Introduction

The word "plantation" evokes images of hot humid locations, far from the highly urbanized communities most of humanity inhabit, producing the necessities of domestic life such as tea, coffee, sugar, spices, and industrial crops such as rubber and

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cotton. The strains of a gospel song are linked with images of slaves picking cotton or cutting sugarcane in the southern USA during the mid 1800s. Similar examples existed throughout the colonial empires in the Caribbean, South America, Africa, India and Australia. The word plantation is linked with colonialism, exploitation of human capital and environment.

The term “plantation” is broad and ill defined yet the essential ingredients of the plantation include;

- commonly owned by local wealthy families or foreign owned,
- a monocrop made up of an industrial, food, fibre or beverage crops,
- located in the tropics ideally suited to the climatic requirements of the crop,
- large production areas,
- low cost, or at times in history no cost slave labour, which allowed for the production of goods at relatively low cost and maximisation of profit.

Definitions for plantations abound and crops included are; bananas, cocoa, coconuts, coffee, cotton, hemp, jute, oil palm, pineapple, rubber, sisal, sugar cane, tea and tobacco (Courtenay 1965; Stephens et al. 1998; Hartemink 2005). The annual production and area under cultivation of these crops is a challenge to accurately quantify. The Food and Agriculture Organisation (FAO) collects and presents data, with qualifications, on its FAOSTAT website. Areas of production and yield data, for 2010, are presented in Table 8.1 (FAOSTAT). Coffee, coconut and oil palm each have production areas which exceed 10 million hectares (Mha), while the area under sugar cane exceeds 23 Mha. The economic value of plantation crops is considerable. Most plantation crops are produced in developing countries located through out the tropical regions of the world. The economies of many developing countries are highly reliant on crop production with plantation crops being prominent amongst them. The world top five producers of palm oil are Indonesia, Malaysia, Thailand, Nigeria and Colombia. The coconut industry is predominately based in developing countries with Indonesia, Philippines and India accounting for 37, 21 and 12.5 % of the value of production respectively. Agro-industrial plantation crops such as cotton and sugar are also important income sources for developed nations. The USA and Australia rank 4th (US$ 5,432 M) and 5th ($US 4,068M) respectively for the value of cotton lint production and 8th (US$ 1142 M) and 10th (US$ 798 M) respectively for the value of sugarcane production. China ranks 1st for value of production of sugarcane and cotton lint producing US$ 31,128 M and US$ 9,700 M of raw product respectively (FAOSTAT).

## Plantation Crop Categories

Plantations in the 21$^{st}$ Century are less likely environments for exploitation of human and environmental capital, although the potential still exists. They are however, linked to crop production on a large scale for produce to be sold, at profit, for export or distant markets rather than local sale. A range of crops can be broadly

**Table 8.1** Plantation crop production, harvested area and average yield adapted from FAOSTAT 2010a[a]

| Crop categories and crops | World production (tonnes) | World area harvested (ha) | Average yield (Hg/Ha) | Average yield (t/ha)* |
|---|---|---|---|---|
| *Beverages* | | | | |
| Coffee green beans | 8,228,018 | 10,234,363 | 8,040 | 0.80 |
| Cocoa beans fermented dried | 4,187,587 | 9,541,698 | 4,389 | 0.44 |
| Tea—manufactured | 4,483,954 | 3,130,566 | 14,323 | 1.43 |
| *Sugar* | | | | |
| Sugarcane raw | 1,711,087,173 | 23,877,378 | 716,614 | 71.66 |
| *Spices* | | | | |
| Nutmeg mace cardamom | 59,198 | 260,964 | 2,268 | 0.23 |
| Pepper sp. | 426,925 | 557,057 | 7,664 | 0.77 |
| Vanilla | 6,680 | 72,512 | 921 | 0.09 |
| Cloves | 135,887 | 533,085 | 2,549 | 0.25 |
| Cinnamon | 202,299 | 209,470 | 9,658 | 0.97 |
| Spices nested | 1,985,226 | 936,257 | 21,204 | 2.12 |
| *Fruit* | | | | |
| Banana | 102,028,171 | 5,014,058 | 203,484 | 20.35 |
| Plantains | 36,387,578 | 5,407,363 | 67,293 | 6.73 |
| Mangoes, mangosteens, guavas | 37,124,742 | 4,946,313 | 75,055 | 7.51 |
| Pineapples | 19,408,581 | 879,175 | 220,759 | 22.08 |
| Citrus Fruits, nested | 11,776,311 | 1,264,642 | 93,120 | 9.31 |
| Papaya | 11,568,346 | 433,057 | 267,132 | 26.71 |
| Avocadoes | 3,891,626 | 462,662 | 84,114 | 8.41 |
| Tropical fresh fruit nested | 18,484,427 | 2,492,813 | 74,151 | 7.42 |
| *Nuts* | | | | |
| Almonds with shell | 2,556,816 | 1,684,746 | 15,176 | 1.52 |
| Brazil Nuts with shell | 99,917 | 640 | 1,561,203 | 156.12 |
| Cashew nuts with shell | 2,757,598 | 4,715,046 | 5,849 | 0.58 |
| Walnuts with shell | 2,555,090 | 844,162 | 30,268 | 3.03 |
| Nuts nested | 807,005 | 574,381 | 14,050 | 1.41 |
| *Oil, fibre and rubber* | | | | |
| Coconut (fresh, copra and dried) | 59,421,273 | 11,376,698 | 52,231 | 5.22 |
| Oil palm fruit | 217,925,795 | 15,410,262 | 141,416 | 14.14 |
| palm oil | 43,573,470 | na | na | na |
| Cotton lint | 23,295,107 | na | na | na |
| Fibre crops nested | 312,840 | 361,608 | 8,651 | 0.87 |
| Natural rubber (dry weight of latex) | 10,004,206 | 9,624,577 | 10,394 | 1.04 |

[a] Calculated by conversion from Hg/ha

**Fig. 8.1** **a** Tea plantation recently harvested by machine, Malanda, Queensland. (©Drinnan). **b** Mechanical coffee harvesting, Atherton Tableland, Queensland. (©Drinnan)

categorized into plantation crops. These can be further categorized as beverage, spice, sugar, fruit and nuts; oil and biofuel, and fibre and industrial crops.

## *Beverage Crops*

Beverage crops, chiefly tea, coffee and cocoa, became rapidly industrialised from the nineteenth century.

Tea (*Camellia sinensis*), native to northern Myanmar and southern Yunnan province in China (Purseglove 1968; Eden 1965) was cultivated in south east China for 2 to 3 millennia in the WuYi mountains in Fuzian province China prior to the plants distribution to other growing regions. The story of how tea departed China for north east India with the aid of the British botanist, Robert Fortune (1812–1880) in 1848, is enjoyably told by Rose (2009). Once tea was established in India by the East India Company, the commercial stranglehold the Chinese had on the tea trade was broken. Successful cultivation and production of tea depended on cheap labour for hand plucking the fresh shoots required to make tea. Tea plantations spread from India to the colonial Malaya with production in the Cameron Highlands and then Tanzania, Kenya, Indonesia and Russia. Newer centres of production include Australia (Drinnan 2008), particularly following the development of mechanical harvesting (Fig. 8.1a). However, purists argue that the finest boutique teas are still picked by hand.

Coffee (*Coffea arabica*), native to the highlands of Ethiopia where it occurred naturally in forests at altitudes between 1,200 and 2,000 m, was reportedly introduced to Arabia by the fifteenth century (Haarer 1962). Coffee spread rapidly via colonialisation (England, Dutch, French, Italian, Belgian, Germans and North Americans) but is now produced dominantly by independent countries in Latin America (Topik and Clarence-Smith 2003; Bigger 2006). The labour intensive nature of picking coffee berries lead to plantation production methods. The development of coffee harvesting machinery lead to expansion of the industry and the development of boutique coffee production in high cost labour countries such as Australia (Fig. 8.1b).

**Fig. 8.2** Low intensity and intensive vanilla production, Vavau Island, Tonga. (©Diczbalis)

Cocoa (*Theobroma cacao*), native to the Amazon basin and cultivated by the Aztecs as far north as southern Mexico, was brought back to Europe by the Spanish (Wood and Lass 1985). Further reference to cocoa and its evolution as a commercial beverage plantation crop is presented in detail as a case study, later in the chapter.

## *Spice Crops*

Although much of the world's spice production is supplied by smallholder growers, the crops are considered to be part of the plantation category. The Journal of Plantation Crops covers all the major spices. Spice production is often carried out as an intercrop with coconut (Newman 1985; Liyanage et al. 1986).

Major historical events were driven by the spice trade (Milton, 1999; Hemphill 2000). Spices naturally distributed throughout the tropical latitudes were rapidly "plantationised" by colonial powers following growing demand from European and British consumers who cherished the fragrant properties of spices to enhance the culinary properties of unrefrigerated meat and food (McGee 2004). Commonly used spices include cardamom (*Elettaria cardamomum*), chilli (*Capsicum spp.*), cinnamon (*Cinnamomum zeylanicum*), cloves (*Syzygium aromaticum*), ginger (*Zingiber officinale*) nutmeg (*Myristica fragrans*), pepper (*Piper nigrum*), turmeric (*Cucurma longa*), and vanilla (*Vanilla planifolia*). A number of spices are reported to have medicinal properties, chief amongst them turmeric which reportedly could clear plaque deposits associated with Alzheimer's disease (Barry 2007). Major centres of spice production include India, Indonesia, Malaysia, PNG and Pacific Islands, Central America and tropical Africa. Boutique industries for pepper and vanilla can be found in Hawaii, Papua New Guinea and far north Queensland, Australia. Intensive methods of production are gaining a foothold in developing countries, as is the case for many plantation crops (Fig. 8.2).

**Fig. 8.3** Mechanical harvesting of sugarcane. (©Diczbalis)

## *Sugar*

The discovery of sugarcane (*Saccharum officinarum*), a tall clumping grass, is thought to have originated in the tropical regions of the western Pacific (Barnes 1953; Barlow et al. 1991). The spread of sugarcane initially occurred to southern China and India and then made its way from Persia (Iraq and Iran) to the Mediterranean, north Africa and Egypt. Sugarcane reached Spain in the eighth century and was widely cultivated in southern Spain during the early twelfth century (Mangelsdorf 1950; Sharpe 1998). Columbus is credited with introducing sugarcane to the islands of the West Indies in 1493 where it spread to the southern USA, and to Central and South America. Brazil is the largest producer of sugarcane with 9.8 Mha in production in 2010 producing 660 Mt (Barros 2010). The evolution of sugarcane production is closely linked to slavery and/or indentured cheap labour due to the requirement for hand planting, cultivation and harvesting. Sugarcane was first introduced to Australia by the First Fleet in 1788. The first viable cane production was recorded near Brisbane, Queensland in 1862 and shortly thereafter indentured labour was imported from the Pacific. A reported 62,500 labourers were imported over the next 40 years until 1904 when the Commonwealth of Australia banned the practice (Irvine 2004). Following the repatriation of indentured workers from 1906, sugarcane production and processing was carried out by higher paid Anglo–Celtic and European labour. This resulted in the rapid mechanisation of the industry with Australian producers leading the development of mechanical harvesting (Griggs 2011). Sugarcane harvesting is primarily mechanised in the major producing countries but still relies on low cost labour in south Asia, India, Central and South America and the Pacific.

Mechanised cane harvesting has contributed to a substantial reduction in pre-harvest burning, necessary when hand harvesting sugarcane (Fig. 8.3). Pre-harvest burning contributes to air pollution through the emission of particulate matter and greenhouse gases (França et al. 2012).

## *Oil and Biofuel Crops*

There are a wide range of oils produced from crops which include castor oil (*Ricinus communis*), coconut oil (*Cocos nucifer*a), cotton seed oil, shea butter (*Vitellaria paradoxa*) and oil palm.

Oil palm (*Elaeis guineensis*), native to West Africa, is the major source of cooking oil produced from processed kernel and mesocarp of this monecious palm. It accounts for 60 % of the traded vegetable oil. Oil palm is a tropical species and, as such, production occurs throughout the tropical regions of the world. World production in 2010 was estimated at 217.9 Mt produced from 15.4 Mha (Table 8.1). Indonesia and Malaysia are the major producers, followed by Nigeria and Colombia (Anon 2011; Soh et al. 2008). Additional production occurs in a number of West African countries, Central America and Brazil. Smaller production areas occur in Thailand, China and the Philippines. The bulk of consumption occurs in China, India and Europe. Oil palm is the quintessential plantation crop (Verheye 2010). The vast bulk of production occurs in the developing world where low wages allow for a large labour force and hand harvesting. Plantations in Indonesia and Malaysia vary in size, often as large as 5,000 ha with production feeding a central processing plant. Oil palm production is controversial with reports of destruction of virgin rainforest, environmental degradation and relocation of native communities by government sanctioned development projects (Colchester et al. 2007; McCarthy and Cramb 2009; Wilcove and Koh 2010; Irawan et al. 2011). Oil palm is also produced as a biofuel in some locations; however the high value of the oil for food production currently makes this economically unsound.

Coconut (*Cocos nuciferia*), the "tree of life" (Foale 2003) plantations are the foundation for the production of copra (dried coconut flesh). Coconuts are primarily produced in Asia (Indonesia, Sri Lanka, Philippines, south India, Sri Lanka, Malaysia and Thailand), Oceania (PNG, Fiji, Tonga, and Vanuatu), Latin America and Africa. Some 59 Mt of nuts are produced from 11.3 Mha (Table 8.1). Coconut oil produced from copra is no longer dominant as a vegetable or industrial oil, however there is a resurgence in production for virgin coconut oil derived from cold pressing of the coconut meat (Foale and Robeling 2006). Coconut based agrosystems are diverse and are often intercropped with a diversity of species (Nobre Lages 1996). With the increasing scarcity of fossil fuels and resultant price increases, oil crops are being increasingly utilised as a replacement "biofuel" product. Coconut oil is also converted into biofuel, particularly on isolated Pacific Islands where fuel oil prices are restrictive due to the high cost of transport. Coconut oil can be used directly in standard compression diesel engines with modifications to allow for its increased viscosity, mixed with diesel or converted to biodiesel (Anon 1983; Walton 2008).

## *Fibre and Industrial Crops*

The principal fibre crop is cotton. There are approximately 30 species of *Gossypium* growing across Africa, Asia, Australia and the Americas. Cotton, primarily produced from *Gossypium hirsutum*, with its centre of origin in Central America, from northern Guatemala, developed rapidly into an industrial crop from the mid 1800s with plantations established in the southern USA, chiefly to supply the growing industrial mills of Great Britain and Europe (Purseglove 1968). Prior to the development of mechanical harvesters, the bolls of cotton required manual picking by an abundant labour source. Cotton is grown extensively throughout Egypt, central Asia, China, Australia, USA and Brazil. Since 1980, average cotton yield has increased 60 % but the area cultivated has remained stable at approximately 30 Mha (Anon 2012a). Much of the world's cotton still relies on intensive labour inputs for planting, management and harvesting. In 2008/2009 India had the largest area sown to cotton (9.4 M ha) with a rapid growth in yields since 2003 due to the introduction of biotech varieties and improved hybrids (Osakwe 2009). Cotton production in the USA, Brazil and Australia is grown on a large scale, mechanically intensive and efficient due to a range of innovative agronomic inputs which include genetically modified insect and herbicide resistant varieties, global positioning system controlled tilling, planting, fertilising and harvesting operations and efficient computer controlled irrigation.

Rubber (*Hevea brasiliensis*) is native to the central Amazon and Orinoco Valleys and is tapped from the trunk of trees for its latex. It is utilised for the production of tyres, mats, wire coatings, shock absorber pads and associated rubberised products. Rubber is a tropical crop and, like oil palm, coconuts and cocoa, is generally restricted to production within 10° of the equator. Temperatures below 18° C will reduce latex production. Rubber was reportedly used by the Amazonian Indians for making balls, simple footwear and for waterproofing fabrics (Purseglove 1968). Initial efforts to commercialise rubber looked at the potential of a number of species, including Ule rubber (*Castilla elastica*), Jelutung (*Dyera costulata*), Indian rubber (*Ficus elastica*) and Zanzibar rubber vine (*Landolphia kirkii*). *Hevea* species, in particular *H. brasiliensis,* was considered the most productive. The commercialisation of rubber is credited to Sir Henry Wickham who collected 70,000 seeds from an area in the central Amazon basin in 1876. The collection and export of the rubber seed to Kew Gardens in London remains controversial with the common view that the seeds were smuggled out. Purseglove (1968) reports that it was done with the goodwill and cooperation of the Brazilian authorities. Although less than 4 % of the seeds germinated, they established the nucleus stock which was sent to Ceylon (Sri Lanka) and later to Singapore, a secondary site for establishment. The first rubber plantations were established in Malaysia in 1890 and Uganda and Nigeria in 1903, the Belgian Congo in1904 and Liberia in 1924. Rubber tapping remains labour intensive with one person tapping approximately 450 trees per day (Fig. 8.4). A yield of 1.6 t/ha is considered reasonable. Some 10.0 Mt are produced from 9.6 Mha, averaging 1.0 t per hectare. Today, Southeast Asia (Thailand, Vietnam, Malaysia

**Fig. 8.4** Rubber plantation and rubber collection following tapping, Guatemala. (©Diczbalis)

and Indonesia) is the centre of commercial production with some production also occurring in Central America and in Brazil, the origin of the crop.

Extensive areas of coconut, rubber, and oil palm, particularly in their establishment phase, are also a valuable grazing resource. Coconut plantations, in particular, allow for permanent integration of cattle because of the relatively low density of palms and penetration of light for pasture growth between trees (Shelton and Stür 1991).

## *Tropical Fruits and Nuts*

Tropical and subtropical fruits, principally dessert bananas such as Cavendish, mango, avocado, citrus, pineapple, papaya and to a lesser degree litchi are increasing being grown in plantation style production units (Paull and Duarate 2011). Banana production is discussed in greater detail as a case study in this chapter.

Pineapple (*Ananas comosus*) is the only fruit in the Bromeliad family, consisting of 45 genera, grown for commercial sale. The Great Giant Pineapple plantation (GGP), is an excellent example of a modern plantation model. Located in Lampung, southern Sumatra, Indonesia, GPP produces 500,000 t of pineapple from 33,000 ha. It is the third largest producer of canned pineapple and juice concentrate in the world. The company exports to 30 countries in the Asia Pacific, North America, Europe, Middle East and South America. The company's own promotional video suggests that every fifth can of pineapple in the world is from the GGP (http://vimeo.com/6938824).

Avocado (*Persia americana*), native to Central America, is widely grown throughout tropical and sub tropical regions. Orchards in Chile, Australia and South America are managed on a plantation model with farms ranging up to 5,000 ha. The

**Fig. 8.5** A large scale (50 ha) papaya farm, South Edge, Queensland. (©Diczbalis)

establishment of avocado orchards in Chile, Israel, Spain and South Africa is primary based on the export markets of North America and Europe whereas Mexico, the largest producer of avocado (1.0 Mt annum), is primary aimed at the domestic market. (Anon no date; Naamani 2007).

Papaya (*Carica papaya*), with a centre of origin between southern Mexico and Nicaragua, is widely produced throughout the tropics and subtropics (Chan and Paull 2006). It is the third largest tropical fruit crop with 11.22 Mt or 15.4 % of total tropical fruit production (Evans and Ballen 2012). India is the largest producer of papaya with an estimated 4.7 Mt produced in 2010. In 2009, world exports of papaya were 279,684 t mainly from Mexico, Brazil and Belize. Papaya orchards, although not at the size of some crops, are being "plantationised" with orchards in Australia up to 50 ha (Fig. 8.5). These large production units need a large skilled labour force and a high level of mechanisation to efficiently harvest, sort and pack the crop.

Litchi (*Litchi chinensis*) and longan (*Dimocarpus longan*) are grown on a large scale in southern China (Yen and Paull 2006; Zee and Paull 2006) with orchards as large as 2,000 ha (Fig. 8.6). Many of the larger schemes were initiated under the direction of regional and provincial governments during the 1980's (Zhang 1977). The farms are state-managed with the workforce drawn from the surrounding villages. Similarly, rambutan (*Nephelium lappaceum*) is grown in plantations in Guatemala with 35,000 plus trees managed by the company, Lafinita. The availability of a relatively cheap labour force combined with a high level of technical and managerial inputs are common ingredients to a successful export orientated plantation.

Tree nut crops are increasingly becoming "plantationised" as the drive to increased efficiency of production, with the aid of technology and mechanisation. Nut crops, in particular Macadamia, are one of the case studies examined later in the chapter.

**Fig. 8.6** A litchi plantation known as the "litchi forest" near Maoming, China. (©Diczbalis)

## *Forest Crops*

Forests planted for timber and wood pulp now occupy approximately 300 Mha or 2 % of global land area (FAO 2006). Forest plantings range in size from smallholder plots to large agro-industrial scale plantations and occur over a range of climatic zones. Planted forests are long-term investments that require careful planning prior to establishment, in order to avoid negative impacts. Hence, issues such as germplasm selection, site preparation, nursery production, planting, agronomic management and harvesting will all impact on the success of the plantation

In 2015 the projected forest plantation area is 327 Mha with approximately a 50 % split between non-tropical and tropical forests. By 2020 an estimated 412 Mha will be produced with 62 % coming from tropical based plantations (Anon 2007). Internationally; plantation forests account for approximately 95 % of wood pulp production, 85 % of reconstituted panels, 25 % of plywood and 22 % of sawn wood production. The situation changes depending on continent with a high proportion of wood products coming from plantation forests in Latin America and the Caribbean while most African forest products are largely dependent on wood supply from natural forests (Anon 2007).

Plantation forest areas are increasing rapidly to meet the rising demand for wood products. The global outlook to 2030 and recent areas of planted forests by country and the role planted forests play for the future of the worlds forest resources is covered by FAO (2009).

## Case Studies

Three case studies are presented which attempt to define the past, evolution and future of plantations.

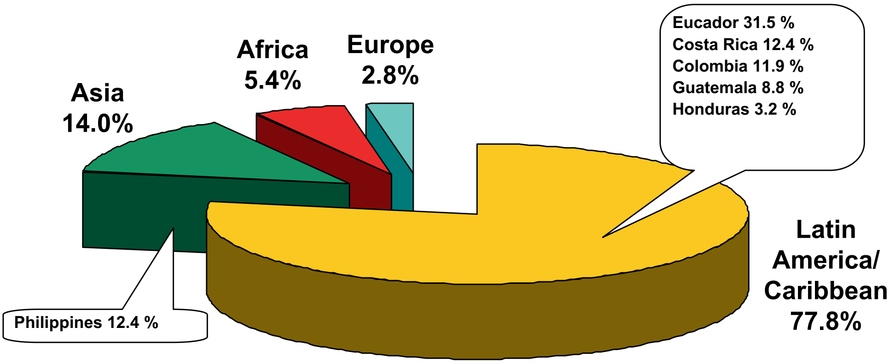

**Fig. 8.7** Values from Lescot (2012) have been adjusted to take into account exportation from non-banana producing countries

## *Bananas*

### Introduction

Banana is the developing world's fourth most important food crop after rice, wheat and maize, with total production estimated at 130 Mt in 2010 (Lescot 2012). Bananas as such include plantains which are a type of banana usually cooked before consumption. The crop is grown in more than 130 countries throughout the tropics and subtropics. Banana is a staple food for millions of people, particularly in Africa (Daniells 2009). It is also the most important fruit crop in world trade with about 16.2 Mt being exported in 2010. It is this latter aspect of export where bananas manifest as the quintessential plantation crop.

The world trade in bananas was valued in excess of US$ 8 B in 2009 (FAO 2012). Over 80 % of the export production comes from just 6 countries in the tropics (Fig. 8.7) and the total area involved is in excess of half a million hectares (Daniells 2006) and employs millions of workers. Latin America and the Caribbean account for 78 % of export banana production because of relative proximity to the major markets of North America and Europe. Most of the production is sold competitively on free markets in North America, Europe, the Arabian Gulf States and Japan.

### Brief History

The banana export trade began in the 1860s with shipments of Gros Michel bunches from Central America and the Caribbean to North America (Simmonds 1966). The trade in bananas expanded rapidly as individuals/companies realised the profits that could be made from the fruit. During the 1870s, there were 114 banana companies registered in the U.S. However, only 22 of these lasted until the end of the century

**Fig. 8.8** Banana plantations can cover hundreds, sometimes thousands of hectares. They are mainly located on rich well drained alluvial soils. Packing sheds are often centrally located. (Photo courtesy MacKay family)

and only 4 were of significant size. United Fruit Company (UFC), the first of the large transnational banana companies, was incorporated in 1899 which marked the beginning of a new era that converted the highly perishable tropical banana into an important item of world trade. UFC was the first truly vertically integrated fruit company having large production in widely separated localities, control of dedicated shipping assets, expertise in fruit transportation methods, a marketing organisation and sufficient capital to develop new production and marketing areas (Roche 2000). Thus, bananas for export took on the many qualities and attributes of plantation horticulture, mostly corporately-owned large estates (Fig. 8.8), especially in the tropics, employing cheap labour on a large scale, monoculture cropping, and producing for sale in distant markets. These ingredients laid the foundation for bananas, little known in the western world 150 years ago, to become the major fresh fruit in temperate zones where they are not grown.

## Laying the Foundations for Plantation Profitability

Banana plantations were at the forefront of industrialised horticulture and the characteristics of these plantations have everything to do with the drive for profitability. To produce the required fruit quality at the cheapest price, the large transnational companies and smaller national growers alike employ the following mix of strategies:-

**Fig. 8.9** Banana production is labour intensive. Harvesting banana bunches is particularly heavy work with ratoon bunch weights typically in the range of 30–60 kg. (©Daniells)

- Banana growing is very labour intensive (Fig. 8.9) so, to minimise costs, country locations are sought where wages are low, such as Latin America and the Philippines.
- Production in tropical equatorial locations facilitates consistent supply of fruit to importing countries throughout the year. These locations are also sought for their high yields of fruit which has not been damaged by in-field chilling which occurs at temperatures <13 °C. Chilled fruit has an unattractive, dull yellow appearance when ripened. Where possible, locations are sought that seldom suffer severe wind damage from cyclones/hurricanes, which would lead to severe market supply fluctuations. Therefore so the closer to the equator the better, as these storms are generally formed between 7–15° latitude and move away from the equator.
- Choice of the most fertile, well-drained, mostly deep alluvial soils, usually on flat terrain. Poorer soils require more inputs for satisfactory yields and require replanting more frequently. In the early 20th Century, great efforts were made by soil survey teams in difficult tropical jungle conditions to locate the best soils for the plantations.
- Good rainfall and supplementary irrigation is required to ensure optimal fruit quality, particularly fruit greenlife ((= transport life).
- Significant capital investment in plantation infrastructure is required. This includes all-weather roads, irrigation systems, elaborate field drainage networks to minimise waterlogging, cableways to transport fruit to the packhouse (Fig. 8.10) and large packhouses to prepare the harvested fruit for dispatch to market.
- About 95 % of export bananas are of the Cavendish type (*Musa* AAA group, Cavendish subgroup) with production restricted to a handful of cultivars which are genetically very similar. Cavendish bananas are high-yielding and are well suited to the requirements of the supply chain. Most other types of bananas are lower yielding [¼–¾ of Cavendish] so it is difficult for them to compete in the market because of the required premiums for profitability (Daniells et al. 2012).

**Fig. 8.10** Networks of cableways are the norm for transporting bunches to the packing shed. They are just part of the significant capital investment necessary in establishing a banana plantation. (©Daniells)

The simplicity of having just one type to manage, in what is a long and complex supply chain, has contributed greatly to successful marketing.

- Transnational companies are divided into administrative units from 250–400 ha each whilst larger national growers range from 50–250 ha. Such size brings with it economies of scale and the capacity to supply 'long lines' of uniform product better meeting the quality specifications of large retail outlets.
- Usually there are from 0.6 to 0.8 workers required to manage one hectare. Thus large workforces are involved and good people management is crucial. Operational procedure manuals which detail the requirements of every on-farm procedure are typically available to staff. Activities are generally broken down into single tasks to be performed by individual workers and this is monitored and necessary feedback provided to ensure standards are achieved.
- Most export fruit is transported to market by ship. In order to efficiently use shipping space and facilitate marketing, it is necessary to predict the amount of fruit available for harvest and sale on a weekly basis. Relatively reliable estimates are possible once the young bunch emerges and this provides predictions about 12 weeks in advance of harvest. Weekly counts of new bunches, coupled with historical information of bunch size, filling rate and expected losses, is commonly used in the calculations.

## Banana Plantations—their Impact and Contribution

The world's banana export industry has been almost entirely controlled by 3 large fruit companies: Chiquita, Dole and Del Monte. Many countries, including those in Latin America, depend heavily on the revenue and employment that these corporations provide. The revenue is so lucrative that many governments have gone out of their way to attract the fruit companies to establish plantations in their country. This has allowed transnationals to become very powerful and influential, leading to a transformation of the economic, political and social landscape of the Latin American region (Bucheli 2006).

Banana growing is economically significant in many banana exporting countries because it is very labour intensive. The range of tasks performed include digging planting holes, hand planting, broadcasting fertilisers, deleafing, desuckering, covering bunches, pesticide application, harvest, dehanding fruit, sorting, and packing. In Honduras and Costa Rica, banana plantations employ 5–10 % of the population. Bananas also deliver a relatively quick return on effort and investment, providing a regular income year round. The crop recovers quickly from hurricanes and other natural disasters, in many ways making it an ideal crop.

Much criticism has been levelled at export banana plantations over the years regarding their environmental credentials and poor social conditions. Certainly, hundreds of thousands of hectares of rich and diverse tropical ecosystems have been transformed into banana plantation monocultures over the last 100 years or so. However, on the positive side, development of these regions allowed settlement in areas that were previously inaccessible.

Despite criticisms, progress is being made to improve the sustainability of export banana production, albeit not quick enough for some. For the past 20 years, organizations, including the Rainforest Alliance, have been working with banana producers to conserve biodiversity and ensure sustainable livelihoods by transforming land-use and business practices, and consumer behaviour. For instance, Chiquita has all their banana crops certified by the Rainforest Alliance. Also, since the year 2000, there has been rapid growth of organic exports from 30,000 t to nearly 400,000 t in 2010 (Dawson 2012). However, market penetration for organic bananas is still comparatively small, representing only 2.5–3.0 % of total banana imports in 2010. Fairtrade International is a group of 25 organizations working to secure a better deal for producers. Growers producing Fairtrade bananas receive a minimum price to cover the cost of sustainable production and a premium to invest in projects in their communities. In 2010, there were nearly 26,000 ha of bananas under Fairtrade cultivation.

The overseas export markets have demanding requirements that greatly influence cultivation methods used by banana growers (Figs. 8.11 and 8.12). Plantations strive to produce blemish-free fruit with quality (fruit diameter, or grade, and length) meeting retail specifications. They also strive to protect fruit from mechanical damage during growing, harvesting and transport to the packing shed (Fig. 8.14). This includes padding inserted between hands of fruit on the bunch during early fruit development and plastic between the 2 whorls of a hand (Fig. 8.13), and bunch covering. As well, shoulder padding is worn by workers carrying bunches to the cableways. Export markets are up to 3½ weeks away so fruit needs to stay green (remain preclimacteric) to allow uniform ripening with ethylene gas at the final destination. A method known as age-grade control is used on the plantation to judge those bunches which are optimal for both fruit size and greenlife which is related to bunch age. Additionally, bunches are monitored in the packing shed by examining the pulp colour of indicator fruit fingers to ensure they have sufficient greenlife. Bananas rejected for export amount to 15–20 % of the crop and contribute to local food supplies.

**Fig. 8.11** Banana tissue culture nurseries supply tens of millions of pest and disease-free plants worldwide for new plantings so reducing pest problems and the need for some pesticides. (©Daniells)

**Fig. 8.12** Aerial application of fungicides for leaf disease control. Monocultures of the susceptible Cavendish-type bananas destined for export are usually grown in wet tropical environments and are highly dependent on pesticide inputs for high yields of the required fruit. (©Daniells)

Serious diseases threaten the future of the banana plantations world wide. These diseases include, in particular, Fusarium wilt tropical race 4 (TR4), black Sigatoka leaf disease and bacterial wilts. All the plantations are monoculture cropped with Cavendish cultivars which are genetically very similar. Thus, they are very vulnerable to disease outbreaks. This was highlighted by the January 18th 2003 *New Scientist* cover story 'Going Bananas' (Pearce 2003). There is still no satisfactory control measure for TR4. The disease, until recently confined to Asia is causing serious losses to plantations in China and the Philippines, has now spread to Africa. In recent years, black Sigatoka has become more difficult to control in many plantations, necessitating weekly fungicide applications which is clearly not sustainable. Major changes in banana culture are needed to face these challenges.

Banana plantations supply most of the western world with its most popular fruit the year round. In just a little over a hundred years bananas have come to be relied upon by the masses as an inexpensive, nutritious fruit. This has largely been

**Fig. 8.13** Blemish-free fruit has competitive advantage in the western marketplace. Growers have to go to great lengths to protect fruit from mechanical damage. (©Daniells)

**Fig. 8.14** Large banana packing shed—mini-factories preparing fruit for market. Export banana production was at the forefront of industrialised horticulture. Large workforces are required to prepare the fruit for market. (Photo courtesy MacKay family)

possible because of the suitability of bananas to this style of horticulture and the efforts of a great many people.

## *Cocoa—An Unusual Plantation Crop*

### Crop Production, Processing and Chocolate Making

Cocoa (*Theobroma cacao*) is a small cauliflorous tree, which produces pods containing seed, referred to as beans, from which chocolate is made (Figs. 8.15 and 8.16). The tree flowers throughout the year but normally there are two distinct harvests that depend on the rain pattern (Knapp 1930). Well-drained soils, constant mild temperature and regularly distributed rainfall of around 2000 mm/year are optimal for cocoa farming, although regions such as West Africa which have an average of 1250 mm/year also produce commercial crops (Wood and Lass 1985). In areas with lower rainfall or a pronounced dry season, cocoa should be irrigated as in Ecuador, Venezuela, India and Vietnam. Cocoa pods require 5–6 months from pollination to maturity and two cycles of pod ripening are normal, with alternating main and secondary harvests.

**Fig. 8.15** High yielding cocoa tree. (©Lambert)

**Fig. 8.16** Ripe cocoa pods with beans ready for fermentation. (©Lambert)

The proportion of cocoa harvested on each occasion depends on climate. Usually, the main crop that starts flowering at the beginning of the rainy season accounts for some 60 % of the total harvest. However, in West Africa with a more distinctive dry season, up to 85 % of cocoa is harvested during the main crop from October to January. In the trials examining the feasibility of cocoa production under high input conditions in northern Australia, there were two peaks in production, each approximately 25 % of total production with the remaining pods produced throughout the year (Diczbalis et al. 2010).

Cocoa pods contain 30–40 beans enveloped into a white, sweet, juicy pulp that ferments when beans are left in a pile or are placed into a fermentation box. Fermentation is crucial to produce cocoa beans that can be used for the production of chocolate as it is during fermentation that chocolate flavour precursors are formed.

**Fig. 8.17** Small cocoa growers in PNG harvesting and opening pods to ferment their beans in small a box fermentery with a kiln drier. (©Lambert)

These precursors react later during roasting, producing the characteristic chocolate flavour. Fermentation is a natural process caused by a microbial succession of yeasts and acetic/lactic bacteria and is performed by cocoa growers after pod opening and bean extraction (Wood and Lass 1985). In Africa, most growers ferment their cocoa in the field in heaps piled on, and covered by, banana leaves but in Asia/Pacific region, cocoa is mainly fermented in wooden boxes (Fig. 8.17).

In Sulawesi, the main cocoa producing region of Asia, growers do not ferment their cocoa, resulting in low quality beans used mainly for extraction of cocoa butter. Following 5 to 7 days of fermentation, the beans are mainly sun-dried on elevated platforms, a cheap method resulting in high quality (Figs. 8.18 and 8.19). However, in many cocoa producing countries, the cocoa harvest coincides with the rainy season and drying can be a big challenge. Many cocoa growers use wood-fired kiln driers (Samoan driers) but, poor maintenance of the fire chamber and flue leads to smoke contamination.. This is a particularly a problem in the Pacific.

Cocoa trees are susceptible to a large variety of pests and diseases that are different on each continent. The most common disease is “black pod” (*Phytophthora palmivora*) which causes pod rot and trunk canker. Devastating fungal diseases in the Americas are witches’ broom (*Moniliophthora perniciosa*) and moniliasis (*Moniliophthora roreri*); in Africa, *Phytophthora megakarya;* and in Asia, *Oncobasidium theobromae* causing vascular-streak dieback The only viral disease of cocoa is the Cocoa Swollen Shoot Virus in Africa. The main insect pests are cocoa pod borer (*Conopomorpha cramerella*) in the Asia/Pacific region and sap-sucking bugs (mirids or capsids) in Africa.

Processing of dry, fermented cocoa is a two phase process that is normally done by different businesses. The first step, cocoa grinding, involves roasting, deshelling, grinding/milling of nibs into a fine cocoa paste called cocoa liquor (mass) that is the base ingredient for chocolate. A good quality chocolate requires additional cocoa butter which is expressed from cocoa liquor in a large hydraulic press, separating it from the cocoa powder.

**Fig. 8.18** Large and efficient cascading box fermentation facility in Papua New Guinea. (©Lambert)

**Fig. 8.19** Cocoa bean drying and rain shelter in Papua New Guinea. (©Diczbalis)

Cocoa grinding is mainly carried out in Europe (40 % of all global cocoa), the Americas (21 %) and the Asia/Pacific region (20 %). The largest producer of cocoa, Africa, grinds only 18 % of the global cocoa production (Pipitone 2012).

The second step in cocoa processing is manufacturing of chocolate by mixing cocoa liquor, cocoa butter, sugar, lecithin and milk (for milk chocolate), and other ingredients depending on the final product (Beckett 2000; Coe and Coe 2000). Cocoa powder is used in production of chocolate confectionary, drinks and biscuits.

### Cocoa Production Statistics

Global cocoa production in 2011/12 reached 4 Mt with West Africa contributing 71 % or 2.826 Mt (Pipitone 2012). Cote d'Ivoire, is the largest producer with production of 1.476 Mt for 2011/12, just below its record in the 2010/11 season of 1,511 Mt, due to favourable environmental conditions and in spite of the political problems during this time (Anon 2012b). Ghana is the second-largest producer, followed by Nigeria and Cameroon.

Although cocoa originated in South America, this region produces only 0.574 Mt or 14 % of global production, mainly in Brazil and Ecuador. In the Asia Pacific region, accounts for 15 %, mainly from Indonesia and Papua New Guinea, with Indonesia being the third largest global cocoa producer.

Consumption figures are very different. Most cocoa is consumed in countries that do not produce it. Europe consumes 48 %, North America, 24 %, South America, 9 % while Africa consumes only 3 % of global cocoa (Pipitone 2012).

Total area planted to cocoa globally is 9.5 Mha with a total production of 4.2 Mt (Table 8.1). Globally, more than 90 % of cocoa is produced by small cocoa growers on 2–5 ha in Africa (Anon 2012c) and 1–2 ha in Sulawesi.

Average productivity per hectare is around 300–470 kg dry bean/ha/year (Table 8.1; Anon 2012c). High yielding cocoa has been achieved in Malaysia with cocoa plantations producing a 5 year average of 3.2 tonnes/ha/year in late 90s (Lass 1999). The highest producing plantations are mainly irrigated plantations in Ecuador and Brazil and some smallholder farms in Asia that have adopted high yielding clonal cocoa, producing between 2–4 t/ha/year.

## From Forest Tree to Small-Holder Crop, to Plantation and Back to Small Holder Crop

The centre of origin of cocoa is the Amazon basin rainforests with a secondary distribution in central America, southern Mexico and the Caribbean, between 20 °S and 20 °N of the equator. The high genetic variability that occurs in these regions can be used in varietal improvement (Bartley 2005). In Central America, cocoa was cultivated mainly in Mexico for more than 2000 years by Mayas and other peoples from this region (Wood and Lass 1985). Cocoa was also highly appreciated by the Aztecs who considered it to be a sacred tree, with health-improving properties, used in traditional ceremonies (Lupein 1999). The first recorded use of cocoa was as a fresh, frothy beverage called “chocolatl” prepared from ground cocoa beans with added spices. When cocoa was “discovered” by the Spanish in 1502 on Guanaja, an island off the coast of Honduras, it was already a well-developed, commercial crop, with dry cocoa beans used as a currency by the local inhabitants (Wood and Lass 1985; Dand 2011). Cocoa beans were taken to Europe by Spanish sailors, and during the following centuries, were widely used as a chocolate drink until 1847 when the first block chocolate was produced in UK by J.S.Fry & Sons (Coe and Coe 2000).

Despite cultivation of cocoa trees starting more than 2000 years ago, domestication and improvement of cocoa varieties was very slow. Even now, more than 70 % of cultivated cocoa trees are unimproved, wild types (Eskes 2006). Most small growers still identify their best trees and use their seeds as planting materials, as they did some 2000 years ago.

After Europeans discovered the pleasures of chocolate beverages in the sixteenth century, the consumption of cocoa increased. The increased demand lead to production expanding from Mexico to the Caribbean islands of Jamaica and Trinidad. The majority of cocoa was still produced by small growers, but in Trinidad, the first 100 and 160 ha plantations were established. As cocoa cultivation expanded into Venezuela in 16th century, the scenario was repeated with mainly small growers and a few family-owned, large plantations. The 140 ha "Chuao" plantation, established 500 years ago, still produces cocoa of high quality.

Large, family-owned plantations of 100–160 ha was the model for cocoa cultivation as it expanded into Ecuador in 1605. Ecuador dominated world cocoa production in the nineteenth century (Dand 2011). In Brazil, cocoa expanded from smallholder plots in the Amazon region in 1746 to Bahia with 100–200 ha farms. In the Americas, few large company plantations were established, the most well-known being the United Fruits Plantation in Costa Rica where cocoa served as a substitute for bananas due to Panama disease (Wood and Lass 1985).

Currently, Ecuador and Brazil continue with medium size family plantations with a few very large plantations in Ecuador, considered to be the most advanced and profitable, with irrigated areas producing high yields. South America currently has the highest proportions of cocoa plantations over 100 ha but most cocoa is still produced by small growers.

In South America, large, traditional plantations face challenges, especially with high production losses due to fungal diseases such as Witches broom (*Crinipellis perniciosa*) and Frosty Pod rot (*Moniliophthora roreri*) and with high labour costs. In Brazil, to counteract high labour costs, some plantations are developed in dry areas to avoid disease, using superior, high-yielding clones managed intensively with optimal irrigation and fertigation.

Cocoa was introduced from Brazil to the islands of Sao Tome and Fernando Po in 1822 and, by late nineteenth century, from there to Ghana, initiating the largest cocoa expansion ever, based almost entirely on the initiative of smallholder growers. The first cocoa was exported from the Gold Coast (Ghana) in 1891 and, until now, African cocoa production is dominated by small cocoa growers with areas of 1–2.5 ha with few growers having more than 8 ha (Wood and Lass 1985).

In anglophone African colonies, foreigners were not permitted to purchase land. A few locally-owned plantations were established, the best known being the Badoo family plantation of 35.9 ha in Ghana (Beckett 1946). In Cote d'Ivoire, some European settlers established cocoa plantations with mixed success but very few remain operational. There were also some large plantations in Nigeria with few surviving as part of Agricultural Development Corporations. In Cameroon, by 1912, over 80% of exported cocoa was produced on plantations (West and Voelcker 1942). Currently, however, the bulk of production in Cameroon occurs on small family farms (Anon 2012d).

In Africa, the domination by smallholder growers (Fig. 8.20) over the plantation production model is due to several issues, including land ownership, lack of investment security, inappropriate planting material, soil nutrient depletion due to a lack of fertiliser and low organic matter content (Rob Lockwood, personal commu-

**Fig. 8.20** A typical scene on a west African cocoa farm. The start of heap fermentation in Ghana and drying fermented beans—producing "golden standard" quality cocoa. (©Lambert)

nication). Additionally, the price of labour, its availability and capacity to manage cocoa correctly also contributed to failure of cocoa plantations in Africa.

In the Asia Pacific region, the expansion in cocoa production happened quite late despite cocoa being transferred from Mexico to Philippines by Spanish colonisers in the sixteenth century (Dand 2011; Wood and Lass 1985). In Indonesia on the island of Java, a few large plantations were established in the nineteenth century under Dutch colonial rule, some still being operational. Most of these large old plantations became government-owned and focused on production of the highly-valued, fine flavoured but low yielding white bean Criollo-type cocoa that attracts a premium price. Later, in 1980s, much larger cocoa expansion occurred in Indonesia on the island of Sulawesi. This was driven by Sulawesi growers returning from Malaysia where they served as labour in large cocoa estates and learned to grow the crop (Dand 2011). Currently, 80 % of Indonesian cocoa is produced in Sulawesi by smallholder growers with one to two ha of land. A recent increase in cocoa production occurred in Sumatra by smallholder growers responding to positive price indicators.

In Malaysia, cocoa expansion started in the 1980s in Sabah (Borneo) with 60 % of production coming from large estates with areas between 1500 and 3000 ha and the remainder from smaller farms less than 100 ha. Large plantations in Malaysia were very active in cocoa research and have developed several high-yielding cocoa clones that are highly valued. These plantations were also the first to start side grafting old cocoa trees with new clones to rehabilitate them and boost productivity.

Malaysian production peaked by 1990 then declined sharply from an annual production of 220,000 t (Dand 2011) to current production of less than 10,000 t due to low prices, lack of labour, cocoa pod borer infestation and plantations reinvesting into oil palm. Oil palm is much less labour intensive with one worker able to manage 8–9 ha of oil palm compared to 1–2 ha of cocoa. Currently, only few smallholders (5–15 ha) still produce cocoa with support from the Malaysian government paying for their planting materials and inputs if they stay in cocoa.

A similar transition from plantation to smallholder production occurred in Papua New Guinea. In 1975/76, 51 % of cocoa was produced in plantations (Wood and

Lass, 1985). Currently only 9 % is produced by plantations and the rest by small growers with land areas of 1–4 ha (Anon 2008).

Cocoa has not performed well as a plantation crop. The reasons behind this are many and varied but include;

- Cocoa is a relatively difficult crop to manage, requiring a high level of inputs and management skills to achieve high yields.
- High labour requirement (1 person for 2 ha) compared to oil palm where 1 person can manage 8–9 ha.
- Cocoa preliminary processing (bean fermentation and drying) does not require a high investment and hence can be carried out on a small scale with negligible infrastructure, often producing a better product. A prime example is the "golden standard" for good quality cocoa produced by small holders in Ghana.
- Smallholders can adapt more rapidly to the fluctuations in world price which are subject to supply and demand. Data from the Malaysian Cocoa Board for 2008 (Dand 2011) shows that the production cost for a plantation "estate" is $ 1,725/ha and $ 1,174/ha for smallholder producers, in spite of the fact that estates employ 50 % less workers than smallholders.
- Cocoa bean prices have significantly decreased in relative and real terms from the 1970s with very low prices in 2000 of less than $ 1000/t. Prices have stabilised in the range of $ 2000-$ 2,500/t of dry cocoa (ICCO 2012). Only plantations with extremely high yields and high technology can still be competitive on the global cocoa market compared to small cocoa growers.

### Examples of Efficient Cocoa Production

The most efficient way to produce cocoa depends on local environmental and social conditions. In countries with relatively high labour cost and more developed technology as in Ecuador and Brazil, large, high "tech" irrigated/fertigated clonal cocoa plantations are producing cocoa efficiently and profitably.

In Africa and Indonesia and many other small cocoa producing countries with low labour costs, cocoa is produced on a small scale and is a driver of rural development with important socio-economic benefits to remote communities.

On many smallholder farms, production is low and inefficient because the growers are poor and have a low level of education. To promote efficient, profitable and sustainable cocoa production, training is required. It is critical to educate small holder producers to help them realise that cocoa farming is a good business that can alleviate their poverty and educate their children. This can be achieved by supplying growers with production training and high quality clonal cocoa material (Figs. 8.21 and 8.22). Many chocolate manufacturers have, over the last decade, worked with growers to achieve this aim. Professional and efficient small cocoa growers of the future will produce 1,500–2000 kg of high quality dried bean/ha/year, significantly improving their income and lifestyle.

**Fig. 8.21** African cocoa growers receiving training on rehabilitation of cocoa by clonal grafting from Indonesian specialist. (©Lambert)

**Fig. 8.22** A well run and operated clonal cocoa nursery in Sulawesi.(©Lambert)

## Future of Cocoa Production

By 2020, chocolate manufacturers will need an estimated 5 Mt of dried bean per annum, an additional one million tonnes of cocoa every year. There is immense need for increased production. Cocoa is likely to remain a predominately smallholder crop, with a proportion of the 5–6 million current smallholder embracing professional management and high inputs, resulting in increased productivity and income. Plantations will remain an important production option, becoming more sophisticated and embracing technical solutions to boost productivity and efficiency.

## *Macadamia Nuts—a Case Study for a Modern Plantation Crop*

### Background

The major tree nuts, almonds (*Prunus dulcis*), cashews (*Anacardium occidentale*), chestnuts (*Castanea sp*), hazelnuts (*Corylus sp*), pecan (*Carya illinoinensis*), pine nuts (Pinus sp), pistachios (*Pistacia vera*), macadamia (*Macadamia integrifolia)*, and walnuts (*Jugland regia*) are often neglected when it comes to considering the world's tree crops. Tree crops such as apples (*Malus domestica*), citrus (*Citrus sp*), oil palm (*Elaeis guineensis*), rubber (*Hevea brasiliensis*), coffee (*Coffea arabica*) and tea *(Camellia sinensis*) dominating the discussion when it comes to the areas devoted to production and their value to world trade. However, this situation is rapidly changing as the tonnage of nuts in world trade rapidly increases (Table 8.2).

Nut crops have rarely been brought into discussions surrounding 'plantation crops' as they did not share many of the same characteristics such as foreign ownership, tropical locations and a history of slave or low cost labour. However, since the 1950s some of the major nuts crops have taken on a few of the characteristics of 'plantation crops' such as large single-crop focused monocultures with an emphasis on the economies of scale. This is particularly true of the almond industry which is dominated by production originating from California. In 2011/2012 California produced 80 % of the world's production; an estimated 887,679 t of kernel from 315,662 bearing hectares (Duerr 2012). Almond production in California consists of both privately and corporately owned large orchards and is highly mechanized. In contrast, Brazil nuts are still largely harvested by hand from the rainforests of Bolivia, Peru and Brazil.

### Introduction to Macadamia

Macadamia is one of the smallest tree nuts in terms of global nut production and, unlike many of the other nuts it is almost entirely grown in the tropics and sub-tropics. Macadamias have experienced a large increase in production, 167 % between 2002 and 2011, and comprise around 1 % of total tree nut production (INC database 2012). Australia has been the leading producer since early in the century but, its share has declined over the last 5 years with South Africa now the number one producer. Africa now accounts for almost 50 % of the world's production (Fig. 8.23). There is also substantial emerging production in China and Brazil.

The emergence of competing producers in low labour cost regions, such as in Africa, has been one of the major factors that has placed pressure on some Australian producers to move to a plantation system of production. While there are still elements of the Australian macadamia industry that are still smallholder-based, the majority of Australian production is moving towards large agro-industrial, highly focused, capital intensive, single crop, plantation style systems of production.

**Table 8.2** Estimated world tonnage (kernel basis) of the major tree nuts crops in 2011, growth in production from 2002–2011 and share of total production. (Source: International Dried Fruit & Nut Council Statistics Database 2012)

| Tree nut[a] | Estimated tonnage (kernel basis) | Total production growth 2002–2011 (%) | Share of world production 2011 (%) |
|---|---|---|---|
| Almonds | 1,109,414 | 228.7 | 35 |
| Cashews | 556,668 | 227.3 | 18 |
| Walnuts | 497,635 | 148.1 | 16 |
| Pistachio | 455,266 | 101.7 | 15 |
| Hazelnut | 354,600 | 87.6 | 11 |
| Pecan | 89,146 | 74.9 | 3 |
| Pine nuts | 34,445 | 363.9 | 1 |
| Macadamia | 29,875 | 167.4 | 1 |
| Brazil nut | 23,995 | 70.4 | <1 |

[a] Information for Chestnuts has not been presented due to a lack of credible statistics

## Brief History of Macadamia Production

The macadamia is native to the subtropical coastal rainforests of northern New South Wales and south east Queensland and is the only major food crop of Australian origin. The macadamia kernel has a delicate, buttery, crunchy texture and is generally considered to be the premium nut in world trade.

While there are four species of macadamia found in Australia the commercial industry is based primarily on *Macadamia integrifolia* and on hybrids of *Macadamia integrifolia* and *Macadamia tetraphylla*. An Australian industry-based breeding program is currently developing new hybrids with the other species to improve kernel quality, reduce shell thickness and tree size, and improve pest and disease resistance.

The macadamia industry is generally considered to be less than 150 years old with the first commercial orchards being planted in northern New South Wales in the 1870s and 1880s. These first orchards were small, generally less than 100 trees, and were composed of *Macadamia tetraphylla* trees (McConachie 1980). Despite the efforts of various Australian state governments and acclimatization societies to promote macadamia, a large scale industry did not develop in Australia until the 1970s, almost 100 years after the first orchards were planted. In contrast, following the introduction of seeds from the 1880s onwards (Shigeura and Ooka 1984) an industry began to develop in Hawaii in the 1930s and by the late 1940s the first large scale macadamia plantations had been established. The Hawaiian Agricultural Experimental Station then went on to select most of the cultivars on which the world's macadamia industry is currently based. The Hawaiian industry dominated world production until the late 1990s when it was overtaken by Australia. Production in Hawaii was, and still is, a mixture of large corporate plantations and large and small private holdings.

Large scale, commercial plantation style production started in Australia in the 1960s when CSR Ltd established a series of orchards along the Queensland coast

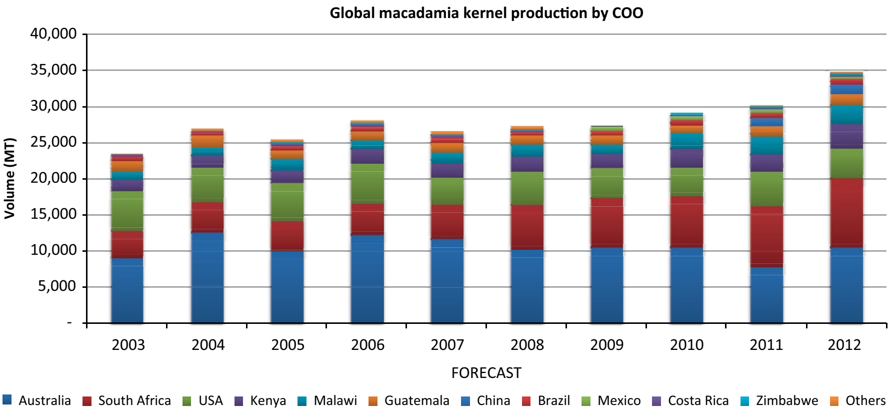

**Fig. 8.23** Global macadamia production by origin. (Source: International Dried Fruit & Nut Council Statistics Database)

(McConachie 1980). These orchards were based on imported Hawaiian cultivars and used equipment imported from the Californian almond industry. This demonstrated the potential of macadamia in their country of origin, and there was steady planting of trees throughout the 1980s and 1990s. However, most of the subsequent plantings were made in the higher rainfall areas of southeast Queensland and northern New South Wales and the majority of these were less than 10 ha in extent. The land in these areas is undulating to steep and when combined with the high rainfall, mechanization is difficult and expensive. The density of the orchards in northern New South Wales today is such that in many areas they appear to be one large continuous plantation, but with multiple owners and, consequently, multiple levels and styles of management, they cannot be considered to be a plantation production system.

In the early 1990s, orchards were established in central Queensland around Bundaberg. Land in this area was cheaper than in the traditional southern production areas, was flatter and had a plentiful supply of irrigation water from various government schemes. The combination of these factors meant that agronomically manipulable, economically reliable, large scale mechanized production could be achieved. These orchards continued to gradually expand until 2003 when a wave of new entrants, largely from the highly intensive vegetable industry, decided to plant macadamias and began to create a modern plantation style system of production that prevails today. This change in crop focus was driven, in part, by the desire of the vegetable producers to move away from managing the large, expensive labour forces required in the vegetable industries, towards an industry where mechanisation was rapidly replacing labour.

## Production Drivers Today

As around 70 % of the Australian crop is exported, producers have to compete with production from low labour cost countries (Anon 2012e). Labour in Australia is, by world standards, highly regulated and expensive, with the basic agricultural wage above US$ 18 (2012) per hour. It is this need to reduce labour costs that has driven innovation and the creation of a modern plantation production system in Central Queensland. This is a fundamental difference from the traditional plantation crops that have had a history of labour exploitation and are still largely based in developing countries with little or no labour regulation. While low cost labour has been traditionally a driver of plantation production in developing countries, it is high cost labour and the difficulties associated with managing a large labour force that is driving the move toward plantation style production in Australia.

As a consequence of the high labour costs, considerable emphasis has been placed on developing a production system that can not only be mechanized using current technology, but also a system that is able to take advantage of future advances in automation. For mechanisation to be efficient, it also needs to be on a large scale so that the high capital inputs are spread over large areas.

Speed over the ground is the key to making macadamias efficient and profitable with long straight rows and smooth inter-rows allowing the rapid passage of equipment through the plantation. With an average of 18–20 operational passes per inter-row per year, small changes in ground speed can, cumulatively, have a significant impact on orchard economics. Orchard floor preparation prior to planting, to allow high operational orchard speeds, in combination with a good orchard design to channel and manage heavy rainfall, has therefore become a priority in modern macadamia plantations. Since 2004, over 70 % of the new plantations in the Bundaberg area have been established using tractors fitted with satellite guidance systems. The accuracy of these systems (±2 cm) allows large machinery to move at high speed through an orchard with minimal risk to the trees. In addition, the satellite systems have allowed micro-mapping of orchard topography on a scale that was not possible when orchards were surveyed using traditional methods. Micro-mapping not only allows the orchard designer to establish a plantation where water movement from heavy rainfall downpours can be carefully controlled, it also allows for the design of more accurate and efficient irrigation and fertigation systems.

Once the orchard has been designed and the tree row mounds and irrigation installed, the trees are planted using a mechanical planter coupled to a satellite guided tractor (Figs. 8.24 and 8.25). This allows a team of 8–10 people to plant between 6 to 10 hectares per day with an accuracy of ±2 cm within the row. A drip irrigation system is usually installed at the same time with the trees receiving water within four hours of being planted.

Irrigation systems are critical for managing trees in this environment with trees receiving irrigation, scheduled using a range of tools, on a needs basis. Fertigation is almost universally employed with trees receiving nearly constant nutrition throughout the year. The drivers for this investment are not only the cost of nutritional inputs, but the marginal nature of the soils used for macadamia production in this area. Australian soils are, by nature, old and highly weathered. Consequently, they are often poorly structured and have low nutrient and water holding capacities, characteristics which allow the good manager some control over their crop but, in turn, present their own set of problems.

**Fig. 8.24** Orchard preparation, tree mounds being prepared. Note satellite relay station in foreground. (©Searle)

**Fig. 8.25** Same area 18 months later. Trees were planted to within ± 2 cm within the row using a satellite guided tractor and planting machine. (©Searle)

Mature macadamias fall from the tree onto the ground where they are picked up by specialist harvesters. The harvest period in Australia typically extends from March through to September. As macadamia are ground harvested, the soil under the tree needs to be kept weed free to facilitate harvesting. In the relatively high rainfall, subtropical environment this requires frequent herbicide use. Consequently producers are moving to technology that detects the green foliage of weeds and only applies a controlled jet of herbicide when a weed is detected (Figs. 8.26 and 8.27). The herbicide sprayer sits in the middle of the inter-row, sprays both side of the tree row at once and is capable of travelling at 10 km per hour thus reducing labour and chemical costs.

Harvesters are also becoming more specialized with large self-propelled units that again, sit in the middle of the inter-row and harvest both sides of the row at once. These machines are capable of harvesting and de-husking up to 35 t of de-husked

**Fig. 8.26** Herbicide sprayer used on newly planted trees. Trees passed between the two shielded hoods. This machine is used until the trees are 2–3 years old. (©Searle)

nut per day using only one man. This high degree of mechanisation, combined with the economies of scale, means that one man can look after 30–40 ha of macadamia plantation (Figs. 8.28 and 8.29).

The continuing cost pressures are likely to maintain the move to large macadamia "plantations" and while they will continue to share some of the traditional characteristics of plantation crops, sub-tropical/tropical locations, single crop focus and an emphasis on the economies of scale unlike traditional plantations, they are likely to be characterised by the use of a small, highly specialised, well paid workforce.

## Conclusion—The Evolution of Plantations

The term plantation, although still loosely defined, is far removed from the traditional association of crops grown on a large scale using low skilled, low cost or at its worst slave labour. Plantation crops are now defined by their scale, efficiency and specialised production techniques using a skilled work force as described in the case studies.

Corporate owned and managed plantations are increasingly striving toward safe working environments linked with economic and environmental sustainability. Consumers are increasingly becoming drivers of agricultural practices (Tuckermanty et al. 2002). Organisations such as the Fairtrade Foundation (http://www.fairtrade.org.uk) seek to influence consumer choice by offering a certification structure that transforms trading structures in favour of third world producers. Corporate plantation owners such as Dole, Great Giant Pineapple, Chiquita and Cargill are increasing their presence electronically on the internet and interacting with consumers *via* social media to assure consumers of their sustainability and ethical production standards.

**Fig. 8.27** Herbicide sprayer used on older trees. A sensor detects the presence of green weeds and applies herbicide directly to them. (©Searle)

**Fig. 8.28** Part of a large modern macadamia orchard. Rows in this photograph are 300m long before a break for water control. The machinery, from left to right, are a small herbicide tractor fitted with technology that detects the presence of weeds, a large double sided nut harvester and a large mower. The water is an irrigation channel that forms part of a government controlled irrigation supply system. (©Photo courtesy of Macadamia Farm Management)

Plantations remain important production platforms for food, fibre, oil crops and timber and they will continue to evolve in response to increasing demand from a growing population.

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**Fig. 8.29** Large harvesters such as this are able to travel at 6–8 km per hour and pick up 98 % of nuts from the ground. A harvester such as this is capable of picking up 35 t of dehusked nuts per 10 h day using only one man. (©Photo courtesy of Macadamia Farm Management)

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# Chapter 9
# Berry Crops

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**Abstract** The global demand for berry fruits has increased significantly in recent years across all the main crops, partly due to the perceived health benefits derived from their consumption and also because of changes in agronomic techniques that have widened the availability and distribution of these crops. As a result, berry fruits can be purchased virtually year-round in many countries, due to season extension from enhanced agronomic strategies and also imported supplies out with the main domestic cropping season. Berry fruit crops are generally of high value, so their production and marketing can make a major contribution to rural economies.

The berry crops described in this chapter are all grown in broadly temperate climatic zones, in both northern and southern hemispheres. Strawberry remains the largest crop in terms of area and also consumer demand, whilst other crops, notably raspberry and blackberry and especially blueberries, are seeing a rapid escalation of production in many areas. The fruits are used for both fresh- and processed con-

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sumption, in proportions that vary according to crop, e.g. blackcurrants are predominantly for processing while in many of the other crops the fresh market outlets are more important. In all of the crops, sales and consumption are currently increasing.

The future for berry crops offers both opportunities and also challenges; the latter are fairly consistent across the various crops, notably the possible effects of a changing climate. The opportunities are often linked to the nutritional benefits of berry fruit components, and as further research-based evidence emerges these can lead to tangible benefits in the future marketing of berry fruits.

**Keywords** Berries · Strawberry · Raspberry · Blackberry · Blackcurrant · Blueberry · *Fragaria* · *Rubus* · *Ribes* · *Vaccinium* · Production · Genetics · Breeding · Fruit quality

## Strawberries

### *Introduction*

Strawberries are the most widely grown of all the berry crops with commercial production in 76 countries and on all continents except Antarctica. In 2010 the total production worldwide was 4.4 million tonnes from an area of 241,974 ha, with a gross value of $ 9,390 million (FAO 2012). Fifty years ago strawberries were widely grown but were considered to be a seasonal crop best suited for production in temperate regions. However, the development of varieties with a low requirement for winter chilling led to a dramatic increase in acreage in regions with warm winters, such as California, Florida and the Mediterranean countries. The combination of short-days and warm temperatures meant that the season could be extended to give cropping through late winter and early spring, giving greatly increased yield per hectare. In areas where there is a combination of warm winters and temper-

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**Fig. 9.1** Strawberry cv. Fenella, from the East Malling Strawberry Breeding Club, UK

ate summers, e.g. the central coast region of California, it is possible to extend production to 10 months of each year.

### *Genetic Resources and Breeding Advances*

The cultivated strawberry (*Fragaria* x *ananassa*) (Fig. 9.1) is a hybrid between two octoploid wild species from the Americas, *F. chiloensis* and *F. virginiana*. The former is found on the west coast from Alaska to southern Chile, while *F. virginiana* is a woodland species restricted to North America. Despite the two progenitors both being native to North America, the first hybridisation to produce *F.* x *ananassa* occurred in Europe, where both species had been introduced to botanical gardens in the eighteenth century (Darrow 1966). All modern cultivars worldwide can be traced back to those early European hybrids, with Sjulin and Dale finding that 134 North American cultivars released between 1960 and 1987 could be traced back to 17 founding clones (Sjulin and Dale 1987; Dale and Sjulin 1990). It is highly likely that cultivars from other countries have a similarly narrow genetic base, but this also demonstrates the plasticity of the cultivated strawberry genome, as 200 years of breeding has resulted in varieties adapted to environments ranging from areas with very cold winters, such as Norway and Finland, to subtropical, such as North Africa. Most breeding has been done within the *F*. x *ananassa* genepool with occasional introgression of traits from wild octoploid germplasm, the most notable of which is the introduction of the day-neutral flowering trait from *F. virginiana glauca* (Bringhurst 1982). In the last 25 years there has been a significant focus on collecting and characterising accessions of *F. virginiana* and *F. chiloensis* which has led to the identification of a core set of elite wild germplasm with a range of novel traits including different flowering behaviour, resistance to pests and diseases and improved tolerance to abiotic stresses (Hancock et al. 2003). These lines have now been used to reconstruct *F.* x *ananassa* (Stegmeir et al. 2010), and the germplasm is gradually being introduced into breeding programmes around the world, from which the benefits will become apparent in cultivars released in the coming decades. It is likely that future cultivars will have a wider range of adaptation, enabling cultivation for longer seasons of production in many areas and improved tolerance to stresses such as drought and extreme temperatures, both hot and cold.

The most notable achievement from over 200 years of breeding has been to transform the strawberry from a plant with a short season of production and a modest yield of small, soft berries to a highly productive plant capable of cropping over a long period with large firm berries suitable for shipping over long distances. The breeding programme at the University of California has been successful in developing cultivars that are grown in many countries around the world, including the Mediterranean region, Central and South America, Australia and China. A comparison of the cultivars released in 1945–1966 with those released 1993–2004 showed yield, fruit size and firmness increased by factors of 2.4, 1.7 and 1.9 respectively (Shaw and Larson 2008).

*F* x *ananassa* is a complex allo-octoploid which is highly heterozygous. This makes it a difficult subject for genetic investigations but in recent years there has been significant progress in *Fragaria* molecular genetics. The first linkage map of the cultivated strawberry was published by Lerceteau et al. (2003) and was based on AFLP markers, which are largely non-transferable. Sargent et al. (2006) produced a linkage map of an interspecific diploid progeny (*F. vesca* x *F. bucharica*) which was adopted as the international reference map for diploid *Fragaria,* and the progeny was distributed to research teams in different countries. This linkage map is based mainly on transferable SSR markers, many of which were used to develop a *F.* x *ananassa* map of the progeny Redgauntlet x Hapil (Sargent et al. 2012), which is currently the most densely saturated published map for the cultivated strawberry. In 2011 an international collaboration resulted in publication of the genome sequence for the diploid *F. vesca* (Shulaev et al. 2011), which is considered to be closely related to one of the diploid ancestors of the octoploid species. The genome sequence has been anchored to the diploid reference map in seven pseudochromosomes and represents a very valuable resource for strawberry geneticists. It has been demonstrated that there is a high level of colinearity between the diploid and octoploid strawberry species (Sargent et al. 2012).

## *Commercial Production*

**Main Global Areas** The world's largest producer is USA, with 1.27 million tonnes but production in China has been increasing rapidly in recent years and is likely to overtake this figure soon, although no official statistics are published for China. Within the USA, California produces 88 % of the strawberries and Florida 9 %. Other major world producers include Turkey (299,940 tonnes), Spain (275,300 tonnes), Egypt (238,432 tonnes) and Republic of Korea (281,803 tonnes) (FAO statistics). The leading producing nations all have climates offering long growing seasons which lend themselves to high levels of production.

**Fig. 9.2** Table-top production of everbearer strawberry under Spanish multibay tunnels in the UK

**Cropping Systems** Producers throughout the world employ either short-day or day-neutral cultivars. Short-day types initiate flowers in response to shortening day length in autumn and have varying chilling requirements. High chill cultivars are suited to temperate regions with long winters whereas the low chill types are suited to areas with warmer winters where they will produce over an extended season. Day-neutral cultivars initiate flowers irrespective of day length and temperature, although flower and fruit development is optimum during longer days.

In most regions of production, growers will use cultivars of both types to extend the season. In addition, a range of techniques are adopted either to advance or delay the cropping period. Plants can be forced into early growth by raising temperatures in the crop zone through the use of fleece/polythene film laid over the plants, low polythene cloches, walk-in polythene tunnels or glasshouse structures with additional heat or light. In areas with cold winters, fruit production can be delayed by the use of a deep layer of straw laid over the plants during cold conditions to trap cold air around the plants and exclude light. The timing of production of short-day plants can also be manipulated by cold storing either bare-root plants (frigoplants) or tray-grown plants and planting them during a growth period (long days and higher temperatures). Depending on light and temperature, such plants will crop approximately 60 days later, permitting scheduled production (Lieten 2012).

A high proportion of the strawberry crop is still produced in field soils but, in some countries, an increasing proportion is grown in soilless substrates (usually peat or coir based). The presence of soil-borne diseases can limit the availability of ‘clean’ soils and where few or no soil fumigants are approved for use, growers are forced to grow out of soil to achieve the yields and fruit quality that are required to maintain financial viability. Substrate production generally takes place in bags, pots or troughs which are either laid on the ground (sometimes on soil ridges) or increasingly on ‘table-top’ structures (Fig. 9.2) where the fruit is produced at shoulder height, helping to reduce picking costs.

When producing in field soils, it is common to plant on raised beds or ridges to increase rooting depth, improve drainage and reduce soil-borne disease. Typically the beds are covered with a polythene mulch to suppress weed growth and manipulate timing of production.

Depending on the cultivar and production system used, plants may be cropped once, twice or three times (in the case of soil-grown crops).

**Problems** The two major problems faced by commercial growers are the cost of labour and the control of diseases, invertebrate pests and weeds. Strawberry production is labour-intensive and high labour costs are a particular problem for growers in USA and western Europe. This has been a driver for the adoption of production systems that increase harvesting speeds, such as ‘table-top’ growing.

A vast number of diseases and invertebrate pests threaten production across the world. The exact nature and species of these varies according to the local climate. Of most concern are fungal root diseases caused by *Phytophthora, Verticillium, Fusarium, Pythium* and *Rhizoctonia*. Fungal and bacterial diseases of the leaves and fruit incur great expense to gain control and viral diseases can cause significant yield and revenue loss.

Of the invertebrate pests, weevils, capsid bugs, thrips, mites, aphids and nematodes give rise to the most serious crop losses across the world, although the spotted wing fruit fly (*Drosophila suzukii*) is a relatively new pest of strawberry which can lead to serious reductions in marketable yield (Dean et al. 2012). Considerable progress is being made across the world in developing novel techniques for controlling many of these invertebrate pests, particularly using biological control methods. Many of these are now used on a commercial scale, thus reducing the dependence on traditional crop protection products.

## Future Challenges and Opportunities

Consumption of fresh strawberries looks likely to continue to increase, with strong demand in countries that have experienced rapid economic growth in recent times, such as China, Russia, Brazil and India. Strawberries can be available throughout the year, so are no longer considered a seasonal crop by consumers and are popular because they are considered to be a healthy food that is affordable, pleasant to eat and requires minimal preparation. The challenge facing producers will be to meet the increasing demand in a sustainable and cost-effective way. Currently all strawberries for dessert use are harvested by hand and in most cases this is the largest cost of production. Many countries currently rely on migrant labour for harvesting but there is also a trend for production to move to countries where labour costs are lower, although these are inevitably further away from the main markets and strawberries are a perishable product. This model is not sustainable and it is likely that robotic harvesting will become a reality in future, particularly for strawberries grown in glasshouses or permanent polytunnels. Prototype harvesters have already been developed and tested in Japan, China, USA and Europe (Feng et al. 2012; Hayashi et al. 2010).

The trend towards protected cropping and substrate-based production is likely to continue, driven by the need for increased intensification and difficulties in dealing with soil-borne diseases. Although these production systems are more expensive to set up, they deliver higher productivity per unit area and reduced pressure from most diseases, resulting in fewer chemical inputs. The combination of cultivars with improved disease resistance and elevated cropping systems under protection will help to achieve the goals of eliminating pesticide residues, minimising waste and reducing harvesting costs.

## Raspberries (*Rubus* spp.)

### *Genetic Resources and Breeding*

Raspberries are among the most globally well known fruits, and are members of the *Rubus* genus, one of the most diverse in the plant kingdom with several hundred species (Jennings 1988). Raspberry is the main crop within the genus, presenting different colours (from black to yellow) and shapes (conic to round). The red raspberry plant *Rubus idaeus* L. has biennial canes attached to a long-lived root system. Raspberry breeding started in the fourteenth century, with the first scientific report published in 1913 (Moore 1979).

The red raspberry can be divided in two main groups according to their flowering behaviour, namely, primocane and floricane fruiting varieties. The first report regarding primocane fruiting behavior dates from 1806 (Brierley 1931). A cultivar is considered a primocane fruiter if flower differentiation occurs during the growing season and if fruiting is sufficient to allow a profitable crop.

There were presently around 30 *Rubus* breeding programmes globally, mainly focused on red raspberry (Finn and Knight 2002), and there have been additional efforts to breed black raspberries due to their high anthocyanin content (Dossett et al. 2012; Weber 2003).

### *Commercial Production*

Raspberries are increasingly popular berries, with sales historically high in the retail market (Sills 2010). World raspberry acreage and production has been stable for the last ten years, around 92,098 ha with 463,447 tonnes for both fresh and processing with Russia Poland and Serbia being the largest producer with more that 63 % of the total (FAO Stat 2012). This achievement has been possible due to advances in knowledge throughout the supply chain, and in particular the development of new cropping methods, which harness the remarkable physiology of the raspberry plant and its plasticity to allow raspberries to be available all year round. For the fresh market several growing systems, often based on the use of protected cropping under

**Fig. 9.3** Primocane raspberry cv. Polka, bred in Poland

polytunnels, have been developed worldwide by growers and researchers in order to produce red raspberries for the fresh market throughout an extended cropping season. Primocane-fruiting raspberries are easily manipulated to further extend the season (Fig. 9.4), and by using high tunnels a double crop is easily achieved. Different methods can be applied but the main system used consists in early summer planting, which is May in the northern hemisphere) for an autumn harvest and cutting the canes at fruiting level for an early spring crop. The spring crop is normally low, with yields depending on chilling requirements of the cultivar used. Some growers prune canes at ground level after the first crop in order to have a larger fall crop (Oliveira et al. 1998). For the early market, long-canes of high yielding floricane-cultivars are used. Growers can use long-canes lifted from high altitude nurseries or can store their own canes in refrigerated containers (Oliveira et al. 2002). The most important cultivars in this long-cane system are 'Tulameen' 'Glen Ample'. In the primocane-fruiting types new cultivars are now available, namely 'Polka' (Fig. 9.3), 'Erica', 'Sugana', 'Amira', 'Kweli', 'Imara', with 'Maravilla' from Driscoll's Strawberry Associates the most productive with uniform, firm and bright berries. Private breeding programs are becoming increasingly important with public breeding programs licensing cultivars to specific countries or regions.

Machine harvesting of raspberry remains of considerable importance in many areas of Europe, particularly for processing and IQF markets (Hall et al. 2002), and there are clear differences in machine harvestability between cultivars. Whilst most breeding of new cultivars is now directed at the more lucrative fresh markets, trials to examine suitability for mechanical harvesting are still an integral part of some breeding programmes.

Irrigation and nutrition are also key aspects in maintenance of productivity, as the use of substrate culture is increasing. Substrate culture is leading to an increased specialization of raspberry growers, and the use of greenhouse production is growing in the southern parts of Europe.

**Fig. 9.4** Field plantation of primocane-fruiting cv. Autumn Bliss

The main disease concern in raspberry is root rot caused by *Phytophthora rubi,* and this has led to serious losses of both crop and new planting opportunities in many raspberry-goring areas, especially in the more northerly and wetter regions. Attempts to breed new resistant cultivars, mainly based on resistance from the old US cultivar 'Latham', are nearing fruition, and the identification of molecular markers linked to resistance (Graham et al. 2011) will hasten this process. In the meantime, improved control of *P. rubi* in nurseries and propagators can reduce the incidence of root rot. Viruses remain a problem, especially the pollen-borne raspberry bushy dwarf virus (RBDV) (Moore and Martin 2008). The incidence of aphid-borne viruses is likely to increase in the future as the effectiveness of existing aphid resistance genes break down (McMenemy et al. 2009). The raspberry beetle *Byturus tomentosus* is a major pest in north European countries, mainly Scotland, Switzerland and Norway (Baroffio et al. 2012), with few controls or resistance genes available. However, a new pest *Drosophila susukii* Matsumura is affecting the berry industry worldwide. Since its outbreak huge losses have been observed in USA and Europe, affecting mainly fruit for fresh market. Little research has been done on this pest and at this point traps for mass capture are the only solution available.

The awareness of berry nutraceutical proprieties by consumers is in part responsible for the big increases in berry sales, and considerable research efforts have been made to determine key health-promoting compounds (Wang and Jiao 2000; Tavares et al. 2011). Raspberries are particularly rich in ellagitannins, and these have been found to have an anti-proliferative effect on human carcinoma cells *in vitro* (Ross et al. 2007), but further studies on bioavailability and effects *in vivo* are required.

## Future Challenges and Opportunities

The major challenge for raspberry production is climatic changes which can affect plant behavior and allow different pest species to develop in new areas. Also, in a changing climate production systems must adapt to high temperatures and extreme weather events, with plant dormancy being especially affected. Water availability and quality is a further consideration throughout horticulture, and the berry industry is not immune from these issues.

The reduction in public breeding programs is shifting the industry towards bigger companies that are able to develop their own private breeding programs, and this can ultimately reduce consumer choices. However, on the other hand, local markets with specific regional cultivars are becoming more popular. Overall, berry consumption is increasing due to their high levels of health-promoting compounds, and research into their nutritional effects, including those from raspberry, is attracting more and more young researchers. These attributes for raspberry can have a positive effect on future production and marketing.

## Blackberries

### *Introduction*

Commercial production of blackberry (*Rubus* subg. *Rubus* Watson) has expanded dramatically from the late twentieth to early twenty-first Century (Finn and Clark 2011; Strik et al. 2007). A few decades ago, blackberries were either unavailable in grocery stores or they were only available from local suppliers during a short season when locally produced berries were ripe. Now blackberries are in the marketplace next to raspberries and blueberries year-round, with off-season fruit being shipped in from warm-season production areas.

Humans have probably always included blackberries in their diet as they are often common and abundant in their native range (Jennings 1988). Archaeologists found evidence of *Rubus* as a food source in central Oregon (USA) that can be carbon dated to about 8,000 BCE (Hummer and Janick 2007). The first mention of blackberries in literature was by Theophrastus in 370 BCE and their representation in iconography extends back to the Juliana Anicia Codex of 512 CE. Blackberries began to be mentioned in gardening books in the late 1600s. Breeding to improve blackberries as a crop began in the late 1800s in Europe and North America (Clark and Finn 2011).

The first large-scale commercial production began on the Pacific Coast of the US in the early 1900s, primarily with the cultivation of cultivars such as ‘Logan’ and ‘Boysen’ that are hybrids between blackberry and red raspberry. This production fed the growing population in this region and it was canned, and, when the technology developed, frozen to be shipped to the eastern population centres. Until the late twentieth Century most fresh fruit was harvested locally often from wild stands. New cultivars, production techniques and new production areas have lead to year-round availability of fresh and processed blackberries (Table 9.1).

**Table 9.1** Important historical and leading blackberry cultivars

| Cultivar | Type |
|---|---|
| Natchez | Erect to semi-erect |
| Navaho | Erect |
| Ouachita | Erect |
| Prime-Ark® 45 | Erect |
| Tupy | Erect |
| Čačanska Bestrna | Semi-erect |
| Chester Thornless | Semi-erect |
| Loch Ness | Semi-erect |
| Triple Crown | Semi-erect |
| Black Diamond | Trailing |
| Kotata | Trailing |
| Marion | Trailing |
| Obsidian | Trailing |
| Olallie | Trailing |

## *Genetic Resources and Breeding Advances*

Several excellent in-depth reviews have been written on the breeding of blackberries, from which much of the following information was drawn (Clark et al. 2007; Clark and Finn 2011; Finn 2008; Jennings et al. 1992). Blackberries are classified into three types based on their growth habit—trailing, erect and semi-erect. Plants produce vegetative primocanes their first year and these usually become reproductive in the second year when they are called floricanes. Primocanes of the trailing blackberry run for 3–6 m along the ground as they grow, and growers lift the canes and tie them to a trellis. Trailing blackberries have historically been more commonly machine harvested for the processing market (whole frozen, puree, juice, and dried). These types of blackberry were predominantly developed from the western dewberry (*R. ursinus* Cham. et Schltl.) native to western North America, but also have an ancestry that includes red raspberry (*Rubus idaeus* L.), Himalaya blackberry (*R. armeniacus* Focke) and the dewberry native to the central and eastern U.S. (*R. flagellaris* Willd.). The erect blackberries have an upright habit with the primocanes emerging from crowns and root buds and growing to 2–3 m tall. While growers typically use a trellis for this type it can be a much less substantial trellis than for the other types. The primocanes from the semi-erect blackberries emerge from a crown and grow vigorously upright until they arch over when they reach 3–4 m tall. A sturdy trellis is required for their production. The erect and semi-erect blackberries are most commonly hand harvested for the fresh market and have a similar genetic background with the predominant species in their ancestry being *R. allegheniensis* Porter and *R. argutus* Link native to the eastern U.S.

These three types of blackberries were only developed and domesticated from wild species in the past 100 years. The first cultivars of trailing blackberry were released in the late 1930s by the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) in Oregon, the first semi-erect cultivars in the 1960s by the USDA-ARS in Maryland, and the first improved erect cultivars by the University of Arkansas in the 1970s. The goals of breeding programs for each of these types include develop-

**Fig. 9.5** Field plantation of blackberry cv. Metolius in Oregon, USA

ing high-yielding cultivars that are thornless and produce fruit with outstanding quality and that are easy to harvest. In the case of the breeding programs for processing blackberries, the most important characteristics include excellent fruit quality, which includes intense colour and flavour with high sugar and acid levels that make them a better processed fruit, and fruit that are machine harvestable. In the case of the breeding programs for fresh market types, excellent fruit quality includes firm fruit that can be harvested firm black with sweet flavour and tough skin. Recently breeders have developed erect cultivars that fruit on current season's growth. These primocane-fruiting cultivars are well suited to the fresh market.

## Commercial Production

North America is the world's leading production area (Finn and Clark 2011). Central Mexico has the greatest fresh- market production of fruit in the northern hemisphere's winter. California, followed by the southeast and northwest U.S., is the major fresh market production area during the summer and Oregon is the leading producer for processing (Fig. 9.5). There is scattered fresh market production in Europe and Asia, and Serbia is a major producer for the processing market.

Blackberries are grown in perennial cropping systems with some sort of trellis. The floricanes are removed after they are done fruiting and the new primocanes trained to the trellis for production in the following year. The erect and semi-erect blackberries are tipped at 1–1–1.5 m to encourage branching that increases productivity. Well-managed fertility, irrigation, and pest management programs are needed to maximize production and quality. For 'Tupy' production in Mexico where no winter chilling is experienced, a unique system using chemical defoliation and growth regulators is used to stimulate and program flowering and fruiting to target market opportunities (Clark and Finn 2011). The primocane-fruiting blackberries are simply cut to the ground in the off-season and the primocanes are tipped at 0.6–0.7 m to encourage branching for greater productivity. Some floricane fruiting of primocane cultivars is conducted by some growers.

Compared to most berries, blackberries have fewer disease problems. Viruses are a major problem throughout the cropping range, and systemic rust fungi and double blossom rosette (caused by *Cercosporella rubi*) can kill plants in the eastern North America. However, most diseases are readily controlled with good cultural practices and the planting of virus-tested stock.

### *Future Challenges and Opportunities*

Blackberry consumption continues to increase worldwide and the future opportunities are endless. Fruit quality, particularly berries with no off-flavours and with less noticeable seeds, is of particular interest in new cultivars. As blackberries are pushed out of their ideal environments into new production areas and systems, it will be critical to develop cultivars and production techniques that will support this expansion.

## Currants and Gooseberries

### *Introduction*

Fruits of the *Ribes* genus are divided into currants (black, red and white) and gooseberries. They are predominantly used in processing, although there have been significant rises in their popularity as fresh berries in some European countries, partly as a result of their perceived health benefits (Brennan and Graham 2008).

Blackcurrants are from the sub-genus Eucoreosma, and most commercial types are derived from the species *Ribes nigrum* L. and its subspecies, notably *R. nigrum* var. *sibiricum* and var. *scandinavicum*. Domestication of blackcurrant has taken place only within the last 400 years (Brennan 1996).

Redcurrants were first grown as garden plants for fruit in the sixteenth century in Holland and Denmark (Roach 1985), at which time the main species progenitor was *R. sativum*. Further red-fruited species that were subsequently introduced were *R. petraeum* and *R. rubrum*, and modern breeding has also incorporated *R. spicatum* and *R. multiflorum* from Scandinavia (Brennan 1996). White currants were described in the seventeenth century and are a mutant form of the red.

**Fig. 9.6** Blackcurrant cv. Ben Starav, bred at the James Hutton Institute, Scotland for the juice processing industry

Gooseberries can be divided into two groups, deriving from Europe and North America respectively. The European group is based on *R. grossularia*, with large fruited types described from the sixteenth century, whilst the North American types are mainly based on the native species *R. hirtellum* and *R. oxyacanthoides*.

## *Genetic Resources and Breeding*

The *Ribes* genus contains around 150 species of shrubs distributed throughout northern temperate Europe, North America, Asia and the mountain regions of South America and North Africa. However, to date only a relatively small proportion of the available species have been used in breeding, and there is increasing interest in the wild genepool as a source of valuable traits (Brennan 1990), particularly for environmental resilience and pathogen resistances.

Breeding of new blackcurrant cultivars has been in progress since the early nineteenth century, and today there are active programmes in Northern and Eastern Europe and New Zealand. The objectives of most breeding programmes are closely aligned with specific end-user requirements, notably from the processing industry (Fig. 9.6). The breeding of redcurrants and gooseberries is more restricted, with programmes in Eastern Europe and the Baltic States, and many older cultivars are still in commercial production. In the case of blackcurrant, there are now significant genomic resources available (Brennan et al. 2008; Russell et al. 2011), and these are being developed to decrease selection time in breeding programmes.

**Fig. 9.7** Machine-harvesting of blackcurrants in Gloucestershire, England

## *Commercial Production*

Most commercial *Ribes* production is in northern and eastern Europe, and in the case of blackcurrant the crop is largely machine-harvested for processing, mainly for juice (Fig. 9.7). Blackcurrant production in 2011 was estimated at 151,000 tonnes in Europe and 196,000 tonnes worldwide (Anon 2012). The largest global producer is Poland, followed by the UK, France and Scandinavia. Accurate production estimates for Russia and China are not available but blackcurrant crop has an increasing economic importance in those countries. Blackcurrant production in North America is small, despite favourable growing conditions, mainly due to white pine blister rust (*Cronartium ribicola*), for which *Ribes* species can be alternate hosts. As a result, restrictions and laws prohibiting cultivation of *Ribes* in the US were implemented, although most states have now removed those restrictions and there is a growing interest in expanding *Ribes* production (Hummer and Dale 2010).

Commercial gooseberry production began at the end of the nineteenth century, and some cultivars from that time have continued to be grown in Europe, notably `Careless' and 'Whinham's Industry'. However, gooseberry mildew (*Sphaerotheca mors-uvae*—the same species as on blackcurrant) has made resistant cultivars increasingly important for cultivation, whether commercially or in home gardens.

One of the key factors in the development of blackcurrant as a crop, at least in northern Europe, is its inherently high levels of vitamin C (ascorbic acid, AsA). In the UK, during and after the Second World War commercial growing of blackcurrant was encouraged in order to produce vitamin C-rich juices for infants. Levels in commonly grown cultivars are between 130–200 mg/100 ml juice, although some breeding lines can have almost twice as much (Brennan et al. 2008) and some wild accessions of *R. nigrum* var. *sibiricum* even more (Volunez and Zazulina 1980). The AsA content of blackcurrant can vary according to the cropping season, but the relative cultivar rankings remain fairly constant (Walker et al. 2010).

Blackcurrants are also rich in polyphenols, including flavonoids such as anthocyanins and flavonols, and cultivars containing elevated levels of anthocyanins are now in demand from both processors and consumers (Giné Bordonaba and Terry 2008; Brennan and Graham 2009).

The most immediate threats to blackcurrant production are pest- or pathogen-based. The blackcurrant gall mite (*Cecidophyopsis ribis* Westw.) causes rapid decline in crop yields, partly due to its role as a vector of blackcurrant reversion virus (BRV). This renders bushes sterile within two years. The incidence of mites has risen in recent years, mainly due to the withdrawal of many control chemicals, and the long-term sustainability of production depends largely on the development of resistant cultivars. Sources of resistance to both the mite and the virus are available: genes *Ce* from gooseberry (Knight et al. 1974) and *P* from *R. nigrum* var. *sibiricum* (Anderson 1971) both confer resistance to *C. ribis*, although the resistance conferred by *Ce* is thought to be more robust. Molecular markers for *Ce*-based resistance are routinely used for identification of new resistant seedlings (Brennan et al. 2009), and similar markers for gene *P* have been reported by Mazeikiene et al. (2012). BRV resistance from *Ribes dikuscha* has been used by breeders, notably in the cultivars 'Golubka' and 'Ben Gairn', although the genetic control of resistance is unclear.

Foliar diseases of importance on blackcurrant include mildew (*Sphaerotheca mors-uvae*), leafspot (*Drepanopeziza ribis*), Septoria leafspot (*Septoria ribis*) and white pine blister rust (*Cronartium ribicola*). Resistance is available for most of these diseases within the *Ribes* genepool, and increasingly breeders are focusing on the production of resistant cultivars as chemical control methods become more restricted (Brennan et al. 2008).

The major pests of *Ribes* apart from gall mite include the leaf-curling midge (*Dasineura tetensii* Rübs.), which has increased in importance and distribution in recent years. Other problems are caused by clearwing (*Synanthedon tipuliformis*) in many production areas, especially New Zealand, and sawfly (*Nematus ribesii*), the latter being particularly serious on gooseberry. Many currant and gooseberry growers are now looking into Integrated Pest and Disease Management strategies for effective control of these problems.

## *Future Challenges and Opportunities*

Environmental resilience is likely to become an important factor in the sustainability of *Ribes* production, especially blackcurrant, in northern areas, due to the reduced levels of chilling during recent winters. This has led to erratic budbreak in some cultivars with a high chilling requirement, and if the trend continues as a result of a changing climate then selection for more resilient cultivars will be required (Jones et al. 2012), although earlier budbreak has already increased the risk of frost damage at flowering time in some northern areas.

The diverse array of health-beneficial compounds in *Ribes* fruits, especially blackcurrant, gives opportunities for an expanded market for these fruits. Current studies are looking at bioavailability of these compounds in human nutrition, together with their activity against specific health issues.

Some emerging pest and disease problems require some attention from breeders; blackcurrant clearwing (*Synanthedon tipuliformis*) has become a major problem in New Zealand on all currants and may already be found in drier and warmer areas of Europe; and stem dieback caused by *Phomopsis* spp. is increasingly problematic on certain cultivars of blackcurrant. Additionally, breeders are developing new blackcurrant cultivars with resistance to white pine blister rust, mainly based on the *Cr* resistance gene from *R. ussuriense*, as this may increase the acceptability of blackcurrant production in North America.

# Blueberries

## *Introduction*

Blueberries are members of the Ericaceae family, within the genus *Vaccinium* in the Cyanococcus section. The genus includes approximately 400 species, and the Cyanococcus section comprises some 10 to 26 species, depending on the taxonomic classification used (Ballington 1990) (Table 9.2).

Commercial orchards exist of highbush (*V. corymbosum* L.) and rabbiteye blueberries (*V.* ashei Reade syn. *V. virgatum* Ait.), whereas the lowbush blueberries (*V. angustifolium*Ait.) are only handled in a semi-domesticated way. Highbush blueberries are further sub-divided, depending on their winter hardiness and chilling requirements, into northern, southern or intermediate types. Highbush blueberries are the types most extensively planted world-wide, and are found in, amongst others, USA, Canada, Chile, Argentina, South Africa, Australia, New Zealand, Japan and China, as well as in several European countries (Strik 2005; Strik and Yarborough 2005). Since the start of the millennium there has been a remarkable increase in the planted area of blueberries on a world-wide level (2003–2008 = +250 %); the largest increases between 2003 and 2008 were in China (2,230 %), Argentina (529 %), Chile (429 %) and Spain/Portugal (363 %). Worldwide acreage is now led by the USA (38,871), Chile (11,300) and Argentina (4,470) (Retamales and Hancock 2012).

## *Genetic Resources and Breeding*

The breeding of blueberries is a relatively recent activity, although many of the wild species of blueberries were harvested for hundreds of years in their original habitats by the native North Americans (Moerman 1998). In 1893 Elizabeth White started the culture of blueberries in Whitesbog (NJ) and, in collaboration with Frederick Coville of the USDA (at the beginning of the twentieth century), collected clones of highbush and lowbush blueberries (mainly *V. angustifolium*). This led to the first hybrid being released in 1908 (Hancock et al. 2008).

Coville was followed by George Darrow, who, in parallel with his other work, began to collaborate in the 50's with Ralph Sharp (Florida). Sharp himself, in collaboration with Wayne Sherman, released the first successful varieties of Southern highbush (Lyrene 1998). In parallel, by the end of 30's, Darrow, Otis Woodard and Emmett Morrow initiated the work with rabbiteye blueberries (*V. ashei*) (Hancock et al. 2008).

**Table 9.2** Species, type and origin of blueberries. (Sources: Ballington 1990; Hancock et al. 2008; Lyrene 1998; Eck and Childers 1966; Eck 1988; Rowland et al. 2011)

| Species | Type | Origin in North America |
|---|---|---|
| *V. darrowi* | Lowbush | South East USA |
| *V. myrtilloides* | Lowbush | North East USA and Canada |
| *V. tenellum* | Lowbush | South East USA |
| **V. angustifolium** | Lowbush | North East USA and Canada |
| *V. myrsinites* | Lowbush | South East USA |
| **V. corymbosum** | Highbush | North East and Central USA |
| **V. ashei** *(syn. V. virgatum)* | Rabbiteye | South East USA |

The most common commercially-used species are in bold

Since then a series of successful varieties have been released, many of them with a complex genetic composition as the products of interspecific hybridizations within the genus (Hancock 2006; Brevis et al. 2008). This has given rise to the current wide pedigrees which offer many breeding opportunities to enhance characters of interest through the use of judicial parents in crossing (yield, small and dry scar, fruit size, flavor, color, plant habit, and nutritional factors and functionality).

In the mid 1990's, Germany, Australia and New Zealand all started breeding programs based on open-pollinated seeds from the United States. Today, there are geographically even more widely dispersed improvement programs, some of which are based in private companies in Spain, Australia, USA and Chile (Hancock et al. 2008) (Fig. 9.8).

Because many of the new production areas around the world are distant from their target consumer markets, postharvest life and fruit condition following long journeys has become an almost universal focus for highbush blueberry breeding. Southern highbush breeders have focused on early ripening with better vigour, yields, disease tolerance/resistance, late bloom (where late frosts are a problem) and better sensorial characteristics. Northern highbush breeders have focused more on lateness and extended harvest dates, while also concentrating on flavour (mainly in very late varieties), disease and pest tolerance/resistance and the ability to be hand- or machine harvested (Hancock et al. 2008).

Much of the breeding to date has been by traditional crossing and selection. However, there is continuing work on molecular markers and gene mapping, in order to increase the efficiency of exploitation of genetic resources as well as improving selection methods (Rowland and Levi 1994; Rowland et al. 2003; Rowland and Hammerschlag 2005; Rowland et al. 2012; McCallum et al. 2012; Novy et al. 1994).

## Commercial Production

Blueberries are deciduous shrubs that, depending on species and cultivar, range in height from 2 to 4 m (Camp 1945). They have a fine, fibrous root system (without root hairs) (Eck and Childers 1966; Eck 1988) that is concentrated (almost 80%)

**Fig. 9.8** Commercial blueberry breeding programme, with raised beds and drip irrigation lines

in the first 30 cm of soil (Bryla and Strik 2007). The roots are sensitive to excess water and so in heavy soils, raised beds are used for cultivation, although rabbiteye blueberries appear to be less sensitive. However, hairless roots require a superficially humid soil with good drainage, for reasons noted above. This makes likely the occurrence of hydric stress, to which the plants are also sensitive but generally do not show immediate symptoms, and also means that soil cultivation close to plants carries a high risk of causing damage or death to the plants.

Blueberries need a certain number of hours of cold accumulation; the amount varies depending on the species but is in the range of 200- to 1100 hours at less than 7.2 °C. The Northern highbush cultivars require 800–1200 chilling hours, while Southern highbush require from 200 to 600 chilling hours (Hancock et al. 2008).

Blueberries are considered to have a low nutritional demand compared to many fruit trees, and optimum growth is normally in soils with acid pH (4.0 to 5.5), where nutrient availability is reduced (Hanson and Hancock 1996; Williamson et al. 2006).

Pruning of blueberries is considered essential and has two main functions: to regulate the fruit load and rejuvenation. The premature aging of orchards is one of the most common consequences of lack of pruning as a balance is needed between new shoots emerging from the crown and the canes of different ages needed for production. Southern highbush plants are also pruned to maintain size (Yarborough 2006).

Levels of self-fertility within cultivars are also a factor. Recent studies have shown fruit set can decrease by up to 57 % and fruit size by 30 % when comparing the reaction of different varieties to self- or cross-pollination (Retamales and Hancock 2012). It is therefore imperative that breeders test the self-fertility of potential new releases as they are usually evaluated in small blocks where outcrossing is common.

The fruit is an almost spherical berry (7 to 15 mm in diameter) with a colour that depends on the variety but can vary from light blue to deep black and which is covered with an appealing waxy coating (bloom) (Fig. 9.9). The fruit contain 20–80 seeds within the endocarp. A feature of the fruit is the bloom scar, which

**Fig. 9.9** Fruiting stem of highbush blueberry, showing fruit at different stages. This can generate a long harvest period.

is commercially sought to be small and dry (thus fungal infection and reducing dehydration) (Gough 1994).

Harvesting can be manual or mechanical, with the harvest times and intervals dependent on variety, weather conditions and availability of labor. The harvest frequency is important in relation to the balance between quality and performance, so that harvesting every 3 to 5 days can result in a higher yield and better commercial quality compared to a harvest on a daily basis (Retamales and Hancock 2012). The fruits destined for fresh consumption must be firm, uniformly blue and undamaged (Gough 1994).

## Future Challenges and Opportunities

One of the major future challenges is that of climate change, resulting in higher temperatures and moisture variability (IPCC 2001).Leaf damage can occur in rapidly growing blueberry plants when temperatures approach 30 °C (Moon et al. 1987; Hancock et al. 1992; Trehane 2004). This may well reflect the fact that, as shown by Trehane (2004) and Lobos et al. (2012), fully expanded leaves can have temperatures 10–15 °C higher than the ambient one. Shading nets are proving useful to control plant (and fruit) temperature in the field (Lobos et al. 2012).

Temperatures ranges during fruit ripening and coloring are also critical (Gil 2000), and the pre-harvest environmental conditions strongly affect the postharvest life of the fruit (Prange and Deell 1997; Nesmith et al. 2005). Additionally, increasing temperatures can affect the behavior of pollinating insects and thus the efficiency of fertilization of the flowers (Gough 1994) (Fig. 9.10).

Another aspect of climate change is the predicted reduction and change in pattern of rainfall per year as well as the increase in temperature. This therefore points to the importance of developing genotypes tolerant of reduced levels of water and efficient in its use. Further studies of water consumption patterns are needed but

**Fig. 9.10** Different stages of floral development on individual blueberry stems require the presence of pollinating insects over an extended flowering period.

equally importantly, detailed extension advice should be given to growers who tend to apply standard irrigation protocols to all varieties despite the obvious differences in water use efficiency, for example depending on whether the cultivars are early, mid or late in maturity.

Another major issue for the coming decades, as with many other fruit crops, is the cost and availability of hand labour, which for blueberry already represents 50–60 % of the annual costs of production). An important and increasing challenge that faces growers each year is the availability of skilled labour for harvesting who each year become scarcer and more expensive at the time they are needed (Takeda et al. 2008). There is still a need for gentler machine harvesters, together with new cultivars appropriate firmness, resistance to bruising, round fruit, easy pedicel removal and skin thickness (Ehlenfeldt 2005).

As with all crop species there is a continuing struggle to control pests and diseases, a problem that is emerging more significantly now for blueberries, due to their more recent domestication. These emerging biotic stresses need to be viewed against the background of climate change and hence the potential for a new spectrum of pests and diseases to appear in the blueberry growing areas.

The consumption of blueberries is still increasing on a world basis and thus the market is still expanding. More emphasis will likely be placed on the quality and functionality of the blueberry in human diets, and this can be enhanced through breeding, selection and appropriate production management.

## Conclusions

Consumption and public interest is increasing across all the crops highlighted in this review, as new cropping areas, systems and products are identified and developed. In most instances, the production industries have evolved into highly efficient operations regarding crop yield and quality, profitability and reduction of waste, and new cultivars can now be targeted at specific sectors of the market. The development and adoption of new technologies, both in agronomic systems and also in new breeding strategies, can assist the industries based on the various crops to meet the serious challenges presented by factors such as climate change and loss of crop protection chemicals. Together with the opportunities for increasing berry consumption based on their nutritional benefits, this should ensure a healthy future outlook for these crops.

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# Chapter 10
# Protected Crops

**Nazim Gruda and Josef Tanny**

**Abstract** The increasing demand by world markets for high quality products has lead more and more agricultural/horticultural crop production systems to protected environments. Covering the crop allows regulation of macro and micro-environments, which facilitates optimal plant performance, extension of the production duration, induction of earliness, and obtaining higher and better quality yields. A spectrum of covered structures is used by growers, depending on the crop, the climatic region and the anticipated benefit. These structures can be generally classified as either screen construction or greenhouse. This chapter comprehensively discusses the effects of the most common types of structures on the major environmental variables: radiation, temperature, humidity, air velocity, ventilation, and carbon dioxide concentration, as well as the effects of these climate modifications on the various crop attributes such as plant growth and development, water and fertilizer supply, and some cultural practices. Moreover, the chapter outlines the objective, measurable aspects that relate to external and internal product quality that are under the influence of intrinsic and extrinsic factors. Finally, some recommendations concerning optimization management in protected cultivations are highlighted, in order to achieve high yields and high quality horticultural products, on time delivery, and energy saving at minimal expense.

**Keywords** Evapotranspiration · Greenhouse · Climate conditions · Cultural practices · Photosynthesis · Product quality · Soilless culture · Screenhouse · Transpiration

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## Introduction

The increasing demand by world markets for high quality yield has lead more and more horticultural crop production systems into protected environments. Covering the crop does not only protect it from external natural hazards, but also allows for artificial manipulation of the crop micro environment to facilitate optimal plant performance, extend production duration, induce earliness of flowering, and improved production, and/or better quality product. According to Kacira (2011) the top 5 worldwide countries by protected cultivation area are China with more than 2,760,000 ha, Korea with 57,444 ha, Spain with 52,170 ha, Japan with 49,049 ha and Turkey with 33,515 ha.

A spectrum of covered structures is used by growers, depending on the crop, the climatic region and the anticipated benefit. These structures can be generally classified into two categories: screen constructions and greenhouses. The former are covered by permeable porous screens while the latter by impermeable transparent plastic films or glass. The two groups can also be classified according to the nature of the internal climate control, passive for the screen constructions and active for the greenhouses, although sometimes a combination of both structures and/or climate control approaches is used. Passive climate control means that once the house is constructed, no actions are undertaken by the grower to artificially modify the microclimate. There is strong interaction between inside and outside conditions and exchange processes between the crop and the outside atmosphere are governed by system attributes. On the other hand, active climate control means that besides the structure and cover, systems are installed that enable manipulating of the inside microclimate. In greenhouse structures the inside is more isolated from the outside, than in screen-constructions.

The simplest type of the first category is a porous screen cover made of plastic threads, horizontally deployed above the crop which protect crops from the sun and physical damage by reducing the incoming radiation and wind speed. A more advanced type of cover is the screenhouse (also called net-house) which, in addition to the horizontally deployed screen, includes screened sidewalls. Such structures, if made of sufficiently dense screens are insect-proof, thus avoiding insect invasion into the crop and allow for a significant reduction of pesticide application. In the analogy with screens, perforated transparent foils are used to cover the plants, in order to improve their earliness of maturity.

A more advanced structure type is the naturally ventilated tunnel or greenhouse. This structure is covered by an impermeable transparent plastic film which may include roof and/or side vents that allow the natural ventilation of the interior by wind or buoyancy forces. Opening and closing these vents can be operated either manually or automatically by a control system. These structures provide better climate control than screen constructions. In northern European countries such structures are covered by glass for higher radiation transmittance.

The most sophisticated structure is the so called Hi-Tech greenhouse. Generally, these structures can be equipped with any climate control system, thus allowing a wide range of growth manipulations. Some examples are shading, cooling by wet pad or fogging, heating and dehumidifying, and providing artificial illumination.

Most of the commercial plastic films and porous screens are made of low density polyethylene with some additives. The latter are used for purposes like, avoiding plastic film degradation due to UV radiation, preventing nighttime radiation cooling by blocking infrared radiation (IR) transmittance to the sky, avoiding dripping of condensed water vapor on the inner side of the film and decreasing dust accumulation on the outside of the cover. Such additives may modify the crop radiation and energy balances and hence greenhouse microclimate.

Microclimate of protected crops is a major factor in determining the internal atmospheric water demand and hence potential crop water use. Shade and reduced wind speed usually decrease the water demand in comparison to the open in tropical, subtropical, semi-arid or desert regions and hence may lead to increased *w*ater *u*se *e*fficiency (WUE) (see box 1). In tropical regions greenhouses, or the so called rainshelters, are used to protect the crops from rain storms. Nearly 90 % of the energy costs in greenhouses in the northern European countries are for heating. Since the first energy crisis at the end of the 1970's, the efforts for reducing the heating costs in these countries have increased enormously. Not only do the growers benefit from increased profitability due to higher yields and quality of produce grown in greenhouses, but this fits very well with our current environmental concerns and the objective to reduce carbon dioxide ($CO_2$) emissions within protected cultivation.

Since each type of structure and cover induces a different microclimatic modification, it is outside the scope of this chapter to review in detail all these effects. Rather, the chapter outlines the effects of most common types of structures on the major environmental variables: radiation, temperature, humidity, air velocity, ventilation, $CO_2$ concentration; and, in turn, how these modifications influence various crop attributes like plant growth, productivity and product quality. For didactic and practical reasons, the main approach of this chapter is to present the reactions of protected crops to singular environmental variables. In order to view the entirety of the concept, the reaction of crops to actual conditions within protected cultivations is illustrated through the use of some examples.

Most crops in protected cultivation are vegetables, followed by cut flowers and potted ornamentals and fruits. The reaction curves of plant growth and development are optimum functions marked by a minimum, an optimum, saturation, and/or a maximum of environmental conditions. However, the optimum points in curve courses are not the same for different attributes or crops. In the past, enormous investigation have been conducted concerning plant growth and productivity of protected crops, and different models have been developed; however the focus in this chapter will be on product quality that in recent years, has become more and more important due to consumer concerns.

Plant growth and productivity are very well defined; the first as a difference for any given parameter in the course of time and the second as a source of production for a given ground area of plant material. Product quality, on the other hand, is a complex issue not only depending on different factors, but also on different perspectives. The different actors involved in the value chain, from breeders through growers, traders, processors to the consumer, have their own expectations on the quality of horticultural products. Furthermore, the aspect of multidimensionality adds to the complexity and specificity of product quality. For instance, the quality parameters could be either intrinsic or extrinsic, the quality either external or internal and the criteria for its evaluation either objective or subjective (Gruda 2005). The chapter outlines the objective, well measurable aspects of quality related to the reaction of plants under the influence of intrinsic factors expressed in both external and internal qualities. Thus, it records a quality evaluation based on market, utilization, sensory, nutritional and health value of horticultural crop protected products. The influence of extrinsic factors and the use of subjective criteria are excluded here.

Finally, the optimization of management in protected cultivations will be highlighted, in order to yield high quality products, on time, applying energy savings methods and at minimal expense.

## The Radiation Balance of Protected Environments

### *General*

Radiation is essential for crop photosynthesis and hence plant production (Hemming 2011). In comparison with open field plant production, light is especially important for greenhouse crops because the amount of daylight that they receive is reduced e.g. by 30 % or more by the glasshouse structure or plastic cover (Wilson et al. 1992).

In regions short in radiation protected cultivation is always a compromise between the required protection and the need to maintain maximum penetration of radiation. Despite new developments such as using new cover materials, changing the size and the height of greenhouses, using reflective covers on the ground, adapting the canopy structure and cultivation technologies to promote growth, the light loss in greenhouses will remain an important issue for the near future. On the other hand, in climates with supra-optimal radiation, the attenuation induced by the cover may sometimes be advantageous in avoiding excess heat and sun damage. Nevertheless, in all cases, the radiative properties of the cover are a significant design feature in protected cultivation.

Covers have three major effects on the radiation balance of crops: (i) attenuating the amount of light or other electromagnetic radiation (Teitel et al. 2012); (ii) increasing the fraction of diffuse radiation that reaches more shaded regions of the canopy (Hemming et al. 2008) and (iii) modifying the light spectrum (see e.g. Shahak 2008, for colored screen materials). These three effects depend on several attributes of the system. The first is the radiative properties of the cover material, including its reflectance, transmittance and absorbance at different wavelengths and solar elevation angles (Möller et al. 2010). Another property is the structure

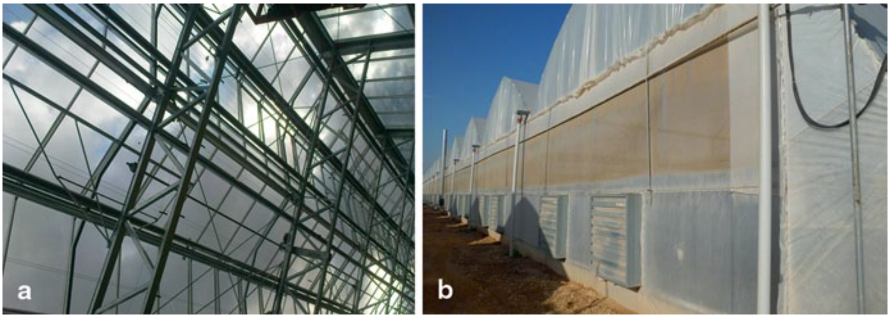

**Fig. 10.1** Most materials used for greenhouse covers are either: **a** glass or **b** plastic. (Source: Gruda 2009, 2012; private collection)

of the roof and the deployment characteristics of the cover (Teitel et al. 2012). The geometrical properties of the crop (height, planting distances, and leaf area index) would also affect the radiation reaching the canopy at different vertical levels (Hemming et al. 2008).

Greenhouses consist of an impermeable material, either glass (Fig. 10.1a) or plastic film (Fig. 10.1b), which transmits part of the radiation, and may convert direct into diffuse radiation. Glass greenhouses are mainly used in northern countries like The Netherlands and surrounding countries, where radiation is limited and transmittance through the cover is crucial. These greenhouses are rather expensive both due to the glass itself and the structure which has to be strong enough to support the glass cover. On the other hand, glass is highly durable, which is an advantage for long-term production. In more southern countries, like the Mediterranean basin, where radiation levels are higher, plastic greenhouses are mostly used both due to their lower cost and the less stringent requirement for light transmittance.

In screenhouses or net-houses the crop is covered by a porous screen. The screen allows transmittance of both light and mass (air and gases) so screens should be characterized by both their radiative and aerodynamic properties. A large variety of screens is available in the market, with different porosities, texture and color. Properties of screens are not always adequately documented in the literature (Teitel 2007) which causes some confusion regarding the properties of screens in each reported study. In addition growers that purchase a certain screen are not always aware of the exact radiative and aerodynamic properties which may result in non-optimal use for a certain crop in a given climatic region. In recent years work has been carried out to characterize radiative (Cohen and Fuchs 1999; Möller et al. 2010) and aerodynamic (Tanny and Cohen 2003; Tanny et al. 2009a) properties of screens.

### *Transmittance of the Covering Materials and the Whole Structure*

The wavelength most relevant for plant activity is the PAR, namely, Photosynthetic Active Radiation, in the range 400–700 nm. Measurements show that transmission of PAR by sheets of cladding material, subject to normal incidence of a parallel beam, was 88–90 % for 3–4 mm thick horticultural glass, 85 % for twin walled acrylic and about 90 % for 180 μm horticultural polyethylene (Critten and Bailey 2002). However, these values may decay with time due to dust accumulation (Möller et al. 2010) and water droplet condensation. Pollet and Pieters (2000) investigated PAR transmission through dry and wet glass. For glass covered structures with condensed water droplets, the transmission loss reached up to 13–15 %, at 50–65° incidence angles. Pollet et al. (2000) also showed that on glass, water droplets increased scattering significantly, from 4 to 81 %, whereas on polyethylene the increase was much lower, from 71 to 82 %.

The parameter of most interest for the grower is the overall transmittance of the structure, which determines the amount of light that would reach the plant and its uniformity in time and space. The overall transmittance may be significantly different from that of the cover material itself, mainly due to structural infrastructure. Transmittance of global radiation for single-cover Mediterranean greenhouses is usually between 55 and 70 % (von Zabeltitz 2011) and for double-cover greenhouses the range is between 50 and 60 %. Measurements (Teitel et al. 2012) and numerical modeling (Critten 1983) have been employed to estimate the spatial and temporal distribution of radiation intensity in multi-span greenhouses. Results in naturally ventilated greenhouses with roof openings showed a significant effect of the openings on radiation distribution. The mean daily PAR level directly below the cover of the greenhouses was 58–66 % of the external PAR; above the crop, the daily mean PAR level along a 10-m transect was 39–51 % of the outside level (Teitel et al. 2012). This reduction in light transmission was mainly caused by structural elements, gutters and roof openings. Teitel et al. (2012) further showed that the largest drop in radiation (15–28 %) was measured at midday, and in the region below the roof openings, it was dependant on the greenhouse type, and was larger than the drop measured at the centerline of the greenhouse span.

Giacomelli et al. (1988) studied the availability of global solar radiation (GSR) and PAR inside a greenhouse by placing sensors at fixed positions: above the crop, at truss level, and outside the greenhouse which showed that the transmittance through a polyethylene film was equal for both GSR and PAR, and its value was about 67 %. In recent years many growers use porous screens to protect their crops. Cohen and Fuchs (1999) measured radiometric properties of screens composed of highly reflective aluminized materials. For short and long wave lengths, screen transmittance varied between 0.18 and 0.5, based on their measurements and data from other sources, which demonstrated that screen radiation properties, can be determined with standard meteorological equipment, i.e. pyranometers, pyrgeometers and net radiometers. Möller et al. (2010) extended the study to show that transmission of direct radiation declined with solar elevation angle and became zero below a cutoff angle depending on screen texture. In a banana screenhouse, Möller et al. (2010) showed that transmission decreased linearly with time by about 0.1 % day$^{-1}$, during the rainless summer due to dust accumulation on the screen but recovered after rain (Fig. 10.2).

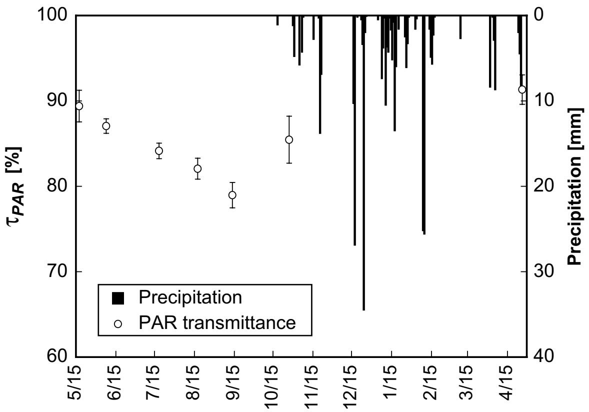

**Fig. 10.2** Midday PAR-transmittance of the CCS, measured at Zemach, Israel, over 7 days from May 2005 to April 2006. Average data from 6 PAR sensors (model LI-190, Licor, Lincoln, NE, USA). *Vertical bars* represent two standard errors of the mean. Daily rainfall measured at the nearby station is indicated on the secondary Y-axis. (Source: Möller et al. 2010)

## *The Use of Additives to Plastic Covers*

Different additives are used in order to improve the performance of plastic covers.

*Ultra-Violet (UV)* Ultra-Violet stabilizers, which are incorporated into the polymer matrix of greenhouse covers, stabilize the harmful UV radiation from entering into the greenhouse and allow for maximum light transmission. When used along with anti-oxidants they protect the film from photo as well as thermal degradation and help in proper and maximum light transmission, by increasing the durability of plastic materials (NN 2012a). UV additives block the invasion of insects into the greenhouse and protect the crop from infestation by insects and the spread of viruses (Antignus et al. 1998).

*Infra-red (IR)* During nighttime, outside temperatures are lower than inside, so the heat that accumulates inside the greenhouse during the day is lost to the outside by irradiation (NN 2012a). During the night the temperature outside the greenhouse falls below the temperature within the greenhouse. As a result there is loss of heat from the greenhouse by radiation towards the outside and the greenhouse temperature drops. This transfer mechanism takes place by the infra-red radiation. To prevent this radiation loss, mineral based additive or special polymers are incorporated within greenhouse films that help to maintain the temperature within the greenhouse and insulate the plants from the cold injury and temperature variation, save energy for nighttime heating and prevent the accumulation of heat during the day in warm climates (Hemming et al. 2006).

*Anti-Fog/Anti-Drip Effect/Anti-Condensation* Condensation of water vapor, results in formation of droplets on the inside surface of the greenhouse film. This has a negative effect on the crop because there is a reduction in morning light transmission, when most condensation may take place (Fähnrich et al. 1989), droplets falling on the foliage which can make plants more prone to diseases; and the burning of petals and leaves, as the intensity of rays passing through the droplet is increased as they act like a lens. To avoid such condensation the addition of additives alters the surface tension of the film (NN 2012a).

*Anti-Dust* Dust particles tend to adhere to polyethylene films. Over a long period of exposure considerable accumulation of dust may lead to significant reductions in light transmission (Möller et al. 2010). This can influence radiation levels and has a negative effect on plants resulting in lower yield and slower growth. Special additives, which migrate to the surface of the film, can prevent dust accumulation (NN 2012a).

## *The Influence of Light Intensity and Duration on Plant Growth and Product Quality of Horticultural Plants*

The primary energy source for protected crops is through natural solar radiation. This source is used throughout the photosynthetic processes that converts the light energy into chemical energy and accumulates as useful biomass. In addition, light plays an important role in controlling the different biological processes, such as germination and flowering and determines plant morphogenesis.

From the total light reaching the plants in the protected cultivation area, only a very small part is used for the photosynthetic process, the remainder is reflected or absorbed and converted into heat. Generally, there is a very strong correlation between the crop yield and the total amount of PAR intercepted by the plants. Apart from the light intensity, the light duration and the spectral quality are of crucial importance with these variables essential in plant growth, the production processes, and ultimately product quality. In the following an overview of the effects of these variables under the specifics of protected cultivation is given.

### Low Light Intensity

It is commonly accepted that yield is roughly linearly proportional to radiation (up to the saturation level). Marcelis et al. (2006) demonstrated that for many greenhouse crops, a 1 % light increment can result in a 0.5–1 % increase in harvested product, and the effect was larger in winter than in summer. On short and cloudy days, and during the winter period in northern latitudes, low light intensity becomes the most limiting climatic factor in greenhouses. The same holds true even for cool season plants such as lettuce grown in winter in the higher northern European latitudes.

Low yields are often associated with reduced product quality. Light intensity can influence the plant architecture, apart from genotype, other climate factors, and cultivation practices. For instance, at low light intensities plants are generally elongated and have less and longer internodes (etiolation) than plants cultivated under higher light intensities but otherwise similar conditions. This is important for ornamental potted plants which, in order to meet a particular market, have to be compact.

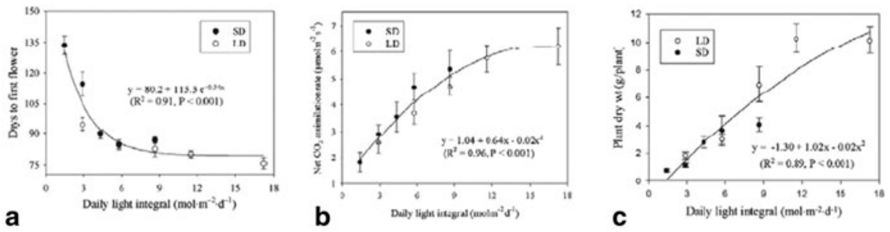

**Fig. 10.3** The effect of photosynthetic daily light integral on (**a**) time to first flower, (**b**) in situ net $CO_2$ assimilation rate, and (**c**) plant dry weight of *Cyclamen persicum* 'Metis Scarlet Red'. Plants were grown under an 8-h short day (*SD*) or 16-h long day (*LD*). Error *bars* indicate SE. (Source: Oh et al. 2009)

In the literature, sometimes the term "daily light integral" (DLI) is used in order to address the amount of photosynthetic light received each day per unit area.

Increasing DLI, generally, increases biomass accumulation, accelerates the developmental processes reduces the plant development phases, and improves final plant quality of many protected crops. For instance, the days to flower of petunia (*Petunia*) and cyclamen (*Cyclamen persicum* cv 'Metis Scarlet Red') decrease as DLI increases when grown at 20 °C (Kaczperski et al. 1991) (Fig. 10.3a). In addition, increasing the DLI increases growth rate by promoting photosynthesis (Fig. 10.3b) which improves the quality of this plant by increasing the number of leaves and flowers, and dry weight (Fig. 10.3c) (Oh et al. 2009).

The external and internal quality of vegetable products is also influenced by light. Grierson and Kader (1986) reported that low radiation and temperature reduced tomato fruit dry matter content, due to insufficient sugar content and in the pepper resulted in flower abscission (Aloni et al. 1996). Furthermore, Canadian researchers Dorais et al. (2001) reported that misshapen tomato fruits, as well as the formation of swollen and hollow fruits, due to low light intensity and inappropriate temperature regimes, were observed during the growing season in spring. In addition, light could be the limiting factor influencing the nitrate concentrations in green leafy vegetables, such as lettuce and spinach, under poor light conditions in greenhouses during winter (Blom-Zandra and Lampe 1985; Steingröver et al. 1986).

In general, as the light intensity declines there is a reduction in the content of ascorbic acid in plant tissues (Gruda 2005). This close relationship between the light conditions and ascorbic acid content have been reported in vegetables, such as spinach, tomato, lettuce, sweet pepper and strawberry. Gautier et al. (2009) stated that for tomatoes leaf irradiance has an impact on photosynthesis and sugar transport to the fruits, whereas fruit irradiance had an impact on ascorbic acid metabolism.

The effect of light and light intensity on carotenoid content in vegetable products is at present being controversially discussed in the literature. McCollum (1954) has shown that tomato fruits exposed to direct sunlight during their development had higher carotene levels than shaded fruits while the rates of lycopene and carotene synthesis can be increased by illuminating tomato plants during the ripening of the fruit at favorable temperatures (22–25 °C). Keyhaninejad et al. (2012) work was contrary to this where foliar carotenoid increased approximately twofold with increased light, whereas carotenoid content in fruit decreased two to threefold under the same conditions. Similarly, Brandt et al. (2006) reported that the production of lycopene was inhibited by excessive sunlight. Helyes et al. (2006) also found that the lycopene content of greenhouse grown tomatoes was 40 % higher than tomatoes grown in the open field and the more direct sunshine the fruit were exposed to, the higher the surface temperature, leading to a lower fruit lycopene content.

Comparing light intensities between field and greenhouse structures is not easy and as a consequence comparisons are difficult to make. Dumas et al. (2003) generally stated that the level of intercepted light may have affected the carotenoid content, but interactions may also have occurred with high temperatures occurring under protected growth conditions. Keyhaninejad et al. (2012) concluded that although there were many differences between the field and greenhouse settings in the above-mentioned study, which could explain the differences in fruit carotenoid accumulation, there were very few differences between the shaded and unshaded greenhouse settings, besides the reduced light.

Light intensity can also affect shelf life of greenhouse grown vegetables. The postharvest shelf life of the long cucumber (*Cucumis sativus*) is generally related to fruit greenness upon harvest. Indeed, the lower the light intensity incident on a cucumber, the shorter its shelf life (Lin and Jolliffe 1996; Heuvelink et al. 2006; Hovi-Pekkanen and Tahvonen 2008).

### Artificial Lighting

Artificial lighting mitigates the adverse influence of low and short radiation levels and creates optimal growing conditions for protected crops. Differences in seasonal light levels can sometimes be very high where in mid-Europe the average day length in the end of June is about 16 h, whereas in December, day length drops to less than 8 h, while the light intensity is approximately 5 times lower.

According to Mitchell et al. (2012) artificial crop lighting is an energy-intensive necessity of the greenhouse industry, particularly with increasing latitude north or south of the equator, and can result in significant changes in seasonal photoperiod. Greenhouse lighting requirements typically fall into these general categories: photosynthetic and photomorphogenic lighting for propagation and transplant production; photoperiodic lighting to induce early or out-of-season flowering, and supplemental lighting to enhance photosynthesis for crop production, especially when grown during light-limited periods of the year (Mitchell et al. 2012) and where replacement lighting that is usually used in growth rooms or chambers. However, only supplemental assimilation lighting (SAL), which is considered the most cost-effective form of lighting when a naturally low ambient photosynthetic daily light source is required, or when crops are grown at a high density, will be discussed in this section.

The main reasons for using SAL are certainly the enhanced plant growth and crop production. Marcelis et al. (2002) reported yearly production increase of 55 %

in greenhouse tomato production. However, recently the reasons are to be seen more and more in ensuring a year-round production and improved quality, which meets market demands and a more regular labor requirement (Marcelis et al. 2002; Paradiso et al. 2011). At present approximately 90 % of rose growers in The Netherlands use SAL, while the use of this form of lighting for other cut flowers, ornamental and vegetable crops is increasing at about 1 % each year (Heuvelink et al. 2006; Marcelis et al. 2002).

Several studies reported better external and internal quality of horticultural crops. For example, increasing photosynthetic photon flux (PPF) increased plant quantity of *Petunia* × *hybrida* flower mass grown in climate chambers (Frantz and Ling 2011), and increased the number of flowering shoots and inflorescence size of Kalanchoe (Carvalho et al. 2006). Dorais and Gosselin (2002) reported a higher sugar content and ascorbic acid concentration in tomato, and Gaudreau et al. (1994) documented increased head firmness of lettuce as a result of supplemental light.

Applications of SAL from 18 October until 20 March in a glasshouse in The Netherlands, improved the yield at a light intensity of 188 µmol $m^{-2}$ $s^{-1}$ in comparison to a 125 µmol $m^{-2}$ $s^{-1}$, by increased fruit set and average fruit weight for two cultivars of sweet pepper, when light was used between sun rise and sun set (Heuvelink et al. 2006). These authors concluded however that the use of SAL is not economically feasible for sweet pepper, tomato, and eggplant due to high energy and production costs. The position of lamps is important as well. Usually SAL is applied on the top of the canopy. Under such lighting systems, light is not uniformly distributed along the leaf layers of some crops such as e.g. tomatoes, cucumbers, and peppers that are usually vertically cultivated, or roses as well as other plants that are usually grown under high plant densities. Particularly, it has been calculated that, considering a crop with a leaf area index (LAI) of 3, even when the light intensity at the top of the plant is 400 µmol $m^{-2}$ $s^{-1}$, approximately 33 % of the leaves in the lower and inner zone of the canopy receive less than 100 µmol $m^{-2}$ $s^{-1}$ because of self-shading (Paradiso et al. 2011).

Both light absorbance and the vertical distribution of light in the canopy are of great importance for crop photosynthesis. Heuvelink et al. (2006) reported that leaves low in the canopy, received higher light levels every day because of interlighting, performed at their maximum photosynthetic capacity, although leaf age and the time of leaf-removing, a cultural practice of lowering high-wire crops, needs to be taken into account. However Pettersen et al. (2010) found in an experiment with horizontally grown cucumbers, that the leaves showed no sign of reduction in photosynthetic capacity rate although the oldest leaves were approximately 30 days older than leaves at the moment of removal in a high-wire cultivated cucumber crop.

Many species demonstrate benefits from interlighting or inner canopy lighting. Grodzinski et al. (1999) found an increased photosynthetic activity in sweet pepper canopy when side lighting was used jointly with top lighting, whereas Hovi et al. (2004) stated a 9 % increase in annual cucumber yield in Southern Finland, when 24 % of the SAL was supplied between the plants instead of all light on top of the

**Fig. 10.4** Application of LED-interlighting in tomato plants by an experimental trial at the Horticultural Center Straelen, Agricultural Chamber of North Rhine-Westphalia in Germany. (Source: Gruda 2013, private collection.)

plants. In addition, interlighting increased first class yield and decreased the unmarketable yield of cucumbers, both in weight and fruit number. Besides interlighting per se, the higher proportion of interlight tended to further improve the fruit quality as well as fruit skin chlorophyll concentration (Heuvelink et al. 2006; Hovi-Pekkanen and Tahvonen 2008).

The addition of SAL, with no adjustments in the climate set points and crop management, may result in improved vegetative growth but little or no yield improvement. The adjustments in temperature, plant density and other factors are needed, in order to optimally transfer SAL into production (Heuvelink et al. 2006).

Future applications could be the development of light-emitting diode (LED) lamps which has several unique advantages over existing horticultural lighting such as being small in size, increased longevity and low heat emission even at very high light intensity levels. In addition LED lamps have the ability to control spectral composition, given the opportunity to select the most favorable light spectrum for photosynthesis (Fig. 10.4) (Morrow 2008; Paradiso et al. 2011).

Martineau et al. (2012) compared LED and HPS lighting technologies for supplementing greenhouse lighting and found on average, that HPS and LED light treatments produced similar shoot biomass of head lettuce (*Lactuca sativa* var. *capitata*), with the LED lamps providing approximately only half the amount of supplemental light compared with the HPS lamps during a 4 week experimental treatment. In addition no significant differences were found in concentrations of β-carotene, chlorophyll a, chlorophyll b, neoxanthin, lutein, and antheraxanthin among the light treatments. According to Morrow (2008), the LED array provides three times more light output for the same Wattage of input power on an equivalent area basis and can be easily integrated into digital control systems, facilitating special lighting programs such as "daily light integral" lighting and sunrise and sunset simulations. In addition LEDs could be used at different radiation angles for different cultivation types and development stages and provided the capability of true spectral composition control, allowed wavelengths to be matched to plant photoreceptors to provide more optimal production, and influenced plant morphology and composition (Morrow 2008). With most plants reaching a major peak in the red region and a relatively lower peak in the blue region, Mitchell et al. (2012), demonstrated the use of LEDs in emitting photon colors that match the absorbance peaks of important plant pigments, such as the red and far-red-absorbing forms of phytochrome, or the red and blue peaks of leaf photosynthetic action spectra. Combining the far red and blue light rate due to LEDs not only avoids the negative effects of assimilation lighting in greenhouses related to changes in carbohydrate metabolism, but also contributes to a reduction of the supply of fertilizer and chemical control, due to an aimed shortening of the vegetation period, bud/flower induction or improvement in plant morphology.

The spectrum of assimilation lighting has recently become more important. The use of LED lamps in a green leaved rose crop increased instantaneous crop photosynthesis per incident photon by up to 12 % and for a crop with reddish leaves up to 17 %, compared to HPS lamps (Paradiso et al. 2011). Moreover, an increased red/far red ratio on rose generally reduced plant height and increased leaf chlorophyll content (McMahon and Kelly 1990) and the number of flowers (Roberts et al. 1993; Girault et al. 2008; Paradiso et al. 2011).

The addition of color to plastic films or porous nets can affect various crop processes (Shahak 2008; Stamps 2009). Due to a targeted application, e.g. by using of covering films, the induction of a range of secondary metabolite accumulation could affect the plant morphology, e.g. the plant height of transplants, as well as the internal quality. Far red light absorbing films seem to be effective in reducing stem elongation, and decreasing the incidence of tipburn of lettuce and blossom end-rot of tomatoes. Recently, Patil and Moe (2009) reported that screening daylight through light quality selective plastic film with a red/far-red ratio of 1.6 in combination with DIF (for more information concerning DIF, see the temperature-section in this chapter) reduced stem, hypocotyl and internode length in the cucumber plants by 45–50 % compared to the control film with a red/far-red ratio of 1.1, indicating an interaction between DIF and the spectral light regime.

Changing the light intensity of different colored shade nets can affect the internal quality of tomatoes. For example Ilić et al. (2012) reported higher lycopene content in greenhouse tomatoes integrated with red shade, in comparison to field-grown tomatoes. By contrast, shaded fruits have a lower content of β-carotene.

### High Light Radiation Intensity

Two different aspects regarding light intensity include the “light compensation point” and the “light saturation point”. The “light compensation point” is reached when photosynthesis and respiration are in balance. The “light saturation point”, is reached when the light intensity is increased to a point where it is no longer a factor limiting the overall rate of photosynthesis. Extreme light intensity combined with excessive radiation can, adversely affect plant growth and quality leading to disorders in the development and appearance. Such is the case for sunscald (Fig. 10.5).

**Fig. 10.5** Sunscald symptom on Bell Pepper, cultivated in a glasshouse in the south of Germany. A cellular death, a collapse of the tissue and papery thin skin are clearly seen in fruits that were directly exposed to solar radiation and were not shaded from leaves. (Source: Gruda 2003, private collection.)

Further disorders caused by high light intensity are uneven ripening, the occurrence of green shoulder, and blossom-end rot in tomato as well as cracking in tomato and pepper fruits.

### Measures to Mitigate the Adverse Influence of High Radiation Intensity

The most common methods to reduce incoming solar radiation include the whitewashing and the use of shade screens. Natural and forced ventilation systems, as well as evaporative cooling devices, are often installed to remove excess heat due to supra-optimal radiation in protected cropping systems. Effective crop transpiration and active evaporative cooling in the form of fog and sprinkling systems, convert plant sensible heat into latent heat. The preferred system depends very strongly on outside climate conditions, greenhouse types and available facilities. In Mediterranean countries whitewashing or shade screens, as well as evaporative cooling, can be successful, whereas in hot humid areas an evaporative cooling system may not be as efficient.

Shading is necessary to limit the temperature rise in the greenhouse. The actual shading percentage of products such as traditional whitewash can be influenced by different climate conditions, the type of the greenhouse construction, plant cultivations and the applied settings and can decrease during the year.

Villegas et al. (2006) reported a positive effect of shading when cyclamen (*Cyclamen* spp.) plants, were cultivated in the Mediterranean area under double shade cloths with an accumulative 50 % of shading. These plants had better quality and were more compact whereas plants under grey shade cloths at the same shading rate had a higher number of flowers. The authors recommend treating the results with caution when growing plants under cool and cloudy environments. For instance, Marcelis (1993) reported that shading can affect cucumber weight by reducing the distribution of photosynthate to the fruits, resulting in a strong decrease in fresh and dry fruit weight. Young fruits are usually relatively more sensitive to a reduction in assimilate supply (irradiance) than older fruits on the same plant. Cockshull et al. (1992), stated that 23 % shade was sufficient to reduce the yield of tomatoes by 20 % in England. Consequently no general recommendations can be made here.

According to Peet (1999), the reduction of light intensity is more likely to be a limiting factor than otherwise; hence a movable shade applied for only a couple of hours during sunny periods, is a possible solution. Lorenzo et al. (2004), for instance, reported a 10 % increase in marketable yield of tomatoes, when mobile shade was applied during a couple of hours of intense sunlight in Spain. In addition, the combination of different measures for different genotypes, and at different plant growth and development phases has to be emphasized here.

## Air Temperature, Air Humidity and Energy Considerations

In protected cultivation, global solar radiation, which is composed mainly of short wavelength, and is transmitted through the cover, is absorbed by the greenhouse structural elements and mostly converted into heat. Heated air cannot be freely exchanged into the free atmosphere, and any reflected energy is of a long wavelength nature, as both atmosphere and greenhouse covers are partially opaque to these wavelengths, such energy is trapped within the greenhouse, causing the so called "greenhouse effect."

### *Greenhouses*

One of the advantages of cultivation in greenhouses is the possibility of controlling the air temperature through heating or cooling. In cases of high global radiation, in hot seasons and arid regions, the plant temperature can exceed air temperature by 5–10 °C. For many plants, ventilation does not provide sufficient cooling. In arid regions, internal humidity should also be increased for crop growth (von Zabeltitz 2011). The combined effect of cooling and humidifying the inside air can be achieved by evaporative cooling, mostly implemented by one of two systems: (i) fan and pad; and (ii) fogging.

In the fan and pad cooling system, air is sucked by fans installed on one sidewall of the greenhouse (Fig. 10.6a). The air entering the greenhouse, which replaced the sucked air, passes through a wet pad, installed on the opposite sidewall and which is fed with water by sprinklers (Fig. 10.6b). The inflow of external, relatively dry air, through the wet pad, cools down the air and increases its water vapor content. This is the so-called "negative pressure" system. In the "positive pressure" system, fans and wet pad are positioned on the same sidewall and push air into the greenhouse which then leaves through openings on the opposite sidewall.

The main drawback of the fan and pad system is the generation of thermal gradients along the direction of air flow through the greenhouse. This is due to the air being heated during its flow along the greenhouse section. To minimize this effect growers tend to shade the downwind half of the greenhouse where the air is al-

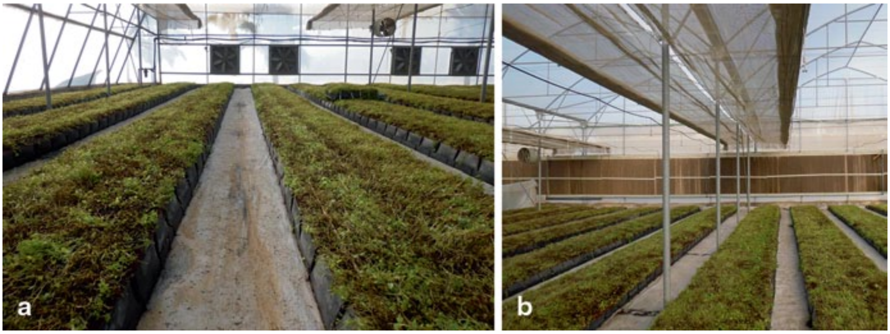

**Fig. 10.6** A negative fan and pad cooling system: **a** fans installed on one sidewall of the greenhouse, and **b** wet pad, installed on the opposite sidewall in a greenhouse at The Jordan Rift Valley. (Source: Gruda 2012, private collection)

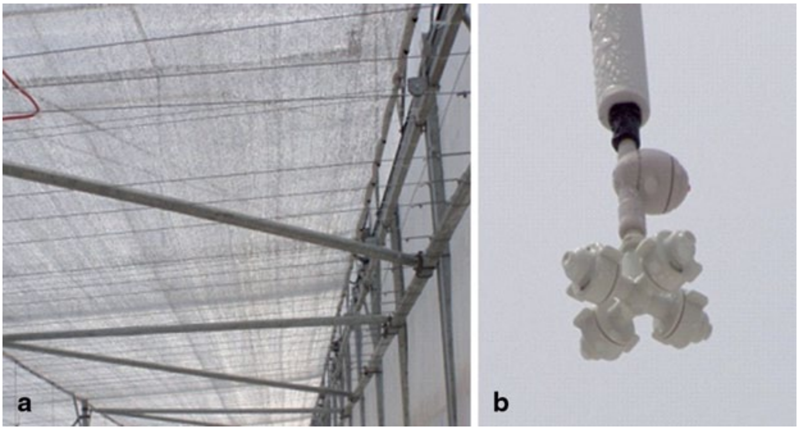

**Fig. 10.7** **a** The aluminized shade system (Aluminet 60-I, 60–64 % shade, Polysack Plastic Ind., Nir-Yitzak-Sufa, Israel) installed at a height of 4.5 m. **b** The mist system designed using high-pressure foggers (Micronet 4-Way Fogger, 30.6 L. $h^{-1}$ with a mean droplet size of 90 microns at 60 psi) from Netafim USA, Fresno, Calif. installed above the plant canopy at a height of 3.9 m from the floor, both in passively ventilated greenhouses located at the Plant Science Research and Education Center in Citra, Florida. (Source: Gruda 2004, private collection.)

ready warm (Fig. 10.7a). Kittas et al. (2003) derived a climate model that predicted the temperature gradient along the greenhouse, incorporating the effects of the fan and pad system, partial roof shading and plant transpiration. In experiments for model calibration, they measured temperature differences of up to 8 °C, along the 60 m greenhouse length from pad to fans. The model showed that high ventilation rates and shading contributed to reduce the thermal gradients. Fuchs et al. (2006b) investigated for a greenhouse rose crop the combined effect of fan and pad cooling and crop transpiration on the greenhouse microclimate. The evaporative pad cooled the air considerably; but the lowering of transpiring leaf temperature was only minor. They have also showed that evaporation from the pad decreased when external humidity increased. When the wet pad operated crop transpiration rate was nearly independent of external humidity and ventilation rate.

The fog cooling system consists of spraying very small water droplets from nozzles positioned above the crop area. The drops should be small enough to evaporate fast, and before reaching the foliage (Fig. 10.7b). Several techniques were proposed for droplet generation (Arbel et al. 1999; Li and Willits 2008) that ranged from twin-fluid nozzles combining compressed air and water; low pressure systems; and high pressure systems (von Zabeltitz 2011).

The advantage of fog cooling systems, as compared to fan and pad, is the possibility to operate in both forced and natural ventilation greenhouses, and the more uniform temperature and humidity distributions in the greenhouse. For example, Arbel et al. (2003) studied a greenhouse equipped with a forced ventilation system combined with fogging. The results revealed that inside the greenhouse an air temperature and relative humidity of 28 °C and 80 %, respectively, were maintained at noon during the summer. Furthermore, the high uniformity of the climatic conditions (the same magnitude of temperature measurements error $\pm 0 \cdot 5\,°\mathrm{C}$), within the greenhouse, in the lengthwise (north–south) and vertical directions were reported. Uniform microclimatic conditions are preferable since they induce uniform crop growth, yield and quality.

Temperature, humidity ratio and $CO_2$ concentration gradients can also develop in fan-ventilated greenhouses without evaporative cooling. Teitel et al. (2010) measured and modeled horizontal gradients in a greenhouse in which pepper was grown. The model results showed that the largest gradients are to be expected at around midday (11:00–12:00), when the intensity of solar radiation is greatest.

Vertical gradients in greenhouses were also investigated by Zhao et al. (2001) who measured vertical gradients of temperature and humidity in a pepper greenhouse grown under different ventilation conditions. Their experiments were conducted in a full-scale, commercial greenhouse, under closed and naturally ventilated conditions. A comparison was made between ventilation by continuous roof openings only and ventilation by opening both roof and side windows. Two cases were considered for each of the ventilation modes: (i) the plants in the greenhouse were mature and big, and (ii) the plants were young and small. With mature plants, the gradients of temperature and humidity ratio before opening the ventilation windows were considerable and they remained so after the windows were opened (either roof only or both roof and side windows). Smaller gradients were observed with only roof ventilation, than with ventilation via roof and side openings. With young, small plants the gradients were much smaller than with mature plants and they could be assumed negligible for either ventilation mode. Both Teitel et al. (2010) and Zhao et al. (2001) results illustrate the interactive effects between plants and greenhouse microclimate.

Greenhouse heating is a common approach in northern countries or in regions susceptible to frost. It is also used in subtropical regions to keep nighttime and even daytime temperature at the biological optimum. Under certain climatic conditions greenhouse heating is necessary, however, it is an economic problem due to the high energy costs. In addition to the direct biological effects of rapid growth and earliness, heating is important in reducing the relative humidity, thus lowering the risk of several common plant diseases, which may also lead to a reduced pesticide application (Baille 2001).

In the literature different approaches for greenhouse heating, and their effects on air temperature, were investigated. For example, Bartzanas et al. (2005) have demonstrated that in a tunnel where tomato was grown, combining heating pipes with air heaters increased the temperature difference between inside and outside from 10 to 15 °C during night. It was also shown that with the air heater, although the mass transfer conductance to the cover was higher, the condensation flux was smaller which resulted in less condensation at the inner surface of the cover.

In 2000 Kempkes and co-workers (Kempkes et al. 2000) developed a simulation model to predict the effects of the heating system on the vertical distribution of crop temperature and transpiration. The simulation model predicted crop temperature distribution as a function of the position and temperature, of the heating pipes, as well as the vertical distribution of crop evaporation. In addition Teitel and Tanny (1998) investigated the effects of pipe positioning and pipe surface temperature on radiative heating of the crop and found that the best pipe position was near the crop at its mid-height and that at low pipe surface temperatures, the radiative heating efficiency increased sharply with the surface temperature.

### *Screenhouses and Screen Covers*

In screenhouses, due to the strong interaction between the inside and outside, heating or cooling is non-practical. It is commonly accepted that climate control in screenhouses is passive, namely, it is governed by factors such as screen type, screen deployment, and structural and canopy properties that cannot be actively manipulated by the grower (Tanny 2013).

Tanny et al. (2009b) demonstrated the effect of shade in reducing the air temperature in an apple orchard in northern Israel. Results showed that during daytime, air temperature under the screened plots and near the foliage were lower by about 1.4 °C than at the exposed plots (Fig. 10.8). During night-time, air temperature under the screened treatments was larger by about 0.3 °C than under the exposed ones due to the reduced long wave radiative cooling effect under the screens. The air humidity under the screens was found to be higher than that in the exposed treatments during daytime, which may lead to lower ET and hence water saving.

Kittas et al. (2012) measured both air and leaf temperature of tomato plants under different shading treatments and showed that although the air temperature under the shade was almost similar to that without shade, leaf temperature of shaded plants was nearly 5 °C lower than un-shaded plants. This temperature reduction was associated with a 50 % reduction in VPD of the shaded plants in comparison with the un-shaded ones. The equality of air temperature under the shaded and exposed treatments was attributed by Kittas et al. (2012) to the fact that the shading screens they used were deployed only on the roof and not on the sidewalls, and that the measurements were done near the coast where sea breeze is significant. Both fac-

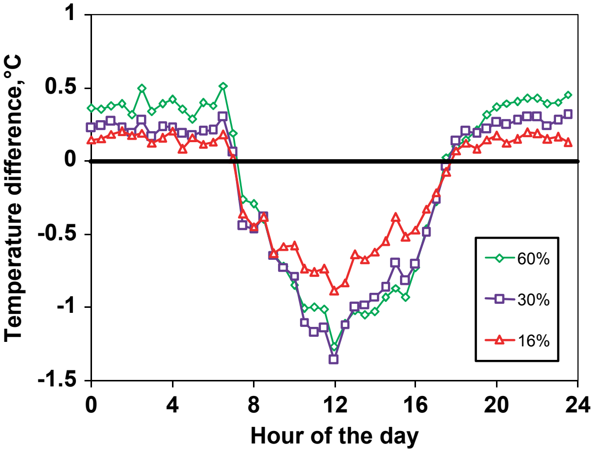

**Fig. 10.8** Diurnal curves of temperature difference between shaded and unshaded treatments for the three shading screens covering apple trees. Each curve represents an average over the 12 days DOY 232–243. *Shading screens*: diamond—60 %; *square*—30 %; *triangle*—16 %. (Source: Tanny et al. 2009b)

tors allowed high ventilation of the shaded plants which eliminated air temperature differences.

Insect-proof screens impose a higher resistance to air flow than shading screens and thus reduce the ventilation, which may cause higher temperature and humidity increases. Rossel and Ferguson (1979) studied a relatively small screenhouse covered with an ultraviolet-stable fine-mesh polyethylene screen which reduced light intensity by ~40 % and was insect-proof and noted that with fan ventilation, the highest inside temperature never exceeded that outside by more than 1.5 °C, but without fan the highest temperature difference between inside and outside reached up to 3.5 °C.

In an insect-proof screenhouse Tanny et al. (2003) analyzed the vertical temperature gradient in relation to the external wind speed. The diurnal variation showed the decrease in the temperature gradient as wind speed increased just before midday because the high wind speed mixed the inside air and thereby decreased the vertical temperature gradient. The temperature gradient remained positive however throughout the daylight hours, which means that it had stabilized the internal air.

In recent years large shading screenhouses for banana cultivation have become increasingly popular among Israeli growers (Fig. 10.9). Measurements showed that inside air relative humidity was higher by 8 % than that measured by a meteorological station in an open area outside the screenhouse (Tanny, unpublished data). Higher internal water vapor mixing ratio (ratio between mass of water vapor to mass of dry air) within a banana screenhouse was also obtained by Siqueira et al. (2012), in their one dimensional model of an infinite horizontal screen cover. They reported an increase of about 35 % in the water vapor mixing ratio under the screen (at 5 m height) as compared to the value at the same height above an open banana plantation. The increased internal humidity in screenhouses is presumably one of the reasons for the potential water saving.

Tanny et al. (2008) investigated the effect of roof height on inside temperature and humidity in two adjacent 60 %-shading screenhouses with different heights of

**Fig. 10.9** A banana screenhouse with a hail trap, located at the Western Galilee region of northern Israel. (Source: Tanny 2007, private collection)

2 and 4 m, in a crop of ornamental ruscus (*Ruscus hypophyllum*) 0.5 m in height, grown under similar conditions (i.e., irrigation, nutrition, harvesting). Although net radiation was almost identical in the two houses, air temperature near the plants, as well as leaf temperature was higher in the lower screenhouse than in the higher one. The average daily air temperature difference between the two houses was 1.5 °C, and the maximum difference in leaf temperature was 2 °C at midday. The vertical temperature gradient within the low screenhouse was ~ 3 times larger than that within the high screenhouse, due to better air mixing and more significant movement of warm air to higher levels in the higher than in the lower house. In addition, it was shown that VPD near the plants was higher in the lower screenhouse than in the higher one due to the higher temperature in the lower screenhouse. Most of the time, the absolute humidity in the higher house was closer to the outside than to that in the lower house, presumable due to the better ventilation in the higher screenhouse.

## *Energy Saving Considerations in Greenhouse Climate Control*

About 90 % of the total energy consumption in greenhouses among the Northern European countries is for heating (NN 2012b). The climograph of one Mediterranean and one North Europe region is shown in Fig. 10.10. This shows that at lower latitudes, e.g. Almeria-Spain, the daytime temperatures are too high for ventilation to provide sufficient cooling during the summer. The attainment of suitable temperatures then requires positive cooling. On the contrary, in temperate climates e.g. in the Netherlands, heating is indispensable and together with ventilation enables the temperature to be controlled over the whole year (Kittas et al. 2013).

A study conducted in Germany stated that sometimes, small glasshouse companies, where oil is the most frequently used energy source, lack state-of-the-art technical equipment and have higher energy costs compared to large greenhouses. In addition, many greenhouses are not optimally equipped in terms of energy con-

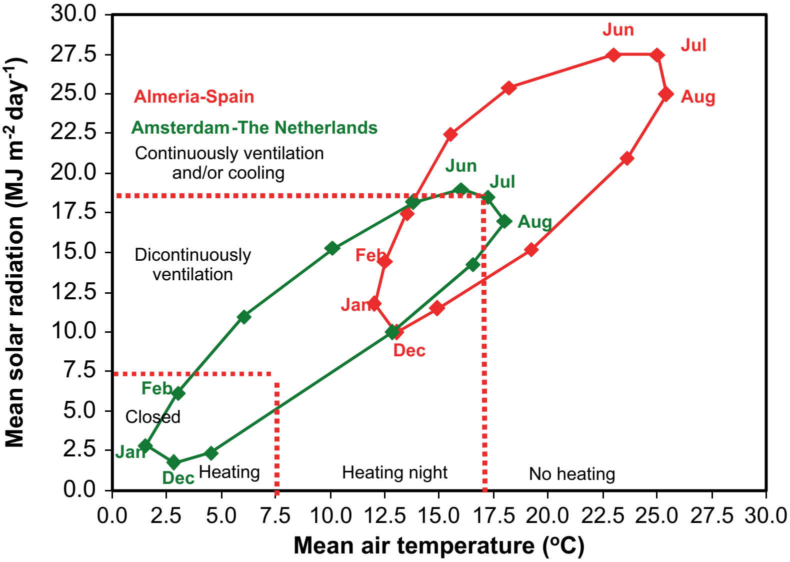

**Fig. 10.10** The mean solar radiation vs. mean air temperature for Amsterdam (The Netherlands) and Almeria (Spain). The climograph: *dotted lines* indicate border lines for different control action in the greenhouse. (Source: Food and Agriculture Organization of the United Nations, Kittas et al. 2013. Reproduced with permission)

sumption (Gruda et al. 2009). The most feasible measures in cost-efficient energy conservation were due to following measures (Table 10.1):

Recently, the reduction of energy consumption using new covering materials, double and triple thermal screens, climate control strategies, energy optimized cultivation programs, and greenhouses as solar energy storage, are some of the new development projects in the Netherlands (de gesloten kas: the closed greenhouse) and Germany (ZINEG: the low-energy greenhouse). All these systematic tools together with the use of alternative and renewable energies, without using fossil fuels,

**Table 10.1** Energy conservation measures in greenhouses. (Source: NN 2012b)

| Nr. | Type of saving | Saving potential (%) |
|---|---|---|
| 1 | Thermal screen | 20–40 |
| 2 | Sealing of vents and windows | 10–20 |
| 3 | Heating system | 10–18 |
| 4 | Optimization of boiler | 10–15 |
| 5 | Climate control | 10–20 |
| 6 | Better use of cultivation area/crop planning | 10 |
| 7 | Special insulation and glazing | 7–10 |
| 8 | Sensors | 5–10 |
| 9 | Irrigation | 5–10 |
| 10 | $CO_2$—Fertilization | 5 |

can contribute to a reduction of the energy consumption by 80–90 % and operate a greenhouse with minimum $CO_2$-emissions.

## The Influence of Temperature on Plant Growth and Product Quality of Greenhouse Horticultural Plants

### *General*

The "greenhouse effect" may have a positive effect on plants at higher latitudes; however, a negative effect on plant growth and development is also possible due to high temperatures in these latitudes. In general, the speed of all biochemical processes is temperature dependent and the reaction rate of different biological processes increases with increasing temperature. Afterwards, enhanced exposition duration and temperature intensity, the reaction rate decreases, because most enzymes lose their effectiveness or have been damaged resulting in reduced plant growth and development. Temperatures are highly affected by light intensity and to a lesser extent, by $CO_2$-concentration together with seasonal growth pattern and plant stage also needed to be considered (Gruda 2005).

Numerous studies have revealed optimum temperature range requirements for various plant species.

The optimum air temperature, regulation of the minimum air temperature and the commencement of cooling measures are three important aspects concerning air temperature regulation and control in protected cultivation. An optimum air temperature is crucial, due to regulation of the setting point of day temperature. As it was mentioned above, optimum temperature has to be regulated according to the particular plant species and/or cultivars and their subsequent development stages. Thus recommended temperatures for the germination of vegetables are higher than those for seedlings, transplants or for further cultivation. Optimum air temperatures are dependent on existing light intensity in protected cultivation. Plants grown under high radiant energy and low thermal energy become stocky, but grow and develop more slowly (Liu and Heins 2002). By contrast, plants grown under low radiant energy and high thermal energy grow and develop rapidly but become thin and weak. Moccaldi and Runkle (2007) reported that the flowering rate of salvia (*Salvia splendens*) and marigold (*Tagetes patula*) was primarily controlled by temperature within the experimental conditions provided with flowering decreasing from 42 to 24 days as temperature increased from 15 to 25 °C. Similarly, Blanchard et al. (2011) found the same trend for two petunia cultivars. (*Petunia* × *hybrida*). Although the flowering rate increased with temperature, plant quality parameters decreased, especially when the daily light integral (DLI) was low (Moccaldi and Runkle 2007).

In order to balance plant growth and development, during the European winter period, the optimum day temperatures in greenhouses have to be lower than in the summer months, with night temperatures generally to be kept lower than day temperatures in order to reduce respiration and heating costs. Minimum air temperatures are the lowest occurring plant-specific temperatures, which plants can tolerate in the short-term without permanent damage. For technical reasons frequently experienced in cold regions when it is snowing, the minimum temperature has to be regulated, so that snow can be defrosted by the greenhouse cover. The stage at which the grower commences cooling under increasing temperatures is of great importance, to avoid extreme heat stress situations. It is necessary to distinguish between optimal physiological and economical temperatures. Physiologically optimal air temperatures are temperatures at which, under the given irradiation, provide for maximum plant development per time-unit. By contrast, economically optimal air temperatures, take other features into account such as culture duration, yield, size, quality, and energy costs. Economically optimal air temperatures are frequently lower than optimal physiological temperatures with the differences usually a little higher for vegetables than for ornamental plants (Jansen et al. 1989).

New ways to increase energy efficiency and reduce costs of production include limiting the cultivation period to periods of adequate solar radiation, and lowering the economically optimal temperatures for heating and lowering the target temperature, to reduce energy consumption. For example, Elings et al. (2005) calculated that lowering day and night temperature set points for tomato by 1 °C lead to a reduction of 8 % per year energy consumption. However, lowering temperatures can adversely affect the leaf area development and light interception, resulting in lower production, extending the development time of the plant and adversely affecting product quality. This could be a problem especially for date cultures, e.g. poinsettia (*Euphorbia pulcherrima*), as well as early protected vegetables crops. Therefore, one of the main decisions that growers have to make is either to have a longer growth period, with lower energy requirements associated with often lower yields, or a shorter cultivation time with higher heating expenses and more often better returns by advancing the crop. Both cases incur additional costs that obviously will be higher for longer than shorter growth periods.

## *Day and Night Temperatures*

Generally, a constant temperature is less favorable than a fluctuating one between day and night, when associated with high temperatures during the day and lower ones at night. Of importance here is the decrease in respiration at lower temperatures (night) and the increased photosynthesis at elevated temperatures (day).

The DIF-concept, or the difference between the day and night temperatures, was introduced in the horticultural literature in the 1990's. The DIF can be positive (day temperature = DT, is higher than night temperature = NT) or negative (DT is lower than NT). Langton and Cockshull (1997) reported that absolute day and night temperatures explained internode length rather than DIF, when an equal photoperiod of 12 h (day/night) was applied to chrysanthemum. Carvalho et al. (2002) went on to clarify the validity of the DIF concept by investigating cut chrysanthemums (*Chrysanthemum* cv 'Reagan Improved'), grown in growth chambers at 16 combinations of 4 day and night temperatures (16, 20, 24 and 28 °C) with a 12 h day length. The research group found that DIF could predict final internode length only within a temperature range 18–24 °C where the effects of DT and NT were equal in magnitude and opposite in sign. Internode appearance rate, as well as stem length formed during the experiment, showed an optimum response to DT, with the authors concluding that plants do not respond to DIF itself, but rather to the combination of independent effects of temperature measured during day and night periods.

Similarly a negative DIF strategy is still used, in order to reduce and substitute growth retardants used in controlling plant height or stem elongation of a number of different horticultural crops. Moe et al. (1992) reported that the most appreciable inhibitory effects on poinsettias were observed when lowering the growing temperature for 2–4 h before the dawn (cool morning strategy).

Peet and Bartholemew (1996) and Abdelmageed and Gruda (2009) emphasized the role of night temperatures on pollen characteristics and reported that total and percentage normal pollen grains were higher in tomatoes grown under normal night temperature than at high night temperatures. High day/night temperature differences or wide fluctuations in temperature can also induce disorders, like the cracking of tomato fruits (Peet 1992).

### *Low and High Growing Temperatures*

Plastic greenhouses are also widely used for horticultural production in warm regions where high radiation and mild temperatures make production successful. By contrast, during the cold season, suboptimal temperatures and low irradiation can adversely affect growth and yield, and reduce the product quality of crops. Since warm-season crops are most likely cultivated under protected cultivation, damages could happen even at temperatures above freezing point. After long low temperature exposure leaves wilt and yellow and show various metabolic process disturbances. Furthermore, low temperature exposure has an influence on external and internal product quality.

Several authors have reported that low temperatures can cause fruit malformation and distortion, seedlessness, pericarp cracking, and pigmentation formation in various fruits and vegetables (Gruda 2005). Moreover, low night temperatures can reduce the number of pollen grains per flower and impair the germination ability of vegetables such as tomatoes and peppers with a tendency to develop parthenocarpic fruits.

Temperature can also influence the color intensity in most flower and fruits. Usually, low temperatures in combination with high light intensities hinder the coloring of flowers, bracts, and leaf parts, whereas some petunia cultivars show an increase in color intensity at higher temperatures. Fruits such as tomatoes, peppers and eggplants require relatively high temperatures for dye synthesis with color and color intensity interacting with growth factors, such as light (Jansen et al. 1989). For

**Fig. 10.11** Anthocyanin formation on the underside of the tomato transplant leaves caused, due to a worse uptake of phosphorus at low temperatures. (Source: Gruda 2005, private collection)

instance, the red color of ripe tomato fruits is attributed to lycopene, a carotenoid synthesized and stored in the chromoplasts. Dumas (2003) reported that, except for *β*-carotene, greenhouse-grown tomato plants reduced carotene content of the fresh fruit under lower temperature regimes and at low air temperatures of < 12 °C may fully inhibit lycopene production. Moreover, Zipelevish et al. (2000) reported that eggplants (*Solanum melongena*) grown under cool winter conditions in unheated polyethylene covered greenhouses displayed a weaker intensity of fruit skin colour than during the normal hot growing period.

Low temperatures could also directly influence the organoleptic properties of vegetable products. For instance, low temperatures will produce less juicy tomato fruits with low acidity content and a mealy taste (Brückner et al. 2004) with Kano and Goto (2003) reporting a higher occurrence of bitter fruits in cucumber (*Cucumis sativus* cv. 'Kagafutokyuri') when grown under lower temperatures rather than higher temperatures. Both water and nutrient uptake can be inhibited at low temperatures. Jansen et al. (1989) reported that water absorption of cucumbers at 5 °C in the root zone is only about 10 % compared to that at 20 °C. In addition there can be a drastic reduction in absorption of nutrients at low temperatures in warm-season plants. Low temperature greenhouse grown tomato seedlings exhibited a lack of anthocyanin formation on the underside of the leaves due to a reduction of phosphorus uptake (Fig. 10.11). Once the seedlings are placed in the heated greenhouse, these symptoms gradually disappear.

Low temperatures make plants more susceptible to some pathogens and under such conditions inhibit the plant's defense mechanisms.

On the other hand, sub optimal low temperatures, when used appropriately, can sometimes improve fruit and vegetable quality. Ventura and Mendlinger (1999), for instance, reported that melon fruits from the unheated greenhouses were smaller and lighter than those from the heated greenhouse and had higher amounts of total soluble sugars (TSS), sucrose and fructose and tomatoes showed an improvement in fruit carbohydrate accumulation (fructose and glucose) when harvested under cooling growing conditions (Islam and Khan 2001).

Due to solar radiation and the “greenhouse effect” temperatures could sometimes rise above the optimal level for plant growth and development. Under such conditions many horticultural crops are exposed to a heat stress situation. Deleterious effects of high temperature can be direct or indirect. Direct temperature can damage cellular membranes, proteins, and nucleic acids. Indirect temperature effects can include inhibited pigment synthesis and thermal degradation of existing pigments as a result of sun scald or systems of sun burn (Kays 1999) as well as desiccate tissue and plant organs induced by water stress. In this case, internal fruit and vegetable temperature is more important than air temperature.

Physiologically high temperatures influence the photosynthesis process by inducing stomatal closure, increasing the rate of respiration and resulting in lowered biomass production and yield. Air temperatures do not only have an effect on plant growth and yield, but rather affect the development processes at different development phases. High temperatures result in “heat delay” a term that characterizes the effect of temperature, on delaying flower initiation. First in line are high night temperatures, but also day temperatures above the optimum for given species and cultivar leading to flowering delays. Warner and Erwin (2005), for instance, reported that high temperatures of 32 °C reduced the number of flower buds and resultant flowering in five annual herbaceous ornamentals, regardless of DLI.

Pollination, fruit set formation and horticultural products quality, are influenced by extreme high temperatures (Gruda 2005). For instance, Sato et al. (2002) reported that a continuous temperatures of 32/26 °C (day/night) led to the disruption of development in the pollen, endothecium, epidermis and stomium of anthers of tomato plants. Similar day/night temperatures reduced the percentage of germinated pollen of pepper plants compared with those at normal temperatures (26/22 °C) as well as fructokinase activity in mature pollen (Karni and Aloni 2002). Pollen grain release and germination has of course an effect on the ability of plants to set fruits. Abdelmageed and Gruda (2009) reported that heat stress associated with high day temperatures of 37 °C markedly decreased fruit fresh weight and the percentage of fruit set of tomatoes, as well as increasing the proportion of parthenocarpic fruits and aborted flowers. On the other hand reducing night temperatures from 27 to 22 °C had a positive effect on the number of pollen grains produced and released and fruit set percentage in the tomato. These results concur with Peet et al. (1997) who showed that low or optimal night time temperatures could compensate for high daytime temperatures in influencing pollen grain production in the tomato.

A combination of increased daily radiation and temperature has increased the incidence of blossom-end-rot (BER) of tomatoes, pepper and eggplant and tipburn of Chinese cabbage and lettuce. Taste, flavor and nutraceutical compounds of fruit and vegetables, grown under protected areas are also influenced by temperature. Gruda (2005) and Castilla and Hernandez (2007) reported that high temperatures can limit tomato fruit acidity, negatively influence taste and flavor, develop poor color and exhibit low lycopene content. Gross (1991) has shown that the optimal temperature range for lycopene formation in the tomato is between 16 and 21 °C, whereas temperatures between 12 and 21 °C favor best tomato fruit color (Dorais et al. 2001). However, both Dorais et al. (2001) and Dumas et al. (2003), agree that very high air temperature (30–35 °C and above) may drastically reduce or fully inhibit lycopene production in tomatoes. Liptay et al. (1986) stated that seasonal variations in the ascorbic acid content of the tomato cv. 'Jumbo' fruit ranged from 70 to 230 mg kg$^{-1}$ fresh mass at the mature-green stage, and are directly correlated with temperature variations, when grown under greenhouse conditions.

Pardossi et al. (2000), Islam and Khan (2001), and Kano (2004) reported that sugar accumulation can be suppressed by high air temperatures when growing melons, cherry tomatoes, and watermelon, respectively. Moreover, preharvest temperatures can influence harvest quality and postharvest deterioration. For example, Kang et al. (2002) reported that cucumber fruit grown at a high average day temperature of 32 °C had a storage life of 16 days at 10 °C and did not exhibit chilling injury, whereas fruit grown at 27 °C developed symptoms of chilling injury after 12 days, at 10 °C. In addition during storage, firmness, vitamin C content, activity of superoxide dismutase, and catalase were higher in high temperature grown fruits than in control fruits.

## *Root-Zone Temperature*

Root temperature is also known to have an effect on plant growth and product quality. Optimum root temperatures are known to stimulate constant new root growth and improve the uptake of nutrients and water in hydroponic or substrate culture systems, during the rapid development stage of the tomato, bell pepper, and cucumber fruits (Schnitzler and Gruda 2002).

Calatayud et al. (2008a) found that rose roots growing in cold solution (10 °C) were thin, white, succulent, short and sparsely branched, whilst in warm solution (22 °C) roots were long, brown, thick and branched. In addition Kafkafi (2001) showed that at the same water potential gradients, and at constant light radiation and air humidity as well as canopy temperature, the rate of water flow through the stem in tomato was increased by 250 % when root temperature changed from 12 to 20 °C.

Studies with lettuce grown in a floating hydroponic system have shown that the head size, leaf color and thickness, as well as root structure, developed best at 24 °C water temperature, regardless of air temperature. Keeping water temperature at 24°C maintained the market quality of lettuce heads even at 31 °C air temperature (Thompson et al. 1998). Benoit and Ceustermans (2001) and Li et al. (2002) reported a much lower rate of BER of soilless culture sweet pepper plants grown on cooled slabs than on non-cooled slabs, possibly due to a higher root activity from better oxygen content in the root environment.

Suboptimal stress, on the other hand, can be used to improve the quality of vegetable seedlings. Chen et al. (1999), reported shorter and more compact plug-grown seedlings, which were irrigated with cold water (tomatoes 5–15 °C, cabbage 5 °C) compared with actively growing warm-season plants, e.g. cucumber, where irrigation with too much cold water sometimes cause irreparable damage from cold shock (Fig. 10.12).

**Fig. 10.12** Cold shock of actively growing young cucumber plants due to cold water (< 10 °C). (Source: Technical University Munich, Germany, 1999)

Furthermore, irrigation with cold water makes the plants more predisposed to diseases, such as those caused by *Pythium* ssp., and *Rhizoctonia solani* (Jansen et al. 1989).

## Humidity Modifications Under Cover and their Influence on Plant Growth and Product Quality of Horticultural Plants

Humidity is an important environmental factor which influences the water status of greenhouse vegetable plants and consequently affects all processes that are associated with transpiration such as the water balance, transpirational cooling and ion translocation (Bakker 1984). In the scientific literature, apart from *r*elative *H*umidity (rH) in percent, very often the term *V*apor *P*ressure *D*eficit (VPD) in kPa (kilo-Pascal) is used to characterize greenhouse humidity. VPD is the difference between the amount of water in the air of current air humidity and the amount by saturation at the same temperature. There are some factors that influence the humidity in greenhouses e.g. ET (i.e. soil evaporation plus plant transpiration) as well as air exchange with the atmosphere, water condensation at the roof level, as well as on plants. The air and crop temperatures also play a role in the control of VPD level. For example, warm air can hold more water vapor and it is more difficult to be saturated than cold air. High or low VPD will adversely influence the plant growth, yield and product quality, depending on the availability of water in the root zone, because in the end it's a question of plant water balance. For instance, in greenhouses with a high VPD, e.g. high outside temperatures in arid regions, the risk of drought stress might therefore be significant. This will increase for crops with high requirements on air humidity, such as cucumbers.

Interestingly, humidity is often neglected in protected cultivation, as long as diseases and pests do not appear. There are two main reasons for that: *firstly,* high humidity seldom causes any direct negative effect on plant growth and development. Grange and Hand (1987) found that vapor pressure deficit (VPD, 0.2–1.0 kPa) had almost no effect on the growth and development of horticultural crops. *Secondly,* until one or two decades ago, optimization of the greenhouse environment has been achieved traditionally by focusing on productivity, while product quality and quality parameters only given prominence in recent research studies (Mortensen 2000; Gruda 2005). On the other hand, according to Holder and Cockshull (1990) VPDs smaller than 0.2 kPa can only be induced for extended periods in modern glasshouses.

The management of humidity has two main purposes: maintaining crop transpiration within boundaries and preventing condensation on the crop. Excessively high or low rates of transpiration may result in local calcium deficiencies, loss of turgor, partial stomatal closure and loss of assimilation. Condensation is known to increase the incidence of disease causing organisms such as mildew and botrytis grey mould (Köhl et al. 2007; Stanghellini and Kempkes 2008). Whereas a high RH or respectively low VPD is successfully used for plant propagation and grafting. Three potentially harmful effects of extreme humidity on plants, can occur with heat damage is likely to occur because of the reduction of transpirational cooling, increased injury by air pollutants due to changes in stomatal resistance, and reducing the translocation of some ions from roots to shoots due to reduced transpiration rate under high humidity.

In the literature the information on the average weight of marketable fruits and fruit size of tomato and sweet pepper plants is inconsistent and contradictory (Gruda 2005). Mulholland et al. (2001), for instance, reported that fewer tomato fruits growing under low VPD may be due an increased rate of flower abortion and a reduction of pollen viability. In addition, the authors interestingly state that VPD of 0.1 kPa can severely reduce the K concentration in young leaves compared with standard air humidity.

Gruda (2005) has shown that controlling VPD could influence the excess or deficiency of calcium content in the fruits or in some fruit parts and consequently the occurrence of at least two related physiological disorders: "gold specks" and "blossom-end-rot" (BER). The physiological disorder known as "gold specks," is a consequence of an increased movement of calcium into the fruit and an accumulation of an excess of calcium, deposited as calcium oxalate, in cells below the epidermis (De Kreij et al. 1992; Adams 2002; Gruda 2005).

Different authors have shown that under conditions of low VPD, a reduction in the incidence of BER in tomato and sweet pepper is achieved (De Kreij 1996; Paiva et al. 1998; Li et al. 2002). High air humidity, especially during the night when the stomata are normally closed, appears to prevent calcium deficiency in lettuce (Collier and Tibbitts 1982). Cariglia and Stanghellini (2001), with Li et al.

(2001) suggested that there is an improvement of taste and flavor of tomato fruits by increasing the salinity, and applying the right humidity management program to the shoot environment. Lowering the transpiration rate can modify the effect of the root zone salinity, both by reducing the proportion of nonmarketable fruits, e.g. by the incidence of blossom end rot and reducing the decline in fresh weight. In general, manipulating the indoor climate, such as humidity, temperature and ambient $CO_2$ level, may offset the negative effect of high salinity on yield and fruit quality such as BER (Stanghellini et al. 1998; Dorais et al. 2001). These results were confirmed by Romero-Aranda et al. (2002) where greenhouse misting increased instantaneously improved the WUE of tomato yield and fruit size regardless of salinity.

On the other hand, low VPD can cause other disorders, such as, cracking and russeting (fine hairline cracks) of tomato and bell pepper fruits. According to Demers et al. (2007), a hypothesis could be drawn that low VPD decreases leaf transpiration but increases root pressure, which in turn increases fruit water supply and turgor pressure. Under such conditions, a greater stress would be applied to the fruit skin and cuticle, which would increase the likelihood of the development of cuticular and fruit cracking. Although, in this study, no significant effect of day/night RH regimes on fruit russeting was observed, it is reasonable to presume that the effect of high RH on russeting would be more pronounced if the high rH occurred at night, when leaf transpiration is already reduced.

By contrast with light and temperature, data concerning the influence of air humidity on internal greenhouse vegetable quality are generally scarce except for tomato fruits (Gruda 2005). Bertin et al. (2000) and Guichard et al. (2001) reported that, the dry matter and sugar concentrations of fruit exposed during their growth to high VPD was higher than those of fruit exposed to low VPD, apparently due to a decrease in water accumulation by the fruit which led to a 30 % reduction in the net accumulation of water by the fruit (Guichard et al. 1999). Investigations by Mortensen and Fjeld (1998) with potted roses demonstrated that increasing air humidity reduced the vase life of roses from 8–13 to 2–5 days and caused the early onset of leaf drying and “bent neck” during the stage of shoot growth. According to Torre and Fjeld (2001) and Mortensen and Gislerod (2005) air relative humidity of 85–90 % during active growth is a critical environmental factor that reduces the postharvest life of cut roses, mainly due to uncontrolled water loss from the cut shoot. Torre et al. (2003) reported that roses subjected to high RH showed differences in leaf anatomy; stomatal morphology and stomatal function, may explain the loss of water control from these plants. The authors concluded that stomatal ontogenesis should occur at RH conditions below 85 % to secure roses with a high postharvest quality potential.

## Air Flow and Ventilation

### *Greenhouses*

One significant effect of covering crops is the modification in air movement near the canopy. The reduced air velocity may have positive or negative effects on crop production as it reduces physical damage to the foliage and fruit, increases the thickness of leaf boundary layers and suppresses the turbulence level of the flow, thus reducing the exchange rates of gases between leaves and their environment and allows for potential water savings. On the other hand, reduced air velocity may reduce the ventilation rate which may avoid sufficient supply of $CO_2$ for plant photosynthesis and adequate removal of excess heat and water vapor. Hence the design of any cover should take into account these effects on the crop.

Greenhouses are ventilated either by natural or by forced ventilation systems. Natural ventilation is generally a reliable, low-cost and maintenance and energy-efficient method to keep temperature and humidity inside agricultural buildings within safe and comfortable limits. Natural ventilation can be generated by two different effects. The first is the buoyancy force (stack effect) which results from density differences between the internal and external environment due to temperature and humidity differences. The second is wind-driven flow which may enhance or hinder the buoyancy-driven flow, depending on the locations and sizes of the openings and the wind speed and direction (Allard 1998). Natural ventilation systems are mostly used in greenhouses located at mild winter climates where climate control needs are moderate.

Forced ventilation systems in greenhouses are mostly based on mechanical fans with some optional cooling devices like a wet pad or a fogging system (Linker et al. 2011). Usually, in such systems, fans suck air out on one side and openings on the opposite side allow for air flow in. In order not to hinder interaction with wind-induced natural ventilation, it is preferable to install the fans on the leeward side of the greenhouse. In forced ventilation systems the air flow rate and hence the ventilation rate can be controlled; Teitel et al. (2004) showed that controlling fan motor speed saved electrical energy. Kittas et al. (2001) compared between forced and natural greenhouse ventilation systems and found that forced ventilation increased significantly the aerodynamic conductance, but did not influence significantly water consumption when compared with natural ventilation, because of the negative feedback between canopy-to-air VPD and stomatal conductance.

Natural ventilation processes in greenhouses were studied using experiments, modeling and Computational Fluid Dynamics (CFD) simulations. In the low investment greenhouses and plastic tunnels, natural ventilation is a cheap and dominant way to manage and control greenhouse climate, such as natural $CO_2$ enrichment to secure normal crop growth (Luo et al. 2005), and water vapor removal to reduce the risk of pest epidemics (Kofoet and Fink 2007).

Natural ventilation in greenhouses is applied through either roof or side openings, or both. Roof openings are usually applied in large greenhouses where ventilation

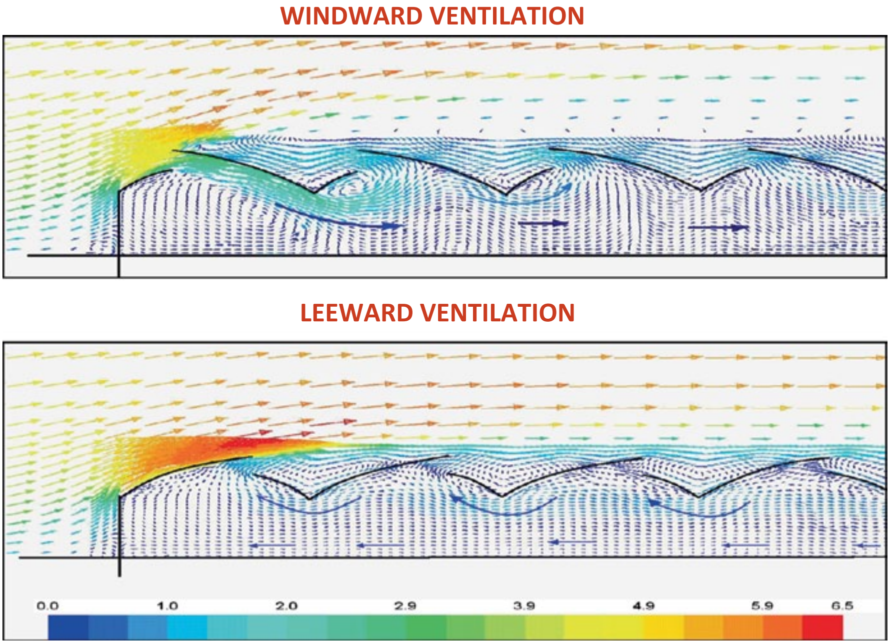

**Fig. 10.13** A *C*omputational *F*luid *D*ynamic (CFD) simulation of air flow patterns in a greenhouse with roof openings under windward (*top*) and leeward (*bottom*) ventilation. (Source: Montero et al. 2011)

by side openings may not be sufficient. To protect the crop from insect invasion, roof and side openings are usually covered with insect-proof screens which not only reduce the ventilation rate, but also affect all other microclimatic variables (Teitel 2001, 2007; Teitel et al. 2006). Teitel et al. (2012) measured radiation distribution in three greenhouses with different roof configurations and clearly showed that roof openings, including the construction elements and insect-proof screens hindered the supply of sufficient radiation to the canopy.

Montero et al. (2011) indicated a significant difference between leeward and windward ventilation (Fig. 10.13), where the windward ventilation internal air flow was in the same direction as the external wind but in leeward ventilation the internal air flow direction was opposite to the external.

Teitel and Tanny (2005) have shown that in leeward ventilation, if the wind is not perpendicular to the plane of the openings there are outflow and inflow, at the windward and leeward edges of the openings respectively. A wind blowing from the back of the openings and nearly perpendicular to them reduced the mean air velocity at the two edges but did not change the turbulent velocity much. Teitel and Tanny (1999) demonstrated by experiments and theoretical models how the sudden opening of roof windows in a greenhouse affects the temporal variation in the inside temperature and humidity. The results showed that the effect of the ventilation (i.e. the reduction with time in the temperature and humidity ratio within the greenhouse) increases with the height of the window opening and the wind speed, and decreases with the solar radiation.

An important issue in natural ventilation systems is the estimation of the ventilation rate, which is responsible for the adequate removal of excess heat and water vapor and supply of $CO_2$ (Boulard 2006). Boulard and Baille (1995) derived an expression for the ventilation rate, based on the Bernoulli equation, which depends on both the buoyancy and wind effects. Kittas et al. (1997) investigated the relative contribution of the two factors to greenhouse natural ventilation and found that under the conditions of their experiments, the wind effect predominated on the buoyancy effect when $u/\sqrt{\Delta T} > 1$, where $u$ is external wind speed and $\Delta$T is the temperature difference between inside and outside of the greenhouse.

In naturally ventilated greenhouses the control of $CO_2$ enrichment is largely related to the climatic conditions. For example, greenhouse $CO_2$ enrichment in warm climates is restricted by the need to ventilate, leading some growers to intermittent enrichment, where enrichment and ventilation alternate several times an hour. This strategy relies on the heat and $CO_2$ capacity of the system, characterized by a heating time constant of the order of 10 min, during which period ventilation may be suspended (Ioslovich et al. 1995). The latter authors have demonstrated that for slowly changing weather, the optimal $CO_2$ enrichment is basically not intermittent, but rather approximately stable. Seginer (1990) considered the combined effect of $CO_2$ enrichment and shading and concluded that under desert conditions, where ventilation is mandatory during most daytime hours, $CO_2$ enrichment was effective only during the morning, before ventilation rate had to be increased in order to cool the crop.

## *Screenhouses and Screen Covers*

Another type of structures which become popular among growers in mild winter climates is the screenhouse or screen cover (Tanny 2013). These structures are much cheaper than greenhouses and under certain climatic conditions may provide the adequate protection for the crop. Since the screenhouse is a semi-open structure, air flow and ventilation are strongly influenced by the external climatic conditions. A major effect of porous screens is to increase the resistance to airflow which decreases the internal mean air velocity.

In an attempt to characterize the effect of horizontal screen covers or screenhouses on air velocity, several field measurements established relationships between inside air velocity and outside wind speed (e.g., Waggoner et al. 1959; Tanny et al. 2006; Siqueira et al. 2012; Tanny 2013). In few cases, the vertical gradient of air velocity was also considered (Allen 1975; Tanny et al. 2010). Obviously, denser screens with lower porosity would induce higher resistance to air flow and hence will diminish inside air velocity more than screens with higher porosity. However, Tanny (2013) suggested that several additional factors (e.g. screen deployment configuration, crop height, velocity measurement height and the travel distance of air, or fetch) affect the inside air velocity in screenhouses.

Tanny et al. (2006) have shown that several important turbulence characteristics were essentially unchanged from their external values, in a large screenhouse in which banana was grown (Fig. 10.9). Tanny et al. (2010) and Siqueira et al. (2012) demonstrated that the friction velocity, which is a measure of the turbulent transport of momentum, was nearly constant with height in the air space between the crop and the screen. Tanny and Cohen (2003) and Tanny et al. (2009a) investigated the boundary layer properties of the air flow above the screen, which controls the exchange of gases and heat between the canopy and atmosphere and showed that screens may inhibit these exchange processes, including ET, and hence lead to water saving.

Screenhouses of relatively light shading screens reduce the absolute velocity of the approaching external wind but preserve the wind direction, and the turbulence properties of the boundary layer (Tanny et al. 2006, 2010). This contrasts with insect-proof screenhouses, which induce a more complicated internal air flow pattern (Möller et al. 2003) where in part of the screenhouse the air flow direction was opposite to the external wind. This latter finding was similar to roof ventilated greenhouses under leeward ventilation (Fig. 10.13).

Ventilation rate of screenhouses was investigated using the water vapor as a tracer in two insect-proof screenhouses in which pepper and banana was grown separately. Tanny et al. (2003) have shown that ventilation rate depended on external wind speed, was significantly reduced as compared to open field conditions, and was non-uniform within the screenhouse, demonstrating a higher ventilation rate closer to the side walls than the center of the house. Ventilation rate estimates were in the same order of magnitude for both crops (Tanny et al. 2006). Teitel and Wenger (2010) have shown the effect of screenhouse roof shape on the ventilation rate, using CFD simulations. Their analysis showed that using pitched roofs increased the ventilation rate as compared to flat roofs, due to higher penetration of air into the house.

## Modifications of $CO_2$ in Protected Environments, $CO_2$ Enrichment and Distribution and the Influence on Plant Growth and Product Quality

Carbon dioxide ($CO_2$) is a crucial component of photosynthesis used for biomass production, and is indispensable for plant growth. Plants take in $CO_2$ through the stomata by diffusion so the concentration of $CO_2$ in the greenhouse atmosphere strongly influences $CO_2$ uptake by the plant. On the other hand, according to Frantz (2011) the $CO_2$ concentration in the greenhouse can be reduced during the day to levels as low as 175 ppm (the normal atmospheric $CO_2$ concentration is about 390 ppm) and this in turn leads to photosynthesis reduction. When greenhouse windows are closed and no ventilation takes place a $CO_2$ supply from the atmosphere can happen only from leaks through the greenhouse envelope. If the internal air circulation is very low, the remaining $CO_2$ deficit is not recoverable.

Whereas the traditional straw bale cultural technique for cucumbers is one of the oldest and simplest methods of $CO_2$ enrichment in greenhouses, its importance has increased with the trend towards producing crops in nutrient film, rockwool, and other substrates, where natural $CO_2$ concentration is small compared to $CO_2$ coming from the soil profile. Indeed, in greenhouses, the soil is frequently covered with plastic sheets when alternative soilless media are used (Hicklenton 1988; Slack 1986a). On the other hand, $CO_2$ enrichment methods have continued to develop sources of nonpolluting $CO_2$ (Mortensen 1987), so that the negative effects associated with the burning of hydrocarbons have been reduced (Gruda 2005).

Maintaining high levels of $CO_2$ is sometimes difficult, when solar radiation and/or inside air temperatures are high inside the greenhouse, because roof and/or side windows need to be opened, to ventilate the greenhouse in order to reduce the air temperature and/or regulate the VPD at optimal values. New perspectives recently developed closed and semi-closed greenhouses which reduce the energy consumption. In such greenhouses window ventilation is usually reduced or replaced by an active cooling system. In addition, energy saving measures have been implemented where excess solar energy is collected and stored, in order to be reused at night or in periods in which the solar radiation is limited, e.g. in cloudy days or in the winter. Under these conditions it is possible and preferable to keep high $CO_2$ concentrations even at high light levels.

Generally, concentrations of 800–1,000 μmol $mol^{-1}$ in greenhouse atmosphere are used for different plants in the daytime, in order to promote photosynthesis and inhibit light respiration. According to Drake et al. (1997) elevated $CO_2$ reduces stomatal conductance as well as transpiration rate and improves WUE, while at the same time stimulates higher rates of photosynthesis and increases light-use efficiency. Many studies reported these positive effects on physiology, growth, and productivity of plants. Besford et al. (1990), for instance, found more than double photosynthetic rates in mature leaves of tomatoes, an increase of the fresh weight per unit area of leaf, and in general increases of crop yields, due to an increase of $CO_2$ concentrations to 1,000 μmol $mol^{-1}$. Mortensen (1987) reported that horticultural greenhouse plants exhibited positive effects due to $CO_2$ enrichment by increasing dry weight, plant height, number of leaves, and lateral branching, whereas Mortensen and Moe (1995) found that the development rate of miniature roses could be accelerated by 4–5 days at elevated $CO_2$. Plant quality of ornamentals, expressed by growth habit and number of flowers, is often enhanced by $CO_2$ enrichment. Peet and Willits (1987) reported that $CO_2$ enrichment significantly increased the yield of cucumbers. Mortensen (1994) showed that increasing $CO_2$ concentration in plastic “field chambers” from ambient to 800–900 μmol $mol^{-1}$ could increase the dry weight of lettuce, carrot, and parsley by 18, 19, and 17 %, respectively. Enrichment with $CO_2$ (900 μmol $mol^{-1}$, 8 h $day^{-1}$) and supplementary lighting for approximately 3 weeks before transplanting, increased accumulation of dry matter in shoots by 50 % for tomato and pepper seedlings, as compared with the control group. Furthermore, the early yield after transplanting to the field was improved (Fierro et al. 1994). Some more examples of benefits for other vegetable crops are compendiously presented by Gruda (2005).

Carbon dioxide enrichment could have a positive effect on plant propagation and promoting the rooting of cuttings. Even at low irradiance growth promotion can be achieved by $CO_2$ enrichment, due to inhibition of photorespiration and the associated reduction of the light compensation point. This is of great benefit in winter/spring period in higher latitudes when light levels are low. The negative effects of low light conditions (Fierro et al. 1994), low temperatures (Frantz 2011), high salinity levels in irrigation water available in Mediterranean countries (Romero-Aranda et al. 2002) or high electric conductivity (EC) levels of nutrient solutions (Li et al. 1999) can be diminished by $CO_2$ enrichment. Supplementary $CO_2$ boosted total leaf number and mass of lettuce even though temperatures were maintained at 1.67 °C (3 F) lower than in a traditionally well insulated greenhouse without added $CO_2$ at a commercial facility (Frantz 2011).

There is less information on the effect of $CO_2$ concentration as an elicitor on the internal quality of vegetables with most publications reporting no effect on product quality (Gruda 2005). However, there is evidence that the enhanced rate of photosynthesis observed during short-term exposure to high $CO_2$ may not be sustained over long periods (Drake et al. 1997; Frantz and Ling 2011). Besford et al. (1990) summarized that growth for a number of weeks in high $CO_2$, involving several vegetable crops and tobacco did not maintain the photosynthetic gain, when plants were measured at normal $CO_2$ ambient condition. This process is defined as the photosynthetic acclimation to high $CO_2$ concentration. Similarly, Frantz and Ling (2011), recently observed a positive effect of $CO_2$ on leaf and flower mass after 5 weeks on the growth of *Petunia* × *hybrida* (second harvest), but there was no $CO_2$ effect on growth with the last harvest. These results show that long-term exposure to elevated $CO_2$ doesn't always lead to enhanced biomass production. Moreover photosynthetic acclimation can lead to adverse effects on the ornamental value of plants (Croonenborghs et al. 2009) such as higher carbohydrate concentration, lower concentration of soluble proteins and RuBisCo, and inhibition of photosynthetic capacity (Drake et al. 1997).

Indeed higher amounts of carbohydrates can lead to a problem of source/sink balances and sink strength. Arp (1991) analyzed the relationship between rooting volume, or the size of the container, and acclimation of photosynthesis of plants in elevated $CO_2$ concentrations and found that plants grown in small containers (< 10 L), were sink limited because of root zone restrictions. These results were in agreement with a survey of 163 studies by Drake et al. (1997), where the assimilation remains the same for plants grown in both elevated and ambient $CO_2$ concluding that the restriction of rooting volume on acclimation is probably confounded with effects of nutrient availability on photosynthesis.

Other factors, such as available nutrients, also could reduce sink strength (Drake et al. 1997). Qian et al. (2012) found that fruit load is important as well. By investigating different fruit loads of tomato in a semi-closed greenhouse and a conventional modern greenhouse it was found that the increase of dry matter production in the semi-closed greenhouse was mainly explained by a higher $CO_2$ concentration when compared to an open greenhouse. Similarly, Dannehl et al. (2012) showed that a combined application of a high pressure fog system and $CO_2$ enrichment in a semi-closed greenhouse were adequate to accelerate plant growth, increase the dry matter in leaves, and promote the formation of fruit set per truss, as well as increase in the maximum total yield by 20 % as well as fruit size. On the other hand, the occurrence of blossom-end rot in tomato fruit was reduced when compared to those grown under conventional climate conditions. Qian et al. (2012) concluded that the photosynthetic acclimation to elevated $CO_2$ concentrations depended on the source-sink balance and a continuously high $CO_2$ concentration in a semi-closed greenhouse does not cause feedback inhibition in high producing crops, because these plants have sufficient sinks (fruits) to utilize extra assimilates.

## Water Supply, Irrigation Management and Systems and their Effect on Plant Growth and Development

### *General*

Water is one of the most important factors influencing plant growth, productivity, and quality and is the main component of plant cells and total fresh biomass content of plants. Typical greenhouse grown vegetables such as tomatoes, cucumbers, peppers, and lettuces may contain 90–96 % or even more water. For protected crops, irrigation and its management have a special importance since natural precipitation is excluded and if soilless culture systems (SCSs) are used, often the groundwater sources are unavailable. Moreover, greenhouse plants are not exposed to drastic changes of environmental conditions. For example, Huang and Snapp (2004) reported a very consistent association between the incidence of shoulder check or russeting of tomatoes grown in the open and precipitation events followed by periods of hot, dry weather during rapid fruit expansion. In addition resultant fruit quality was higher and the incidence of defects lower in fruit produced under plastic rain covers than in open field-grown tomatoes.

Water supply is significantly higher in protected cultivation than in the open field, mainly due to the intensity and quantity of year-round biomass production. High temperatures, which can be reached in greenhouses during summer, may also increase water demand. On the other hand, the requirements on water quality are considerably higher. Generally, the majority of protected crops is warm-season species that are sensitive to low temperatures. Therefore water temperature must be as close as possible to the plant root temperature. Increased salinity in the irrigation water is more likely to have a more negative impact than in the open field, over all in a closed loop-system.

Either too much or too little water can induce plant stress. For instance, a typical disorder of tomato fruits is blossom end rot—usually occurring due to water deficit, whereas cracking is due to an excess of water supply. According to Peet and Willits (1995), the application of excess irrigation water to greenhouse tomatoes induced a two-fold higher incidence of radical cracking in fruit compared to the recommended water regime. Photosynthesis and transpiration are negatively affected by water and/or drought stress. Most of the water consumed by plants is used in the transpiration process, as well as regulation of internal temperature. Plants react to water fluctuations firstly by stomata regulations with stomata closing during the night and opening at dawn (light-induced stomatal opening). Transpiration increases with increasing temperature until midday and decreases significantly by cooling, due to a gradual closing of stomata.

With inadequate water supply, or extreme heat and drought, the stomata close much earlier with negative consequences for gas exchanges and $CO_2$ assimilation. Because of the reduction in $CO_2$ assimilation in leaves, the metabolic processes are impacted resulting in many of the integrated physiological and biochemical processes that cause yield and quality reduced. The loss of turgor pressure in the cells leads to wilting that initially manifests in a withering of leaves followed by leaf necrosis and plant desiccation.

According to Bolla et al. (2009) greenhouse water shortages in roses can have a negative effect on photosynthesis with a simultaneous reduction in the photosynthetic rate and a significantly lower quantum yield of photosystem II, without any limitation made on the intercellular $CO_2$ concentration levels. This, as well as the increase in carbohydrate content (glucose, fructose and sucrose) and inorganic solutes (potassium) of the stressed plants during the dry-down period indicate that the plants are able to maintain their metabolic and physiological function. Apart from the stomatal closure the ability to continue functioning also plays a role, by means of turgor maintenance and osmotic adaptation.

Niu et al. (2008) also indicated that during dry-down, fluorescence measurements indicated some damage in the photosystem II of four clones of oleander plants (*Nerium oleander*). In addition, shoot dry weight was reduced, while root-to-shoot dry weight ratio was increased; as substrate volumetric moisture content decreased from 30 %, leaf net photosynthetic rate, ET rate, and stomatal conductance decreased in all clones.

Plants express a response to water stress by changes in their morphology such as decreasing leaf area, in order to regulate water loss and prevent further dehydration (Gruda and Schnitzler 2000a), or by an adaption in their root system. According to Kulkarni and Phalke (2009), under drought stressed conditions, plants would increase their water uptake from deeper soil layers by restricting the horizontal proliferation of lateral roots in the topsoil and allocating more resources to the growth of primary roots. The plant can be considered a hydraulic system, connecting water in the soil, or in the case of SCS the substrate or nutrient solution, with the water vapor in the atmosphere (Taiz and Zeiger 2010). In the literature, sometimes the term “soil-plant-atmosphere continuum” is used to characterize the water pathway. The water movement processes are explained using the water potential concept (negative pressure). The factors influencing water movement along this pathway are water tension in the root zone, soil or substrate type, physiological plant status and atmospheric water demand. Hence, greenhouse environmental conditions, such as air temperature, radiation, air movement and air VPD will directly or indirectly influence water movement. This sub-section only considers soil water and its effect on protected crops.

In greenhouses, plants obtain water mainly from the soil. Thus, the regulation of soil moisture is very important. Excessive amounts of water, due to an incorrect irrigation can result in nutrient losses by leaching, particularly of nitrogen. Moreover, overwatering should be avoided, because of a likely oxygen deficiency and a probable production of other adverse gases in the soil such as methane and/or carbon dioxide. In this case the roots may not successfully uptake water and nutrients. The optimum water content in greenhouses is in the range of field capacity, and sometimes higher, with substrate cultures with a high pore volume. The regulation of soil moisture is also important for microbial transformation in the soil, for mobilization of nutrients from the soil organic matter, and for solubility of nutrients. For instance, adequate soil moisture is necessary to facilitate diffusion of potassium ($K^+$) to plant roots for uptake which according to Lester et al. (2010) accounts for $>75\,\%$ of $K^+$ movement. Therefore, soil moisture deficits can limit soil K transport as well as uptake into the plant, thereby causing K deficiency.

Simulated drought conditions are sometimes used as a tool to control plant habit and generative development. As it was stated earlier, one of the quality requirements for ornamentals is to be compact plants and to possess a good number of buds and blooms at sale time and where the stature of the plant benefits the consumer and grower; namely, a high-quality product, and savings in production and transportation costs, less water and space requirements. Different methods have been developed to induce compact morphology. The inhibition of growth with chemical agents is certainly one of these methods. Very limited licenses as well as an increased consumer consciousness however have led to increasing pressure in developing alternative methods for growth inhibition. The use of techniques for lowering temperatures and/or "cool morning", and thigmomorphogenesis and restrictive water management are some of these alternative methods. Röber et al. (1986) demonstrated that decreasing moisture leads to a reduction of height, diameter, and leaf area of ornamental plant species. Precisely performed induced sub-drought stress can produce compact high quality plants, comparable to those treated with growth inhibitors. Liptay et al. (1997) reported that carefully regulated, moderate stress can slow down growth of vegetable transplants under certain circumstances without influencing yield or product quality loss. Gruda and Schnitzler (2000b) have proved that size differences in head lettuce transplants, induced by variable irrigation levels and different organic substrates, were no longer detectable 3 weeks after transplantation. In addition, moderate stress can reduce susceptibility to pathogens, such as *Pythium ultimum* (Schnitzler and Gruda 2002). A modification of water availability can also be achieved by adjusting the concentration of nutrient solution in soilless culture and this is used by growers in order to improve the quality of some fruit vegetables, such as tomato.

## *Crop Water Requirements and Evapotranspiration*

Water scarcity has become a significant limitation in agricultural production worldwide. Hence it is necessary to accurately estimate the crop water needs, or whole canopy ET, under different conditions in order to optimize irrigation and increase the water saving.

Evapotranspiration can be either measured or estimated by models, the common measurement techniques being the lysimeter and sap flow gauges. One lysimeter application is based on installing several planted pots on load cells and continuously monitoring their weight. From this data, and knowledge of the irrigation, the amount of water consumed by the plant during a certain time period can be extracted which can then be used to guide the next irrigation. The lysimeter technique is useful for small and moderate size plants but for large plants or trees it is rarely used due to obvious technical limitations (Ghavami 1973; Israeli and Nimri 1986). Sap flow gauges are based on measuring the sap flow rate in the stem using stem temperature variations induced by sap flow. Common sap flow techniques are the heat-pulse (Cohen 1994) and thermal dissipation (Granier 1985). In recent years the use of the eddy covariance technique to measure whole canopy ET was examined in screenhouses, and is discussed below.

Crop water requirements for protected crops can be estimated using the well-known Penman-Monteith (PM) equation, which is derived from principles of energy balance and transport processes. The general expression for the PM equation is (Allen 1998):

$$ET = \frac{\Delta(R_N - G) + \rho_a C_p (e_s - e_a)/r_a}{\Delta + \gamma^*} \tag{10.1}$$

in which

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right).$$

In Eq. 10.1, ET is the evapotranspiration (W $m^{-2}$), $\Delta$ is the slope of the saturation vapor pressure-temperature curve (kPa $K^{-1}$), $R_N$ is the canopy net radiation (W $m^{-2}$), $G$ is the soil heat-flux density (W $m^{-2}$), $\rho_a$ is air density (kg $m^{-3}$), $C_p$ is air specific heat at constant pressure (J $kg^{-1}$ $K^{-1}$), $e_s$ and $e_a$ are the saturated and actual vapor pressure (kPa), $\gamma$ is the psychrometric constant (kPa $K^{-1}$), $r_a$ is the aerodynamic resistance (s $m^{-1}$), and $r_c$ is the canopy resistance (s $m^{-1}$).

A common method for estimating crop water requirements for canopies in open field conditions is to use the concept of reference evapotranspiration, ET0, and then apply a crop coefficient, Kc, which is an empirical parameter, specific for each crop and growth stage (Allen et al. 1998). The ET0 is calculated for a well irrigated and uniform reference grass crop at a height of 0.12 m, conditions which dictate certain values for the resistance terms, $r_a$ and $r_c$, in Eq. (10.1). Substituting these values in Eq. (10.1) results with the equation of daily ET0 (Allen et al. 1998):

$$ET0 = \frac{0.408\Delta(R_N - G) + \gamma \frac{900}{(T_{mean} + 273)} u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \tag{10.2}$$

where $u$ is air velocity measured at 2 m above the ground. Details for calculations of daily values of the other parameters in Eq. 10.2 are given in Allen et al. (1998).

Obviously the conditions of most protected crops are significantly different from those of the reference grass for which Eq. 10.2 was derived. Therefore adjustments should be made according to actual climatic conditions and canopy properties in order to obtain the actual crop evapotranspiration (ETc). For mild climates, von Zabeltitz (2011) suggested increasing daily mean maximum and minimum temperatures by 4 and 2 °C, respectively, using mean relative humidity of about 75–80 %, and assuming transmittance of the global radiation by the cladding material (mostly for plastic greenhouses) of about 0.6–0.7. In addition, recommendations for actual crop coefficient (Kc), relative area of crop to ground and irrigation loss are given (von Zabeltitz 2011).

Fernandez et al. (2009) demonstrated the use of the ET0 approach (Eq. 10.2) for an unheated plastic greenhouse in Almeria, Spain using two sub-models: one for radiation and the other for the crop coefficient for pepper cultivation. They conducted experiments in a naturally ventilated greenhouse in the Almeria region in which pepper was grown. The measurements included inside and outside climatic variables, and ETc was measured by lysimeters. Good agreement was obtained regarding estimated and measured values of ET0, ETc and Kc.

In an attempt to optimize water use in greenhouses, several studies measured crop ET, mainly by the lysimeter technique, and compared the measurements with theoretical models, adapted to the greenhouse conditions. For example, Jolliet and Bailey (1992) examined the effects of inside climatic conditions on tomato transpiration and compared their transpiration measurements with five transpiration models. Their results showed that transpiration rate increased linearly with solar radiation, VPD and air velocity; however air temperature and $CO_2$ concentrations had no significant influence on crop transpiration. Among the five transpiration models they investigated, they found two (Stanghellini 1987 and Jolliet and Bailey 1992) to be in best agreement with the measurements as these two models represented most accurately the solar radiation and VPD effects on the stomatal conductance.

A different approach in simulating the ETc in Mediterranean plastic greenhouses was examined, by Boulard and Wang (2000). They suggested that unlike north-European glasshouses, Mediterranean plastic greenhouses are strongly coupled with the external environment, such that ET modeling can be based on the relationships between the external and internal greenhouse conditions. Their results showed that when the greenhouse was closed, i.e., strongly decoupled from the external environment, ET predictions based on external conditions deteriorated in comparison with periods when the greenhouse was well ventilated. This was due to strong interaction between inside and outside in the ventilated greenhouse. In their model, Boulard and Wang (2000) applied the general Penman-Monteith equation (Eq. 10.1)

**Fig. 10.14** Two eddy covariance systems installed in a large banana screenhouse, located at the Western Galilee of northern Israel. The systems measure whole canopy turbulent fluxes of water vapor, heat and $CO_2$. Their deployment above the canopy does not interfere with the crop. (Source: Tanny 2007, private collection)

using specific expressions for the different parameters, based on the greenhouse ventilation rate, specific stomatal resistance and leaf boundary layer resistance. Experiments conducted in a greenhouse with a tomato crop resulted with very good agreement between estimated and measured (by lysimeters) ETc.

The use of evaporative cooling devices like pad and fan or fogging (see Sect. 3.1) increase the greenhouse air water vapor concentration and hence should be taken into account when crop water requirement is considered. For example, Fuchs et al. (2006b) demonstrated in a rose crop that operating the wet pad cooling system reduced transpiration. Such result may have implications on irrigation needs of greenhouse crops. Although crop transpiration is reduced, the additional water is supplied through the wet pad, such that the total amount of water required is not changed much. The operation of the wet pad also cools down non-transpiring organs of the plants like flowers or fruits, which is an advantage.

In fan ventilated greenhouses, and provided there is no water condensation, the total amount of crop transpiration can be measured through a mass balance of the water vapor (Teitel et al. 2010), implemented between air inlet and outlet. In screenhouses this approach cannot be implemented. Therefore, Tanny et al. (2006, 2010) and Dicken et al. (2013) have examined using the Eddy Covariance technique to measure whole canopy ET in large screenhouses. In this technique, vertical air velocity and water vapor concentration are measured at a high sampling rate, usually 10 Hz; the covariance of these two variables is the net vertical turbulent flux of water vapor, i.e., ET.

Usually air temperature is also measured at high frequency such that sensible heat flux can be obtained as well. If $CO_2$ concentration is also measured at high frequency, its vertical flux can also be determined by this approach. This latter measurement also facilitates the calculation of the water use efficiency as the ratio between $CO_2$ and water vapor fluxes. Eddy covariance sensors are installed within the air boundary layer above the canopy, so this approach has the advantage that there is no interference with the crop or the soil (Fig. 10.14).

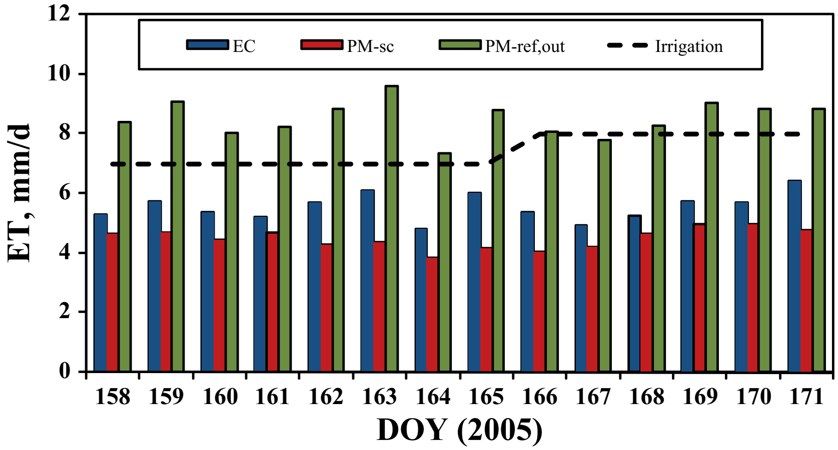

**Fig. 10.15** Total daily evapotranspiration as measured by the Eddy Covariance technique (*black bars*) and estimated by two models. *PM-sc*: screenhouse evapotranspiration model (*gray bars*); *PM-ref, out*—reference evapotranspiration for external conditions (*empty bars*). The *dashed horizontal line* is the irrigation supplied by the grower. *JD*: Julian Day. (Source: Tanny et al. 2012)

To model ET accurately in screenhouses, Möller et al. (2004) suggested a modified Penman-Monteith model which includes an additional boundary layer resistance due to the boundary layer occupying the air gap between the canopy top and the screen. They measured transpiration of pepper plants in an insect-proof screenhouse, using sap flow and eddy covariance techniques; they found good agreement between the two measurement approaches and between the measurements and the newly derived model.

In a study conducted in a large banana screenhouse near the Sea of Galilee in northern Israel, ET was measured by an eddy covariance system (Tanny et al. 2006) and the measurements were compared with two types of models; the Penman-Monteith model of ET0 (Allen et al. 1998) under external meteorological conditions, and the modified ET model for internal screenhouse conditions. Figure 10.15 presents the results of measurements over a period of 14 days in June 2005. The results show that the screenhouse model is somewhat lower than the measurements. The model for ET0 is significantly higher however, illustrating the effect of the screenhouse in reducing ET. The results of Fig. 10.15 show that irrigation (dashed horizontal line) was consistently higher than the actual crop water use. Note that this irrigation level was already about 70 % of the irrigation supplied to open banana plantations in this region and that although irrigation was increased from JD (Julian day) 166, actual crop water consumption did not change suggesting the possibility of water savings.

**Box 1** *Water use efficiency*

Water use efficiency (WUE) of agricultural and horticultural production can be generally defined as the ratio of the volume of water used productively (Stanhill 1986). It is also termed as water productivity and expressed in units of product weight per volume of water applied. From a physiological point of view, WUE can be defined as the ratio between $CO_2$ assimilation flux, and transpiration rate on the plant level. It can also be defined as the ratio between $CO_2$ flux and the rate of water applied.

As reviewed by Castilla (1999), protected cultivation can improve the water productivity due to the ET reduction, and using advanced technologies like drip irrigation, sophisticated climate control and soilless culture. Pardossi et al. (2004) summarized typical values of WUE for Mediterranean greenhouse crops. Mean values presented were 21.8, 14 and 30.3 kg $m^{-3}$, for tomato, cucumber and sweet pepper, respectively (Pardossi et al. 2004 and von Zabeltitz 2011). These values were lower by more than 50 % than corresponding values of 58.2, 28 and 77 kg $m^{-3}$, obtained for the same crops in sophisticated greenhouses in the Netherlands. Van Kooten et al. (2004) reported that for a kilogram of tomatoes produced in the field, on average used about 200 ± 100 L of water. Using drip irrigation, this amount is reduced to about 60 L per kg, (e.g. in Israel). In high-tech greenhouses in The Netherlands, the average use at that time was approximately 20 L per kg. However, applying new techniques and new irrigation methods as well as modifying the environmental management can significantly improve water use efficiency. The techniques include the use of light selective shading or movable screens as well as the use of the evaporative cooling system. According to van Kooten et al. (2004), it is possible to get WUE of 1.5 L water per kg tomato by closing the greenhouse and regaining the condensed evaporated water.

Water use efficiency of screenhouse crops was estimated as the ratio between yield and applied irrigation. In an irrigation trial conducted in a large banana screenhouse in the Jordan Valley, different levels of irrigation were applied (100, 85, 70 and 55 %) and yield measured for each treatment. The 100 % irrigation level was actually 70 % of the irrigation supplied to open banana plantations in this region. The results of Tanny et al. (unpublished data) showed that at 85 % irrigation the yield did not decrease as compared to the 100 % level. Irrigation at 70 % reduced the yield but this reduction was statistically insignificant. The lowest irrigation level of 55 % did cause a significant reduction in yield. Hence, the results showed that water use efficiency can be increased by about 20–30 % by growing the banana in screenhouses in this region of the country.

Dicken et al. (2013) defined WUE of a screenhouse banana plantation in two ways. One definition was the ratio between total daily values of net $CO_2$ uptake and ET as measured by the Eddy Covariance system ($WUE_{ET}$), and the second was the ratio between total daily net $CO_2$ uptake and applied daily irrigation ($WUE_{irr}$). Results showed that $WUE_{ET} > WUE_{irr}$ due to the fact that measured ET was less than the daily irrigation. Results also showed that the ratio between the two fluxes, namely, $WUE_{ET}$, was essentially unchanged with plant growth (with an average of 0.00894 for small plants and 0.00946 for large plants). On the other hand, $WUE_{irr}$ (based on irrigation) increased with plant growth suggesting that the crop was over-irrigated during its initial growth stage. This finding may be important for improving irrigation management and increasing water savings. Dicken et al. (2013) also presented diurnal courses of the $WUE_{ET}$ (daily values only, 10:00–17:00) for small and large banana plants in the screenhouse. Larger plants' $WUE_{ET}$ was essentially unchanged during the day whereas for the smaller plants a small increase (not significant) of WUE was observed during the day. The results also showed that during the morning hours (10:00–12:00) $WUE_{ET}$ for the larger plants was significantly higher than that for the smaller plants. This, together with the observation by Dicken et al. (2013) that photosynthesis per leaf area was about the same for both cases may indicate over-irrigation of the smaller plants in the early morning. Such observations could assist growers in increasing water use efficiency of screenhouse banana plantations by fine tuning irrigation during the morning hours.

### *Irrigation Management*

Irrigation management includes all measures that guarantee sufficient water supply for plants. One could assume that for a specific plant species "only" the right water demand should be ensured and generally, the amount of evapotranspired water should be compensated. However, customizing irrigation is a multi-faceted activity and the amount of water used in protected crops is still higher than the theoretical calculated values. For instance, Fuchs et al. (2006a) reported that roses grown in greenhouses on artificial substrates transpire annually an estimated 1,500 mm of water in Israel. However, in order to prevent solute accumulation in the root medium, growers use nearly twice this amount for irrigation. The excess water leaches out, leading to a considerable waste of water and fertilizer (for water use efficiency (WUE), see box 1; and for fertilizer use efficiency (FUE), box 2).

Questions like "how long?" (= duration), "how often?" (= frequency), and "how much?" (= water amount), deserve answers to greenhouse management (climate conditions) for each plant's growth phases (young or ripening stage), particularly, to control the water status of a crop for a proposed level of plant performance. According to Saha et al. (2008) targeted performance levels and optimizing irrigation input can be used to either maximize yield or economic return, or increase the WUE.

Different irrigation controls range from hand irrigation through to simple timer-based to computer-based monitoring and control systems. In commercial

**Fig. 10.16** Examples of drip irrigation systems in protected crops, (**a**) by ornamental plants, (**b**) strawberry, and (**c**) tomatoes. (Source: Gruda 2005, private collection)

**Fig. 10.16** (continued)

greenhouses, irrigation is usually automated and water supply adapted for plant need. According to Savvas et al. (2013), the common approaches in irrigation control are the use of timer-based, sensor-based or model-based irrigation control methods. Whereas the timer-based method involves using a timer, sensor-based control depend on water status measurement, either in the soil/substrate or in the plant, model-based control methods depend on the estimation of plant water loss related to one or more environmental or crop variables.

Past research and practical experience has shown that irrigation management practices must be simplistic, useable, flexible within the existing system design and maintenance constraints, and understandable by growers, in order for them to be widely adopted and used. Therefore, it is not surprising that the predominant irrigation scheduling method is decision making by the growers, based on their own experience (Warren and Bilderback 2004).

### *Irrigation Systems*

From a spatial point of view and according to Savvas et al. (2013), greenhouse irrigation systems can be categorized in: (i) overhead surface, (ii) surface and (iii) subsurface or sub-irrigation system.

Overhead surface irrigation is based on a top-down principle and involves overhead nozzles, where the water is sprayed onto the plants. The nozzles are installed either in static pipes or in rigs, so called automatic irrigation booms, which move through the greenhouse above the plants. Overhead irrigation is appropriate for watering plants with low stature and at a similar uniform growing stage. In addition, it is of benefit for plants that like regular cooling, such as different lettuces and salad greens, spinach or seedlings. These systems have relatively low installation costs. The irrigation uniformity and WUE are however low by these systems. In addition, the risk for residue on leaves and flowers as well as the risk for spreading diseases is high, because the water is applied to the aerial part of plants.

The most popular irrigation system in greenhouses is the surface system or drip irrigation (Fig. 10.16), mainly due to high efficiency and uniformity. In addition, drip irrigation is easy to install and design, as well as being precise with less run-off of water. One of the great advantages of drip irrigation is that it can be used to deliver nutrient solution as well as plant protecting agents. Drip irrigated water with or without fertilizer is delivered slowly where needed, through the soil or substrate surface to the plant roots. Apart from low-pressure irrigation, pressure compensating emitters are used, in order to deliver a constant water-amount per time unit. One of the disadvantages of drip irrigation is the clogging of emitters.

Subsurface or sub-irrigation systems provide plants with water through the base of pots and/or other containers used, and include capillary mats, troughs, ebb-flood benches as well as flooded floors. In this system water reaches the roots mainly by capillary forces. Ebb-flood benches are generally used for production of pot ornamentals and seedling plants, troughs are used for pot plants and vegetables grown in substrates, and flooded floors for seedling production and large ornamental plant production. One of the disadvantages of this system is the accumulation of salts in the upper layers of the soils or substrates. Sometimes pipes that are usually used in drip irrigation, e.g. porous pipes, are installed in the soil in form of a sub-irrigation system. By an appropriate use, the WUE could be improved.

## *Impact of Irrigation on Crop Yield and Quality*

Producing high quality horticultural products requires a proper efficient irrigation management. Generally, supplying optimal water amounts improves growth and yield of protected crops. However, according to Gruda (2009), high yields do not automatically imply high quality; therefore, a compromise needs to be established. For instance, increasing water availability in tomato enhances fruit size and acidity. On the contrary, fruit quality of tomatoes can be significantly enhanced in terms of dry matter, TSS (total soluble solids), and sugar content in the fruit when plants are grown under moderate water stress conditions, with no significant yield loss (Pulupol et al. 1996; Wu et al. 2004). Moderate deficit irrigation is useful not only in reducing production costs, but also in preserving water consumption and minimizing leaching of nutrients and pesticides into the groundwater (Pulupol et al. 1996).

Furthermore, water shortage might increase the content of so called nutraceutical or health-promoting substances. Mattheis and Fellman (1999) and Kleinhenz et al. (2003) reported that water availability relative to crop development may also influence the flavor of vegetables. In a review article concerning the antioxidant content of tomatoes, Dumas et al. (2003) reported that, depending on cultivars, water shortage generally tends to increase the ascorbic acid content of the fruits. Moreover, a higher color intensity and lycopene content of tomato fruits were found under water shortage (Wu et al. 2004); Dorais et al. (2008), and Dumas et al. (2003) reported conflicting results concerning the lycopene levels depending on cultivar as well as other growth conditions.

Several aspects of plant development and physiology are controlled by root-sourced chemical signals in contact with drying soil. These signals, carried by the xylem, can act to modulate growth and gas exchange in the shoot (Davies et al. 2002; Campos et al. 2009). On this basis, an irrigation approach called "partial root zone drying" (PRD) has been developed, where half of the root system is kept near field capacity, and the other half is kept under water deficit. In an investigation with tomatoes, Campos et al. (2009) found that yield, number of fruits and total soluble fruit solids content were similar among the control and PRD-treatments with an increase of 25 % in the fruit titratable acidity reached in one PRD treatment. Fruit firmness, was increased up to 31 % in PRD treatments. In addition, PRD treatments allowed a water irrigation saving of up to 46 %.

According to Kader (2008), the key for growers to adopt appropriate cultural practices is encouraged by the willingness of consumers to pay a premium price for preferred products, essentially compensating the producer for the loss in yield. Reducing water availability as a method to achieve positive effects on yield and product quality of vegetables should not be applied however in all protected crops. For instance, Mediterranean greenhouse growers of watermelon and green bean crops tend to slightly reduce the soil water availability during the flowering phase to enhance fruit number and yield. González et al. (2009) investigated this deficit irrigation strategy and found that overall, mild water deficits, during the flowering of watermelon and green bean crops grown in Mediterranean greenhouses, did not improve the final fruit number or the yield of these crops, but reduced vegetative growth. Continuous water stress throughout the season can also diminish leaf area, fresh and dry weight, but did not hasten ripening, necessary for mechanical harvest, but rather delayed fruit maturation in relation to other treatments. Water deficit, either sustained or applied at the fruit ripening phase, was detrimental to commercial yields of pepper (González-Dugo 2007). Patanè et al. (2011) also reported that full irrigation is required to maximize marketable yield in processing tomatoes cultivated in semi-arid climate conditions. The authors stated however that an adoption of deficit irrigation strategies could be considered, especially in areas such as those of the Mediterranean basin, where water resources are increasingly scarce. Indeed, besides the conspicuous irrigation water savings (up to 48 %), full irrigation resulted in a yield reduction proportionally less than the water deficit (Patanè et al. 2011).

## *Oxygen in the Root Environment*

Optimal root development requires a sufficient oxygen supply. In soilless cultures, oxygen deficiency in the root environment causes root dysfunction, with negative consequences for water and nutrient uptake (Morard and Silvestre 1996; Gislerød et al. 1997). According to Schapira et al. (1990), the oxygen dissolved in the nutrient solution of the cucumber crop was depleted within approximately 60 min (25 g fresh roots per liter nutrient solution at 20 °C). This process, which is driven by root respiration and microbial activity, is affected by factors such as the nutrient solution temperature, root biomass, light and $CO_2$ concentration (Schnitzler and Gruda 2002) as well as the stage of plant growth. Whereas, for instance, young tomato plants were able to adapt to hypoxia in the root environment and survive, mature plants wilted 2 days after aeration interruption in a hydroponic system and consequently died rapidly. Hypoxia in the root environment can result in decrease in leaf photosynthesis, changes in the transpiration rates and efficiency of the photosystem II and a slow change in leaf diffuse reflectance (Kläring and Zude 2009).

Morard and Silvestre (1996) reported that root asphyxiation is difficult to carry out in a substrate culture as plants exhibit considerable tolerance to temporary hypoxia and anoxia (several hours) and greenhouse growers have expressed concern that the oxygen content of nutrient solutions may be sub-optimal for plant growth (Ehret et al. 2010). Ehret et al. (2010) investigated the oxygen enrichment of the irrigation solution of cucumbers and pepper, grown in sawdust, and found that in only one instance out of three trials enrichment increased the yield of cucumbers and that there was no effect of enrichment on the pepper yield. Gruda et al. (2008) reported that individual factors such as organic substrate, irrigation, and aeration caused changes in $CO_2$ concentrations in the root zone of tomatoes and cucumbers.

## Plant Nutrition, Nutrient Management and their Effect on Plant Growth and Development in Soilless Culture

### *General*

Correct crop nutrition is essential for successful plant production (Bailey and Nelson 2012) and even more for protected crops. The nutrient uptake of the protected plants is generally higher compared with field cultivation, because of high production intensity and potentially higher yields. For instance, yields of more than 500 t $ha^{-1}$ $a^{-1}$ are not an exception for tomatoes and cucumbers produced in High-Tech greenhouses. Since harvest residues are totally removed from the greenhouse the nutrients used for biomass production of follow-up crops have to be fully compensated by the fertilizer and if high temperatures are encountered, the mineralization rate of organic matter in the greenhouses is higher than in the open field. Similarly, the movement of nutrients in soil is high particularly potassium and nitrogen levels, and leaching losses are often high, due to frequent watering and the attempt to keep up soil moisture. Special attention needs to be paid to the control of nutrient and salt contents in soil and soilless culture systems in protected cultivation. Appropriate fertilization (especially with nitrogen) requires more frequent analyses in shorter intervals, e.g. once in every 4 weeks. A combination of both *ferti*lization and irri*gation* is sometimes used. This combination process is known as "*fertigation*" and such systems are "*fertigation systems*". If fertigation systems are used, soil analysis has to be limited to the wetted root zone. Particularly important is the nutrient control in soilless culture, because their restrictive root volume and a very low buffer capacity. Here, at least daily analyses of EC- and pH-values of the nutrient solution are required. Since fertigation management in such systems is usually carried out by computer programs these two characteristics are however continuously controlled: some equipment allows separate management for each element. In all cases nutrient solution has to be tested periodically. Another way to control the nutrients is to analyze crop leaves where young leaves from the same age are used (Drews and Fischer 1992).

In soil culture, preplant and post-planting fertilization have to be differentiated (Bailey and Nelson 2012), however, in soilless culture only a post-planting fertilization or an accompanied fertigation with a nutrient solution is provided. Dolomitic limestone is often added to raise the pH of peat and other acid substrates (Jackson et al. 2009).

### *Soilless Culture*

The term "soilless culture" is defined as the cultivation of plants in systems without soil "*in situ*" and this method is the most intensive and effective in today's horticultural industry. In recent years, a multitude of innovative cultivation procedures using bags, mats, and containers, in addition to nutrient solutions, have been developed. These growing methods include systems without a solid medium, as well as aggregate systems, in which inorganic or organic substrates are used (Gruda 2009). The distinction between soilless culture and other systems is sometimes blurred. For instance, the growth and maintenance of indoor ornamental pot plants or the outdoor production of hardy nursery plants in containers is considered soilless culture. On the other hand, the supply of nutrient solution to plant roots has become a custom cultural practice for soil-grown greenhouse crops as well, similar to using drip irrigation in outdoor horticulture.

Soilless cultural systems (SCS) offer significant advantages in comparison to direct cultivation in soil. These include cultivation of protected crops independent from soil characteristics. Therefore they exhibit a great degree of flexibility, even in areas with poor or adverse growing conditions, such as poor soil structure or high soil salinity. The main reason for using soilless culture however is the reduction of soil-borne pathogens and the control over water and nutrient supplies. The majority of nutrients used in such systems is soluble or in liquid form applied in a nutrient solution. In soilless culture either a liquid or aggregate medium is used. Such production systems and mainly the liquid method are called hydroponic systems as well, whereas periodically spraying plants with a nutrient solution is called aeroponic.

The main characteristic of SCS is the restricted volume of a rooting medium in comparison to soil-grown crops. The common issue in this system is the precise amount and ratio of the desiderated nutrients. In case of liquid systems and the use of inorganic substrates no interference of organic matter or cation exchange capacity (CEC) in the soil is observed. There has been an improved product quality however through more precise dosage of water and nutrients within closed systems (Gruda 2009). In Europe, Canada, and in the large horticultural industry complexes in the U.S., 95 % of greenhouse tomatoes are produced in SCSs (Peet and Welles 2005). Despite the considerable advantages of commercial soilless culture, there are still some disadvantages, such as higher costs that are normally required for their initial installation and increased technical skills that are needed to cope with its installation and management (Savvas et al. 2013).

Savvas et al. (2013) classified soilless culture and growing media systems into water/hydroponic culture and/or deep water culture, float hydroponics, nutrient film technique (NFT), deep flow technique, aeroponics, and substrate/aggregate culture. Gruda et al. (2013) differentiated between inorganic and organic growing media, where inorganic growing media included rockwool (the most used substrate in soilless culture), perlite, tuff, volcanic porous rock, expanded clay granules, vermiculite, zeolite as well as some other synthetic materials, sand and gravel. Organic growing media included peat, composts, bark, coir, and wood fibers as well as other wood residuals. In addition, several peat substitute/alternative growing media have been introduced worldwide, due to an increased environmental awareness of consumers, the constant dismantling of ecologically important peat bog areas and pervasive waste problems. Recently, biochar, a form of charcoal which is manufactured from organic matter by heating in an anoxic situation (pyrolysis), has been used in agriculture and introduced in horticulture as a growing medium as well (Gruda 2012; Gruda et al. 2013). Each substrate

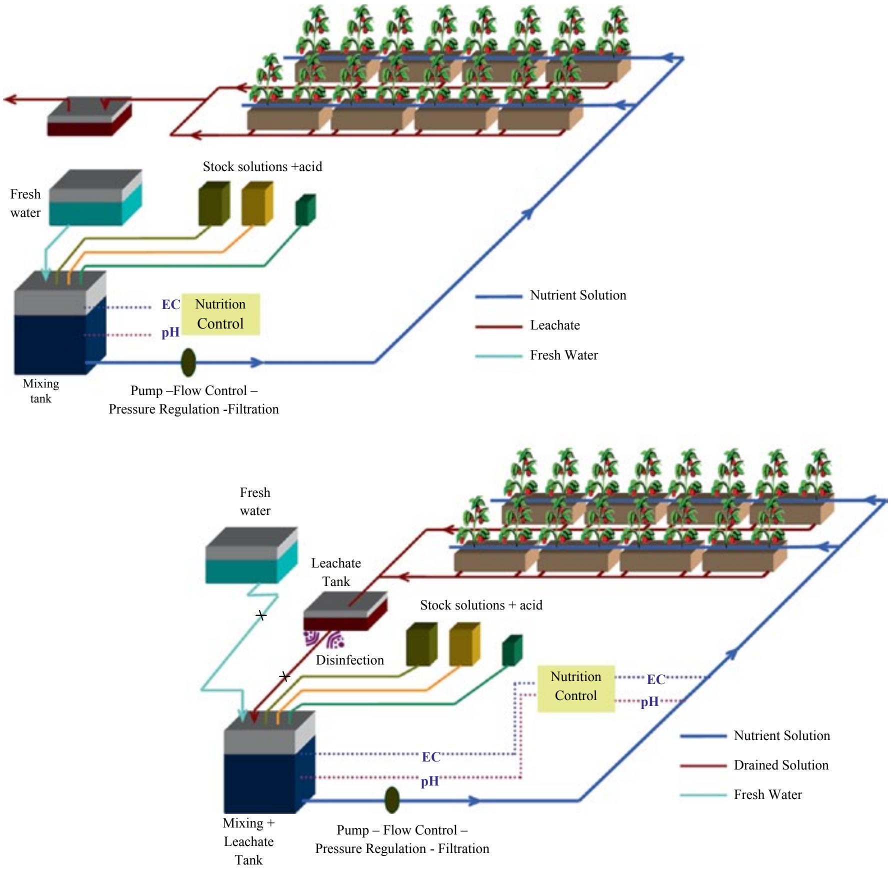

**Fig. 10.17** Schematic diagram of a simple open- (*top*), and closed-loop (*bottom*) soilless culture system. (Source: ecoponics, In: Food and Agriculture Organization of the United Nations, Savvas et al. 2013. Reproduced with permission)

requires its own optimum growing technology and management approach with an adapted fertigation system (Gruda 2009).

### Open and Closed-Loop Culture Systems

In soilless culture, methods of fertigation management and the recycling of nutrients in solution are categorized as either an open or a closed-loop system (Fig. 10.17). In an open system, any excess water and nutrients is drained to waste and not recycled. In a closed-loop system any drainage is captured, recovered and recycled. Closed systems also increase the risk of spreading root diseases through the system; hence treating the captured drainage water before recycling has to be considered (Wohanka 1992; van Os et al. 1999). Most pure hydroponic systems are inherently closed systems, but some aggregate systems were open until recently. When drip irrigation is used (which is most common) overwatering to the extent of 20–30 % is common, in order to prevent drying of the substrate and salt accumulation. In an open system this results in an expensive loss of water and fertilizer and a potential source of nutrient pollution of the environment (for WUE, see box 1; and for FUE, box 2). Many recent installations are closed systems and this will become mandatory in the future as nutrient management planning is implemented in many countries. A closed system requires higher water quality to prevent a build-up of unwanted ions. It also means that the composition of the nutrient top-up solution has to match nutrient ratios closely when taken up by the crop. In the past, nutrient top-up has been done on the basis of electrical conductivity measurement but in the future this may be replaced by the use of specific ion sensors (Inden et al. 1999; Gieling et al. 2001).

According to Papadopoulos et al. (1999) and Tüzel et al. (2001), there were no significant differences between open and closed-loop culture systems in tomato fruit quality due to applying adequate culture practices. Similarly Raviv et al. (1998) found no differences in rose production or quality when comparing open-loop systems with three different recirculation techniques.

In experiments with *Chrysanthemum indicum* hybrids, carnations (*Dianthus caryophyllus*), *Gladiolus* hybrids (Leinfelder and Röber 1987, 1989, 1991) and *Gerbera* spp. (Özçelik et al. 1999) no differences were found in terms of flower quality between diverse substrates in closed-loop culture systems. Rodriguez et al. (2006) investigated different combinations of media (coarse perlite, medium perlite, and pine bark) and containers (polyethylene bags and plastic pots) used in the production of ‘Galia’ muskmelons (*Cucumis melo*) and found that fruit yield and fruit quality were not affected by any combination of media and containers. Similarly, Serio et al. (2004) investigated the use of washed disposal of the posidonia (*Posidonia oceanica*)—a marine species belonging to the *Potamogetonaceae* family and found no differences in total yield of cherry tomatoes grown in this substrate or rockwool.

## Plant in Soilless vs. Soil Cultures

Gruda (2009) points out that the only reliable way to compare soil with soilless systems is to place both systems under the most optimal growing conditions for the same crop. In soilless culture, higher yields and earliness of cropping can be achieved when compared to soil cultivation. For example Selma et al. (2012) showed that a growth period of 102 d was needed for fresh-cut lettuces (*Lactuca sativa*) to reach the same maturity stage in soil compared to 63 d in soilless culture. According to Gruda (2009) using SCSs does not automatically guarantees high-quality vegetables. Numerous studies confirm that SCS enables growers to produce vegetables without quality loss compared to soil cultivation. An adaptation of the cultural management to a specific cultural system, as well as the crop requirements, can further result in improving the quality of the horticultural product.

## *Effect of Nutrition on Plant Growth and Development*

Either a deficiency or an excess of any nutrient will deteriorate plant growth. For instance, among the many plant mineral nutrients, potassium is one of those cations that has a strong influence on quality attributes that determine fruit marketability, consumer preference, and the concentration of critically important human-health associated phytonutrients (Lester et al. 2010). Growers and researchers should consult general plant nutrition literature for any given species (e.g. for tomato plants, Passam et al. 2007). Schnitzler and Gruda (2002) provide a detailed review of different nutrient elements and their effects on the product quality of ornamentals and vegetables.

Commercial greenhouse growers use nutrient concentrations based on the plant species needs in order to maximize crop yield. Strategies need to change however where high irrigation frequencies and high levels of nutrients are sometimes delivered to the plant roots, to avoid salt accumulation in soil, and where we have limited growing media volumes and restricted root mass. Recent investigations have shown that these strategies do not present an economically optimized production and excessive nutrients do not necessarily translate into higher yields (Rouphael et al. 2008). For instance, Siddiqi et al. (1998) have shown that reductions of macronutrient concentrations from 50 to 25 % of the control level can be applied without any adverse effect on growth, fruit yield and the quality of tomatoes. Similarly, Zheng et al. (2004) and Rouphael et al. (2008) demonstrated that current nutrient application rates can be reduced by at least 50 % without any detrimental effect on growth and quality of potted gerbera and geranium, respectively. On the other hand, high concentrations of different elements can be detrimental to plant growth and development as well.

## *Salinity*

The accumulation of salts on the soil can be an important issue during hot and dry conditions most notably in arid or semi-arid regions, where there is a high crop evaporative rate. Due to water movement and capillarity action the upper soil layer can be over-salted. The use of poor irrigation water with high salt content and an inadequate irrigation system may aggravate this problem. Under such conditions plants suffer from a high osmotic potential, due to impaired water absorption. Moreover, certain ions, such as chloride, borate, and sodium ions can provide specific phytotoxic effects. The accumulation of sodium in the soil, and the availability of the exchange complex with sodium, can reduce flocculation and impair soil structure.

As noted earlier, water quality is very important in greenhouse management. Poor quality water, both chemically and biologically, has an adverse effect on production and product quality. According to Lycoskoufis et al. (2005) the growth of pepper at high salinity levels (60 mM NaCl, 8 dS $m^{-1}$) was affected through stomatal closure, presumably due to high salt concentrations in the leaf apoplast, inhibition of photosynthesis at chloroplast level, which is partly associated with reduced chlorophyll concentration, and alterations in carbon allocation and utilization aimed at the adaptation of plants to a saline environment. Grieve (2010) reported that some plants can adjust osmotically within hours, where cell volumes and turgor are restored, but irreversible damage has already been done. Cell elongation and cell division are reduced, and, as a result, shoot growth decreases. Roots are also reduced in length and mass. Moderate salinity levels, which are crop depended, usually restrict growth without any overt injury symptoms and the plants appear normal, but stunted.

Even in SCSs, high salinity levels can be detrimental to plant growth. Rouphael et al. (2008) investigated the growth and quality of zonal geranium (*Pelargonium* × *hortorum* 'Real Mintaka') in closed soilless systems, in order to evaluate the effects of the irrigation system (drip and sub-irrigation) and nutrient solution concentration under various conditions of radiation and temperature. The authors found that the ECs during the spring season at the end of the growing cycle was two-fold higher than that observed in the winter season, due to higher solar radiation and higher air temperature, and was almost double in a full than in a half strength nutrient solution. Consequently, plant growth with sub-irrigation using a full strength nutrient solution during spring season resulted in lower shoot biomass, growth and quality index than those grown using drip-irrigation. Similar results were obtained by Santamaria et al. (2003) with cherry tomatoes and Rouphael and Colla (2005) with zucchini squash. The increase of EC in the upper layer of the substrate reduced the fruit yield of both crops cultivated in sub-irrigated systems. In other trials, however closed-cycle sub-irrigation systems were successful for tomato production using saline water (Incrocci et al. 2006; Montesano et al. 2010). According to Incrocci et al. (2006), the process of fast water salinization made it necessary to flush out the nutrient solution in six different occasions in a closed-loop aggregate culture using the drip irrigation system, with a subsequent loss of water and fertilizers. On the contrary, in sub-irrigation culture, the upward water movement in the substrate, coupled with selective mineral uptake by the roots, caused salinity build-up and sodium accumulation in the upper region of the substrate. Here the authors conclude that sub-irrigation conducted with saline water can be a tool to reduce water consumption and nutrient runoff in closed-loop substrate culture of tomatoes and retain fruit yield and quality of tomatoes.

### Improvement on Product Quality Due to a Moderate Salinity Stress

According to Grieve (2010), moderate salinity can improve the quality of vegetables, due to changes in two classes of phytochemicals: compatible osmolytes and antioxidants. Many investigations have shown that using solutions with moderate electrical conductivity, achieved by adding sodium chloride or nutrients, the first one being more common due to economic concerns, can improve the tomato fruit quality, in terms of organic acidity and total soluble solids (Mizrahi and Pasternak 1985; Sonneveld and Welles 1988; Adams and Ho 1989). These results are in agreement with Serio et al. (2004), who found an improvement of organoleptic quality and nutraceutic properties of cherry tomatoes and also intrinsic the quality parameters of dry matter, total soluble solids, vitamin C and α-tocopherol, and antioxidative potential. According to Hasegawa et al. (2000) and Plaut et al. (2004), an increase in the dry matter of tomato fruits occurred under high saline conditions due to an active osmotic adjustment of plants to guarantee further water uptake. Furthermore, the correlation network analysis showed that compared to other traits, sugar is one of the key traits for an improvement of tomato fruit quality (Zushi and Matsuzoe 2011). Sato et al. (2006) however found an increase not only in sugar content, but also in organic and some amino acids. The authors reported that taste panels indicated that NaCl treatment increased sweetness, acidity, umami (i.e. the taste of deliciousness), and overall preference. Hexose concentration of the fruit grown on NaCl treated plants significantly increased. At the same time, chloride ions, organic and amino acids had higher concentrations in sodium chloride treated plants than in the control group. A review of these effects is presented in Dorais et al. (2001), Gruda (2009) and Schnitzler and Gruda (2002).

Recently, consumer awareness increased concerning health promoting compounds and properties that can act in an antioxidant capacity and improve nutritional value in vegetables (D'Amico et al. 2003; Dumas et al. 2003, Gruda 2009). Krauss et al. (2006) investigated the influence of three different salt levels (EC = 3, 6.5, and 10 dS $m^{-1}$) on tomato growth and yield. Rising EC-values of the nutrient solution increased vitamin C, lycopene and ß-carotene (the precursor to vitamin A) in fresh fruits by up to 35 %. Phenol concentration was tendentiously enhanced, and the phenols' antioxidative capacity and carotenoids increased on a fresh weight basis. Since the authors did not record any change in dry weight basis, they suggested that the observed increase of lycopene was due to the concentration—caused by reduced water flux to the fruit. However, Wu et al. (2004) reported an increase of lycopene (34–85 %) for five cultivars tested under high EC compared to low EC, while the increase of total soluble solids was only 12–22 %, suggesting that the lycopene increase might be due to a plant stress response to osmotic and/or salt stress rather than the result of high concentration caused by reduced water content of the fruit. These results are in concordance with the results of Fanasca et al. (2006) where these authors observed an increase in lycopene concentration on both a fresh weight and dry weight basis in tomato by raising the EC from 2.5 to 8 dS $m^{-1}$. However other authors (Krumbein et al. 2006; Fernández-García et al. 2004) did not find differences in lycopene content, when plants were grown under high EC-values. According to Wu and Kubota (2008a) the reason is the time of analysis because the physiological status is very important, in respect to parameters of product quality (Schnitzler and Gruda 2002). According to Wu and Kubota (2008a), lycopene analysis should be done throughout the fruit ripening process (from late green to the fully ripened stage) rather than at the last stage of ripeness to better understand lycopene synthesis since lycopene concentration in the tomato fruit increases rapidly during the process. Therefore, Wu and Kubota (2008a) carried out a study where lycopene content was analyzed at six tomato ripeness stages and found that the

**Table 10.2** Effects of EC and application timing of EC on lycopene content of tomato fruits at different ripeness stages. (According to Wu and Kubota 2008a)

| Treatment | Lycopene concentration (mg $g^{-1}$ DW) | | | |
|---|---|---|---|---|
| | G | B and T | P and LR | R |
| High EC | ND | 0.07 | 0.39 a | 1.39 a |
| Delayed high EC | ND | 0.10 | 0.32 b | 1.29 a |
| Low EC | ND | 0.08 | 0.25 c | 0.99 b |
| ANOVA ($P=0.05$) | – | NS | * | * |

The six fruit ripeness stages characterized by color development, which include green (G), breaker (B), turning (T), pink (P), light red (LR) and red (R) (USDA 1976). Low and high EC were 2.3 and 4.5 dS $m^{-1}$, respectively. The high EC and the delayed high EC treatments were applied immediately after anthesis and 4 weeks after anthesis, respectively. ANOVA, Analysis of Variance for treatment significance: * or NS at $P=0.05$. Means with the same letters are not significantly different according to a Tukey HSD test at $P=0.05$. NS = no significance. ND = not detected. DW = dry weight (Source: Wu and Kubota 2008a)

lycopene content of tomato, *cv*. 'Durinta', increased 12–20-fold as fruits developed from the breaker/turning stages to the red stage (Table 10.2).

Wu and Kubota (2008a) suggested that ethylene synthesis triggered by osmotic and/or salt stress is central to the increase in lycopene concentration within the tomato fruit. The reduced water flux is linked to an increase in TSS and under these environmental conditions tomatoes mature earlier and accumulate more lycopene during the pre-harvest time.

Similar results, where an increased EC-value enhanced health-promoting substances, were also obtained for sweet pepper, cucumber (Sonneveld and van der Burg 1991; Trajkova et al. 2006), eggplant (Savvas and Lenz 1994), celery (Pardossi et al. 1999), watermelon (Colla et al. 2006), as well as zucchini squash (Rouphael et al. 2006). Seo et al. (2009) reported that the EC-value of the nutrient solution as well as the concentration of S and P can strongly influence the concentration of sesquiterpene lactones; and therefore have an effect on bitterness and acceptability of lettuce.

Adjusting the salinity of the nutrient solution allows growers to modify water availability to the crop and hence improve the quality of tomato fruits. However, increasing the salinity, limits marketable yield, increases the incidence of BER, and reduces fruit size (Dorais et al. 2001; Gruda 2009). For instance, although cherry tomatoes are considered to be more tolerant in respect to adverse effects of EC-values, the total yield of cherry tomatoes was reduced at a higher salinity (6 dS $m^{-1}$) in comparison to 3 dS $m^{-1}$ (Serio et al. 2004). One of the disadvantages of increasing TSS by a high EC treatment is the reduction in fruit size due to a reduction of water content in the fresh fruit (Adams and Ho 1989) where fruits were smaller, mainly due to a reduction in fresh weight (Ehret and Ho 1986). This resulted in total yield reductions and an increased occurrence of the physiological disorder blossom-end rot (BER) (Petersen and Willumsen 1991), caused by a reduction of calcium absorption by the roots and increased resistance to xylem transport inside the fruit (Ho and Adams 1989). According to Ho et al. (1999), accelerated fruit enlargement may be the principal cause of BER in tomatoes, even when the uptake of calcium by the plants seemed to be adequate.

Dorais et al. (2001) and Wu and Kubota (2008b) examined the effects of electrical conductivity (EC) on tomato fruit yield and found that it is not reduced when EC was increased moderately to approximately 5 dS $m^{-1}$. Wu and Kubota (2008b) reported that for all cultivars tested the plant physiological response under elevated EC was cultivar and growth-stage specific, and increasing the inflow EC to moderate levels during the reproductive growth stage did not adversely impact photosynthesis, transpiration, and leaf conductance of tomato plants. According to Zushi et al. (2009), salt stressed fruit developed protection mechanisms against salt-induced oxidative stress during the ripening in both the pericarp and pulp. In addition, the growers and investigators have developed some growing strategies to overcome or mitigate the detrimental effects of salinity.

### Strategies to Overcome or Mitigate Salinity Stress

Numerous strategies have been tested for minimizing crop yield loss due to salinity, and at the same time maximizing inner (nutrient value, taste, texture) and outer (appearance, color, firmness, shelf life, aroma) quality characteristics of the marketable product. Those management practices include nutrient management of salt-stressed crops, timing of salinity application or withdrawal, method and scheduling of irrigation, and the choice of rootstock (Grieve 2010). Generally, it could be said that high water supply has a mitigation effect on salinity, and vice versa: drought situations increase these effects. The important fact is however the choice of the right cultivar. Salt tolerant cultivars are the best tool to avoid or mitigate this kind of stress, e.g. in semiarid greenhouse conditions and with limited environmental control capacity.

There are other irrigation and agronomic strategies that can also minimize salinity damage. One of these strategies involves crop spraying or the application of supplemental nutrients, fluctuating EC-values and the use of a split root system with unequal ECs. For instance, Tuna et al. (2007) reported that salt stress significantly decreased plant growth and fruit yield. Supplementary calcium sulphate was added however to the nutrient solution and it significantly improved plant growth and fruit yield and improved membrane permeability.

Buck et al. (2008) lowered the EC-values during the midday, in order to mitigate high water stress on the tomato plant, and achieved a premium-grade tomato yield comparable to the high EC-treatment. These results are in agreement with those of Santamaria et al. (2004) where the authors found that a 2 dS $m^{-1}$ daytime EC combined with 6 dS $m^{-1}$ nighttime EC level did not affect total yield, fruit number, fruit weight, or plant water consumption in the cherry tomato. This strategy makes sense for use in semiarid greenhouse conditions with limited controlled-environment technology. Sonneveld (2000), Mulholland et al. (2002), Tabatabaie et al. (2004), and Lycoskoufis et al. (2005) suggested for crop growing in soilless culture an unequal EC, achieved with a “split-root” system, in order to avoid or mitigate high salinity issues, and as a consequence, to improve both

**Table 10.3** Yield and fruit weight of tomato, cv. ‘Counter’, on a split-root system whereby the two halves were supplied with nutrient solutions of the concentrations indicated. (According to Sonneveld 2000)

| EC value | Yield (kg $m^{-2}$) | % | Fruit weight (g) | % |
|---|---|---|---|---|
| 2.5/2.5 | 24.0 | 100 | 77 | 100 |
| 5.0/5.0 | 21.1 | 88 | 71 | 92 |
| 2.5/5.0 | 23.7 | 99 | 80 | 104 |

**Box 2** *Fertilizer use efficiency (FUE)*

Efficient use of fertilizers has become of economic and environmental importance in greenhouse production. One can calculate fertilizer use efficiency as the ratio of marketable yield to total fertilizers used. Greenhouse production can be very intensive and there are great differences between the fertilizer usage in an open field and the greenhouse. Similarly, the loss of fertilizer could be drastically reduced, using closed production systems. Marcelis et al. (2000) estimated the data for both, an open and a closed production system. They noted that whereas in standard greenhouses in many Mediterranean countries the yearly losses were approximately 300–350 kg N and 125–300 kg P, in a “closed loop” greenhouse production system, in north Europe approximately 120 kg N and 20 kg P per ha and year can be lost. It is now clear that fertilizer losses can be reduced even further.

yield and product quality. This system is similar to a ‘partial root-zone drying’ irrigation system (with the difference that instead of different soil moisture, different osmotic potentials are realized). In this case, the most favorable part of the root system experienced the largest water absorption, the plant as a whole does not show any restriction and the yield and fruit weight was nearly the same as in normal EC-value (Table 10.3).

Jokinen et al. (2011) also reported that the split root fertigation approach provided complementary benefits over traditional fertigation, in terms of water and nutrient uptake and ultimately yield improvement. The peat-based split root fertigation (SRF) method improved cucumber yield in both open (21 %) and semi-closed (17 %) greenhouse conditions over the traditional fertigation method. This indicates that the response is governed by root exposure to high sodium chloride concentrations and not by water absorption inefficiency of the roots (Lycoskoufis et al. 2005).

Moreover, better root aeration (enhancing oxygen supply to root cells) may considerably enhance salinity tolerance of tomatoes in heavy clay and saline soils (Bhattarai et al. 2006).

More detailed information concerning soilless culture apart from Savvas et al. (2013) and Gruda et al. (2013), can be found in Resh (2012), Savvas and Passam (2002) and Raviv and Lieth (2008) and for information concerning plant nutrition of greenhouse crops, the book by Sonneveld and Voogt (2009) is recommended.

## Some Agronomical Aspects and Cultural Practices

### *Genotypes and Cultivar Choice*

Sources of genetic material have a great influence on yield and product quality of protected crops. Different tolerances between hybrids and genotypes have been documented for temperature (Ventura and Mendlinger 1999; Abdelmageed and Gruda 2009), drought stress conditions, water shortage (Dumas et al. 2003; Niu 2008) and salt stress and fertilizer level (Wu et al. 2004; Wu and Kubota 2008b; Zushi and Matsuzoe 2011). In the future, plant breeding will form a strategy on its own, adding to growth conditions improvement. Breeders can address improvements of tolerance to diverse stress situations, as well as improvements in respect to yield, earliness, and product quality. For example, Higashide and Heuvelink (2009) investigated yield improvement of tomatoes and found that an increase in yield over the past 50 years in Dutch tomato production was caused by an increase in light use efficiency of tested genotypes, resulting from a decrease in the light extinction coefficient (a morphological change) and an increase in the leaf photosynthetic rate (a physiological change).

### *Grafting*

Although less frequent than the well-known fruit tree grafting, vegetable grafting is getting more and more important. Interestingly, the early use of grafted vegetables was associated with protected cultivation which involves successive cropping, and is currently being globally practiced (Lee et al. 2010). The majority of grafted plants belong to the *Solanaceae* and *Cucurbitaceae* families where the rootstocks of plant genotypes have shown resistance to different soil-borne diseases. Since wild species possess these properties, they are used as rootstock as well. By contrast, the scions are usually used good productive and high qualitative genotypes. Although first used to avoid serious problems caused by soil-borne diseases (Bletsos 2006; Lee et al. 2010; Louws et al. 2010) this practice has been used to increase plant vigor and yield (Lee et al. 2010; Gisbert et al. 2011), reduce stress situations caused by adverse environmental conditions such as low soil temperature (Lee et al. 2010), high salinity (Colla et al. 2010), high temperatures (Abdelmageed and Gruda 2009; López-Marín et al. 2012), inadequate fertilization (Savvas et al. 2010) and water stress and organic pollutant challenges (Schwarz et al. 2010). Recently, Flores et al. (2010) and Rouphael et al. (2010) also reported an influence of grafting on vegetables product quality. Despite these advantages, some disadvantages are noted such as high costs of grafting seedling and sometimes low earlier yield. In order to cut high costs, vigorous rootstocks are so far used in two and sometimes three-or-four-stem-pruned-systems in tomato greenhouses. According to Lee et al. (2010), research has been focused on developing efficient rootstocks and handy grafting tools as well as grafting machines or robots to reduce the higher price of grafted seedlings.

**Fig. 10.18** Single stem tomatoes in (**a**) non-lowering system and (**b**) lowering system. (Source: Gruda 2010, 2011, private collection)

## *Plant Density*

Plant density depends on plant species, the cultivar or the genotype used, and the associated environmental and agronomic conditions. An increase in plant density is to some extent positively correlated with yield, however negatively correlated with the size of the marketable plant part. The reason for that is thought to be the insufficient supply of photo-assimilates caused mainly due to a competition for light interception, influencing the photosynthetic rate and carbohydrate distribution.

## *Plant Training*

Training is applied to indeterminate vegetable crops such as the tomato, pepper, and cucumber where the main objective (through a combination of plant density and pruning) is to improve light interception of leaves. In addition, the positive effects on air movement can also influence disease spread and control. For instance, tomato plants are supported by plastic twines and are hitched around a wire (Papadopoulos 1991; Schwarz 1995) (Fig. 10.18a). However, in modern soilless greenhouses with supporting wires of 2 m or higher, as tomato plants reach the wire, they are untied which allows the plants to be lowered and grown horizontally to the slabs or system ground. The green slip is hanging vertically from the wire and has very good assimilation conditions (Fig. 10.18b). With this training system the plant length of tomatoes can reach more than 12 m and if environmental conditions are adequate to plant growth, spring cropping can be extended to a single full cultivation period (or in a so called one-crop-per-year). However, in areas with hot summers, usually a two-crops-per-year production strategy is applied. In some regions, a single-cluster strategy or five-crops-per-year is used as well (Logendra et al. 2001).

The prevalent system practiced on greenhouse cucumbers is V-training or the umbrella system which involves removal of all emerging flowers and laterals up to the 8–9th node (approx. lowest 60 cm of the main stem). Thereafter, just one fruit per lateral is allowed for the next 60 cm of the main stem. One fruit and one lateral are allowed to grow from each leaf axis on the rest of the main stem. After the main stem reaches the wire, the growing point is pinched out allowing an extra 2 or 3 leaves above the wire. Afterwards, the two strongest laterals from the top of the plant are allowed to grow over the wire and then to hang down. The next steps differ depending on plant variations described by Papadopoulos (1994). In addition, the author recommends the control of fruit numbers due to selective fruit thinning, in order to avoid plant exhaustion and to improve fruit quality.

Similarly, pepper plants can be trellised to the Dutch "V" (a two-stem pruned) system or to the "Spanish" (non-pruned plants) system. Jovicich et al. (2004) compared the "V" with the "Spanish" trellis system and found no differences in total marketable fruit yield. Labor requirements for the Spanish system were reduced however by at least 75 % compared with the "V" trellis system.

## *Pruning*

Pruning is a (manual) operation used to support training, with the aim of improving light relationships, equilibrating plant growth and development, providing for a better control of diseases with consequences in minimizing yield losses, and improving product quality. Pruning helps to facilitate cultural operations in the greenhouse. Both vegetative (e.g. 'leaves' by tomato and cucumber, 'new side shoots' by tomato and pepper, 'shoot apices' by tomato and cucumber) and generative organs (e.g. 'flower removal' by roses, and 'fruit thinning' by tomatoes) are pruned.

Navarrete and Jeannequin (2000) investigated the frequency of lateral shoot pruning in greenhouse tomato crops, and found that the de-shooting frequency affected both vegetative growth and yield and pruning time. When de-shooting was performed every 21 days, the stem diameter and the number of fruits per $m^2$ was also reduced, leading to a significantly lower yield in comparison with a 7 day deshooting cycle. Moreover, the tomato harvest was delayed, presumably due to dry matter partitioning and better light interception due to the pruning process.

Plants, such as roses, possess high plasticity, rapid and dynamical acclimation in response to changes in incident sunlight established by pruning (Calatayud et al. 2007). Similarly, roses showed a higher maximum efficiency of photosystem II (PSII) in dark-adapted leaves, a higher actual quantum yield and a higher proportion of open PSII reaction centers when pruned. They also showed lower non-pho-

**Fig. 10.19** Bumble bees, ready for pollination application in a greenhouse. (Source: Gruda 2013, personal archive)

tochemical quenching, indicating a lower energy dissipation in heat, compared to non-pruned plants. The results related to chlorophyl-a fluorescence, indicate that pruned plants have a higher capacity for better promoting a photosynthetic light reaction than non-pruned plants (Calatayud et al. 2008b).

In addition Cockshull and Ho (1995), found that tomato fruit production and fruit size can be adjusted to the level of available photo-assimilates if cluster pruning is coordinated with the growing period. The number of fruits (fruit load) as well as the fruit to leaf ratio are important in fruit vegetables. Logendra et al (2001) reported 25 % higher tomato yields at single-cluster plants pruned to allow two leaves above the cluster than plants pruned directly above the cluster. Furthermore, both fruit yield and harvest index were greater for all single-cluster plants at a higher light level. According to Ho (1992) however since fruit constitute a major portion of photo-assimiliates, the variation in number will influence their size rather than the fruit to leaf ratio. On the other hand, according to Dorais et al. (2001) severe deleafing of plants reduces photosynthetic capacity of the canopy and the remobilization of mobile elements. Therefore, Slack (1986b) recommended that deleafing in commercial tomato crops should not exceed the level of ripening fruits.

## *Pollination*

For a range of greenhouse vegetables such as melons, pepper, tomato, eggplant, zucchini, and strawberry, extra pollination is needed to assure good fruit setting and productivity. Pollen quality can be adversely affected by high temperatures, limited air movement and high humidity in greenhouses. Since most cucumber cultivars are parthenocarpic they do not need extra pollination. Plant pollination can be enhanced by using a mechanical (vibration) or biological method (e.g. bumble bees, Fig. 10.19). The latter used more frequently in greenhouses because they are natural agents of pollination and growers benefit because of lower production costs, increased yields, and improved fruit quality (Velthuis and van Doorn 2006).

### *Integrated Plant Management and Plant Hygiene*

Optimal climatic conditions under protected cultivation are not only favorable for growing crops, but also for the development of pests and diseases. Therefore, integrated plant management and plant hygiene in greenhouses are of utmost importance. Generally, plant protection in greenhouses is applied according to the principles of the integrated pest management or organic production principles. Both these methods aim to reduce pest and disease incidences in greenhouses crops due to a minimal use of pesticides or application of alternative methods to control pest and diseases, respectively. Moreover, both these methods are oriented towards an adaption of sustainable greenhouse production.

## The Interaction of Factors, their Multiplicity and Effects on Plant Growth and Development

Many specific environmental and agronomic factors influence plant growth, yield and product quality of protected crops. Only when all these factors are in optimal level, in balance, and well managed and sustainable can it be expected that plant growth and development will be at its best. Liebig's Law of the Minimum, states that growth is controlled not by the total amount of resources available, but by the scarcest resource available (limiting factor). Optimum growth and performance will be a function of the genotype used, with the developmental and maturity stages, and a function of interaction between all environmental conditions and agronomical measures. Furthermore, according to Raviv et al. (2008), when multiple factors are limiting, the interacting effects are more complex than simply suggesting causality of suboptimal production to the most-limiting factor. This is particularly important in practice because it is extremely rare that all production factors can be simultaneously optimized in a living system.

Increased light intensity leads to an increase of the photosynthesis rate until light saturation level. However, under high $CO_2$ concentrations, light saturation may shift to higher light levels. Similarly, optimum temperature of the net photosynthesis rate can increase by increasing light intensity. Optimum temperature of net photosynthetic rate is also affected by $CO_2$-concentration. Similarly knowledge of greenhouse design and the technology are associated with effective crop management. Singular actions such as these are extended into complex questions of entire measures, in order to improve the sustainability of such systems. Based on advanced sensors and robotics, it is possible to involve all environmental factors in greenhouse climate control. Sustained efforts to balance the greenhouse climate conditions with other factors such as outside conditions, weather forecasts, light and energy efficiency, water and fertilizer use efficiency must be undertaken. In turn, these factors could be integrated together with crop management and plant growth rate to optimize the greenhouse utilization.

Many possibilities exist to increase yield, reduce production costs per unit area or plant, retain the longer cultivation period long, and improve the product quality of greenhouse crops. This is due to an introduction of innovative approaches (originated in horticulture and other activity fields), and the use of a combination of optimum performance measures associated with protected cultivation.

## Conclusions

There is a wide spectrum of approaches in protected cultivation that enable growers in different climatic regions to adopt and adjust the preferred technology for each specific crop. High-tech greenhouses produce high yields but also require high initial cost whereas the naturally ventilated plastic tunnels and greenhouses, as well as screenhouses, are a low-cost alternative suitable for growers with limited capital or in regions with a fluctuating demand.

Significant progress has been achieved in both practical application and basic understanding of protected cultivation principles and practices. Due to the energy crisis and the increasing price of fuel, growers now need to adopt climate control approaches that reduce conventional energy consumption, and increase the use of renewable energy sources like solar, or geothermal. Researchers and growers need to fine tune the irrigation needs to meet the exact needs of horticultural crops in close consideration with a climate control strategy.

The use of sophisticated materials and additives in order to fine tune the radiation intensity and spectrum are becoming important in efficiently utilizing the heat associated with solar radiation and reducing the cooling requirements in mild climates to increase the energy savings. Advances in genetics and molecular biology are leading to the development of crops that are much less prone to stresses and hence can be grown in many different regions in terms of climates and soils.

Future research will focus on more durable and efficient structures, sustainable covering and substrate materials, more efficient climate control systems that increase energy savings, the breeding of varieties that are more resistance to biotic and abiotic stresses, and improving the development of production management strategies. These studies are needed in order for the horticultural industry to meet the growing food demand under future uncertainties such as climate change and changing global economies and markets.

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# Chapter 11
# The Role of Ornamentals in Human Life

**Jaap M. van Tuyl, Paul Arens, William B. Miller and Neil O. Anderson**

**Abstract** The integration of flowers in daily human life has a long history and substantiates our appreciation for their delicacy and wide variation in possible shapes and colours. Since the very early civilizations flowers were used for medical purposes and above all have been part of important cultural and religious customs. Records of their use have been preserved over centuries in different parts of the world and in most if not all major religions flowers have a featuring role. Whereas in the past flower production for floral design was local and probably limited and restricted to wealthy and powerful people that could afford gardens for pleasure, nowadays floral production has become a knowledge and infrastructural intensive, highly specialised industry with trading networks on a global scale and floricultural exhibitions being organised all over the world. As with all intensive industry, concerns on environmental aspects including carbon footprints as well as the well-being of labourers have been raised and have led to certification programs that resulted in impressive reductions in energy and resources as well as environmental impact. It can be expected that given the global environmental and economic issues, ornamental production will have to even intensify these efforts substantially to provide flowers at low environmental costs for people to enjoy in and around their homes.

**Keywords** Floriculture · Flowers · Celebration · Exhibition · Carbon foot print

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## Introduction

Flowers form an integral part of human life, they are presented at birthdays, weddings, graduations, funerals and other special occasions. Ornamental plants are grown for their beauty and function in gardens, parks, and homes of people. Production is in nurseries as bedding plants, pot plants, foliage or as cut flowers. Flowers are produced worldwide on a large scale for commercial purposes by growers and distributed to wholesale, markets and flower shops to be sold to the consumer. A second use of ornamental plants is their uses in gardening and landscaping. Ornamental plants are used by humans because of their beauty, symbolic significance (Mendonca de Carvalho 2011; Koehn 1952; Ferguson 1966), colour (Kaufman and Lohr 2008), fragrance, therapeutic (Matsuo et al. 2008) and emotional value.

In this chapter the role of ornamental plants in human life is summarized and focuses on cultural, environmental, horticultural and genetical aspects.

## Cultural Aspects

Flowering plants (angiosperms) produce colourful, showy flowers as a mean of attracting insect, bird, bat or animal pollinators to produce seed for the continuation of the species. In contrast, wind pollinated plants, particularly conifers (gymnosperms), grasses, sedges and other woody shrubs/trees have less showy flowers. While foliage, plant shapes, and fruit frequently have ornamental qualities, flowers have always captured the attention of human eyes. As a result, flowers have been highly integrated into human cultures and societies throughout the world in all ages being used for art, adornment, decoration, fragrance, medicine, food and floral design.

Flowers come in a wide variety of sizes—from the microscopic duckweed (*Wolffia columbiana*) to the gigantic aroids (*Amormorphallus paeoniifolius*); shapes—star or actinomorphic, yolk or zygomorphic, actinomorphic flowers produced in a plant that normally is zygomorphic—also known as peloric types; colours—all are possible across the spectrum of plants, although some species and genera have only a few colours; black, blues and greens are rare in most species. In floral designing, the design elements (line, form, texture, colour and fragrance) are all provided by flowers and their stems used in each design (Hunter 2000). All flowers can be categorized into distinctive forms for floral designing: mass, line, form, and filler (Hunter 2000). Mass flowers have one or more flowers or florets clusters in a single spot at the tip of each stem, providing a mass appearance, such as:- dahlia (*Dahlia pinnata*), chrysanthemum (*Chrysanthemum x grandiflorum*), or rose (*Rosa x hybrida*). In floral designing, mass flowers are typically used for the focal point or centre of interest. Line flowers are stems with multiple flowers or florets occurring up and down each stem, e.g. gay feather (*Liatris spicata*), gladiolus (*Gladiolus x hybridus*), or snapdragon (*Antirrhinum majus*). In floral designing, line flowers help create geometric forms and provide a line of similarity for the viewer's eye to follow. Form flowers are unusually shaped and call attention to themselves due to their exotic appearance, e.g. King or Queen proteas (*Protea cynaroides, P. magnifica*), banksias (*Banksia marginata*), or alstroemerias (*Alstroemeria pelegrina*). Filler flowers are smaller sized stems with multiple flower or florets and can be used to “fill in” floral designs, e.g. baby’s breath (*Gypsophila paniculata*) or statice (*Limonium sinuatum*).

## Historical Aspects

In ancient civilizations, flowers were widely used indoors. While many records of ancient uses have been lost, several significant cultures have detailed documentation of the cultural integration and use of flowers: for instance the Egyptian, Greek, Roman, and Byzantine cultures (Hunter 2000). Archaeological excavations in the Shanidar IV cave in Iraq uncovered the use of flowers as far back as the Neanderthals for sympathy floral designs and medicinal purposes (Solecki 1975). A variety of flower stem remnants (pollen clusters where the flowers would have been positioned) were found in male gravesites: yarrow (*Achillea spp.*), cornflower or bachelor’s button (*Centaurea cyanus*), St. Barnaby’s thistle (*C. solstitialis*), groundsel (*Senecio vulgaris*), grape hyacinth (*Muscari racemosum*), joint pine or woody horsetail (*Ephedra distachya*) and hollyhock (*Alcea rosea*) (Solecki 1975).

The earliest records of cultivating chrysanthemum flowers (*Chrysanthemum* x *grandiflorum*) date back 5,000 years to the ancient Chinese, who first valued its pharmaceutical properties and then its floral attributes (Ackerson 1967). Other flowers popular in ancient China, include spring flowering branches, camellia, aster, iris, lily, lotus, narcissus, orchid, peony, and rose. In 385 AD, chrysanthemum seeds were introduced to Japan as a gift from Korea (Ackerson 1967). The Japanese cultivated the chrysanthemum on such a large scale and incorporated it into their culture and annual festivals to such an extent—with the Japanese Emperor sitting on The Chrysanthemum Throne—they are more associated with it than the Chinese. Chrysanthemums were imported to Europe via Holland in 1688, then to England and the USA by the 1700s (Clark 1962) and have become one of the most appreciated flower crops worldwide.

Japanese use of flowers, particularly chrysanthemums, evolved into a highly specialized art form. The oldest floral design schools of Ikebana encouraged the arrangements of flowers in temples, for ceremonies and festivals, as well as the home (Hunter 2000). Flowers were used to depict religious and spiritual connections of humans in the Buddhist traditions. Current Japanese use of flowers reflects this methodical and philosophical connection of humans with their surroundings. In ancient Egypt, there were numerous reliefs, paintings and inscriptions in tombs and temples that depict the widespread love and use of flowers. In addition to cultivating native ornamentals such as papyrus and lotus flowers, other cultivated flowers were imported from foreign countries. For instance, cultivated chrysanthemums were brought back to Egypt from King Solomon’s royal gardens by Pharaoh Thutmose III (ca. 900 BC) (Schweinfurth 1919). Thus, many early civilizations often cultivated common flowering plants such as rose, chrysanthemum, and lily. The

**Fig. 11.1** Floral arrangements of flowers and foliage depicted in ancient Egyptian art. This painting shows the children (*right*) of King Ipuy and his wife (*left*) bringing lotus bouquets to them. (Source: Egyptian Expedition of the Metropolitan Museum of Art, Rogers Fund, 1930 (30.4.114), The Metropolitan Museum of Art, New York)

Gardens of ancient Egypt were, at first, designed for growing edible vegetables and fruit but later evolved into ornamental pleasure gardens with the inclusion of flowers and ornamental trees (Baridon 2000). These could be found in private residences, temples and palaces; funeral gardens were also common. Models of these gardens were also inscribed in tombs for enjoyment in the afterlife (Baridon 2000). Cut flowers and foliage arranged in floral designs were commonly depicted in ancient Egyptian wall paintings (Fig. 11.1). The classic Egyptian floral design period was from 2800 to 28 BC with flowers being used on banquet tables, in temples, self adornment (as wreaths, chaplets, garlands, flower collars), in religious or royal processions or given in honour of someone held in high regard (Hunter 2000). Egyptian floral designs commonly used flowers or fruit in orderly rows. Bowls of arranged lotus flowers, the flower of Goddess Isis, were placed on banquet tables. Other commonly used cut flowers (lily, rose, gladiolus, straw flowers) and foliage (ivy, myrtle, olive, palm, papyrus) are still widely used today across the globe (Hunter 2000). Wearing flowers in wreaths or chaplets rose to a higher level and usage in the ancient Greek floral period (600–46 BC). Professional wreath and garland makers were employed in the art since wreaths were widely used in Greek culture, and awarded to heroes of the arts, sciences, and athletics (Hunter 2000). Flower colour was less important to the Greeks, but they sought to incorporate herbs along with flowers for added fragrance. Commonly used flowers by the Greeks included lily, rose, honeysuckle, larkspur, hyacinth, violet, and tulip (Coats 1970). The Cornucopia or horn of plenty (Fig. 11.2) was one of the common mechanisms used to strew

**Fig. 11.2** Greek uses of the Cornucopia or horn of plenty shown here raining flowers and fruit. (Photo credit: Neil Anderson)

flowers and fruits on the ground during festivals and grand festivities. Cornucopias are still used in modern celebrations to denote the abundant harvest, particularly on Thanksgiving Day in Canada and the USA. Florists in the Roman Empire (28 BC–325 AD) continued the Egyptian and Greek traditions of making wreaths and using garlands in celebrations. Roman wreaths and garlands became more decorative with brighter colours and fragrant flowers (Hunter 2000). Fragrant petals and flowers were commonly used at Roman banquets, in the streets and floated on lakes. As guests dined and reclined in the opulent Roman banquets, rose petals often rained from the ceilings and piled up at their feet—often as deep as ~0.5 m. The first artistic rendition of a naturalistic floral design can be found in a mosaic in the Vatican Museum. Sympathic floral traditions included the "*Dies Rosationis*" where the family would gather around the rose-covered grave of the recently deceased and place additional roses in remembrance (Nicol 1826). Another Roman floral tradition was the "*Sub Rosa*" where a wreath of white roses was hung from the ceiling and all conversations beneath it were to be kept secret.

European aristocratic and monastic usage of flowers through the Byzantine period, the Middle Ages, the Renaissance, Baroque and Dutch-Flemish periods, to the French, English and Victorian eras, all showed a progression of techniques, employment of principles and elements of design, and the creation of floral industries to supply the vases, containers, palaces or estates to enable florists to make the designs (Berrall 1968). Many such changes in the art and science of floral design are depicted in European paintings (Mitchell 1973; Newdick 1991).

The Byzantine period (320–600 AD), named after the city of Byzantium (later Constantinople and now Istanbul in Turkey) was in the eastern sector of the Roman Empire, and continued the Romantic flower uses and floral designs, although garlands evolved into floral or fruit banks alternating with foliage. Symmetrical

**Fig. 11.3** Emilia in her medieval garden weaves a wreath of flowers for her hair. Painting entitled "Arcita and Palemone admire Emilia in her garden", from a manuscript of Boccaccio's Teseida (1339–1340), Vienna, Österreichische Nationalbibliothek, Cod. 2617 Han, 53r

floral design compositions resembling highly pruned trees and shrubs were kept in large containers (Hunter 2000). During the Middle Ages (476–1450 AD) flowers maintained their importance particularly in everyday medicinal, food, drink, and body freshening uses with Medieval gardens an important source of floral materials (Fig. 11.3).

In the Renaissance, which began in Italy in the fourteenth century, floral designs in vases commonly appeared in paintings and flowers for specific purposes and as a source of symbolism. For instance, in the painting "The Annunciation" by Leonardo da Vinci (1452–1519) and Andrea del Verrocchio (1435–1488), *Lilium candidum* became known as the Madonna lily and was associated with fertility as well as chastity (Brown 1998). Since that time, other flowers have symbolic meanings in paintings (Bos 2012; Segal 1990) and sculptures (Janick et al. 2010). The Language of Flowers developed after the publication of the monograph, *Le Language des Fleurs* by Madame Charlotte de la Tour in 1819, which was followed by Kate Greenaway's, *Language of Flowers,* in 1884, provides a list of over 200 plants and what they mean to people.

Mixed bouquets during the Renaissance period demonstrate that a wide variety of flowers were cultivated, ranging from daffodil, rose, carnation, lily, anemone, bell flower, iris, lily of the valley, lupin, pansy, poppy, primrose, and stock to tulip. During the Baroque and Dutch-Flemish periods (seventeenth to eighteenth centuries) the wide array of cultivated flowers continued with a particular interest in the "broken" tulips streaked with colours (Fig. 11.4; Segal 1990).

The Victorian era (1837–1901) was one of the most influential European periods that encouraged the use of flowers in everyday life (Maas 1969). This period greatly influenced the emerging American use of flowers in mass arrangements for

**Fig. 11.4** Vases of flowers from the Baroque and Dutch-Flemish periods, displaying a wide variety of cut flowers preferred during this time. Flowers in a Niche, Ambrosius Bosschaert (1614–1654), The Hague, Holland, inv. Nr. 679

the home during the Federalist, Greek Revival and Art Nouveau periods (Marcus 1952; Benz 1960; Schmutzler 1962; Warren 1972; Anon 1997). In the Victorian Era, the Language of Flowers enhanced floral symbolism with the use of flowers and floral arrangements to send unspoken messages to the recipient. Current floral symbolisms abound and may be specific to particular cultures or countries rather than having a wider global meaning. For instance, red roses are indicative of passionate love, particularly for St. Valentine's Day (February 14), yellow for devotion and pink coloured flowers indicate a lesser interest.

Historic uses of flowers and their popularity have influenced current day usage. For instance, while there are thousands of flowering plant species and cultivars on the cut flower market, only a few are used widely for floral designing: rose, chrysanthemum, carnation, lily, gladiolus, and orchid are among some of the examples. All of these have been used since ancient times in China, Egypt, Rome, and Greece and largely due to their wide adaptability to cultivation in different environments, long vase and garden life, and their ability to be shipped long distances without a loss of integrity.

Around the world, modern countries have chosen their National Flower as a national symbol. During the National Day (of independence or unification) these flowers are promoted and printed on flags and other emblems. For instance, the rose is the national flower for several countries, i.e. England, the USA, Ecuador, Bulgaria, Iraq, Iran, the Czech Republic, and Slovakia (Fig. 11.5). The tulip is the National Flower for the Netherlands, Hungary and Turkey while the chrysanthemum and cherry are the National Flowers for Japan and China, respectively. France

**Fig. 11.5** The rose is the national flower in a number of countries. (Photo credit: Jaap van Tuyl)

and Croatia chose the iris, while Brazil favours orchid (Anon 2013a, http://www.theflowerexpert.com/content/aboutflowers/national-flowers). *Usually the National Flower reflects some association of each country with the species, even though they may not be native to a respective country.*

## Flowers in Traditions and Celebrations

In human life a number of traditions and celebrations are known in which flowers play an important role. Flower festivals are held typical in each country, like in the Netherlands during the flowering of the spring flowering bulbs (April/May) or the National Cherry Blossom Festival (March/April) in Washington, DC or in Japan over January/April. The annual Rose Bowl parade in Pasadena, California, on New Year's Day (January 1) incorporates the use of flowers and plant parts to decorate all floats entered into the parade. Conservatories, arboreta and municipalities throughout the world sponsor flower shows, exhibitions, and special celebrations to highlight particular flowers of the seasons or for special holidays (Easter, Christmas, Mothering Sunday). In northern latitudes these are particularly important during the winter months to bring fresh flowers into people's lives during the cold winter months. In China the most important floral holiday is the Chinese New Year, also known as the Spring Festival. Narcissus in pots and cut lilies are produced and exhibited in large numbers. In other countries, specific flowers may be invoked for religious celebrations such as the use of native marigolds (*Tagetes erecta, T. patula)* for the Mexican Day of the Dead or Día de los Muertos (31 October–2 November) which predated the Spanish invasion. Other countries have recurrent floral celebrations to honour specific native flowers that have played important historic roles. For instance, in the Chrysanthemum City, Xiaolan, millions of people come to see the chrysanthemum shows (Fig. 11.6).

**Fig. 11.6** China Grafted and potted chrysanthemums are grown for the widely popular chrysanthemum exhibitions held every 4–6 years in the Chrysanthemum City, Xiaolan Town, PR. (Photo credit: Neil Anderson)

During the year a number of special days or events are famous for giving flowers as gifts: St. Valentine's Day (February 14), Mothering Sunday (4th Sunday in Lent), Mother's day (first Sunday in May), Julian and Orthodox Easters (Varying from end of March till beginning of May), All Saints Day (November 1), Jewish Hanukkah, which in 2013 falls from Sunday November 27 to nightfall December 5, and Christmas Day (December 25). Besides these annual celebrations other important moments in life for which flowers are used are birthdays, marriage and funerals. Sympathy work for funerals and memorials always involves flowers as they are reflective of the shortness and fragility of life. Floral gifts in many countries, either as potted flowering plants, fresh cut flowers, or flower arrangements are also popular hostess gifts when invited to someone's house. Their freshness, bright colours, artistic arrangements and fragrance are always welcome.

## Floricultural Exhibitions

The most important modern-day flower production areas in the world have traditional national and international exhibitions in which industry professionals (breeders, producers, distributors, brokers, growers, retailers, and landscapers) are involved. In the Netherlands, the International Hortifair (Anon 2013b, http://www.hortifair.com/) is the most well-known, while the IPM (Messe Essen) in Essen, Germany Anon (2013c, http://www.ipm-messe.de/en/ipm_essen/index.html) is another important European event. The International Florist Organisation for the European ornamental plants industry (Fleuroselect) holds annual European Spring Park Trials for breeder, producer and distributor companies to display their new bedding plant cultivars Anon (2013c, http://www.ipm-messe.de/en/ipm_essen/index.html). Fleuroselect also awards outstanding new cultivars in these prestigious awards. In the USA, the comparable California Spring Trials occur in the early spring of each year across California so that breeder, producer and distributor companies can also display their new bedding plant cultivars Anon (2013d, http://www.ofa.org/OFA/Events/2013_California_Spring_Trials/ofa/Events/spring_trials.aspx) The All-America Selection (AAS) trials and awards in the USA are a national trialling organization which awards AAS winners each year for their top-performing annual bedding and vegetable plants Anon (2013e, http://www.all-americaselections.org/). In the USA, numerous floral exhibitions and conferences include the Ohio Florists Association meeting in Columbus, Ohio Anon (2013f, http://www.ofa.org/), the Northwest Flower & Garden Show in Seattle, the Northwest Flower and Garden Show in Washington and the Philadelphia Flower Show in Pennsylvania Anon (2013g, http://www.gardenshow.com/; 2013h, www.theflowershow.com). Throughout the rest of the Americas, numerous floral events keep the public and industry up-to-date with the latest and best products and services. For example Agriflor, in Quito, Ecuador is usually held biennially during September to October highlighting an array of cut flowers, especially cut roses Anon (2013i, http://www.eventseye.com/fairs/f-florecuador-agriflor-8221-1.html; 2013j, http://www.youtube.com/watch?v=dT9BYsm7Pv0). Proflora is another central American conference held biennially in Bogota, Colombia to highlight numerous cut flower crops produced in Colombia Anon (2013n, http://www.proflora.org.co/home.php).

## Horticultural Production

Historically many flowers were harvested from fields, forests, natural areas, and home gardens. As cities grew there was a corresponding cultural awareness and an increase in aristocratic demand for high quality flowers, there was a move to their commercial production in cultivated fields, and specifically controlled environment structures (e.g. cold frames, hot beds, shade houses, greenhouses, conservatories, low/high tunnels), all of which were designed and built for the growth and harvest of flower and food crops. The first structures preceding those of greenhouses were forcing houses for vegetables, built in 500 BC by the Romans. Seneca (who died in 65 AD) later described "…the use of window-panes [*specularia*] which admit the clear light through a translucent slab of mica (*lapis specularis*)" or transparent stone (*perspicua gemma*) as a glazing material (*cf.* Epistle XC; Bromehead 1943). Such specularia were used to let sunlight in but keep wind out, such that Emperors Nero (37–68 AD) and Tiberius (17–37 AD) both had cucumbers grown year round (Pliny the Younger, XXXVI 22 § 46; XIX 64; *cf.* Smith 1893; Bromehead 1943).

As the invention of walls with translucent mica, flues for heat circulation (100 AD) and sheet glass (300 AD) occurred, larger wall areas could be used for light although the roof was still solid with tiles or shingles. The building of orangeries commenced in 1545 (Padua, Italy) and by the early 1600s, all major castles and aristocratic families installed them across Europe (Nelson 2003). While the citrus flowers provided fragrance and the fruit Vitamin C for visiting guests, the main attraction was the botanical collection of flowering plants used to grace the banquet tables with floral designs. The development of the Golden Age of The Netherlands, with its immense sea power and the Dutch East and West India Companies in the 1600s, gave rise to the creation of the modern greenhouse industry (Nelson 2003). The Dutch discovered how to dig and force lilac bushes (*Syringa vulgaris*) into

**Fig. 11.7** Lithograph by Ackerman of The Crystal Palace in London; view is from the northwest. (De Maré 1972)

flower, shipping the cut stems to the seventeenth century royal courts of Germany, France, and Great Britain (Nelson 2003).

The inventions of embedding glass in putty for greenhouse roof and walls was developed by company of Lord and Burnham in 1840 and casting plate glass in 1848 allowed for larger greenhouses to be built for exhibitions and commercial flower production. For instance, in 1851, The Crystal Palace was built in Hyde Park, London, England with an exterior surface area of 71,721 m$^2$ of glass (Fig. 11.7; de Maré 1972). Lord and Burham and other companies subsequently pioneered the building of numerous types of greenhouse structures for commercial and home production of flowers, fruits and vegetables (Figs. 11.8 and 11.9; Lord & Burnham Co. n.d.; The Weathered Company 1908).

Modern-day greenhouses (Fig. 11.10), used primarily for flower production throughout the world, are large expanses of structures that use sheet glass, flexible polyethylene, and rigid fibreglass, polycarbonate, or exolite as glazing materials (Nelson 2003). The three top greenhouse producers are The USA, Japan and The Netherlands, producing as much as 46 % of the global floriculture products (Nelson 2003). Typical crops grown in these structures include a range of cut flowers, cut foliage, potted flowering and foliage plants, bedding plants, and herbaceous perennials. Due to the advent of air transport, the evolution of flower production changed from local growers who produced all crops for local sales, to areas of global specialization. Specific field cut flowers are still produced in the warmer areas of the globe such as California or Florida, USA, and include crops such as stock (*Matthiola incana)*, baby's breath (*Gypsophila paniculata),* statice (*Limonium sinuatum)* and

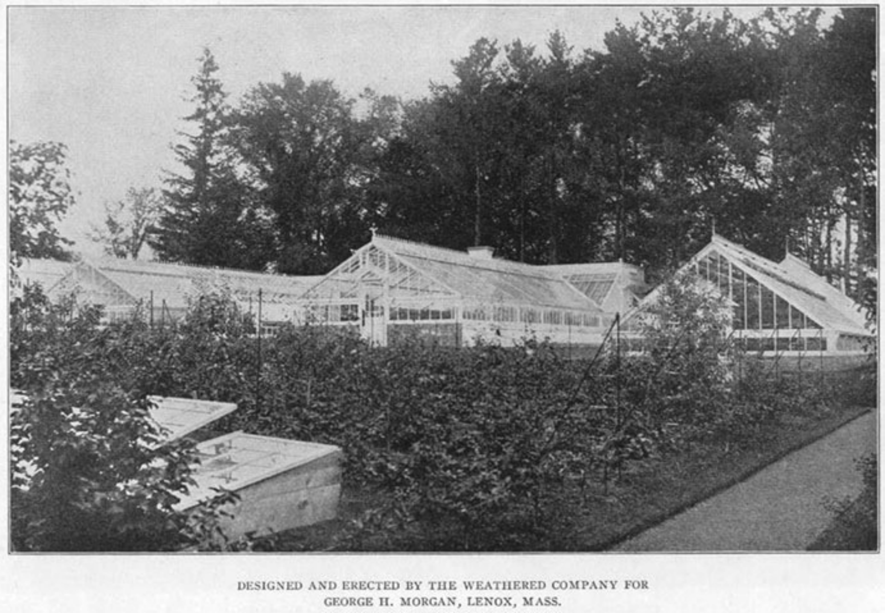

**Fig. 11.8** Commercial, free-standing equal span greenhouses, typical of the early 20th century. (The Weathered Co. 1908)

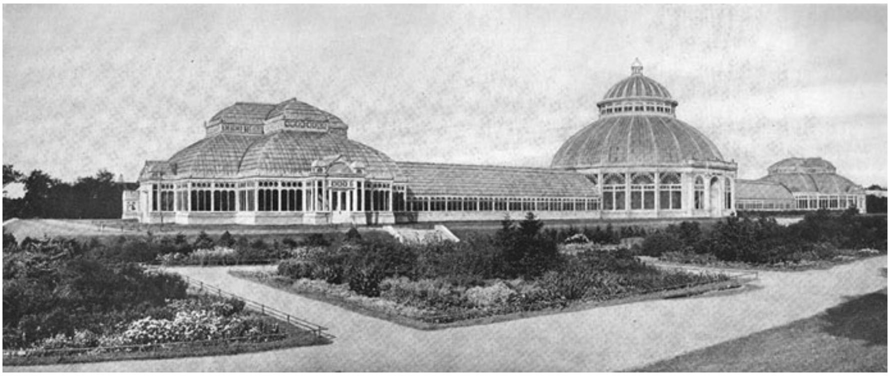

**Fig. 11.9** Example of a conservatory, built for the New York Botanical Gardens by the Lord & Burnham Company. (Lord & Burnham Co. n.d.)

gladiolus (*Gladiolus x hybridus*) (Nelson 2003), while some cut flower crops requiring higher temperature or are more susceptible to insect and disease are moved into high tunnels or greenhouses (Ortiz et al. 2012). Cut tropical foliage and flowering plants such as the *Vanda, Oncidium, Cattleya*; *Anthurium* orchids) are grown in Thailand, Hawaii, and the USA with the more heat-loving Mediterranean crops, such as the protea and banksia, that both belong to the family Proteaceae, produced in California USA, Israel, South Africa, India and Australia. High quality cut green-

**Fig. 11.10** Example interior of a modern-day greenhouse range in Canada, glazed with rigid Exolite for growing cut snapdragons, *Antirrhinum majus*. (Photo credit: Neil Anderson)

house crops such as the rose, carnation, and chrysanthemum are produced in two primary areas, due to their higher light and temperature levels: namely Central and South America (Colombia, Honduras, Guatemala, Ecuador, Mexico, Costa Rica) and Africa (Kenya, Tanzania, Zimbabwe, Zambia, Uganda, Morocco). Crops such as these are less costly to produce than cut flowers grown in greenhouses of northern latitudes due to expensive heating and lighting costs (Nelson 2003). Likewise, plug growers at northern latitudes, such as Wagner's Greenhouses (Minneapolis, MN, USA) may produce cool season bedding plants (pansy, viola, *Nemesia*) during the summer months for fall/winter sales in southern regions of the USA. Many northern latitude countries specialize in potted plant production (The Netherlands, Denmark) where cooler climates and lower light levels provide ideal conditions for the growth and development of *Cyclamen, Exacum, Calceolaria,* and other potted genera. China and Chile are two emerging floral production countries are now competing on the world market for these and other potted material. The net effect of these changes is year-round production for most commercially grown flower crops.

The flower industry is characterized by "flower power" and "convenience" (Anderson et al. 2006a, b) and numerous innovations have occurred which now aid in the global increase in sales and popularity of floricultural crops. Until the end of the nineteenth century, flowers were transported without refrigeration by bicycle, on foot, by ship or horses (Nelson 2003). The first major change was the creation of rail and road systems which increased transportation distances that floral and cut flower

**Fig. 11.11** Claude Hope, one of the founders of PanAmerican Seed Company, whose flower breeding resulted in the first commercial F1 hybrid Impatiens walleriana and Petunia xhybrida. (Uchneat 2006)

products could move. Thus, three factors emerged for sustainable production: quality, production and transportation costs (Nelson 2003). Air transport developed post-World War II and dramatically affected shipping. A second major change was the creation of $F_1$ hybrid seed products, notably with *Impatiens walleriana* and *Petunia x hybrida* by the PanAmerican Seed Company (bred by Claude Hope) in the 1940s (Fig. 11.11; Uchneat 2006). These products displayed hybrid vigour or heterosis that outperformed the standard open-pollinated types. Currently a high proportion of seed-produced flower crops are hybrids. Another innovation was the Plug Revolution of the 1980s, which transformed the heavy, cumbersome clay or wooden containers into lightweight plastics (Figs. 11.12 and 11.13) (Armitage and Kaczperski 1994). Plug trays, all made the same size of 10″ × 20″ (25.4 × 30.5 cm) were created to grow and germinate seedlings or root cuttings and held from 32 to 512 small plants. Finishing containers (explain what these are for the reader) are moved from bulb, azalea and standard pots to 4- and 6-packs that fit into 10 × 20 trays in specific sets, each with their own trade code. This enabled automation to come to greenhouse production with the advent of automatic plug and container filling machines, seeders (drum, needle), transplanters, and benching systems as well as computerization for climate control (Nelson 2003). With the use of in-floor heating, soil temperatures of adjacent bays or areas could be set at differing values, allowing for the first-ever production of cool and warm season crops in one greenhouse (Fig. 11.14).

Current commercial production and marketing of floricultural crops follows a complicated, ever-changing horticultural distribution supply chain that has been created through globalization and highly specialized growing, brokerage and marketing firms (Drew et al. 2010). The chain begins with the collection of wild species with ornamental potential, their subsequent breeding and selection to create seed or vegetative products. Producers then sell on the propagules to distributors who subsequently sell directly or via brokers to grower types (plug producers, pre-finishers, finishers). These products are then sold to the customers either through independent or big box store retailers, garden centres, nurseries and landscape contractors (Fig. 11.15; Drew et al. 2010). Another level of complexity arises when

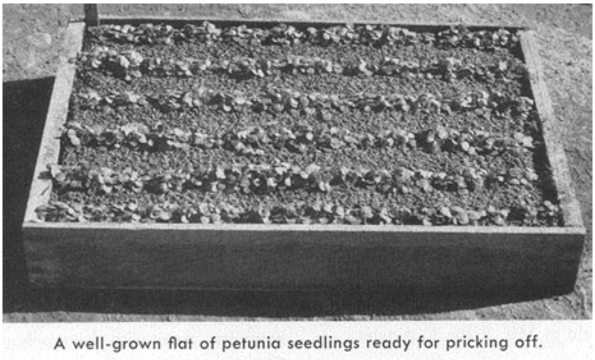

**Fig. 11.12** Wooden flats typical of those used for sowing seeds, rooting cuttings until transplanting; such heavy wooden flats were used until the plastics plug revolution of the 1980s. (Sheldrake and Boodley 1965; Rowley 1978)

firms do more than one activity task, such as a breeder and producer company or act as a distributor and broker. Prior to 1960, all marketing of floral products occurred through full-service florist retail shops (Nelson 2003). Sales then moved to include groceries, discount stores and street corners followed by mass marketers (Nelson 2003). With global experience, a product could be grown in one country by a producer, distributed to another to be grown, and then final sales could occur in multiple countries.. For example, Easter lily bulbs for the USA market are grown in Smith River, California and Brookings, Oregon (USA), and are sold to greenhouse forcers and growers in Canada and then shipped back to the USA market. Cut flowers may pass through several countries, originating in one country where the grower is located, shipped and marketed through a large floral auction house (e.g. Aalsmeer in The Netherlands), and then brokered and distributed to any country on the globe. The marketing of flowers has become specialized with many products (cultivars, series) having specific websites, e.g. ‘Purple Wave™’ petunia Anon (2013k, http://www.wave-rave.com/), and Proven Winners branding Anon (2013l, http://www.provenwinners.com/). This creates consumer interest ascending back through the distribution chain, where they ask retailers for a specific product by name (‘Purple Wave™’ petunia) rather than simply a purple petunia type (Anderson et al. 2006a, b; Drew et al. 2010). Other forms of marketing, such as intellectual property (IP) have specific rights and have created interest and product value, such as Plant Patents, Plant Variety Protection, or Utility Patents in the USA vs. Plant Breeder’s Rights in Canada, Europe, Australia and Japan. (Aguirre 2006).

## Environmental Aspects

As a commercial venture, flower production, or floriculture, is a highly developed and specialized form of agriculture. For maximum value, a flower must be perfect, without disease or insect infestation, be free of physiological or physical injury, and possess maximal vase life or shelf life. The modern, global flower production industry has evolved over many decades to reflect these requirements. And in tandem,

**Fig. 11.13** Example clay pots used to produce an Easter lily crop, wrapped for shipment, in 1912 at Minneapolis Floral Company, Minneapolis, MN USA. (Photo credit: Prof. Cady, University of Minnesota)

**Fig. 11.14** A modern greenhouse with heated floor which can grow different temperature-requiring crops side-by-side in the same house. (Photo credit: Neil Anderson)

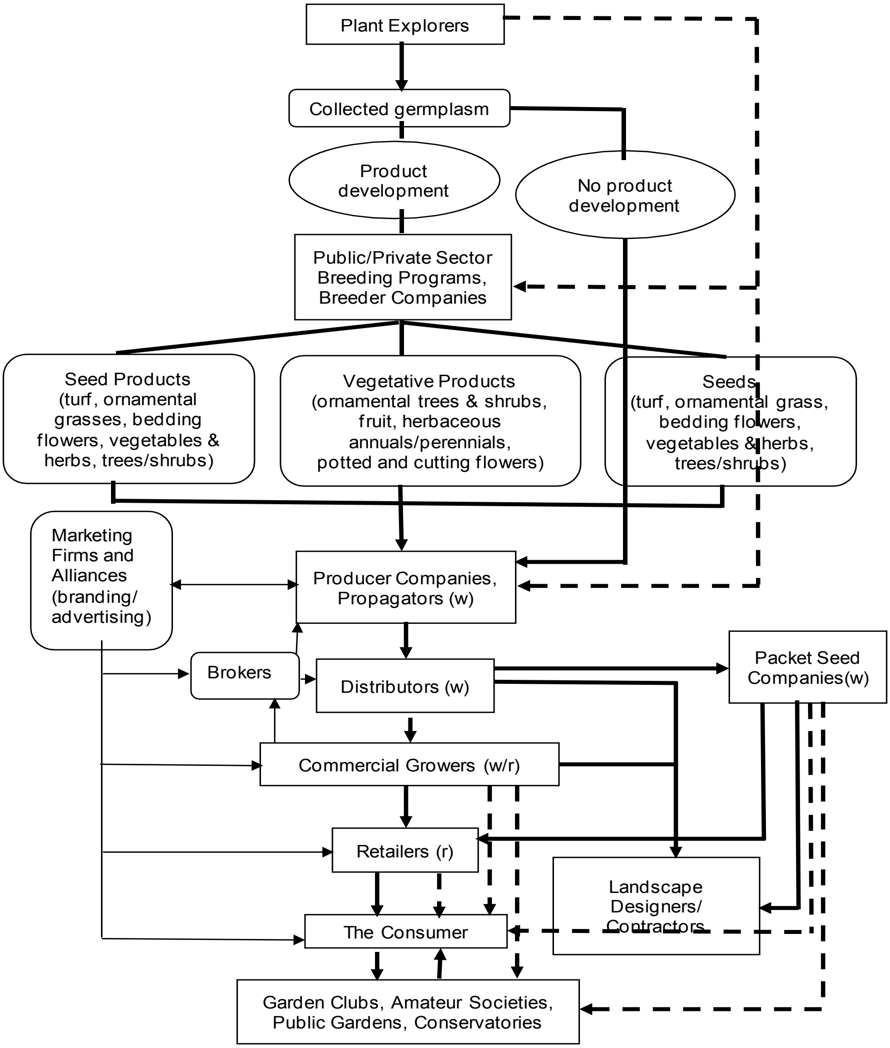

**Fig. 11.15** The horticultural distribution chain showing linkages between varying firms and players involved in the collection, breeding, propagation, distribution and purchase of floricultural crops (Drew et al. 2010). *Dashed lines* indicate *e*-Commerce; *solid lines* are all other forms of distribution (truck, rail, air, ship)

as the capabilities of the industry for producing and delivering such products has improved, so have the demands on the product by the consumer. Large buyers of flowers or flowering plants place rather exacting standards on products delivered to them (e.g. number of flowers, or height). Until recently, these standards have been mostly related to visual or ornamental characteristics of the plant or flower. Commercial flower growers strive to maximize profit by operating their greenhouses in a way so as to produce and deliver the required plants or flowers in the most economical manner possible.

Economists refer to "externalities" as the side effects or consequences of industrial or commercial activity. In many areas of horticulture, we have become increasingly aware of unintended effects of our activities, and floriculture production is no exception. In this chapter, we have already discussed the emotions and human linkages with flowers, but for some consumers, emotions related to the authenticity, environmental friendliness, sustainability or ecological purity are important drivers of a purchase decision. Against this background, floriculture producers are increasingly aware that promotion of ecological friendliness of flowers can influence purchase decisions. To this end, in recent years, there has been increased interest in programs that "certify" or "label" plants or flowers as having met specified requirements related to environmental and/or social responsibility. Most readers are probably familiar with such labelling, perhaps the most commonly known being "Fair Trade" for coffee and other delicacies (Table 11.1).

## Certification Programs

In floriculture, the first certification program was the Milieu Programma Sierteelt (MPS), started in The Netherlands in 1994 (White 2012). At its inception, the main goal of MPS was to help the Dutch greenhouse industry reduce the use of pesticides and to this day remains an important goal. The MPS organization works with individual floriculture growers worldwide setting organizational goals that relate to chemical, water or fertilizer use, social responsibility and related areas. The MPS program has a number of levels depending on the complexity and depth of program the grower wants. The basic program is the "ABC" program, where MPS provides support to help growers record and monitor pesticide, fertilizer, energy (and other inputs) used on a monthly basis. The grower is responsible for collecting this information, and enters it onto a database. On a quarterly basis, MPS provides a simple grade (A, B or C) to the grower. This designation can be used by the grower for various purposes, including qualification for higher level certification (see nectalinea). A major value of MPS-ABC is the ability of growers to benchmark themselves to other similar businesses, or to growers in other countries. Part of this is because the system tracks the usage of chemicals, not money spent on them, so direct comparisons based on active ingredient applied are possible.

Beyond MPS-ABC, there are higher level certifications for worker safety, health, employment conditions and human rights (MPS-Socially Qualified). MPS-GAP (GAP stands for Good Agricultural Practice) aims to help growers anticipate market demands of the retail channel for safe, sustainably-cultivated, high-quality and traceable products that require Global GAP standards. MPS-Quality aims to assist growers in producing the highest possible quality crops. There are also specific certifications for the wholesaler and trader sides of the industry. The MPS program is the most extensive certification label within floriculture. Aside from MPS, at least 8 related programs exist in the realm of "flower certification" (Table 11.1). These

**Table 11.1** Summary of the major certification programs in floriculture. (Adapted from White 2012)

| Label/certification | Web site | Comments |
|---|---|---|
| MPS-ABC | www.my-mps.com/ | The original floriculture/greenhouse certification program. Widely established in many countries |
| GlobalGAP | www.globalgap.org/ | A non-governmental organization that sets voluntary standards for the certification of agricultural products around the globe. Started in 1997 as EUREPGAP |
| Fair Flowers/Fair Plants | http://www.fairflowersfairplants.com/ | Initially within MPS. Funded through the Dutch auction system. Requires the equivalent of MPS-A plus adherence to 10 social areas including the right to collective bargaining with the employer, right to a living wage, work guarantees, See (http://www.fairflowersfairplants.com/en/consumers/certification-requirements.aspx) |
| Fair Trade | http://www.fairtradeusa.org/ | Fair trade labels are specifically for developing countries |
| Florverde Sustainable Flowers | http://www.florverde.org/ | Widely used by Colombian flower growers and includes environmental and social, worker and family elements |
| Veriflora | http://www.veriflora.com/ | Certification is by Scientific Certification Systems and is based on a number of horticultural, logistical and human and worker rights criteria |
| Flower Label Program | http://www.fairflowers.de/ | A limited program (as of 2011 in 6 countries) that promotes "socially and environmentally responsible flower, fern, plant and foliage cultivation" |
| Food Alliance | http://foodalliance.org/nursery | A very new label (first used for greenhouse and nursery certification in 2012), mainly USA based, with more than 330 certified organizations managing 5.5 million acres of production |
| USDA Organic | http://www.ams.usda.gov/AMSv1.0/nop | USDA Organic certification only refers to methods of production and is not an endorsement or certification of "sustainability" |

all have the common goal of affirming that labelled products meet the minimum standards as defined for each program. The existence of multiple standards within the industry has been confusing for growers and industry members who have questioned the ultimate importance (economic, environmental, societal) of certification. Anecdotal evidence from growers suggests that having a range of MPS opinions consider "it's the right thing to do" to "whether I like it or not, my large customers are or will soon demand it". Evidence from greenhouse producers in The Netherlands suggests a 23 % reduction in the use of "crop protection agents", and 25 % decrease in energy use between 1995 and 2005 (Hering 2012). It is unclear to what extent this can be ascribed to the MPS program, or if other factors are involved. In any case, the existence of the program gives a very important platform for growers to document their production inputs and provides a firm basis for making other production and marketing decisions.

Presently, in the United States, there is little movement towards a label requirement by major grocery or big box retailers (Hering 2012), but this is subject to change. Conversely, the Fair Trade label system, that was initially for food products such as coffee and tea, but increasingly for spices and other food ingredients, has grown rapidly in the USA (Gunther 2011).

Growers and their individual customers are confronted with a number of competing labels, and it is hoped that over time one of just a few major labels will emerge. However no one really knows the importance of this issue to the end consumer. To what extent is "responsible", "sustainable" or "organic" important to the consumer? Our prediction for North America is that while such labels and products will increase in importance over time, price will be the ultimate determinant of product availability and selection. If labelled products are more expensive than standard product, the product will remain as a niche item.

## Carbon Footprints in Floriculture

Well before we had highly developed transportation systems, local greenhouses grew flowers for use within a limited area. Greenhouse firms were located very close to cities and villages, and the flowers that were produced were available to the customer within hours of harvest. In the United States, the post World War II boom in transportation infrastructure saw the movement of large-scale cut flower production to areas such as Colorado where higher elevation meant cooler summer temperatures and generally higher light availability, both key environmental factors in the production of a higher quality product. Thus, growers could grow better quality flowers and deliver them more quickly due to improved technology and improvements in infrastructure.

By the early 1970's it became clear that other production areas could be developed to serve the North American market, principally in South America (Colombia and Ecuador). Their even higher elevations and near-equatorial location provide excellent growing conditions, with high light, even day length and cool growing conditions all year round. In addition there is adequate air transportation to get flowers to the consumer (or, at least the wholesaler) within a few days of harvest. An added benefit at the time was very low wages, a lack of environmental, worker safety and social regulations. This led to very low production costs, and the opportunity for large profits to be made.

Thus, the route to maximum profit was to exploit the best growing regions (minimal cost for greenhouse structures, remove the costs for ventilation or heat, artificial assimilation lighting, and r elaborate environmental control systems, and source greatly reduced labour costs as against the traditional North American or Northern European production system of expensive glass greenhouses, extensive heating and cooling systems, elaborate environmental monitoring and controls, a need for artificial lighting, winter carbon dioxide supplementation, and very high labour costs). The main disadvantage of the low-cost production areas was the need for relatively long distance transportation of the harvested flowers (invariably air transport). In earlier times there was little visible consideration of the environmental footprint (externalities) of flower production in low-cost regions, or where large projects were built in developing countries, partially on the basis on the grounds of improving local employment, wages and living standards.

By the early 2000's, people began considering the carbon footprint of many products including transportation, lifestyle, food and, ultimately flower production. A carbon footprint may be defined as: "the quantity of greenhouse gases (GHG), expressed in carbon dioxide equivalent ($CO_2e$), emitted across the supply chain for a single unit of that product" (Bockel et al. 2011). Ideally, a cradle to grave, full life cycle assessment is made, including the consumer phase, but with many products, flowers being one, the $CO_2$ cost of nominally tossing them onto the compost pile is minimal compared with carbon costs for heating greenhouses, operating assimilation lights, air freight or surface delivery. By necessity, many assumptions are made when calculating the carbon footprint. The International Organization for Standardization (ISO) has guidelines to help determine the carbon footprint. The main steps are to (1) define the goal and scope of the study to define boundaries, limitations, exclusions and procedures for determining the impact of processes when multiple products or functions can contribute; and (2) create a life cycle inventory, which for carbon dioxide, is the flow of $CO_2$ to and from nature and which carefully considers all inputs from the natural or man-made supply chain and emissions back to nature. The third step assesses the impact of the life cycle impact of all factors noted in the inventory are compared in equivalent terms to determine their environmental impact. Factors may be normalized or weighted according to parameters set out in the goals and scope process. The fourth step interprets and summarizes the results of the assessment phase with the ultimate goal. The ultimate goal "identifies the data elements that contribute significantly to each impact category, evaluating the sensitivity of these significant data elements, assessing the completeness and consistency of the study, and drawing conclusions and recommendations based on a clear understanding of how the LCA was conducted and the results were developed" (Anon 2013m).

Based on the above, there are few full and accurate $CO_2$ footprint assessments of floricultural products. One of the few is the life cycle comparison of $CO_2$ emissions for rose production in Kenya (sunny, excellent climate, requiring only minimally protective greenhouses, but requiring air freight shipment of the roses) versus "local" production in the Netherlands (high technology greenhouses, assimilation lighting, large heat requirement, but minimal local transportation requirements). The study at Cranfield University, England (Williams 2007) was essentially a "cradle to gate" analysis that ended with delivery of Dutch or Kenyan flowers to a distribution centre in the Netherlands. This allowed a direct comparison of the $CO_2$ cost of each production system in the supply chain.

Key findings were that carbon dioxide represented more than 90 % of the global warming potential (GWP) emitted by both systems. Production of 12,000 roses in

**Table 11.2** Comparison of CO2 emissions and global warming potential for roses produced in the Netherlands and Kenya, and delivered to a common point in The Netherlands

| Emission | Relative magnitude of (Dutch emissions/Kenyan emissions) | Altitude effect included? |
|---|---|---|
| $CO_2$ | 16 | No |
| $CO_2A^1$ | 5.8 | Yes |
| $GWP_{100}A^{1,2}$ | 6.0 | Yes |

Kenya and air freighting them to Holland required 53,000 MJ of primary energy and the emission of 2,200 kg $CO_2$. Dutch production was much more expensive: 550,000 MJ primary energy and the emission of 35,000 kg carbon dioxide. Dutch production required large inputs of natural gas (greenhouse heating) and electricity (assimilation lighting for photosynthesis) and ultimately yielded significantly fewer stems/hectare. The major carbon dioxide cost for Kenyan roses was air freight. In total, growing roses "locally" in The Netherlands incurred ca. 6-fold greater carbon dioxide emissions than growing roses in Kenya, even including the carbon cost of airfreight and specifically, allowing for a greater GWP for Kenyan airfreight due to the high altitude of greenhouse gas emissions of the cargo jet. A summary of this comparison is in Table 11.2.

This is highly contrary to instinct, as most people would believe that the air-shipped flowers would incur a much greater carbon cost. But this is not the case. Other horticultural examples are available, including apples, where southern hemisphere production and ocean shipment incur less carbon dioxide cost than "local" northern hemisphere production coupled with long-term cold storage (DEFRA 2008). Based solely on GWP and carbon dioxide footprint, Kenyan roses are much better for the environment and discerning consumers would be expected to choose these products and avoid purchasing the "local" Dutch-grown product. It should be noted that the Cranfield study apparently omitted other possibly significant emissions, such as… from the Kenyan rose farms that could have effects on nearby Lake Naivasha, its wildlife and ecosystem. Certainly, some consumers do base their purchasing decisions on carbon dioxide footprints and other attributes, but the proportion is not significant. Results of air mile labelling by two major British food chains revealed that air mile stickers had no effect on overall consumer preference and relative sales, suggesting that consumers, were only concerned with price and were not so concerned with carbon emissions that they avoided air-freighted fresh produce (Shah 2008).

Within horticulture, and perhaps floriculture especially, we must be constantly concerned with highlighting the value and improvements to our quality of life that flowers, plants and landscaping provide to humans. Studies such as that from Cranfield, while dispelling notions that all "local" product is more environmentally friendly, also highlight just how costly floriculture production can be to both the grower and consumer. Protected cultivation and the constant availability of flowers and plants that improve our lives (to say nothing of fresh fruits and vegetables) do indeed have an environmental cost. One can visit websites informing us that boiling a litre of water is the equivalent of 40 min of a Briton's projected daily 2050 carbon allocation, that a single beer is equivalent to 7 h, and a bunch of Dutch grown flowers a whopping 24 days carbon allocation, or more environmentally correctly, only 4 days carbon allocation for Kenyan flowers! (Green Ration Book 2013). Using or ignoring such data is a personal decision but should be of concern for those wishing to improve the environment of our planet.

Ultimately, consumers (people) are presented with a dilemma when making a purchase choice. Do I chose the more carbon friendly product that also helps to employ many people and improve the local economic base (Kenyan roses) or do I purchase roses grown "locally" (in the UK, or the Netherlands) at a greater carbon cost? Another question might be do I try to consider the entire environmental footprint of production, where externalities such as water use and general environmental damage (as in Kenya) are increasingly known? The choice is not an obvious one, and it is likely the vast majority of people are unaware of the issues and for those who are, there is a lack of consistent and credible information. The worst case scenario is a consumer who is dissuaded from making a flower or plant purchase at all, based on fragmentary knowledge of these issues. Few things in life come without costs. Flowers, fruits and vegetables are no exception.

Perhaps the decision is best summarized in the poem below (Doughty 2013):

*A Conversation Between Two Roses*
"Choose me" said the white rose from Holland
"I am grown in a greenhouse, covered under special polythene
To protect me from heavy rainfall and harsh sun beams.
My soil is prepared from farmyard manure
And I am raised on a bed to make me secure.
Gravel sand at my roots to provide better drainage,
With a lush, porous soil to provide air without shortage.
Grown for six weeks I remain disease free
Avoiding desiccation through 80% humidity!
Irrigated with acidic low-saline water,
To pitch-perfect pH and just the right moisture.
Fertilized daily for the first 13 weeks,
I dine on micronutrients until I reach my peak.
As I blossom and spread I am cut by machine
Then packaged and sprayed with protective citrine.
I have travelled by air to lie here in your store—
Nature and science combine in my core."
"No, choose me" said the red rose of Kenya.
"I was born and matured under natural sun-rays,"
I felt the four winds' caresses throughout my days.
African workers earned money from me—
The fourth biggest export from Kenya's economy!
My only regret is flying four thousand miles
And the crystals and vapour I left in my trails.
Despite my long journey I am still young and fresh
As I kiss British nostrils with my vibrant scent.
Who needs glass-houses or strange sediment?
To traditional farming I pay testament.
Side by side the roses wait
For the customer to decide their fate.
Pondering, she picks the Kenyan rose
To delight her conscience as well as her nose.

**Fig. 11.16** Genetic variation in a Chrysanthemum breeding programme. (Photo credit: Jaap van Tuyl)

## Genetic Variation

The variation of ornamentals across the world is enormous. Thousands of species are used as ornamentation, as they occur in nature and as complex hybrid where the variation is enlarged by application of breeding techniques. In the case of some ornamental species like rose, chrysanthemum, tulip, lily, narcissus, tens of thousands of cultivars have been bred. The history of breeding of ornamental plants goes back many centuries, but only a few crops have been well documented (Kingsbury 2009). For tulip, hyacinth and narcissus it has been described for 300–400 years (Doorenbos 1954). For rose and chrysanthemum (Fig. 11.16) it can be traced back to around 200 years (Zlesak 2006; Anderson 2006a, b). This is in contrast to the lily with a relative short breeding history of less than 100 years (Van Tuyl and Arens 2011). During domestication of the cultivated ornamental plant both inter-specific hybridization and polyploidization played an important role. All available genetic variation was used and through recombination, mutation and selection the variation pool has been enlarged continuously. More recently modern breeding techniques and tools like induced mutation induction, embryo rescue, artificial chromosome doubling, haploidization, genetic modification, molecular assisted breeding and genetic mapping are applied in ornamental breeding as well. Nowadays The Netherlands is leading in professional ornamental breeding (Van Tuyl 2012).

## Conclusions

Flowers form an integral part of human life. Flowers are beautiful, have important symbolic significance, therapeutic and emotional value. Historically flowers are used globally in traditions and celebrations in human life.

Current commercial production and marketing of floricultural crops follows a complicated, ever-changing horticultural distribution supply chain.

There is increased interest in certification programs in order to grow ornamentals environmental friendly.

Innovation of the flower assortment is a continuous process. At national and international exhibitions developments are presented.

Ornamentals are grown worldwide. The Netherlands plays a central role in the trade, production and breeding of ornamentals. The large scale production (of roses) takes place more and more in the countries with an optimal climate (Kenya, Ethiopia) followed by transportation to the auction of Aalsmeer.

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# Chapter 12
# New Ornamental Plants for Horticulture

**Kevin Seaton, Andreas Bettin and Heiner Grüneberg**

**Abstract** Introduction of new plants is critical to the survival and profitability of the horticultural industries. These provide a marketing edge and can offer real benefits in terms of utilisation to fill special needs, such as providing screening a residential area from traffic noise, using living walls of plants, or providing an area to remove nutrient run-off from suburbia and prevent nitrification of sensitive wetlands. This chapter discusses the diversity of plants in the world's biomes from tropical, cool and warm temperate forests to deserts and alpine tundra environments. It covers a wide diversity of new plant material that includes the magnolia (*Magnolia* spp.), the Christmas poinsettia (*Euphorbia pulcherrima*), the conifers (pines, firs and cedars), the holly (*Ilex* spp.) to the diverse and unusual Australian and African xerophytic wildflowers such as the banksias (*Banksia* spp.), and kangaroo paws (*Anigozanthos* and *Macropidia* spp.). There has been a world history of discovery and selecting plants from known plant hot spots. This search started in earnest from the 1500s and continues to the present day with collectors looking to find new forms and colours and to introduce new qualities into established plants. It also introduces the developments in breeding new cultivars from existing genomes, including straight crossing to cellular techniques. Introducing a new plant is a complex process involving a number of steps from establishing a market, meeting production requirements to ensuring that the new plant survives and flourishes, often in a different environment to its native habitat and can involve use of greenhouse and chemical treatments. Considerable research has been expended on tailoring production management systems best suited to a particular plant given the diverse range of plant responses possible. This involves the development of propagation techniques such as tissue culture where cutting propagation fails, and the

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development of correct irrigationand nutrient scheduling to maximise production and manage growth stages. It also involves ensuring the plant achieves the level of performance expected in terms of vase life or yield and maintaining the right form and colour. These requirements are particularly critical where trade and transport is involved. An area often difficult to get right is to ensure that the new plant is actively protected, ensuring that the investment is properly rewarded and provides value to ensure continuation of further plant development.

**Keywords** Biomes · Production schedules · Marketing · Novelty · Diversity · New cultivars · Bedding plants · Cut flowers · Plant introduction · Intellectual property

## Introduction

Demand for nursery plants as container, amenity and cultivated crops has encouraged an increase in world trade in floriculture estimated to be worth between US$ 11 and US$ 60 billion in 2003 (van Uffelen et al. 2005). World floriculture trade in 2009 and 2010 was worth over US$ 24 billion (APIH/Union Fleurs 2011), with over half occurring in the Netherlands, USA and China followed by Japan, Germany and Italy (Fig. 12.1). Thailand, Malaysia, Singapore and India are becoming increasingly important export suppliers of floricultural crops (Hadiwigeno 1995).

As cities and towns become more crowded with high density living there is an increasing consciousness to utilise the free space of parks and buildings to improve their aesthetic value. This space can be inside or on top of buildings (such as roof gardens) or in the green open space found in cities and towns. Ornamental plant use can vary from potted plants in the home, to amenity plants along verges in parks and public recreation areas, plants in conservatories, on the roofs of buildings, formalised vertical garden walls on buildings, to field-grown flowers that provide cut flowers and foliage for use in displays in conventions and hotel foyers and vases in homes and hospitals.

Introducing the right new plant is complex, given the diverse range of plant species available and the wide range of selection characters that can be utilised. These include greenery plants with different coloured foliage, compact plants with natural dwarf characters as potted or border plants, e.g. box (*Buxus* sp. and other hedging plants), to plants with large showy flowers e.g. the red hibiscus (*Hibiscus rosa-sinensis*) and the hybrid tea rose (*Rosaceae*). Plants can also be grown *en masse* producing a magnificent display such as everlasting flowers (*Asteraceae—Helichrysum, A. lawrencella* and *A. rhodanthea*). Other opportunities are planting out contrasting beds using a range of kangaroo paws (*Anigozanthos* spp.) with stems varying in height from 0.5 to 1 m in height i.e. 'Bush Ranger' to stems to 2.5 m high of either red or yellow kangaroo paws. There is also available the striking black kangaroo paw (*Macropidia fuliginosa*). Other plants suitable for hanging baskets and floral walls, include climbing plants such as ivy (*Hedera helix*) or tall architectural

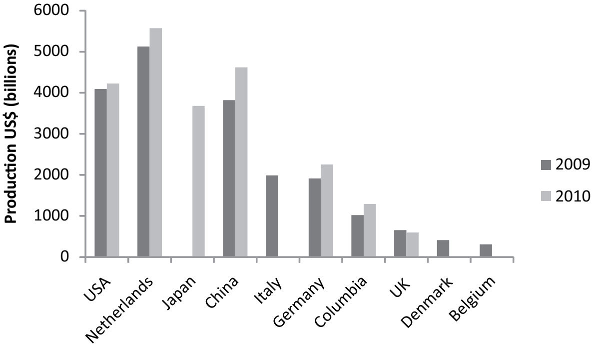


**Fig. 12.1** Value of production of flowers and pot plants in selected countries using an exchange rate of US$ 1.357 to EUR (Source: Adapted from Association Internationale des Producteurs l'Horticulture AIPH/Union Fleurs 2011)

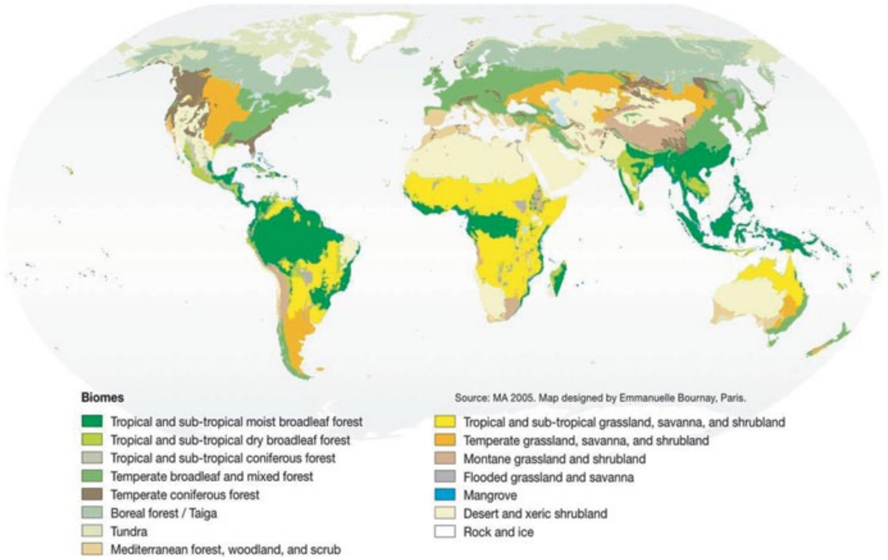
plants that command attention in the garden such as oaks (*Quercus* spp), various eucalyptus trees (*Eucalyptus* spp.) and the red flowering gum (*Corymbia ficifolia*), cone-shaped conifers and pines and the large flowered *Magnolia grandifolia*. There are also plants that provide a changing vista such as the Japanese maples (*Acer* spp.) with leaves that turn lime green, yellow to golden colours in the fall. Still other plants provide sharp distinct foliage such as the dragon plant (*Dracaena draco*)) or the variegated the canna (*Canna* x *generalis* hybrids) with large coloured flowers (Burke 2002).

One area that needs to be continually well managed to ensure that there is continuous funding for investment in breeding and developing new plant material is the protection of intellectual property rights (Dixon and Ogier 2007). This is a means of ensuring the science and effort by the breeder is rewarded although this can be difficult because intellectual property can easily be eroded. The establishment of international agreements, such as The International Union for the Protection of New Varieties of Plants (UPOV) and the development of intellectual property rights such as Plant Breeding Rights and Patents, are ways of ensuring this protection.

## Plant Diversity

To fulfil the market need there has been increasing effort to secure new types and cultivars of plants. This has involved selecting new species from wild populations as well as breeding programs to improve existing cultivars and develop new ones. The world flora numbers some 282,000 species (Chapman 2009), and can be divided into a number of floral taxa or geographical areas each with a number of biomes or dominant forms of vegetation (biographical regions depending on climatic factors) that include tropical rain forest, sub-tropical forest, warm and cool temperate forest, desert, and tundra (Reich et al. 1997) (Fig. 12.2).

These can be broadly grouped into six biomes based on Fig. 12.2.



Source: MA 2005. Map designed by Emmanuelle Bournay, Paris.

**Fig. 12.2** The main biomes of the world. (Source: United Nations Environmental Program (GRID-Arendal UNEP), http://www.grida.no/graphicslib/detail/the-main-biomes-of-the-world_f8c1 Vital Forest Graphics, 2009. Rekacewicz et al. 2009)

- *Tropical rain forest*-in middle America and Gulf of Mexico, Venezuela, West Africa, South East Asia, far northern Australia. Ferns with high rainfall (2,000 mm) requirements throughout the year include Amazon basin of South America, the Congo basin of central Africa, Indonesia, and New Guinea.
- *Subtropical moist deciduous forest*-with less than 2,000 mm of rainfall in South America, in Central America and around the Caribbean, in coastal West Africa, parts of the Indian subcontinent, and across much of Indochina.
- *Cool temperate forest*coniferous trees (pines, firs and cedars) or mostly deciduous broad (thin) leaved evergreens that shed leaves in winter or examples of olive, holly, tea and eucalyptus) which have thick leaves resistant to water loss with rainfall over 1,400 mm in North Europe South America, South Africa, Europe, Asia (Iran, Taiwan, Japan) and Australia (Victoria and Tasmania).
- *Warm temperate forest*-Mediterranean woodlands and scrubland, a climate characterised by wet winters and dry summers, trees that have some xerophytic characters but where winters are not severe and plants are evergreen. These occur in the Mediterranean basin, Chilean Matorral, Californian chaparral, Cape Province, Southwest Australia with a high diversity of plant species dominated by broadleaf trees (oak woodland) and evergreen sclerophyll forests and shrubland including fynbos in South Africa and kwongan in Southwest Australia.
- *Deserts*-in New Mexico, Sahara (North Africa), Gobi (Mongolia and China), Kalahari (Angola), Patagonian (Argentina and Chile), Great Victoria, Great

Sandy and Simpson (Australia) and Great Basin and Colorado (United States) typically grow cacti and having < 250 mm of rainfall annually.
- *Alpine tundra*-subalpine forest occur near the north pole with winter 34°C and summers 3-12°C being warm enough in the alpine tundra for plant growth such as stunted plants like sedges, mosses and grasses when the surface layer of permafrost melts, rainfall and snow 150 to 250 mm.

There are also mountainous zones such as the Andes and Himalayas and grasslands steppes in Eurasia and across Russia, prairies of north America, pampas in south America and savanna grasslands in northern Australia, and the veldt in South Africa that complete the world bioms.

The diversity of habitats for plant growth is highest in the equatorial zones in tropical rainforests (Schmitt et al. 2010) and lowest in higher latitudes of the arctic zones with most ornamental plants selected from tropical rainforest or cool temperate zones. For instance, pines (*Pinus* spp.)*,* firs (*Abies* spp.) and spruces (*Picea* spp.) are selected from Europe and North America with the United States selling 25 million trees over the Christmas season and predicted to be sold for around US$ 800 million in 2011 (Euteneuer and Campbell 2011). These plants are well suited to a cool temperate climate and are able to withstand cold winters. Also the tropical poinsettia (*Euphorbia pulcherrima*) from Mexico and the South American rainforest are extremely important potted plants, sold in Europe over the Christmas season and as a garden plant in warm temperate regions.

Some notable examples of families of ornamentals that have been domesticated and grown around the world are:

- China and SE Asia, Costa Rica, Guatemala, Mexico, Panama, Peru and Ecuador feature hydrangeas (*Hydrangea* spp.); a popular ornamental plant with over 1,000 cultivars from 220 species originating mainly from Asia (China, Taiwan, Japan, the Himalayas, and Indonesia).
- China, Colombia, Latin America and the Caribbean prefer the magnolia (*Magnolia* spp.) with 245 species of which 48 % are in cultivation (Botanical Gardens Conservation International 2008). The cultivation of the magnolia appears to be adapted to a narrow temperature range growing best below 18 ºC with growth decreasing at higher temperatures (van Iersel and Lindstrom 1999).
- Himalayas and SE Asia are largely responsible for the Rhododendron (*Rhododendron* spp.) with 1,157 species (Botanical Gardens Conservation International (2007) that range from creeping plants to tall trees. The main centres of diversity originate in the mountain ecosystems of North America, Himalaya, Myanmar, Southern China and Europe, growing mainly on acidic soils in regions of high rainfall, high humidity and a temperate climate. Some 25 % of species are under threat (Gibbs et al. 2011) including the scented tender Vireya type rhododendrons.
- USA with the honeysuckle (*Lonicera* spp.) from southern United States and Mexico and the Chilean butterfly bush (Buddleia americana) from south eastern United States to Chile.

- South American poinsettias largely originate from Mexico and South American tropical forests and feature a range of coloured bracts (Barrett et al. 2009).
- Australian wildflowers include Geraldton waxflower (*Chamelaucium uncinatum*), Hooker's banksia (*Banksia hookeriana*), the red kangaroo paw (*Anigozanthos rufus*), Qualup bell (*Pimelea physodes*), scaevolas (*Scaevola aemula*), leschenaultia (*Lechenaultia biloba*) and the Cootamundra wattle (*Acacia baileyana*) (Horlock et al. 2000; Seaton 2005; Anon 2013a).
- South African flora include the proteas (*Proteaceae*), the restios (*Restionaceae*), cape grasses and reeds, and lachenalia (*Lachenalia* spp.).
- New Zealand species include the foxglove (*Hebe* spp.) and the New Zealand teatree (*Leptospermum scoparium*).
- Western and southern Europe, northwest Africa, and southwest Asia includes the European holly (Ilex aquifolium) which is drought and frost tolerant down to −15 °C.

In developing new plants for use by people for different places, opportunities exist to select from a diverse range of new plants from warm temperate and arid regions in Australia and South Africa when compared to well used tropical and sub-tropical ornamentals. Plants from these areas have evolved by adapting to a range of different and often harsh habitats of temperature, humidity, salinity, soil water limitations and space. In doing so they have produced some unusual plant forms, flower shapes and colours such as the Australian Qualup bell (*Pimelea physodes*) with has enlarged burgundy coloured bracts (Fig. 12.3), the smoke bush (*Conospermum* spp.) with smoky grey racemes, Oleria (*Helichrysum* spp.) with grey green soft foliage tolerant of coastal environments, the paper daisy (*Helichrysum bracteatum*) with large golden daisy flowers, *Atriplex* saltbush with glaucous spongy jagged leaves, the desert eremophila (*Eremophila glabra*) which is covered in white dense hairs and the diverse range of eucalyptus species with interesting fruit such as the mottlecah (*Eucalyptus macrocarpa*) with large showy red flowers and large white leathery leaves, the large red compound bracts of the waratah (*Telopea speciosissima*) and the small tough leathery leaves of the drought and frost tolerant rice flower (*Ozothamnus diosmifolius*). Also of interest are the large red flowers of the South African proteas (*Proteacea* family) with highly developed colourful bracts such as the King protea (*Protea cynaroides*).

In terms of the value of ornamental plant species to the consumer, their suitability and selection depends on their marketability and ability to adapt to different climates and habitats as well as conditions imposed by the man-made city environment. By careful plant selection and manipulation of the soil media and environmental conditions in the glasshouse it has been possible to grow an increasing number of plant species in locations distant to their origin where they perform well as ornamental plants. This has allowed the transference of germplasm globally to regions where these plants would not normally survive and give people the opportunity of enjoying the rich diversity of another country's native plants in their everyday lives.

**Fig. 12.3** Western Australian Qualup bells (*Pimelea physodes*) flowering stems. (Photo courtesy of K. Seaton, Department of Agriculture and Food, Western Australia)

## Ways to Source Variation in Plants

Plant hunting has been pursued from Europe, North America, Australasia, and Asia since the fifteenth century sourcing new plant forms for ornamentals, agriculture, horticulture and medicinal purposes. This has led to the collection of new plants in botanic gardens around the world particularly throughout Europe. Plant hunting has also provided new products that compliment diets, such the introduction of tea (*Camellia sinensis*) sourced from Asia, the Himalayas, Japan and Indonesia. Some notable early plant collectors were Hans Sloane (1660–1753) from the West Indies; James Cunningham (died 1709) to China; Georg Eberhard Rumpf (Rumphius) (1627–1702) the Moluccas; Sir Joseph Banks (1743–1820) Newfoundland, Labrador, South America, Tahiti, New Zealand, Australia, the Malay Archipelago, Hebrides, and Iceland; Francis Masson (1741–1805) and Carl Per Thunberg (1743–1828) to South Africa; David Douglas (1799–1843) to North America and Alexander von Humboldt (1769–1859) to Spanish America (Janick 2007; Fry 2009). The early botanic gardens were established to propagate and display a wide array of exotic plant material such as the Royal Botanic Garden, Kew in London where 7 million herbarium specimens included the collections of Charles Darwin (1809–1882), Joseph Hooker (1814–1879), David Livingstone (1813–1873), Ernest Wilson (1876–1930) and Joseph Berkeley (1803–1889), (Kew 2012). The Berlin Botanic Garden at Dahlem is another world class botanic garden with 22,000 living plants in cultivation (Anon 2010). An example of a special plant collecting expedition included those of Sir Joseph Banks (1743–1820), who accompanied James Cook (1728–1779) from 1668 to 1771 to the southern ocean, in HM Bark *Endeavour* which included Rio de Janeiro, in Brazil, Tahiti, New Zealand, and Australia where he collected many new plant specimens and gave them to Kew Gardens on his return from the expeditions (Gilbert 1966; Kew 2012).

Sourcing new forms of plants for commercialisation can be achieved either from plant selection from natural populations or by direct breeding.

*Surveying natural populations* In the first instance sourcing variation involves surveying natural populations to find different and unusual plants that are of interest to the ardent collector, botanist and nursery person for commercialisation. A rich diversity of plant species occurs around the world for instance. The Australian floral kingdoms contain 19,324 species that include flowering plants (18,706), fern and allies (498) and gymnosperms (120) (Chapman 2009) Significant designated biosphere reserves around the world now contain much of this diversity. Such plant material can be found in the south west of Western Australia, the tropical rainforests of North Queensland, South Africa's fynbos, the tropical rainforests of the Amazon basin in South America, and in California, USA. For example The Fitzgerald River National and Park Biosphere Reserve (Moore et al. 2001), on the south coast of Western Australia covers 329,039 ha and comprises only 0.2 % of Western Australia's land surface, but contains over 20 % of that State's plant species. This includes nearly 1,800 species of flowering plants, and some 75 plant species and offers a rich diversity of plants such as *Banksia* spp., bottlebrush (*Callistemon* spp.), feather flowers (*Verticordia* spp.), and the unique Qualup bell (*Pimelea physodes*). Similarly a rich diversity of plants exists in the Cape Biosphere Reserve north of Cape Town in South Africa and includes the fynbos. This park is 378,240 ha in size and includes ca. 8,900 flowering plant species, some 6,000 being endemic to the region. It includes a number of plants that have developed under harsh conditions such as Sea Guarrie (*Euclea racemosa*), Cape Hyacinths (*Lachenaliai bulbifera*), *Aspalathus callosa* and the Cape reed (*Restionaceae*). Cape heaths include the white to mauve *Erica caffra*, the red to pink *E. mammosa* and the red *E. coccinea*, as well as *Proteas, Leucospermums* and *Serrurias* such as *P. repens*, *P. cynaroides, Leucospermum conocarpodendron* and *Serrurias trilopha* that offer exciting possibilities for selection and domestication (Goldblatt and Manning 2000; UNESCO 2005).

Surveying natural populations involves a number of steps including locating populations, surveying the extent of variation, the collection and propagation of material, and evaluating the plants' performance in a cultivated environment. Locating populations can be done through existing databases that provide historical records of where specimens have been collected and preserved as herbarium voucher specimens. In Western Australia these records and some specimens date back over 100 years. Not always but often, these records have been updated by more recent surveys or from information from collectors or bush pickers. The next task is to select from these records a location for a species, obtaining appropriate licences and visit sites. This can be a frustrating process as often for such old sites the original flora have long since disappeared through settlement, disturbance or herbivore and weed infestation. Frequent visits are often necessary as different flora may dominate in different seasons. It is usually best to visit the site during the predicted flowering season for a particular flower. There is also the question of phases of dominance

**Fig. 12.4** *Impatiens walleriana* hybrids ready for sale. (Photo courtesy of A. Bettin)

as one type of flower may dominate for a period to the exclusion of other flowers. Under temperate Australian conditions it may take a major event such as a bushfire to clean out competing vegetation and stimulate the germination of the plants being sought. For example, in Western Australia approximately half of the *Banksia* species in the family *Proteaceae* are killed by fire (Collins et al. 2009). Seed germination and seed dispersal are also stimulated by fire, while other species regenerate quickly re-sprout from ligno tubers (i.e. new growth from old surviving buds) and dominating recruitment.

*Direct breeding* The second source of domestication is the direct breeding of new plants using existing genetic diversity. This has been highly successful for a number of plants especially producing new roses. De Vries and Dubois (1997) show that the rose is the highest sold cut flower in the Netherlands with 499 ha being grown under glass and in the open in 2010 (APIH/Union Fleurs 2011), with chrysanthemums (*Chrysanthemum* spp*.)* and lillies *(Lilium* spp.) and gerberas in order of popularity. In the US pot plant industry the most produced indoor plants are orchids (13.3 million pots), poinsettias (7.6 million pots) and floral roses (5.6 million pots) and for annual bedding and garden plants, the *Impatiens* and New *Impatiens*–New Guinea hybrids (Fig. 12.4), as well as pansies and violas, petunias, begonias and marigolds were most popular (APIH/Union Fleurs 2011). Other flowers such as the camellia (*Camellia sasanqua*), carnations (*Dianthus* spp.), gerbera, hydrangea (*Hydrangea macrophylla*) and rhododendron (*Rhododendron* spp.) are also popular and have undergone considerable breeding to produce new

**Fig. 12.5** Fields of cultivated Geraldton wax (*Chamelaucium uncinatum*) flowers in Western Australia. (Photo courtesy of K. Seaton, Department of Agriculture and Food, Western Australia)

cultivars. The *Impatiens*-New Guinea hybrids have become a very popular summer bedding plant similar to petunias (von Hentig 1995), and in general new cultivars of *Impatiens* have been more popular with 9 million pots sold in the US in 2010 (APIH/Union Fleurs 2011).

There have also been successes in hybridising Geraldton wax (*Chamelaucium* spp.) (Growns et al. 2000; Shan and Seaton 2009), teatree (*Leptospermum* spp.) and kangaroo paw (*Anigozanthos* spp.) from Australian wildflower collections. Some of these plants, such as Geraldton wax hybrids, are now being grown commercially as cut flowers in California, Israel and Peru as well as Australia (Fig. 12.5).

Breeding can involve simple crosses to more complex processes such as early embryo rescue and tissue culture to overcome dormancy restraints to germination. Breeding can also involve direct intervention to overcome pollen-ovary incompatibility when parents from wide species are to be hybridised. Somatic hybridisation techniques are being applied to *Chamelaucium* breeding to produce wide hybrids (Ratanasanobon and Seaton 2010). The breeder has the advantage of some control by selecting particular parents to determine the outcome of the progeny, although with native flora the outcome of crosses is not as predictable as rose breeding which has a considerably longer history.

## Keys to Successful New Plant Introduction

Opportunities to develop new ornamental plants are immense with the vast and diverse range of the world's botanical heritage. Selecting and introducing the right plant for a particular situation is more complex. To be successful there are a number of requirements for new plant introductions (Table 12.1).

*Marketability* The first step is to determine the market needs of a new plant and how best to meet these needs. This information can be obtained from discussions with nurseries and the breeders to seek out sales statistics that with determine where and what is likely to sell. Questions are asked on popularity and why is it popular? Past

**Table 12.1** Requirements for successful introduction of high productivity new crops. (Source: K. Seaton unpublished)

| Development area | Requirements and considerations |
|---|---|
| Marketability | Offering new and exciting plant characteristics |
| | Filling a unique niche |
| | Promoting special features of new plants |
| | Maintaining sales and plant introduction schemes |
| Customer requirements | Need for novelty |
| | Continuity of supply |
| | Consistent performance |
| Production requirements | Ability to flower profusely if a flowering plant and the environmental conditions, and possible chemical treatments, are required to ensure they flower |
| | Suitability of form or is there a need to manipulate this by pruning or chemical manipulation to produce a suitable form |
| | Special water and nutritional requirements and agronomic intolerances |
| | Ease of propagation or are special techniques needed |
| | Resistance to pest and disease in the new environment |
| | Ability to withstand extremes of temperatures and weather when plants grown outdoors or indoors |
| | Restrained by short production time, especially if grown in heated greenhouses |
| | Type of specialisation—is the nursery specialised on the complete production of a few plants or specialised in certain steps of the propagation.(e.g. does a plant fit within a production program of the supplier |
| | Meeting environmental constraints to production in terms of poor soil texture, high nutrient loads and adverse pH, as well as temperature and water extremes. Especially in urban environments with associated pollution |
| Plant introduction schemes | Develop schemes to successfully introduce plants |
| | Evaluate the effectiveness of the introduction |
| | Possibilities of automated production (e.g. plant climbers need a lot of manual work, automated spacing difficult, uniform plant production necessary, low genetic variability) |
| | Royalties and the ability to protect the breeder of new plants, collection of royalties (this provides the supplier with an advantage that make the plant commercially viable to provide an advantage compared with competitors) |
| Trade requirements | Ensuring that during export cut flowers or pot plants maintain vase life and that dormant plants are primed to be flower evenly on arrival at their destination |
| | Ensuring plants are easily transported and maintain their quality on arrival at their destination through packaging and environmental conditions in containers |
| | Selecting plant shape to minimise freight costs and met the need for minimum dense packaging as required in Europe and Asia |

success in an area can be used as a guide, but may not always provide the answer. The market niche needs to be carefully defined to determine where a particular plant can be successfully marketed. It requires determining the distinguishing feature of a plant, the end user requirements and where the plant will have the biggest impact on the market. For an established ornamental plant such as hydrangea or poinsettia, which has already a large established market, plant breeding is used to produce the new features such as inflorescence shape or petal colour shades while maintaining all the desirable features such as pot plant compactness, bract shape, and profuse flowering.

The end use of the plant, and in particular its functionality, is critical to its marketability. It may be best used as a bedding plant, pot plant, border or hedge row, or as a mass planting or as a feature plant or background greenery. In deciding on this use, account needs to be taken of the plants cultural and management requirements. Some plants are easy to manage while others may require more detailed management which may limit their use. For example some robust plants are best suited to hedge-rows or green-cover or use as focal point plants. These are generally hardy deciduous plants that once produced, will survive in the outdoors. For example the deciduous Japanese barberry or Thunberg's barberry (*Berberis thunbergia*) is a hedge-row plant tolerant of pollutants with over 30 cultivars available; including a reddish-purple leaves "Harlequin" and yellow "Aurea" forms (2012b, c, d) which have been successfully introduced into Europe as hedge row plants, green-cover or focal point plants. Originating in Japan and being deciduous, the Japanese barberry are much easier to manage than many other evergreen plants which can't survive outside the severe frost conditions of winter in temperate northern Europe. This illustrates that the horticulturist needs to be aware of the climatic conditions from where the plants come from and the need to modify that climate before they are introduced. Another example are the Australian native plants from the dry Mediterranean climatic region of Western Australia such as the Geraldton waxflower (*Chamelaucium* spp.) and banksia species such as *Banksia menziesii* and *B. prionotes*. Geraldton wax are hardy plants that have low water requirement, provide a long flowering period of 50 to 60 days and provide vibrant colours in late winter to late spring. In addition this plant has a level of frost and drought tolerance and is able to survive during hot dry summers (20 to 30°C) with minimal maintenance. Hence this species are suitable for dry climates of moderate temperatures but will not tolerate severe frost having evolved under a dry Mediterranean climate of cool wet winters and hot/dry summers. The Geraldton waxflowers are sold as cut flowers and exported to Europe, USA, Canada and Japan, and are becoming popular as amenity or garden plants in California, thriving as garden plants in San Diego (Fitzsimmons 2001; Wigand 2007; Walker 2010) such as the cultivar 'Matilda' (San Marcos Growers 2011; Ball 2013) and as border amenity plants in golf courses in California surviving through the dry summers.

In Australia, overseas and elsewhere, successful nursery businesses, *Plant introduction schemes* have been employed, which have been developed to maintain interest and continuity of product. This enables expansion of the market by continuous introducing new variants of a particular type of plant based around a specific theme i.e. hardy plants from Australia, or in the US where of the highly successful

**Fig. 12.6** Potted poinsettia with cream and red flowered bracts. (Photo courtesy of K. Seaton, Department of Agriculture and Food, Western Australia)

poinsettia (*Euphorbia pulcherrima*) pot plant offers new colour forms (Fig. 12.6) (Ecke et al. 2004).

In 1985 the United Kingdom introduced HAPIE or the Hardy Amenity Plant Introduction and Evaluation scheme. This was based on the realisation that there were a large number of plants in existing botanic gardens that were unused or not realised by the nursery and garden industry. Through agreement between nurserymen, scientists and the Royal Botanic Garden, Edinburgh, the HAPIE Plants were developed to trial and develop methods to propagate, grow and evaluate these plants to introduce the most suitable of these plants into the nursery and garden trade (Dixon 1989). The Canadian scheme: University of British Columbia Plant introduction Scheme of the Botanical Garden (PISGB) was run by the late Bruce MacDonald at Vancouver Botanical Gardens and was very successful at bringing new plants to the garden, trialling, propagating and distributing them to local nurseries. These were sourced from plant enthusiasts and working with overseas collections and collectors. These plants included *Arctostaphylos uva-ursi* 'Vancouver Jade' and *Genista pilosa* 'Vancouver Gold' collected from Vancouver Island by E.H. Lohbrunner, and *Penstemon fruticosus* 'Purple Haze', a wild collection by Al Rose from British Columbia. New forms of orange flowered honey suckle (*Lonicera* spp.) 'Mandarin' hybridised by Wilf Nicholls, the *Clematis chiisanensis* 'Lemon Bells' from Korean seed 'Blue Ravine' were tested and promoted (Justice 2002).

*Customer requirements* One of the most difficult questions is working out what the customer wants in purchasing ornamental plants. This can often be gauged by introducing new plants to trade fairs and demonstrating the range and uses of a plant. Working groups are an effective way of achieving a consensus of new plants to introduce into the market. In 1981 Germany involved the cooperation of a large group of people including growers, botanical garden personnel, researchers and others concerned with plant development in the establishment of their working group (WG) New Ornamental Plants in seeking consensus of new plant material (von Hentig 1995). These working groups now exist in most of the developed world, where the exchange of information occurs on the performance of a large number of plants tested from numerous overseas collections. The participants regularly met to decide the best candidates to promote and work with in the following year. Working groups also support research institutions to conduct programmes to determine production and biological studies into ornamental plants. In Australia funding has been provided by the Federal Government by the Rural Industries Research and Development Corporation (RIRDC). This has supported many research projects in the development of Australian wildflowers. One project has been the Best Bet Program in which exporters collectively list crops of high demand that are undersupplied (Slater and Carson 2003).

However, to answer the question "does the plant have exciting and unique plant characters?" means often that plants must be sought from the more exotic climates. This has been used as a way of sourcing something new. This however can pose a number of challenges; namely, will these features of the plant, appeal to people in another city or country, and if they do will the introduced plant successfully fit into a new environment and be able to flourish under different climatic constraints.

New characters have been a driving force for many plant introductions. These include the new colours and forms of *Brachyscome multifida, Helichrysum bracteatum,* and *Lobelia erinus* from South Africa and *Scaevola* (*aemula*) originating from Australia, as well as *Impatiens*–New Guinea hybrids (von Hentig et al. 1995). Many members of the hydrangea family, such as *Hydrangea paniculata, H. macropylla, H. quercifolia and H. serrata* came originally come from tropical regions. Other examples include *Helichrysum bracteatum* which provides striking tall stems with large golden coloured compound flowers and *Scaevola saligna* which provides striking blue flowers. The particularly showy display of lobelia can be attractive as it cascades over pots and hanging baskets and can make a striking bedding plant. Introducing a new ornamental requires detailed work by the horticulturist to explore all the forms and shades of the plant to maximise the flower's impact such as the different shades of colour which may have an impact on the market. This is best illustrated with the introduction of the hydrangea into Europe. These flowers have been successfully marketed for a long time and part of the reason is the wide flower choice available and the continuing development of new cultivars. In 2012 European different nurseries listed 18 to 32 cultivars for sale that included colours ranging from red, white, pink, pink/white and blue (Vandeputte 2012; Wiley De Nolf 2012).

In recent years new ornamentals were successfully introduced into Europe because of the following reasons:

*Novelty* In the late 1980s *Centradenia* (*Heterocentron*) *inaequilateralis* 'Cascade' was introduced as a bedding plant to Central Europe. It is a day-neutral plant which needs temperatures of 12 to 15 °C to induce prolific flowering (Friis and Christensen 1989). Because temperatures are well above this range in summer (i.e. 21 °C) the plants remain largely vegetative, losing potential market appeal during this season. These impact on sales and customers replace the plant for others, and then sales have to be reignited in the following summer. To achieve ornamental value of the plant throughout the whole season, selection and careful management should be provided for healthy vegetative growth over summer and sustainable flowering over winter. Similarly in the late 1990s a *Plectranthus* form was introduced and advertised to have a repellent effect against cats and dogs. It is still offered, but sales numbers dropped as internet platforms pointed out that the repellent effect is not as clear as promised. However, these example show clearly that customers buy plants not only for ornamental value but also for other novelty purposes such as being a repellent.

*Production requirements* To meet production requirements and to introduce a plant successfully requires an understanding of plant growth and development that includes methods to control growth, flowering and form manipulation so as to suit the market. For example, in the US, rose production is geared around Valentine's Day. These techniques are gained through a combination of experience and scientific endeavour. It also requires practical knowledge of the growing requirements, soil or potting media, temperature, light and shade regulation.

*Ability to flower* This depends on the environmental factors driving the phenological (vegetative/flowering) phases. Plants varying in their photoperiodic requirements regulate their flowering response to day length. This process is complex and can involve sensitivity to infra-red signalling (Weller et al. 1997). In addition plants may have specific temperature requirements which determine the rate at which flowering occurs. Flowering can also be promoted by application of hormones and fertilisers. This will allow early flowering to be synchronised to produce flowers ready for a special calendar day, such as Mother's day. Plants are either short-day (less than 12 hours), day-neutral or long-day (14 to 16 hours). For example, flowering in Qualup bell (*Pimelea physodes*) under short-day conditions (10 hour day length) can be promoted by a cool pulse for 2 weeks at 10/15°C followed by warm temperatures (24/12°C) (Seaton and Plumber 2004). This technique can then be used also for *P. ferruginea.* Another example is the marigolds which are obligate short-day plants requiring day length shorter than a certain critical length to flower with some being facultative flowering faster with shorter days. Whereas the snapdragon, sunflower, salvia, and petunia are considered long-day annuals, other plants such as the zinnia are day-neutral with flowering not being affected by day length. There can be considerable variation in photoperiod response between cultivars and the grower needs to recognize the response of individual cultivars to match display and location requirements. For many bedding plants the use of black cloth may be necessary to initiate flowering. Other techniques available are to produce plants ready for planting by providing black cloth in the case of short-day plants supplementary high pressure sodium lights (HPS) if plant plugs are grown during winter in heated glasshouses during the last 2 weeks before transplanting (Cox 2009). Research has shown that there can be side effects of supplementary lighting such as extension growth which may need to be controlled to retain plant compact form.

*Plant form* Having the right shape of plant is critical to the range of uses plants can be put to in the landscape. Plant form such as height and bushiness can be manipulated by chemical application, pruning and pinching strategies. For example Geraldton wax, which is normally grown as a cut flower producing long stems, can be shortened and made more bushy with more flowers per plant by application of the growth inhibitor paclobutrazol (if permitted) while cytokinin 6-benzylaminopurine (if permitted) can reduce plant height but does not increase flower numbers (Seaton et al. 2007). Other approaches are to manipulate plant gibberellin biosynthesis genetically to control plant height (Bhattacharya et al. 2010).

**Fig. 12.7** Zamio (*Zamioculcas zamiifolia*) leaf cuttings being propagated (left) and at 32 weeks ready for sale (right). (Photo courtesy of A. Bettin)

*Propagation* Each plant presents a challenge. There are several methods available including seed, vegetative cuttings, and tissue culture. The most appropriate method needs to be selected for each species as in the case of the single species of Zamio (*Zamioculcas zamiifolia*) (Fig. 12.7). The Wollemi pine (*Wollemia nobilis*) has been a success producing many plants by tip cuttings and is sold as an ornamental plant around the world (Trueman and Peters 2006). The use of *in vitro* propagation techniques has rescued the endangered *Rhododendron maddenii* from the Himalayas (Kumar et al. 2004) and the use of vegetative techniques saved the threatened pencil cedar (*Juniperus procera*) (Negash 2002). The application of biotechnology that includes innovations in tissue culture micropropagation technology has the potential to preserve and produce a number of valuable plants for floriculture that include Christmas Bells (*Sandersonia aurantiaca*) (Finnie and van Staden 1989), the artificial seed encapsulation; transgenic technology for *Pinus patula* (Jones et al. 1993; Jones and van Staden 1995; Sparg et al. 2002; Malabadi and van Staden 2005) and Nigro et al. (2004) and agriculture as in the case of the rare South African plant *Lapeirousia silenoides* (Louw 1989; Moyo et al. 2011).

*Cultivation schedules* Successful introduction of a plant into an environment requires the development of an effective production schedule. This requires that the timing and type of treatments applied result in a successful display as a bedding or pot plant. The schedule must take account of the climate, soil medium, position or aspect the plants are grown in and any stress factors that may impinge on the plants' survival and display. Successful schedules have plants flowering or fruiting in time for the market.

*Water and nutritional requirements* The essential features of water requirements depend on the plant and the environment in which it grows. The need for water and nutrients can be greatly influenced by the media in which the plant is to be grown. The drainage, slope and clay or percentage organic content of the soil in which the plant is grown have a large bearing on the success of cultivating the new plant. On sandy plain soils in Western Australia that contain less than 5 % water-holding capacity, special irrigation and fertiliser management techniques have been developed for growing the wild waxflower (*Chamelaucium* spp.) in Australian plantations (Seaton and Poulish 2010). This has resulted in yield increases of 30 to 45 % (Seaton et al. 2007) and allowed large scale sustainable cut flower production. In some cases it may be necessary to introduce new soil media more suited

**Fig. 12.8** Roof garden containing a range of Sedum pp. (Photograph courtesy of A. Bettin)

to a particular plant. Reclaimed gardens set up on waste land pose a particular challenge and may require special amelioration to make them suitable for ornamental plants. Another special consideration is roof top gardens where soil depth is limited, or where containerised plants have been established in shopping malls. The presence of green space in cities has been found to make important contributions to the sustainable development of urban and peri-urban communities by improving the environment and contributing to conservation and helping to reduce global warming, remove pollutants and reducing dust and carbon dioxide, as well as reduce sound while reducing stress levels of city dwellers (Aldous 2007). The inclusion of ornamental vegetables, medicinal and aromatic plants have also been known to benefit city communities (Arslan and Yanmaz 2010). Development of roof top gardens (Fig. 12.8) requires special attention to be sustainable, choosing the right plants such as sedum (*Sedum* spp.) to tolerate the more severe conditions as well as species of *Zoysia matrella, Verbena* hybrids, *Thymus vulgaris* and *Targetes* sp. (Sendo et al. 2007). The sedum species have been known to survive on shallow substrates on roof top gardens in Germany (Monterusso et al. 2005).

*Environment* The environment plays a crucial part in the growing of ornamental plants, particularly the right temperature and light conditions suitable for flowering. For instance, to grow Geraldton wax in Europe would require careful manipulation of local temperatures to ensure that the plants flower. Alternatively, these plants could be grown in a warmer climate such as Portugal or Spain then transported to Northern Europe. Figs. 12.9a and b demonstrate the appropriate internal and external temperatures that initiate flower development of Geraldton wax. Production involves a 16 month life cycle to produce plants of sufficient size and flower cover.

*Special case environments* Many landscapes pose a challenging environment for growing plants. Within a city environment the thermal mass of buildings, roads and pavements introduces a heat load and with traffic the air can be higher in carbon dioxide carbon monoxide, sulphur dioxide and nitrous oxide levels as well as altered light levels. All these features can affect plant growth and development in confined areas. In these situations careful design of gardens is needed to cope with or maximise the benefits of these environments. There are many good examples of successfully domesticating plants for people in cities where plants can improve environments that pose a challenge from extreme heat from radiant heating or from

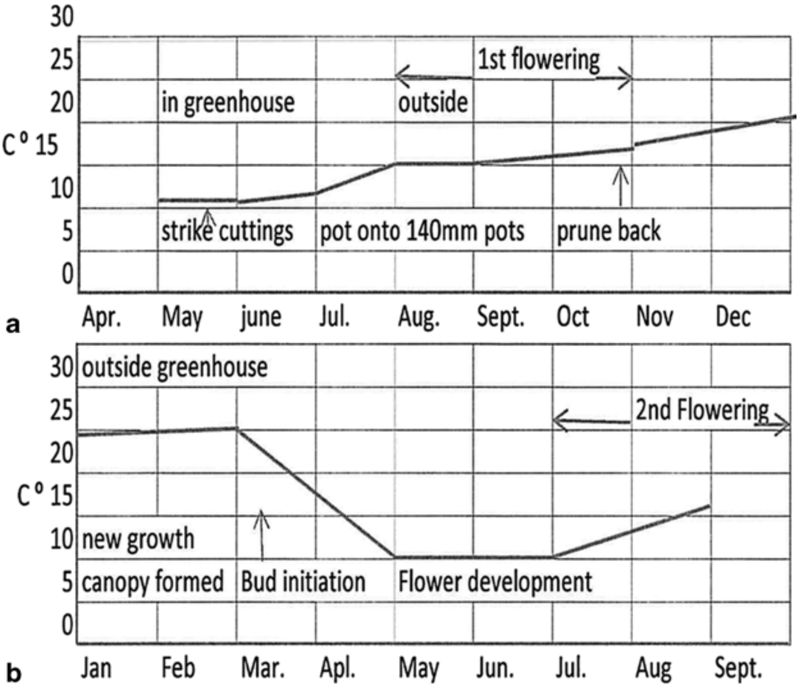


**Fig. 12.9** **a** and **b** Production schedule for producing Geraldton wax pot plants in the northern hemisphere. (Seaton unpublished data 2012)

the effects of wind Exposure to salt in seaside environments is another consideration where special plants find purpose. Plants can also be used to moderate climate in indoors, roof greening and green wall buffer environments.

*Trade requirements* It is critical that plant quality is maintained during transport to markets. This may require special packaging and post-harvest conditions, to ensure that the quality of plants is preserved. It is also essential that all trade/quarantine conditions are adhered to ensure the smooth flow of product to the market. Plants should be clearly labelled and have all necessary paperwork completed prior to transportation. It is also essential that freight costs are minimised to retain profits prior to and during transit.

## Plant Production Systems—Some Case Studies

*Bedding and pot plants* The major advantages of bedding plants are that they are transportable, capable of being grown in one place, easy to grow using natural light and space, and can be readily transported to the point of sale, such as a city market where they are not normally grown. Transport may involve rail or trucking across country or overseas sea transport unless not allowed due to the presence of soil (like potplants or beeddinplants) such as bring plants with soil into the EU from other countries. In many Asian countries, such as the Philippines, they grow and ship large quantities of orchids to Europe and Japan. Further the availability of cheap land and labour and resources in India have enabled this country them to be competitive in the production of orchids, *Anthurium* spp. and carnations (Dadlani 1995).

With all plant production processes a production schedule needs to worked out to be successful. The production schedule needs to fit into the current conditions of the production region especially if the plant is to be grown outside its home environment. The production schedule requires a detailed understanding of seasonal conditions and managing plants to work within those conditions. The same applies to Europe where one is adapting plants from warm temperate to tropical environments. Operational options available to meet these environmental restraints include growing plants in heated houses for part of their life cycle during winter then taken outdoors during summer. One example is the *poinsettia* (*Euphorbia pulcherrima*), a very popular Christmas flower with 7.6 million pots produced in the United States in 2010, 25.9 million in Germany in 2008 and 6 million in Sweden in 2010 (AIPH/Union Feurs 2011) and one nursery in the United Kingdom that produces 220,000 plants a year (Daily Mail 2011). Poinsettias are also much sought after in Europe because of their red bracts and green foliage with many colours and forms available on the market (Ecke et al. 2004; Barrett et al. 2009). To produce these tropical plants in cool temperate regions relies on a production schedule in a heated glasshouse timed to achieve full display over the Christmas season. To achieve this, softwood cuttings are taken in spring-summer. These cuttings will root in 10 to 14 days, under ideal conditions, after sticking into a propagation mix. Rooting can be more uniform with the addition of rooting hormones such as indole-3-butyric acid. Applying growth regulators such as paclobutrazol, chlormequat or ethephon can retard elongation and make for more compact plants (Ecke et al. 2004). Grow young plants in a warm (15–20 °C) humid environment. Pinching-back plant material may also be necessary to maintain a compact form and combined with short days will induce flowering. Plants should not be overwatered and need to be transferred out of the glasshouse over summer, then returned to the greenhouse until Christmas in the northern hemisphere or remain outside in the southern hemisphere until Christmas. High light tends to intensify the colour of the bracts.

Other operational successes have been with *Hydrangea paniculata, H. macropylla, H. quercifolia and H. serrata* which originated from the wet tropical regions of Costa Rica and Ecuador and need to be carefully managed within the cool temperate conditions of Europe, where the severe winters may decline down to −20 °C. Hydrangea production takes two seasons to produce a flowering plant and is achieved over two stages. The first stage involves taking semi-hardwood cuttings in greenhouses from April to May in the northern hemisphere. The plants are potted on and grown outside from May to October in containers to develop plant structure, then returned to the greenhouse over winter. The second step occurs in the following year where plants are grown in a greenhouse to achieve early flowering (March to May in the northern hemisphere) to set flowers over July to August before temperatures drop in winter (Morel 1999) The plants are then ready for sale for Christmas.

By this process consumers are able to buy plants in full flower and enjoy these as potted indoor plants over the Christmas season.

For other plants the process is less complicated as production is completed within one year as in the case of annuals such as pansies. The plants are propagated from seed in April to May, and the seedlings potted on the heated greenhouse until June to July. The seedlings are then either planted up outside for a display, held in the greenhouse or moved back into the greenhouse in August to September to flower and to be sold.

*Cut flowers* In recent years a number of native Australian warm temperate cut flowers have been introduced into Europe and the US and include examples such as pink mulla mulla (*Ptilotus exaltatus*) which has large tapered pink-mauve flower spikes and is used as a bedding plant, pot plant and cut flower (von Hentig 1985) in Europe. Ptilotus "Joey®" was released by the German seed breeding company Benary (Degraaf 2008) onto the European market. *Ptilotus* species originate from the central Australian desert and north-west Western Australia and have been successfully grown in Europe by carefully adapting their production schedule to the different conditions. As such they will crop within approximately 12 to 16 weeks from sowing (Degraaf 2008). To achieve a summer flowering target of June through to August seed is sown and grown at 21°C in April of the same year for pot plants (Fig. 12.10a) or in November of the previous year for cut flowers (Fig. 12.10b) when grown under greenhouse growing conditions. Supplementary lighting may need to be applied in winter to extend day length and surface heating applied to 22°C to encourage growth in central Europe. These plants are ready for pricking out and potting on into large pots and then planted out for a summer flowering (von Hentig et al. 1995)

*Introduction of warm temperate plants to Europe* In recent years the introduction of ornamentals into Europe has to be planned and scheduled with precision. Most young or emerging plant companies in Central Europe undertake extensive breeding and testing to avoid negative feedback from their customers. Two world-wide examples of the extent of this planning shows on the development of vegetative propagated petunias and verbenas, as well as angelonia (*Angelonia angustifolia*). The numbers of these new species and hybrids became so vast in the 1990s that the Chamber of Agriculture in Germany advised customers on how plants could be arranged and managed on balconies. A concept involved horticultural companies providing their colleagues with early planted balconies of these species to demonstrate to the customers how their balcony plants could provide early flowering after the summer holidays. Similarly, several companies dealing with young plants took the innovative step of looking for perennials and small shrubs, where the leaves have a decorative value (variegated and coloured), and put them together in series for autumn plantings. Plants with berries and late flowering species have been added as well as grasses. The early flowering cultivars of Christmas rose (*Helleborus niger*) and the eastern teaberry (*Gaultheria procumbens*) have become popular for autumn production over the last two decades. These plants also offer the producer a saving in heating costs. To extend the bedding plant season in Europe, a number of plants for late winter and early spring have been tested and introduced into the mar-

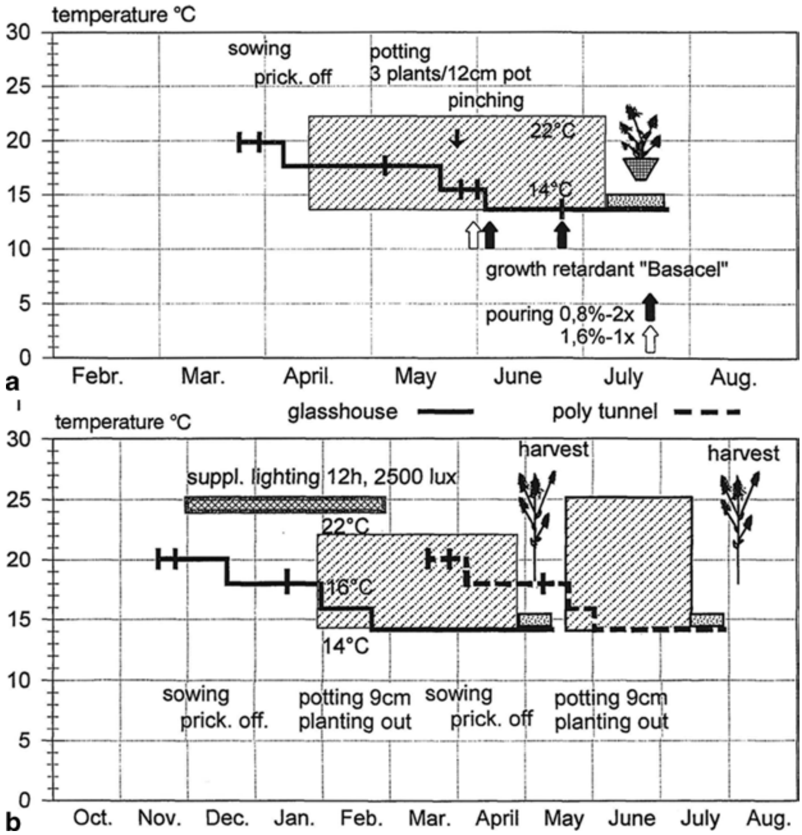


**Fig. 12.10** **a** Cultivation schedule for small pot plants of *Ptilotus exaltatus* Nees **b** Cultivation schedule for small cut flowers of *Ptilotus exaltatus* Nees. (Source: von Hentig et al. 1995)

ket. These include the bedside bulbs, pansies (*Viola tricolour*), primrose (*Primula vulgaris*) and early flowering perennials such as *Aquilegia* cv., *Tiarella* cv., *Lewisia cotyledon*, *Pulmonaria* sp., *Armeria maritima*, *Astilbe* cv., and *Saxifraga x arendsii*. While the number of new types of bedding plants is vast, the selection and number of seasonal indoor plants offered for the Christmas season has been relatively small in Europe. The market still has potential for new material and is largely dominated by the red and white colours of the poinsettias, hippeastrums and hellebores.

In Europe the introduction of new permanent indoor plants and plantings has also been limited. However, some very successful examples can be cited. These include the new spiral form of *Dracaena sanderiana*, and *Zamioculcas zamiifolia,* a tropical plant from Africa, that was introduced from Dutch nurseries in the mid-1990s and has exhibited good tolerance to drought and low light, and is relatively resistant to a range of pests and pathogens. Although their flowers last for more than a week the flower is insignificant. These plants in the first decade of the new millennium have emerged as important pot plants.

*Introduction of warm temperate plants to the Mediterranean region* Introducing warm temperate plants into the Mediterranean-type countries of Australia, South Africa, California and South America has been an easier task. Here the major consideration has been to develop systems that ensure the plant can cope with extremely dry conditions, often experienced over summer. In Mediterranean environments high saturation deficits can be frequent and rapidly dry out plants in pots. A responsive irrigation system is critical to prevent this occurring. The use of soil moisture sensors has been very effective in controlling irrigation variables of timing, amount and frequency. Examples of amenity plants that have been successful in these locations are the *interspecific hybrids* between *Chamelaucium uncinatum* and *C. megalopetalum* which have been bred in south west Western Australia and has been grown successfully in California as an amenity plant (San Marcos Growers 2011), where it enjoys a similar climate to Western Australia and tolerates the hot summers and infrequent rainfall. The Geraldton waxflower (*Chamelaucium uncinatum*) is one of the main Australian wildflowers to be grown for cut flowers and sold on the domestic and international markets with many new cultivars becoming available (Helix Australia 2014)

## Urban Environments

In the urban landscape a number of ornamental plants have been found to be environmentally valuable in providing climatic amelioration to courtyards, street scapes, roof gardens, balconies, walls and pavements to enhance the use of these inner city spaces and increase building value. Defining the best use of these plants is critical. This will determine whether a pot plant, amenity or bedding plants, or cut flower are most suited and the way they enhance the experience of people living in urban locations. For example, the use of conifers, such as the *Abies* spp., *Cedrus* spp. have value in providing a focal point within an urban landscape or dwarf forms used as hedging plants.

*Roof gardens* Another way to use plants in an urban environment is in development of roof gardens that can enhance the quality of limited space. These can cover the whole roof with plant materials such as turf, or planter boxes to display different foliage colours or seasonal flowers. Roof gardens have required engineering solutions as well as innovative approaches in the development of suitable planting media that include substrates with superabsorbent polymers, and irrigation systems. One notable development has been the use of specially designed and blended growing media which has a suitable water-holding capacity (WHC) and air-filled porosity (AFP), and the use of organic fertilisers. The design of green roofs have been well established in Germany (Lösgen 2008) with prescribed Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) guidlines developed originally by The German Landscape Research, Development and Construction Society. Development of technology to produce sustainable green roofs is becoming increasingly important in other countries including USA and Australia.

There are a number of requirements for plants to perform in roof gardens including their ability to withstand heat and high temperatures, and exposure to pollutants and wind. Plant survival can be compromised by a shallow soil media. Changes in temperature and shading may affect flowering. The increasing use of plants to trap and absorb both run off and pollutants in inner city parks has been seen as a new and valuable use of plants. The incorporation of a waste water treatment system that passes through a well designed garden allows for community use and filtering of an otherwise source of pollution. For example the creation of absorption beds connected to run-off areas within street scapes involving hit and miss paving where porous areas with turf grass to allow storm water to infiltrate are connected to a reed bed before entry into the groundwater. Horizontal and vertical filtration beds with gravel and macrophytes typically with members of the *sedge* family (*Cyperaceae*), can also accommodate plantings of reeds such as common reed (*Phragmites australis*) and Giant reed (*Arundo donax*) and members of the rush family (*Juncaceae*), as high nutrient absorbers that remove nitrogen, orthophosphates, ammonia and total soluble salts (TST) and pathogens (Mink et al. 2002). Other macrophytes such as *Baumea* spp., *Juncus* spp., and *Cyperus* spp. are effective in removal of phosphorus and prevent their transport into rivers or lakes where they can cause algal blooms. These systems have been employed by the Melbourne City Council in Victoria, Australia to manage nutrient inflows to the Ramsar Edithvale-Seaforth wetlands in the Port Phillip and Western Port Bays (Melbourne Water 2013). Floating reed beds on Gold Coast, Queensland, are also used to manage high nutrient levels (Anon 2013b).

*Living wall gardens* There is an increasing use of plants as living walls that have been shown to provide environment benefits, such as noise barriers, aesthetics, wind, pollution, and insulation of buildings when used in association with these structures and do contribute to the longer term sustainability of the urban environment. These can take the form of trees such as the Australian native plant drooping she oak (*Allocasuarina verticillata*) or *A. cunninghamii*, the *Melaleucas* and *Grevilleas* as well as the woolly bush *(Adenanthos sericea).* All make excellent barriers depending on the height to be screened or as a plant growing on artificial structures. In the case of a vertical greening system plants such as common ivy (*Hedera helix*) creepers (Ottelé et al. 2010), aromatic plants such as the true myrtle (*Myrtus communis*) and the Australian native lilac (*Hardenbergia comptoniana)* all make good natural barriers and can soften a building's facade. Stress tolerant plants such as those from the Mediterranean region can be more successful in reducing the energy requirements in managing these plants.

A number of plants have been introduced into Australia from overseas as hedgerow plants or as green cover. The red barberry (*Berberis thunbergii*) is a native to Japan and eastern Asia, generally hardy, deciduous and tolerant of pollutants. There are well over 30 cultivars available of *Berberis thunbergii* including a reddish-purple leaved "Harlequin" and the yellow "Aurea" forms (Missouri Botanic Gardens 2012, Vandeputte 2012, Wiley De Nolf 2012). The red barberry grows 1 to 1.2 m and tolerates cool temperate conditions and has proven to be very popular plant in Europe.

*Indoor environments* These conditions require careful choice of plants that tolerate low light and dry conditions of low humidity produced by air conditioners. Many rainforest plants such as the dumb cane (*Dieffenbachia* spp.) are suitable as indoor plants. However, to overcome the low light conditions it is necessary to rotate or replace plants in the indoor environment to maintain their longevity. This can be done on a programmed basis with the plants being grown outside or in heated glasshouses and then moved inside for a period. in winter. enabling plants to survive an environment where they would not normally grow.

*Cut flowers* People across the globe have enjoyed a wide range of Australian native flowering plants, often available through the cut flower trade. Such plants may be grown in their native country or countries with similar climates and then airfreighted to destinations sometimes with a considerably different climate, or to fill in during the opposite growing season in either hemisphere.

Many native Australian flowers grow best in mild winters (2 to 18ºC) and warm to hot summers (24 to 35ºC). These plants grow mainly on sandy or friable soils in the field on a broad scale making them more economical to grow in comparison to greenhouse grown material. The main cost is the freight that contributes approximately a third of the cost. The main flower species are Geraldton waxflower (*Chamelaucium* spp.), *Banksia* spp. and the kangaroo paw (*Anigozanthos* spp.), with the major foliages being Christmas bush (*Ceratopetalum gummiferum*), emu grass (*Podocarpus drouynianus*) and koala fern (*Caustis blakei*).

Considerable research has been expended on selecting, breeding, and maximising production and postharvest quality. Each species has been shown to have specific production and postharvest requirements. In terms of selection and breeding there are now over 100 cultivars of Geraldton wax which have been produced from natural populations and cultivars developed as well as deliberate crossing within species, between species and also between genera.

The production requirements for Geraldton wax include:

- Need for short days and cool temperatures (10°C) to flower
- Propagation from cuttings
- Production of long stems and terminal flower heads
- Low susceptibility to pests and pathogens, or methods available to treat pests and pathogens and
- Good vase life and respond to an allowable anti-ethylene treatment.

In order for growers and exporters to achieve the best production of quality flowers a number of manuals and technical notes have been produced. For example the Production of Premium Waxflower by Seaton and Poulish (2010) and the Banksia Production Manual by Parlevliet (2009) document every stage in the production system from selecting the right growing mix, propagating quality plants, and appropriate nutrition, irrigation, pest and disease management and postharvest treatments. These documents are themselves a form of intellectual property and some producers are protecting these by copyright, where sufficient novelty is apparent by patents (Dixon and Ogier 2007).

## Reinventing Plants for Novel Uses

To capture the market, plants not only need to be produced environmentally, and economically but also need to be well publicised (von Hentig 1995). Often plants are reinvented to suit the market. It may not always be necessary to breed new cultivars but rather show new uses for an old previously popular cultivar. For example pansies (*Viola tricolor*) and scaevola (*Scaevola coriacea*) have been used as potted plants in providing a kaleidoscope of colours in a landscape setting. However, by combining different colours in larger pots to represent a theme, e.g. a country's flag during an exposition, it is possible to provide a whole new impact. In addition, by combining plants of different heights, textures and colours an immediate visual effect can be achieved.

## Intellectual Property Considerations

To ensure the continued maintenance of plant quality, there is a need to protect intellectual property and safeguard investment providing return to the plant breeder (Dixon and Ogier 2011), the industry has developed the International Union for the Protection of New Varieties of Plants (UPOV Convention http://upov.int). The protocols of UPOV were adopted in Paris in 1961 and revised in 1991 (UPOV 2012). The member countries, of which Australia is one, have agreed to adhere to the principles of plant protection for the benefit of society to ensure that any new cultivars are afforded protection. This protection can also be afforded, depending on the country, by some form of Plant Breeder Rights (PBR) or a patent. For instance, within Australia a PBR is used to protect new cultivars that are distinguishable, uniform and stable (IP Australia 2012). PBR involves an application that describes the origin, parents, and a field examination that compares the new strain with similar cultivars. Results of successful PBR are published in the *Plant Varieties Journal* (IP Australia 2012). The collection of royalties that provide for an ongoing income stream for new cultivars for breeding and development may involve a pot plant levy placed on the plant material together with a licensing agreement for a nursery to produce the plant material. The World Trade Organisation (WTO 2012) and World Intellectual Property Organisation (WIPO 2013) provide the legislation to protect intellectual property rights and investment in a new cultivar and encourage global trade (Dixon and Ogier 2011). Other approaches to offer protection of new cultivars has been the use of devitalisation techniques to render the stems unable to be propagated as a quarantine requirement to keep out foreign diseases (DAFF 2012). This technique has been applied in the export of wildflowers from Australia where cut flower stems are devitalised using a solution of glyphosate (Seaton et al. 2010) to render the flowers unable to be propagated where new cultivars are being exported. Developing efficient and cost-effective commercial production processes is a challenge for industry longevity and being able to utilise the vast genetic heritage available across the world's biomes.

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# Chapter 13
# Postharvest Care and the Treatment of Fruits and Vegetables

**Peter M. A. Toivonen, Elizabeth J. Mitcham and Leon A. Terry**

**Abstract** This chapter describes existing postharvest care of fruits and vegetables in both the developing and developed economies of the world. Food waste is the metric which reveals the success or failure of the existing postharvest care. Figures vary depending on the source and the assumptions made to arrive at the estimated waste values but all agree that fruit and vegetable waste is at least 30 % of the production. Reasons for losses in the developing economies of the world relate to lack of basic postharvest technologies and access to adequate and reliable cooling. However, there are many societal issues that also impact on successful distribution of fruits and vegetables in developing economies. In developed economies, waste is associated at the distribution/retail/consumer levels and the underlying reasons for these losses are not so much the lack of or access to technology, rather to structure and function of the marketing chain. Capability to store product longer or transport it further does not necessarily lead to lower losses, however it does lead to greater distribution of availability over time or over distance. Consumer behavior and psychology play a significant role in waste at both the retail and home levels. While there continues to be numerous challenges for postharvest care of fruits and vegetables, the chapter provides some insight to the directions that must be followed to reduce wastage and enhance the availability of good quality, nutritious fruits and vegetable to all in developing and developed economies.

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## Introduction

Postharvest handling encompasses operations at harvest, transport to a packing facility, storage and transport technologies to preserve horticultural products until delivery to a customer whether they be local, national or international. The best possible outcome that can be achieved in postharvest operations is the preservation of the quality of the fruit or vegetable in its original condition at harvest. While that is the optimal goal, it can rarely be achieved in reality.

The final consequence for inadequate postharvest care is the loss or waste of that fruit or vegetable. Extent of postharvest loss varies depending on the industry context, i.e. whether we are discussing practices in developing or developed economies and whether we are discussing local/regional or international distribution/marketing chains. It is interesting to note that total losses of fruits and vegetables are generally 40–50 % in both developed and developing economy countries, with the exception of industrialized Asia where losses are estimated at less than 40 % (Gustavsson et al. 2011). It is instructive to analyze where the losses occur in the postharvest continuum. Generally, losses in postharvest handling, processing and distribution are greater in the developing world, where much greater proportional losses are found at the marketing/distribution/consumer level in developed economies, including industrialized Asia (Gustavsson et al. 2011). This observation leads to the conclusion that the postharvest care challenges and issues facing the developing world economies versus the developed world are quite different in nature and more importantly are produce and even cultivar specific.

A number of technologies have developed over the last century which has enabled remarkable quality retention for most products. The greatest impact has been due to implementation of refrigeration technologies. The widespread use of modern mechanical refrigeration systems has allowed for longer term storage and transport of most commodities from local to international scales. Refrigeration still continues to be a challenge to successful postharvest care of fruits and vegetables in developing economies where lack of infrastructure is a constraint on access to refrigeration (Anon 2011). This issue will be discussed further later in this chapter.

Other technologies have been employed to augment refrigeration in modern postharvest handling chains. These technologies include ethylene control (either treatment with or methods to remove), ethylene action inhibition (1-methylcyclopropene), modified atmosphere packaging, controlled atmosphere storages, controlled atmosphere transport trailers, coatings and waxes, and postharvest disease and insect control (Yahia 2009). Such technologies have been important largely for long term storage and/or long distance shipping in national and in international marketing chains. In fact, without the development of these other technologies, a large component of international trade in fruits and vegetables would not be possible.

Whether these developments have always reduced total losses for specific fresh produce types is debatable as often technologies which have extended storage have not ultimately reduced waste but increased availability and the prospect of sourcing from different origins.

Implementation of storage technologies has been a consequence of need to extend the duration for availability of fruits and vegetables (Yahia 2009). The most successful example of postharvest technology is that of controlled atmosphere storage of apples (Yahia 2009). As international transport and postharvest transport technologies have evolved, the goal was transformed to enabling orderly, profitable marketing of fruits and vegetables to whatever market demands the product (Yahia 2009). Despite the driving force of optimizing profit, there are layers of marketing chains that attempt to continue to serve the original purpose, that of preserving product to local and regional consumers such that the season for availability is extended as much as possible and yet this does not always translate to minimization of losses.

Clearly, postharvest care for fresh fruits and vegetables is a complex issue, impacted by the location of the producer (developed or developing economies), the intended market (local, regional, national or international) and the sophistication of the distribution chain and ultimately the changing factors and drivers which influence consumer demand. The intent of this chapter is to gain an appreciation for issues surrounding postharvest care in developing economies, sustaining horticulture in developed economies and in reducing losses and ensuring optimal quality and nutrition for consumers.

## Role of Postharvest Technology in Developing and Emerging Economies

Postharvest losses in the developing world can be substantial. Losses range from 30 to 80%, depending on the commodity (Kitinoja et al. 2011). For example, leafy greens which are subject to physical damage and high rates of water loss can suffer 80% loss after harvest. In addition, in the developing world, losses tend to occur between the grower and the market, rather than at the consumer level; opposite to the developed world (Kader 2005, 2010). With the world population expected to exceed 9 billion by 2050, there are urgent calls to greatly increase food availability. Reduction in postharvest losses is a key factor in increasing food availability in a sustainable manner.

Postharvest losses are very high in the developing world due to a number of factors, including harvesting at improper maturity, rough handling and poor packaging leading to physical damage, lack of protection from water loss leading to wilting, shrivel and loss of saleable weight, inadequate transportation to market, and lack of cooling or cold storage capabilities (largely due to unreliable electrical power supplies).

## *Challenges to Adapting Postharvest Technologies to a Developing World Scale*

Why is postharvest handling so poorly managed in these regions? A number of factors clearly play a role, including a lack of incentives to improve practices in anticipation of a higher market price, lack of awareness of improved practices that might be used, lack of resources to invest in supplies or technologies, particularly for smallholder farmers, lack of availability or high tariffs on imported supplies, and policies that provide a disincentive to changing practices (Kader 2005, 2010). Also, poor access to developing markets and poor distribution channels and the lack of vertical integration in the supply chain contribute to the challenge (Kader 2005, 2010).

For farmers and traders to be encouraged to adopt improved postharvest practices, there must be a benefit gained from the sale of higher quality produce. Grade standards or specifications are often non-existent in many parts of the world and there is a lack of trust between buyers and sellers. Also, products often change hands many times between the farm and the market, reducing the vertical integration between care in product handling and potential for better prices.

Lack of knowledge is another challenge. Many who grow and handle produce have no experience with or knowledge of improved handling practices. Training and demonstrations can illuminate the benefits of simple practices like harvesting early in the day, protecting product from the sun, or using plastic bags to reduce water loss.

Farmers and handlers in developing countries often lack the resources to invest in postharvest technologies. Access to capital through microfinance or savings programs is possible, but farmers must be convinced of the return on their investment. This requires linkage to a reliable market that will provide a fair price for the product's quality. More expensive technologies, such as small scale cold rooms, would generally require that an association of farmers or a village pool their resources for such an investment.

In many countries, supplies taken for granted in the developed world, such as thermometers, packaging materials, clippers, and sanitizers are not manufactured locally and are either unavailable for purchase or are only available at a much higher price due to shipping costs and tariffs.

There are a number of examples of policies that create disincentives to improved postharvest practices. For example, in some cases, transportation costs are based on the number of packages, not the size or weight of the package. This has led to use of extremely large crates for transport of bulk produce, leading to crushing of fruit on the bottom as well as challenges in careful handling of these products. In other cases, extra tall sacks are used for produce packaging so that they fill the width of the truck bed for maximum space utilization during transit. In India, a law related to produce marketing required that all produce be sold through wholesale markets (Kitinoja et al. 2011). This had precluded farmers from developing relationships for direct marketing to supermarkets or export markets. This law has recently changed in some parts of India and it has only just been

**Fig. 13.1** Scientists at the United States Department of Agriculture, Agricultural Research Service developed a process (going from front to back in the photo) by which chicken feathers are shredded, powdered, converted to pellets, and then transformed into biodegradable plastics. Photograph is used with the kind permission of the USDA-ARS

abolished throughout the country. It is likely that this change will open up markets to multiple retailers thereby resulting in greater efficiencies as seen in other parts of the globe.

## *Needs for Research and Implementation of Logistics and Supply Chain Management.*

There are three critical research needs for improving postharvest handling in the developing world: development of inexpensive, sustainable packaging, food safety strategies that work when water supply is scarce, and affordable strategies for cold storage and cool transport. Regarding packaging, there is a need for inexpensive but sturdy crates or boxes (Kitinoja et al. 2012). Returnable Plastic Containers (RPCs) are a possible option, but are expensive, subject to theft, and generally not produced locally. The benefits of a reusable packaging system may outweigh however, the challenges to its effective implementation (Manalili et al. 2011). Perhaps a package could be developed from locally available, natural materials. Chicken feathers have been suggested as one possible material that might be feasible (Fig. 13.1). Plastic bags are very useful to reduce moisture loss of harvested produce, but their use for many purposes (mostly not related to produce) have resulted in extreme pollution due to ineffective waste disposal systems. The problem is so bad that many countries are considering banning their use and Rwanda has already banned the use of plastic bags. An alternative technology should be developed that is inexpensive and sustainable, and serves the purpose of maintaining high relative humidity around the product.

Food safety is the most important topic for marketing of fresh produce. Unsafe use of pesticides during production of fruits and vegetables is a frequent issue, including use of unregistered materials, application at higher than approved dosage, lack of protective clothing and training of operators, and applications close to harvest and consumption. Microbial safety of fresh produce is also a significant problem. Consumption of raw fruits and vegetables increases the chances that microbial contamination can sicken consumers. Many of the recommended strategies for reducing the risk of contamination with human pathogens are particularly challenging to implement in the developing world. For example, the recommendation to wash one's hands after using sanitary facilities is a luxury in many locations. Water for hand washing is often not available in adequate amounts, and clean water is often unavailable. Soap for washing is also not readily available. Research is needed to develop convenient and affordable strategies to overcome these obstacles to human hygiene to make significant progress in microbial safety of fresh produce.

Finally, a lack of cooling, cool transport, and cold storage facilities is a major challenge to reducing postharvest losses in developing countries. Cooling technology is generally expensive and requires electricity that is often unavailable. A number of small-scale, inexpensive coolers have been developed (Kitinoja and Thompson 2010), but many are based on evaporative cooling which has limited cooling capacity, especially in humid environments. Innovative engineers must be incentivized to develop strategies to address this need in a cost-effective and scale appropriate manner. Technologies have been developed for keeping life-saving medicines and blood cool. These technologies can potentially be adapted for use on a larger scale for produce transport. Improved insulation can be used to maintain products at lower temperatures after harvest and can be effective when combined with harvesting at the coolest time of the day.

## *Successes*

There have been a few modest successes in adoption of technologies for postharvest handling in developing countries. A small-scale, lower cost cold room technology, the Cool-Bot, is beginning to be adopted in several parts of the world (Anon 2012a). The Cool-Bot uses a special controller developed by Keep It Cool, Inc. based in New York, USA (http://keepitcoolinc.com) together with a window air conditioner. The two are installed in an insulated room that can be made of a variety of materials, including locally sourced natural materials. The cost of this unit is considerably less than a traditional cold room, and the unit can be run using solar power in remote areas. Research is underway to adapt this technology this for cool transportation. These small-scale cold rooms have been adopted by a number of small-scale farmers in the U.S. as well.

The concept of a Postharvest Training and Services Center was developed by Dr. Lisa Kitinoja, founder of the Postharvest Education Foundation. Two such centers have been created, one in Tanzania and one in India. The centers have facilities for training of trainers and farmers in postharvest practices, including demonstrations of the effects of improved practices. In addition, the Centres have a supply of materials needed for improved postharvest handling, such as packaging, harvest umbrellas, clippers and thermometers that are available for sale. It is hoped that this type of center will be replicated in many parts of the developing world. The Postharvest Education Foundation and the Horticulture Innovation Lab (formerly Horticulture CRSP) have funded the training of several individuals in Africa and Asia who can provide training in postharvest practices to farmers, handlers and technicians who work with farmers and handlers (Anon 2012b).

### *Future Outlook*

There is tremendous room for improvement in postharvest handling of harvested horticultural products. By increasing awareness of simple practices, we can reduce losses and improve the quantity and quality of food available to consumers. Hopefully, improved practices will allow fruits and vegetables to eventually be sold at lower prices to increase consumption and result in improved health. Development of innovative, adapted technologies will assist resource poor farmers in adoption of improved practices.

## Role of Postharvest Technology in Sustaining Horticulture in Developed Economies

### *Importance of Quality Management in Advanced Supply Chains*

Supply chains in developed economies and even those within some emerging economies, which service their burgeoning populations, have over recent decades become ever more globalized and more interconnected. This situation together with the increased use of just-in-time logistics and lean manufacturing has undoubtedly led to greater efficiencies, but perhaps to more risk in terms of resilience.

Food prices in recent times have generally been increasing across the world, notably with spikes in 2008, 2010 and 2012 (Fig.13.2) (Anon 2013). This trend is causing concern amongst governments, consumers and industry. In many parts of the developed world profits within the fresh produce sector are being forever squeezed

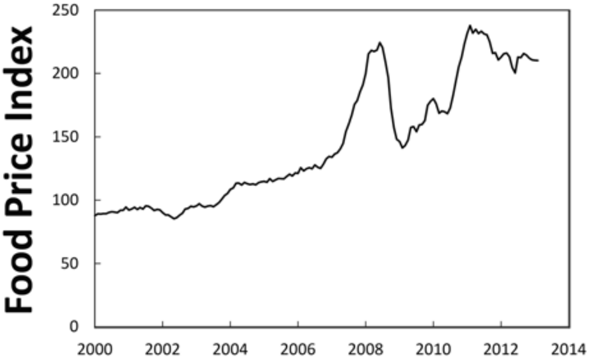

**Fig. 13.2** World nominal food price index for the new millennium. The FAO Food Price Index is a measure of the monthly change in international prices of a basket of food commodities. Data for January 2000 to March 2013 extracted from FAO database (Anon 2013)

in the present economic environment, whilst inflation for fruits and vegetables remains stubbornly high. Demand is also relatively static, with some standard lines for many fresh produce types falling out of favor to products of lower specification. The problem is compounded by consumer purchasing power and confidence being at an extended low ebb. Yet a dichotomy exists whereby quality demands for horticultural products keep increasing or at least are at an unsustainable level, such that something has to change or break in order for the industry and growers to remain competitive and continue to invest in new postharvest technologies. The incentives for doing so seem to be centered on gaining market share in a period of austerity and reducing waste through implementing stricter key performance indicators with the view that things will eventually turn and become more favorable. The scope for introducing new postharvest technologies in a stagnant market is therefore limited.

Quality remains the mainstay of many supermarket offerings as it can markedly influence footfall, market share and the incidence of customer defections. Quality is intimately linked with postharvest technology and biology, yet the drivers of demand are increasing centered on price and promotions (e.g. buy one get one free and multi-buys). Since 2008, promotions are being used more widely by retailers in the developed world to increase the affordability of fruit and vegetables as well as attract new customers (and stop customer defecting to other stores). In this sense they are part of the discussion about price/value and can increase footfall.

The effectiveness of fruit and vegetable promotions on demand is difficult to analyze. For example, promotions are usually time-limited and are traditionally used to celebrate the season and clear ‘gluts’. Where flushes or gluts are predictable (e.g. release from end of storage apples) then they can perform a valuable role in promoting greater product utilization and decreased waste, but even so may not increase demand overall. Another possible impact is that consumers’ simply switch away from a product that is not being promoted to one that is. If both are fruits, for example, there is no overall increase in fruit purchases—a process known as product ‘cannibalization’. Promotions can have other unforeseen consequences that may not be accounted for in forecasting. For instance, where a promotion works too well, it may lead to the necessity to supply product from a lesser standard or different quality tier so as not to fall short (e.g. not satisfactory conditioning potatoes before packing which can increase waste or using premium potato variety in a lower tier). When customers over-purchase as a result of being tempted by promotions then complaints can increase not only because of the pressure to deliver in full, but also because consumers may store more product at home. Often this product is kept under sub-optimal storage conditions, and the consumer becomes disappointed when they attempt to consume the product beyond its inherent home-life. This then may lead to increased waste in the home and/or depression of future sales due to customer dissatisfaction.

Promotions are being overused in the current climate such that consumers are suffering from 'promotion fatigue' and are confused over the basis of some such offers. The overuse of promotions (e.g. up to 50–80 % for some categories now sold) is destroying the price structure of the whole fresh produce category and actually making promotions less effective (Terry et al. 2013). It was highlighted by Terry et al. (2011) that the impact and mechanics of promotions should be better understood from both an industry and consumer perspective and this recommendation still holds. Although the vast majority of promotions are collectively agreed between retailers and suppliers, there are some which are imposed with little thought on availability and how postharvest technology might be better utilized. The frequency and timing of some promotions is often governed more by retailer positioning rather than by being aligned to the biology of the product, to oversupply/availability or even recognized seasonal demand. Multi-buy promotions and changing pack sizes across a range of categories may be confusing consumers. It is now unclear whether consumers understand promotions and indeed the true price of different fruit and vegetable lines as they have little to compare prices with (Terry et al. 2013).

Even though the choice of fruit types available to the consumer in developed economies is now vast there is contraction in that varietal choice within many fruit species can be limited. For example, out of the hundreds of mango cultivars grown worldwide barely 10 are available through the global market (Table 13.1) (Araújo and Garcia 2012; Anon 2012c). Most of these preferred cultivars have been selected for their inherently long postharvest life so that they can withstand global trade. They have rarely been selected for flavor or taste and this problem stands for many other fruit and vegetables such as avocado [Hass and Fuerte], and banana [Cavendish]. Thus, despite postharvest technologies being available to extend storage there is often a trade-off between taste and postharvest life. The industry often selects cultivars which have longer postharvest life rather than investing in technologies which might be used to increase the postharvest life of better tasting types. Concomitant to this, many fruits are still harvested at premature horticultural stages to ensure extended storage or shelf life even though postharvest technologies might be available to allow fresh produce to be harvested later and thus ensure greater consumer appeal. Implementing postharvest technologies is costly so that a reasonable return must be realized on that investment and financial outlay. If there

**Table 13.1** Major cultivars of mango marketed in the European Union and the United States. Cultivars in italics are the most important in terms of sales volume for each market

| European Union | US |
|---|---|
| *Haden* | *Ataulfo* |
| *Kent* | *Francis* |
| *Keitt* | *Keitt* |
| *Tommy Atkins* | *Kent* |
| *Alfonso* | *Tommy Atkins* |
| *Julie* | *Alphonse (Alphonso)* |
| *Zill* | *Edward* |
| *Osteen* | *Kesar* |
| *Maya* | *Manila* |
| *Shelly* | |
| *Palmer* | |

is declining propensity from consumers in developed economies to pay more for fruits and vegetables then the slow decline in fresh produce diversity and increase in commoditization will continue amongst middle income social economic groupings.

There is no uniform approach to quality in the retail market. Instead, each of the multiple retailers has developed a 'quality position' in terms of the products they sell as well as the shopping experience they provide (Terry et al. 2013). Retailers will use their 'quality position' to differentiate themselves from each other, to attract particular types of customer to their stores and to develop specifications for their suppliers. These specifications are particularly important for the retailers 'own label' ranges including the majority of fruit and vegetables.

In many developed economies the major multiple retailers have developed three quality tiers for their fruit and vegetables (Terry et al. 2013). These have various names depending on the retailer but can be broadly categorized as follows: Premium, Standard and Basic/Value. These three tiers provide a basis for understanding fruit and vegetable quality across large parts of the retail market but cannot be applied in every case. Even in the retailers that recognize three quality tiers it does not follow that all fruit and vegetables are offered at every quality level, for example typically bananas are just offered as a standard or value range whereas apples are commonly sold at all three levels. Indeed, some products may be offered in the premium tier for only certain periods because they depend on a particular cultivar being available in the season.

Some fruit and vegetables have additional branding like Organic or Fair Trade or carry a carbon label or some other differentiator for example 'Red Tractor'. These types of branding are not generally used as a quality attribute, that is the presence or absence of one or another mark does not lead the retailer to automatically assign that product to a particular quality tier. In other words these attributes have only a secondary influence on the retailers' quality positioning for fruit and vegetables.

In the fresh produce industry in developed economies, there are few truly dedicated supply chains; instead the major growers/suppliers tend to have multiple customers (Terry et al. 2013). The advantage of this approach is that it ensures the crop is better utilized. Typically the way this works is that suppliers have multiple primary customers among the major retailers (and in some cases foodservice operators). Specific crops and cultivars will be grown for a specific primary customer according to pre-determined planting programs which are, where possible, agreed upon ahead of the season and are informed by historic data on consumption and other market intelligence. For products where demand is predictable and is less affected by weather or where extended storage can better ensure extended availability (e.g. apples, onions and potatoes) these procurement programs tend to work well. For products where demand is more volatile then there is an increase risk that procurement programs fail. Growers will usually over produce to ensure that product can always be supplied in full and this may have an influence on crop utilization and waste (Terry et al. 2011). It could be argued that excess volume is in commercial interest and that growers must fulfill orders or risk losing business. There is recognition that over-programming can result in increased waste, but it is also understood that some degree of buffering against unforeseen problems in supply is essential.

Procurement programs are influenced by planned promotional activity. For example for strawberries, retailers determine promotional campaigns and these plans are discussed with suppliers, yet they are based on key dates, e.g. events in the social calendar viz. Wimbledon Lawn Tennis Tournament and predictable crop flushes and are aimed to maximize crop utilization.

As a season progresses and crops near maturity allocations can be made between quality tiers and customers (Terry et al. 2013). For example, if a crop grown for the premium tier fails to meet the desired specification then it may be switched to the standard or even value tier. This practice can undermine however, the differentiation between the quality tier offerings if noticed or understood by consumers. When a crop does not meet a specification and where there are limited alternatives for downgrading or alternative sourcing then specifications can be relaxed. Often the difference between tiers is largely subjective and will vary from time to time and according to variety, sizes and pack formats. The flexibility of the fresh produce industry in many developed economies enables the shifting of crop between quality tiers depending on shortage/surplus position such that specifications will differ by tier but can be fairly flexible depending on volumes available. Fruit ‘tiering’ is more resilient as it is more based on cultivar whereas vegetables and salads are more difficult to tier.

Although specifications are regarded by all retailers as key to defining and differentiating apparent product quality and are stringently adhered to, there is still some degree of plasticity when availability is stretched (i.e. as seen in 2012/2013 as a result of the poor weather conditions in Northern Europe during 2012). The advantage of the three tier system allows for some degree of product differentiation. If the crop does not meet the specification of any primary customer then it is usually switched to processing or wholesale markets (though increasingly both these ‘secondary’ markets also require products grown to a specification) (Terry et al. 2013).

It is inevitable that there will be product that does not meet any market specification. The amounts will vary product by product and season by season (Terry et al. 2011). These products will suffer quality defects including disease that may make them unsuitable for human consumption. These products will be variously used for animal feed, as feedstock for anaerobic digester (AD) plants and as soil amendments applied to land. It is clear that no successful grower intentionally grows lower grade products as the returns are less and they will endeavor to utilize crop where there is an economic gain in doing so.

Underpinning each of the quality tiers is a specification which is usually much more detailed than the EU or other international marketing standards. These specifications are usually commercially sensitive. Inevitably, however, there is often some degree of commonality between specifications used by many retailers, especially when considering a specific product in a single quality tier. Indeed, many suppliers supply more than one retailer and the differentiation between specifications is less than might be assumed. In developed economies, specifications are fundamentally based on visual appearance (e.g. size, shape and color uniformity) and freedom from defects (e.g. disease, blemish, bruising or even susceptibility to bruising physiological disorder); however cultivar and other attributes such as taste and flavor which are also related to consumer preference (for some products) are also important e.g. apples attaining threshold firmness and total soluble solids content. Specifications are enforced by internal quality control inspections by suppliers and retail customers. This said, the statistical validity of these inspections is questionable. There is typically little tolerance for severe aesthetic defects even for basic/value tiers. Specifications determine the assignment of products to each quality tier, yet it is true that some specifications for certain product types are solely based on physical attributes such as appearance. This does not mean that these specifications are not useful as the importance of appearance should not be underestimated (Terry et al. 2013).

It is easy to criticize specifications, but it should be acknowledged that non-adherence to most specifications can markedly influence consumer preference and purchasing decisions (Terry et al. 2013). Customer complaints and increasingly other feedback mechanisms are used to judge whether specifications reflect consumer purchasing behavior. Yet, the accuracy of customer complaints is questionable.

## *Research Needs and Impact on Sustainability*

There is a misconception that extending postharvest life always will reduce waste and loss. The relationship is more complex and is related to appreciation of the influence that management practices have on postharvest biology. For example, where demand is predictable then waste and loss levels will be minimized even if a product has a short shelf life (e.g. post climacteric bananas). On the other hand, where demand is unpredictable because of weather influencing consumption (e.g. unforeseen cold weather reducing strawberries and salad consumption even when hot weather has been forecast) then there may be a propensity to oversupply such that the residence time of product in store (often at sub optimum conditions) is increased leading to greater risk of waste (Terry et al. 2011). Thus, although the use of innovative postharvest technologies is often needed it is their implementation that also needs to be taken into account in the context of supply chain management. Despite this, numerous technological advances have been shown to reduce waste and extend availability; yet it is questionable whether all technologies are sustainable in the long-term. The ubiquity of low temperature storage in recent decades has helped to significantly reduce postharvest waste of fruit and vegetables. Most in the postharvest community believe that maintaining the cool chain is a pre-requisite before any other technologies are considered. It is true that cold storage can vastly increase postharvest life. But the overreliance on cooling systems in developed supply chains and allied just-in-time logistics may not be sustainable or resilient in the long term.

Alternative or supplementary technologies which might allow for extended postharvest life without the over-reliance of cool storage may become more common place. For instance, the targeted use of next generation controlled atmosphere storage (e.g. ultra low oxygen and dynamic controlled atmosphere systems (Watkins 2008a), ethylene control, genetic modification, and novel packaging innovations may allow for products to be stored at slightly higher temperatures.

The removal of ethylene and/or inhibition of its action in stored environments are fundamental to maintaining the postharvest quality of most climacteric produce. In recent years, however, there has been a paucity of research on developing new and more efficacious ethylene scrubbing materials. In contrast, there has been an exponential increase in research using the ethylene binding inhibitor 1-MCP (Lu et al. 2008). Despite availability of various ethylene scrubbing technologies (e.g. high temperature catalytic degradation, activated carbon) most commercial ethylene control systems rely on both adequate ventilation (often periodic) and oxidation of ethylene using potassium permanganate. Ventilation, however, is not appropriate in sealed environments (e.g. controlled atmosphere or some packaging formats) or where precise ethylene control is required. Ethylene supplementation has been shown to extend storage life of onions and potatoes even though they are low ethylene producers Cools et al. (2011). Ethylene inhibition using substances like 1-methylcyclopropene (1-MCP) (Blankenship and Dole 2003; Watkins 2006; Watkins 2008b; Lu et al. 2008) and ethylene scrubbers (Terry et al. 2007; Smith et al. 2009; Meyer and Terry 2010; Elmi et al. 2012) have been shown to improve postharvest storage.

## *Future Outlook*

The disparity in quality of fresh produce between developed and developing economies is unsustainable. Yet, despite this realization and much talk, little in the way of a global consensus and viable action planning has been forthcoming. Developed economies have had an unparalleled period of relative and sustained growth until 2008 and this has inevitably affected fresh produce supply chains. The large multinational retailers continue to dominate at the expense of less efficient outlets that do not possess the market intelligence, buyer power, convenience offerings and mass market appeal. The future dominance of emerging markets is becoming more likely, such that it is unclear whether all socio-economic groupings within developed economies will continue to have access to the quality and choice of produce which they might have expected or have become accustomed to. Better and more targeted implementation of innovative postharvest technologies is required to ensure the sustainable supply of a diverse range of fruit and vegetables in the future.

## Role of Postharvest Technology in Reducing Losses and Ensuring Optimal Quality and Nutrition for Consumers

### *Challenge of Postharvest Losses in Existing Marketing and Distribution*

Most losses at the retail and consumer levels are incurred in the developed economies of the world (Parfitt et al. 2010) and therefore the discussion in this section will pertain to issues in developed economies. Produce retailers have many options that have been developed over the decades to help in reducing losses and shrinkage. One of the most beneficial at the retail and consumer level has been packaging, since it can provide physical protection for the product, help to control weight loss, provide produce in portions suitable for consumers, and provide increased levels of protection from microbial and/or chemical contamination during the handling of the product on the shelf and to the consumers table (Anon 2011). However, there are many societal and environmental issues that are yet unresolved with the lifecycle for package use, such as ubiquity of recycling programs for used packaging (Anon 2011). Despite these issues, it has been estimated that use of packaging results in significant reductions in terminal food waste (disposal to landfill) and as such has a much lower environmental impact than does not using packaging and incurring losses of fruit and vegetable mass that generates methane when it rots and thus contributes to global warming (Gooch et al. 2010).

While icing and misting are in prevalent use in many retail produce displays (Thompson and Crisosto 2002), concerns are emerging regarding the effects of free water on the quality and safety of exposed produce at the consumer level, especially if stored in a home refrigerator for any length of time (Rossman et al. 2012). Indeed, misuse of misting or icing is prevalent for packaged fruits and vegetables and can lead to problems, while not providing any benefit to such products. Recently fogging systems have been developed for commercial use (e.g. Samarketing SL 2013) and these may provide a superior humidity control for non-packaged fruits and vegetables on display while avoiding accumulations of free water on the surface.

Lack of refrigeration is a significant issue, despite the general adoption of modern technologies in the developed economies of the world. Local distribution can be subject to poor logistics practices, breakdowns and inconsistent refrigeration (Gunders 2012). In the retail stores packaged whole and fresh-cut produce on display can face significant problems associated with overstocking (Gunders 2012) which results in poor temperature control.

Waste at the consumer level exists for several potential reasons. First, many times fruits and vegetables are packaged in formats that are too large (Gunders 2012) for smaller families, single persons or couples with no children at home. This can lead to leftover produce that sits in the refrigerator after a first use. Secondly, while many households purchase nutritious fruits and vegetables with good intentions and the interest in their healthfulness, quite often in the rush of a busy life, convenience food, takeout food and meals out lead to the non-use of the purchased produce (Anon 2011; Gunders 2012; Parfitt et al. 2010). This behavior is thought to be linked with the obesity crisis in the developed world economies since many of the options have higher calories and are more energy dense than the fruits and vegetables that go uneaten (Drewnowski and Darmon 2005). Third, many consumers do not have sufficient understanding of the correct storage conditions for fresh fruits and vegetable or for managing their refrigerator to ensure proper storage conditions (Anon 2011; Gunders 2012).

## ***Research Needs***

Many of the issues related to produce losses in marketing and distribution can be resolved with improved education of produce handlers in the chain. Value chain systems are beginning to emerge which may help to spur on improvements in cold chain handling (Gooch et al. 2010). A value chain model involves ownership of responsibilities and valuation of partners in the distribution chain with the desired outcome that all partners benefit from the relationship and maximum returns accrue for each member (Gooch et al. 2010). While there is some evidence that value chain systems can result in improvements in marketing and distribution, there is a need to document issues facing the current *status quo* and research to demonstrate the benefits of a value chain approach to the enhancing retail quality and reducing shrinkage of perishable fruits and vegetables.

While packaging has been an area of research for some time (Toivonen et al. 2009), more research is required to adapt packaging to ever increasing demands for new package formats, produce combinations and enhanced convenience to the consumer and also to enhance flavor quality (Kader 2009). Packaging is essential to continue in development of a convenience factor for the consumer and reduce the losses occurring in the distribution chain. The convenience of a food for consumption will continue to become more of an issue as cities grow and the pace of lifestyle increases and hence the need to adapt fresh fruits and vegetables more and more to a convenience format (Pollack 2011). The variety of products available to the consumer in a single package is increasing in a highly competitive sector: new product introductions are important and issues around product compatibility must be resolved in the package system design (Fig. 13.3).

Technology has been developed to also cue customers to the edibility or ripeness of fruit which do not normally show visual changes with ripening. A technology to tell consumers the ripeness in green pear cultivars has provided retailers and

**Fig. 13.3** Potential for a co-release technology sachet to control compatibility problems when ethylene producing tomatoes are packaged in salad mixes containing ethylene sensitive vegetables such as lettuce and carrot shreds. Packages of salad mix were obtained directly from a fresh-cut processor and stored at 5 °C for 4 weeks. A full description of the technology is provided by Lu et al. (2008)

consumers with an on package incorporated color patch that will change color as the fruit softens and develops sweetness for eating quality (http://www.ripesense.com/). Technologies providing similar cues to retailers and consumers will help to reduce waste by indicating which fruit are ready for immediate consumption and which require time to ripen. Such technologies would be useful for fruits such as kiwifruit, avocados or melons. Similar technologies could be developed for packaged fresh-cut product indicating remaining shelf life for the product, thus encouraging timely product cycling on the retail shelves and consumption for the consumer.

## *Is it Possible to Reduce Losses and/or Enhance Retention of Nutritional Value to the Consumer?*

It is possible to both reduce losses and enhance retention of nutritional value for the consumer? Nutritional value is linked to fruit and vegetable retaining appearance and texture expectations of the consumers. Generally when produce is of good visual and tactile quality the nutritional value is high (Gil et al. 2006). Therefore, the challenge is to minimize the rate of perceptible deterioration in quality for the product and the goal of nutrition retention should be achieved. Two factors probably have most effect on both quality and nutrition retention; (1) temperature, and (2) water loss. Nutritional components such as vitamin C may decline when significant water loss occurs (Lee and Kader 2000). Temperature has a two-fold effect, it will govern the rate of biochemical processes leading to over-ripening and also warmer handling temperatures also lead to greater water loss. Modified atmospheres have also been shown however to improve vitamin C retention (Lee and Kader 2000). Losses of labile vitamins can be resolved through development of better packaging systems and through better education of the consumer regarding home refrigeration management.

## *Future Outlook*

The challenges in this new millennium are that consumption of fruits and vegetables requires an understanding of societal values, lifestyles and environmental issues. Complex and increasingly busy cities pose challenges to the distribution and retail requirements for produce. Generally, portion-sized packages and fresh-cut product are continuing to develop since urban consumers have preference for convenience and may have limited skills or time for meal preparation (Pollack 2011). The carbon footprint for packaging is relatively small when assessed relative to the alternative of greater losses in unpackaged fruits and vegetables during distribution and marketing (Gooch et al. 2010). A key for future reductions of losses in fruits and vegetables during distribution and marketing lies in successful implementation of new models, likely involving value-chain systems (Anon 2011; Gooch et al. 2010) and introduction of intelligent packaging with formats that will encourage ongoing improvements in quality, nutrition and flavor for the consumer (Toivonen et al. 2009).

## Conclusions

Many of the challenges facing success in postharvest care of fruits and vegetables do not depend on the development of new technologies, although there are still some needs that were identified. Looking in a broader perspective, some of the challenges can be met by successful adoption or adaption of existing technologies to the context of the country and economy in question. It appears however, that perhaps a larger issue is that of the constraints that societal, business and consumer behaviors place on the logistics and marketing of fruits and vegetables. Clearly, improvements in delivering quality, nutritious fruits and vegetables to consumers will depend on better co-operation and some rethinking of existing distribution systems and the goals of sellers, buyers and marketers. Technology can make all things possible, but it is willingness of the participants in the fruit and vegetable trade to take advantage of the opportunities that will determine the outcome. Since the stakes are huge in terms of current waste estimates and the challenges increase every year in terms of world population growth, the urgency to improve the situation becomes also greater.

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# Chapter 14
# Designing New Supply Chain Networks: Tomato and Mango Case Studies

**Jack G. A. J. van der Vorst, Rob E. Schouten, Pieternel A. Luning and Olaf van Kooten**

**Abstract** Consumers expect product availability as well as product quality and safety in retail outlets. When designing or re-designing fruit and vegetables supply chain networks one has to take these demands into consideration next to traditional efficiency and responsiveness requirements. In food science literature, much attention has been paid to the development of Time-Temperature Indicators to monitor individually the temperature conditions of food products throughout distribution as well as quality decay models that are able to predict product quality based upon this information. This chapter discusses opportunities to improve the design and management of fruit and vegetables supply chain networks. If product quality in each step of the supply chain can be predicted in advance, good flows can be controlled in a pro-active manner and better chain designs can be established resulting in higher product availability, higher product quality, and less product losses in retail. This chapter works towards a preliminary diagnostic instrument, which can be used to assess supply chain networks on QCL (Quality Controlled Logistics). Findings of two exploratory case studies, one on the tomato chain and one on the mango chain, are presented to illustrate the value of this concept. Results show the opportunities and bottlenecks for quality controlled logistics depend on product—(e.g. variability in quality), process—(e.g. ability to use containers and sort on quality), network-(e.g. current level of cooperation), and market characteristics (e.g. higher prices for better products).

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This paper is partly based on the following published paper (Van der Vorst et al. 2011, pp. 94–105).

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## Introduction

Consumers expect food in retail stores to be of good quality, to have a decent shelf life and to be fit for purpose (Smith and Sparks 2004). Furthermore, consumers demand product diversity, safety, convenience (e.g. ready to eat products), and sustainable food production and supply production systems. Well-informed customers are stimulating retailers and other actors in the food supply chain network to adapt new business concepts. They require year-round availability of high-quality fresh products (such as pine-apples, citrus fruits, kiwi fruit), which has stimulated partners in food supply chains to pursue a coordinated approach to establish more effective and efficient supply chains.

Design of supply chain management (SCM) has received a lot of attention in the academic (IJOPM 2007) as well as business world (Simchi-Levi et al. 2007; Chopra and Meindl 2007; Christopher 2010). SCM is about matching supply and demand; it is about the integrated planning, coordination, and control of all business processes and activities in the supply chain to deliver superior consumer value at less cost to the supply chain (Van der Vorst and Beulens 2002). Aim of SCM is to produce a consistent view on how a supply chains should look like in terms of supply, production and distribution processes and their coordination.

The design and management of AgriFood Supply Chain Networks (AFSCNs) is characterised by a focus on product availability and its quality. The way in which food quality is controlled and guaranteed in the supply chain is an important performance indicator and very much linked to another performance indicator, food safety (Luning et al. 2009, 2011). Investments in chain design should not therefore only be aimed at improving logistics performance but also at the preservation of food quality so that products are delivered with the right quality at the right time (Van der Vorst et al. 2011).

Typically, food degradation is related to intrinsic properties (initial microbial contamination, respiration rate and specific cultivar characteristics), environmental conditions (temperature and humidity) and the time the product is exposed to these conditions. Environmental conditions may be influenced by, for example, the type of packaging, and the availability of temperature conditioned warehouses. In food science literature, much attention is paid to food quality decay modeling and the development of Time Temperature Indicators (TTI) to monitor the temperature conditions and assess the impact on the quality deterioration throughout distribution (Sloof et al. 1996; Taoukis and Labuza 1999; Schouten et al. 2002; Bobelyn et al. 2006). When we combine these food quality change models with logistics decision support models, new opportunities arise to improve the performance of AFSCNs (e.g. Rossi et al. 2012).

This paper discusses opportunities to use time-dependent product quality information to improve the design and management of AFSCNs. Product quality in consumer markets is influenced by the product quality at origin (when harvested) and the conditions that the products have been exposed to during in the supply chain network. The logistics concept therefore influences market opportunities and vice versa. If quality is known in advance, goods flows could be steered in all phases of the AFSCN. This chapter describes a preliminary diagnostic instrument, which can be used to identify improvement opportunities in the supply chain as to increase product availability of the right quality at the right place and time. Two exploratory case studies are presented to illustrate the value of this diagnostic instrument.

## Temperature-Controlled AgriFood Supply Chain Networks

A temperature-controlled AFSCN requires products to be maintained in a temperature controlled environment, rather than exposing them to whatever ambient temperatures prevail at various stages of the supply chain (Smith and Sparks 2004). In this paper, we focus on fresh fruits that need controlled temperatures to maintain or even improve product quality (due to ripening of fruits: ripe-on-arrival). Considering the increasing consumer demand for ready-to-eat products (like ready meals and prepared salads) the ability to optimize temperature-controlled AFSCN becomes increasingly important.

There are a number of difficulties in managing temperature-controlled AFSCNs such as the short shelf life, which puts additional requirements on speed and reliability of logistics systems and require specialized transportation and storage equipment. Furthermore, modern chains distribute multiple types of products—often with multiple temperature regimes. This means that a ‘best fits all’ solution is taken, which means that the temperature is not optimal for any of the products. Moreover, one must be careful for product interferences, for example, bananas produce ethylene, which accelerates the ripening process of other fruits. Finally, in these chains temperature control and prevention of product interferences are very important from the perspective of food safety; typical safety problems concern *Listeria* in cheese products, *Salmonella* in chickens and eggs, *BSE* (bovine spongiform encephalopathy) in cattle, *EHEC* (enterohaemorrhagic *Escherichia coli*) in vegetables. These typical food related issues should be considered when designing a AFSCN, using risk assessment as an important tool (Luning and Marcelis 2009).

It is clear that the design and management of temperature-controlled FSCNs is a complicated process; how can a retailer ensure that products are always under the appropriate temperature regime? Fruit and vegetables might look fresh from the outside, but what is the remaining period of consumer acceptance? Retailers and chain partners realize that they can distinguish themselves in the market place by setting up a reliable temperature-controlled FSCN that guarantees product quality and reduces shrinkage (price cuts) in retail outlets.

## State of the Art

In a recent special issue in *OR Spectrum* (Grunow and Van der Vorst 2010), Akkerman et al. (2010) presented a review of the design and management of agri-food distribution networks. They concluded that the limited shelf lives of food products, requirements with regard to temperature and humidity, possible interaction effects between products, time windows for delivering the products, high customer expectations, variability in supply and demand (e.g. weather dependability), and low profit margins make distribution management of fresh products a challenging area. This has only recently begun to receive more attention in the operations management literature.

The introduction of unbroken cold chains, an uninterrupted series of storage and distribution activities which maintain a given temperature range, has improved the quality of food products at the market place. Quality assurance guidelines and standards such as Good Manufacturing Practice (GMP) and HACCP (Hazard Analysis and Critical Control Points) have been developed and implemented in food supply chains (Luning et al. 2008, 2009). Moreover, breeding and cultivation practices have improved in order to increase the initial product quality at harvest. From a logistics point of view, emphasis has been on developing management concepts that improve delivery reliability and lead times. This is accomplished via increased information exchange and changes of roles in the chain, e.g. Cross Docking, Vendor Managed Inventory (VMI), Efficient Replenishment, Collaborative Planning Forecasting and Replenishment (CPFR) and Factory Gate Pricing (FGP). Also innovations in logistic means, such as reefers and RFID's (radio frequency identification) have been important. It is clear that logistics improvements go hand in hand with technological developments and quality assurance systems. However, up to now a complete integrated perspective has not been taken.

Temperature monitoring and recording is a prerequisite for chain control and any logistics management system that aims on product quality optimization. New technological developments, such as time-temperature integrators or indicators to individually monitor the temperature conditions of food products throughout distribution, offer possibilities to improve temperature monitoring throughout the distribution system (Giannakourou and Taoukis 2003). This allows for shelf life estimation using quality prediction models, as is for example shown by Tijskens (2004) for fruit and vegetable chains, Raab et al. (2008) for pork and poultry chains and Dalgaard et al. (2002) for fish chains. The additional information gained from these technologies would allow for advanced logistics decision making during the complete distribution process knowing the required product quality at its final destination, a concept called "Quality Controlled Logistics" (Van der Vorst et al. 2007, 2009, 2011).

## Quality Controlled Logistics

Fresh AFSCN are characterized by heterogeneous batches of products (i.e. product quality differs within the batch and between batches) delivered by a diversity of producers to multiple market outlets that have different demands. Long supply chains of perishable products suffer from risk of quality degradation. Storage, handling, transport, and distribution conditions have a strong impact on freshness and shelf-life of the produce. The common strategy for dealing with the variability in quality is tailoring the supply chain towards 'average' quality. This might not be the most effective approach, since variability can also be strategically exploited through flexible management of quality differences for specific market outlets. Instead of homogenizing product quality in the chain, we advocate differentiation of product flows based upon the batch quality at different stages in the AFSCN. This might improve chain revenues via improved product quality on retailer shelves and/or improved matching of supplied products at a certain price to specific market segments. Batches of high quality could be sent to different market segments with higher added value.

Quality Controlled Logistics (QCL) makes use of variation in product quality, developments in technology, and heterogeneous needs of customers, and the possibilities to manage product quality development in the distribution chain. QCL can be defined as that part of supply chain management that dynamically plans, implements, and controls the efficient, effective flow and storage of food products, services, and related information between point of origin and point of consumption. The goal is to meet customers' requirements with specific attention to the availability of specific product qualities in time by using real-time product quality information in the logistics decision process. QCL starts with obtaining detailed knowledge on customer requirements in the different market segments (Table 14.1). At the harvest stage, products are collected and characterised based on variation in quality attributes. For example, due to sun light exposure apples or mangos on the outside of the tree have different quality attributes compared to products inside the tree, or between the sun-side and the shade-side of the tree. QCL makes use of the quality distribution profile of each batch by matching them with customer demands for specific products and the price that is paid for each batch. Instruments for this approach are to either redirect the goods flows to other markets/consumer groups or to influence the quality level of the products by changing, for instance, storage time, temperature or gas atmosphere (for instance during long term apple storage or modified air packaging of fresh cut fruits or vegetables).

In order to put the QCL concept in practise we identified the following six elements based (Van der Vorst et al. 2011):

### *a. Consumer Preferences and Acceptance Period of Product Quality Attributes*

This element refers to (1) the quality attributes that consumers prefer as well as the target values of each attribute, and (2) the acceptance period (AP; Schouten et al. 2007b). The AP refers to the time period consumers find all attributes of a product acceptable. By consumer research it becomes possible for a specific consumer group to determine the limits of acceptability for the specific quality attributes like color and firmness or taste. If this is known it becomes possible to aim for these specific characteristics for the products in retail shelves.

**Table 14.1** Generic logistics decisions versus specific QCL decisions. (Van der Vorst et al. 2011)

| Generic logistics decisions | Specific QCL decisions |
|---|---|
| *Determine generic customer service standards*<br>Customer needs (e.g. quantity, quality)<br>Customer service levels (e.g. lead time, reliability)<br>Determine requirements on supply of products in each stage of the chain | Determine customer acceptance levels and periods for specific market segments using accepted and measurable quality standards. Translate this into specific product quality requirements for each stage in the supply chain (next to of course volume and timing requirements) |
| *Determine facility network design*<br>Number, location of stocking points<br>Equipment selection, capacity planning | Use customer requirements data, information on supply qualities and volumes and transport scenarios with quality predictions to determine the required network design and equipment |
| *Determine inventory management*<br>Position Customer Order Decoupling Point (CODP); push-pull strategies<br>Warehousing policies | Use supply chain data to determine the optimal position of inventory points in the network taking predicted quality changes (and thus environmental conditions) into account |
| *Determine information flows and order processing*<br>Ordering rules<br>Order inventory interface procedure<br>Order picking procedures | Determine Critical Quality Points (CQPs) to monitor quality changes. Use quality prediction models and product quality information to apply optimal picking policies (e.g. first-expired-first-out policy). Re-sort batches if needed. Aim for homogenous batches for specific market segments |
| *Plan order fulfilment*<br>Allocate harvested produce to customer orders and deliver the products without dealing with quality changes and differences that occur in the supply process. A batch is not re-sorted or re-allocated unless serious issues arise.<br>Determine transport management (mode, scheduling) | Dynamic logistics planning in the complete chain based upon real time product-quality information (using critical quality points and predictive models). If needed, batches are re-sorted into homogeneous batches, re-allocated to different market segments, transported with different modes or environmental conditions are adapted to meet customer requirements. Technologies such as data loggers, RFID and GPS are used to capture all relevant information, translated into meaningful information through models |

### *b. Critical Quality Points*

A critical quality point (CQP) refers to a point in the process where variation in product properties and or processes results in unacceptable and or irreversible deviations in required quality attributes of the final product (Luning and Marcelis 2009). By studying chain conditions and relating the findings to the dynamic behavior of quality attributes, it becomes possible to determine the effects of different chain configurations (and thus logistics decisions in different stages in the chain) on the product quality and product availability. This supports the determination of locations in the chain where certain measurements should be done and logistics and quality control actions should be taken. As a result, one can change conditions such as temperature, storage time, and order picking procedures as well as moment of positioning the product in the shelves (Schepers and Van Kooten 2006).

### *c. Product Quality Measurement and Prediction*

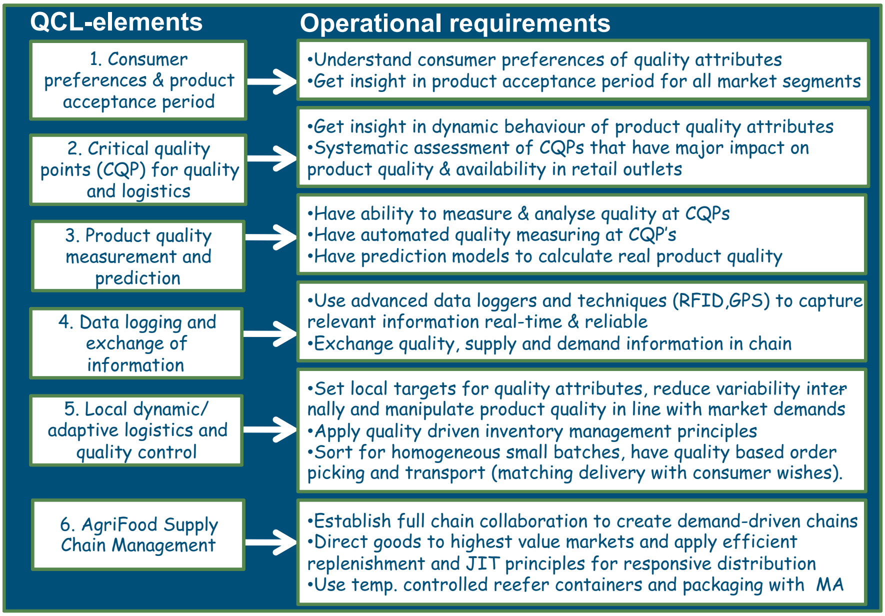
Several techniques are available and in development that enable us to measure and predict the dynamic quality development of fresh food products in the AFSCN. They enable us to predict the ripening or quality decay development under different environmental conditions, which allows the development of Quality Controlled Logistics in fresh AFSCN and positioning of food in retail shelves precisely when consumers expect and accept them. Provided consumer preferences (step a), chain conditions are known, measurements are carried out at the CQPs (step b) and predictive quality models are available (step c) it becomes feasible to direct batches varying in quality attributes though the chain in a way that all batches end up with the same quality at the consumer. This is the essence of the next steps of QCL.

### *d. Logging and Exchange of Information*

The fourth element relates to data logging and exchange of relevant information with supply chain partners. The quality of fresh food products depends on its temperature history, from production through distribution and storage to consumption. Monitoring the temperature in the chain—as well as all other relevant environmental conditions—allows prediction of shelf-life if product quality models are available to replace the sometimes meaningless expiry dates on fresh produce (Bobelyn et al. 2006). New technologies like RFID and GPS (global positioning system) provide innovative means to capture data. Next to product quality- and environmental data also demand, inventory and supply data could be exchanged in the supply chain. This facilitates advanced logistics decision making central in the following two elements.

### *e. Local Dynamic/Adaptive Logistics and Quality Control*

In the end, QCL comes down to adaptive control by supply chain stages based upon customer wishes and current product quality, i.e. to change the flow of products and environmental conditions to which these products are exposed to. Furthermore, new stock rotation and order picking systems can be implemented by individual supply chain partners, which are not based on First-In-First-Out (FIFO) or Last-In-First-Out (LIFO), but on First-Expired-First-Out or Right-Quality-First-Out (RQFO). In the case of FEFO, the products with the closest expiration date are advanced first,



| QCL-elements | Operational requirements |
|---|---|
| 1. Consumer preferences & product acceptance period | •Understand consumer preferences of quality attributes<br>•Get insight in product acceptance period for all market segments |
| 2. Critical quality points (CQP) for quality and logistics | •Get insight in dynamic behaviour of product quality attributes<br>•Systematic assessment of CQPs that have major impact on product quality & availability in retail outlets |
| 3. Product quality measurement and prediction | •Have ability to measure & analyse quality at CQPs<br>•Have automated quality measuring at CQP's<br>•Have prediction models to calculate real product quality |
| 4. Data logging and exchange of information | •Use advanced data loggers and techniques (RFID,GPS) to capture relevant information real-time & reliable<br>•Exchange quality, supply and demand information in chain |
| 5. Local dynamic/ adaptive logistics and quality control | •Set local targets for quality attributes, reduce variability internally and manipulate product quality in line with market demands<br>•Apply quality driven inventory management principles<br>•Sort for homogeneous small batches, have quality based order picking and transport (matching delivery with consumer wishes). |
| 6. AgriFood Supply Chain Management | •Establish full chain collaboration to create demand-driven chains<br>•Direct goods to highest value markets and apply efficient replenishment and JIT principles for responsive distribution<br>•Use temp. controlled reefer containers and packaging with MA |

**Fig. 14.1** Operational requirements of QCL elements

and with RQFO exactly that batch is delivered, which has the right quality for that particular customer.

## *f. Supply Chain Management (SCM)*

Finally, all SCM practices as discussed earlier (like CPFR, VMI) can be applied in the complete supply chain to match supply and demand using the advanced product information exchanged in the supply chain and collaborative logistics decision policies; production and distribution lead times can be shortened, full chain transparency created and waste and costs reduced.

These six elements can be combined in a preliminary diagnostic instrument that indicates the operational requirements of each QCL element (see Fig. 14.1). The next step is to develop different performance levels to assess specific supply chains and to analyse the relationship between QCL elements and supply chain performance. To get some first insight in this the next sections describe case studies in the tomato and mango supply chain network.

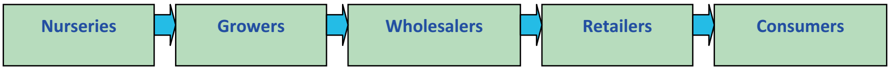


**Fig. 14.2** Supply chain for tomatoes in the Netherlands

## Case Study in the Tomato Supply Chain

### *The Tomato Supply Chain*

The supply chain for fresh tomato starts with nurseries that produce young plants from hybrid cultivars. Growers will deliver tomato fruit (sometimes as part of a grower association), to wholesalers or, direct to retailers. Tomatoes are harvested after reaching the breaker stage of ripening (Schouten et al. 2007a). They are then stored and transported. The period of storage and transport is kept to a minimum given the constraints of the logistics of large quantities and market demand. Supermarkets are the main distribution channels of vegetables, with a market share of 85 %. The period between moment of harvest and positioning in the retail shelf for sale generally varies between 2 and 10 days. Retail managers try to procure amounts that can be preferably sold within one day. The last chain actor is the consumer. Figure 14.2 shows a typical tomato supply chain in The Netherlands.

### *Tomato Quality*

In practice, color and firmness of tomatoes in the shelves varies considerably over time. Also the taste can vary from acceptable to far below acceptability (Bruhn et al. 1991) even within the same cultivar and origin of production. This leads to complaints from consumers and retail managers about insufficient quality (van Kooten 2006). Growers associations produce tomatoes with differences in quality due to differences between individual growers and between batches of one grower. Current practice in the horticultural chain is to harvest tomatoes after they reach the breaker stage and transport them at the prescribed temperature of 12 °C to slow down ripening while also avoiding chilling injury. This may result in an insufficient color (pink color stage) and firmness (too firm) at the moment of consumption. On the other hand, when tomatoes are harvested and transported over long distances or stored too long in retail shops, firmness can become a limiting quality attribute, now due to tomatoes being too soft. In other words: the quality attributes of both color and firmness are of importance for consumers (Tijskens and Evelo 1994) and thus determine the willingness to buy and consequently the price settings.

## *QCL Analysis in the Tomato Supply Chain*

Schouten et al. (2006, 2010) determined the acceptance limits for both color and firmness of round tomatoes when consumers want to buy them for direct consumption and also for consumption after several days. As indicated before, the acceptance period (AP) consists of the period that all quality attributes are considered acceptable and takes into account that tomatoes can first be unacceptable due to being immature, then be acceptable, and then be unacceptable again, due to being over-ripe. Based on a hybrid (kinetic-stochastic) quality model, calibrated on (non-destructively measured) color and firmness data gathered at different storage temperatures, predictions on the development of both color and firmness through time at variable temperatures could be established. By combining this calibrated model with the acceptance limits it becomes possible to predict the time it takes, depending on the chain temperature conditions, when a batch becomes acceptable and how long the batch will stay acceptable.

The acceptance period model was calibrated for 10 tomato cultivars from one Dutch breeder. All tomatoes from all cultivars were grown in the same greenhouse and harvested on the same day for each maturation level, i.e. breaker, pink and red. A tomato supply chain from a well-known Dutch producer group, known as Prominent, was studied. From this study 12 different actual and possible supply chains were designed. The chains were typical for different seasons, e.g. in the summer the supply is large and so the chain duration lengthens, while in winter the supply is small and the chain duration is short. When the tomatoes were harvested on Friday there was a weekend effect prolonging the chain duration. Some of the results are depicted in Fig. 14.3.

Figure 14.3 shows the duration of the AP between 12 and 13 days for the best Dutch tomato cultivar compared to the worst Dutch cultivar with an AP duration varying between 1 and 3 days. Four scenarios depicted as horizontal bars are shown starting at day 0 (harvest). The colors indicate the different chain temperatures the tomato batch experiences throughout the chain. It is clear that a short AP (lower plot) results in a batch that is still unacceptable at the moment the batch hits the shelf. In most cases the tomatoes are far from optimal when displayed to the consumer. Except in Scenario 3 (whole chain at 25 °C), where the tomatoes are mainly overripe when the consumer can buy them. The only case that we have a good match is in scenario 4 when the tomatoes are harvested in the pink stage of maturity. It is clear that if tomatoes have a short AP duration this demands high precision chain management. This situation could be dealt with, but that would mean an exact knowledge of all chain conditions ahead of time and adapt accordingly. These are, for now, unrealistic in fast flowing high volume chains like tomato chains. Even for the best Dutch cultivar (upper plot) suboptimal chain performance may occur. As we see in scenario 1 the chain is too short for the AP. A proper logistic decision in this case would be to store the tomatoes or keep them at a higher temperature to make sure they reach the shelf in an optimal state. Scenario 3, at 25 °C, shows that part of the AP is lost due to early ripening within the chain. A proper logistic decision would be here to lower the chain temperature.

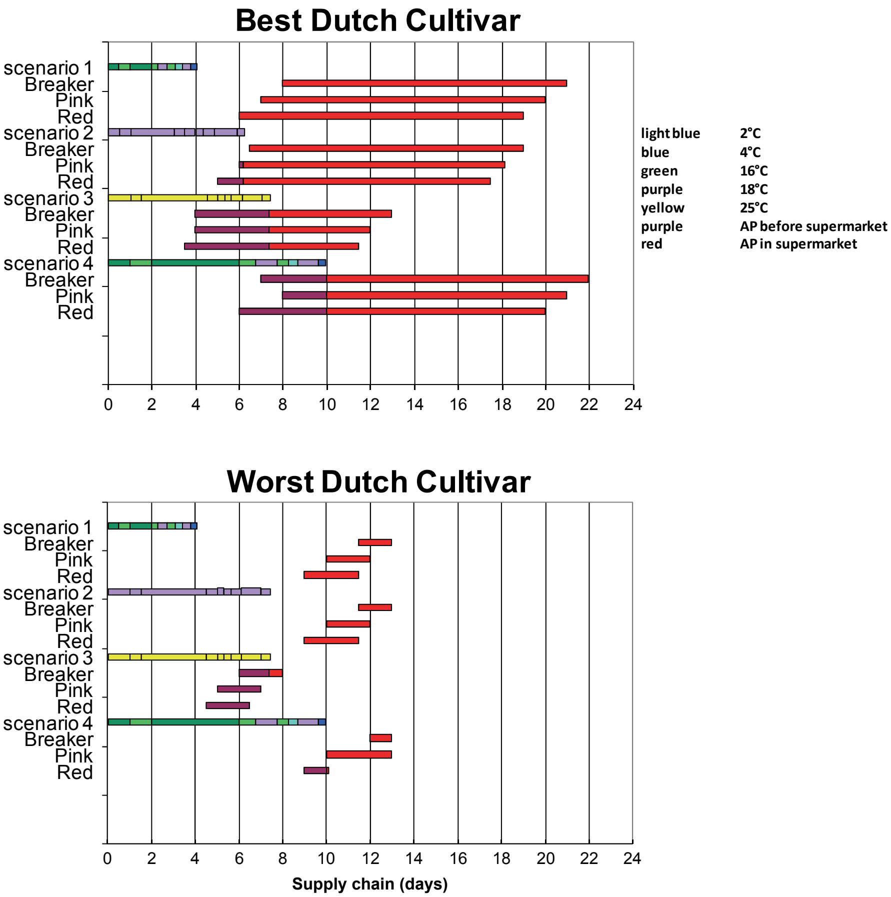


**Fig. 14.3** Scenario analysis of the best and worst Dutch tomato cultivar with regard to the start and the duration of the acceptance period. (Schouten et al. 2010)

Table 14.2 presents an overview of improvement opportunities when implementing the QCL concept in the tomato and mango supply chains.

## Case Study in the Mango Supply Chain

### *The Mango Supply Chain*

Typically, mango fruits are picked in an unripe stage in tropical or sub-tropical countries and cooled during weeks of sea transport in reefers to slow down the ripening process. Most mangoes are harvested when they reach a sufficient size

**Table 14.2** Overview of identified improvement opportunities in real life tomato and mango supply chains

| | QCL element | Improvement opportunity in the chain |
|---|---|---|
| 1. | Consumer preferences & AP | Different market segments and its customer requirements should be identified. Next, the APs for these specific markets should be determined |
| 2. | Critical quality points (CQP) | More insight should be gathered on the CQPs<br>Transport conditions such as temperature need to be set. This setting depends again on the travel/ storage time and how far the products need to be developed at the retailer |
| 3. | Product quality measurement and prediction | Different quality classes are defined with help of procedures and standards, such as colour scale card for manual grading. Batches should get their own ID code showing quality score<br>As the product arrives at wholesaler site, there should be advanced measurements of products quality<br>Regular monitoring should take place to adjust product offerings related to APs<br>Predictive models of product quality at the grower should be used to support the decision to harvest products at a certain stage and time |
| 4. | Data logging and exchange of information | Detailed information on quality status of cargo and environmental conditions should be registered and communicated to chain partners using information standards and data loggers. Then all chain partners know now the origin, quality level, the storage and travel conditions of that particular batch including the quality development<br>Retailers should predict demand and pass this information to other chain actors enabling responsive demand driven logistics |
| 5. | Local dynamic/adaptive logistics and quality control | Products should be harvested in uniform stage of maturity for specific market segments. If there is variation in the harvested fruits, sorting and grading on products should result in classified batches based on their quality level<br>With the help of the different quality classes harvested, a planning/prediction can be made about how fast the product needs to go from the grower to wholesaler and also the conditions (such as temperature) needed to maintain or change the quality<br>Inventories should be managed and allocated to customers based on quality category |
| 6. | AgriFood Supply Chain Management | With support of information about APs and real product quality (using predictive models), the environmental conditions needed should be adjusted in the chain according to wished final development/maturity stage of fruit at arrival<br>Quality levels of product batches and their related AP should be considered when applying SCM practices in order to deliver the right amount of product at right place at right time with the right quality. The products must be in the right stage of development and maintained at appropriate temperature to be able to present within the acceptance period by the time they arrive at retailers |

**Fig. 14.4** Supply chain for mangoes in the Netherlands

and are subsequently sorted on skin colour and size. Within these harvested fruits significant variation in the maturity at harvest exists, varying from immature to mature enough to ripen. Harvesting too early will result in tropical fruits sensitive to chilling injury during sea transport (Gonzalez-Aguilar et al. 2000) and will not ripen properly resulting in poor consumer quality. Harvesting tropical fruits just before the onset of ripening is crucial in determining eating quality (Brecht and Yahia 2009). Harvested too late will result in tropical fruit that either cannot withstand postharvest handling or will be overripe when arriving in Europe to be discarded in the last part of the supply chain. In total, losses due to no ripening and over ripe mangoes are very variable but can surmount to 30–50 %. Immature or overripe fruits that are sold to the consumer will create a disappointment. If these disappointments occur regularly, this will have a strong influence on the buying behaviour. This, in turn results in a lower turnover and a lower willingness to pay an appropriate price (Schepers and Van Kooten 2006). Figure 14.4 shows a simplified mango supply chain in The Netherlands.

Tropical fresh fruits take up a significant part of the fruit and vegetable segment in supermarkets. Turnover of tropical fruits in Dutch supermarkets rises every year and have now a share close to 10 % of the total fruit turnover in supermarkets. The main reason for the rapid increase in turnover of mango is the introduction of the Ready To Eat (RTE) concept that resulted in a yearly increasing mango sales volume at a 50 % increase price. The RTE concept is based on manipulation of the ripening process of tropical fruit that have been transported for 2–3 weeks in sea containers. The RTE concept at wholesalers involves storage for typically a few days at 21–23 °C. After storage the tropical fruit may be returned for additional time in the ripening chambers or packaged and marketed as RTE. An increasing percentage (up to 50 %) of tropical fruit is ripened and marketed as RTE for domestic consumption. Dutch wholesalers are increasingly ripening for Scandinavian and middle European markers. The RTE concept adds value to the fresh fruit chain resulting in increased consumer sales and minimised product waste.

## *Mango Quality*

Apart from blemishes and size, firmness is considered to be the most important quality attribute and varies widely between batches of mangoes arriving in the Netherlands. Within and between batches there is a large variation in firmness because of their agronomic history and harvest stage. Manipulating postharvest conditions is, next to switching of cultivars and origins, the key to produce RTE mangoes in the retail shelves. Interacting factors are involved in the ripening of mangoes, which

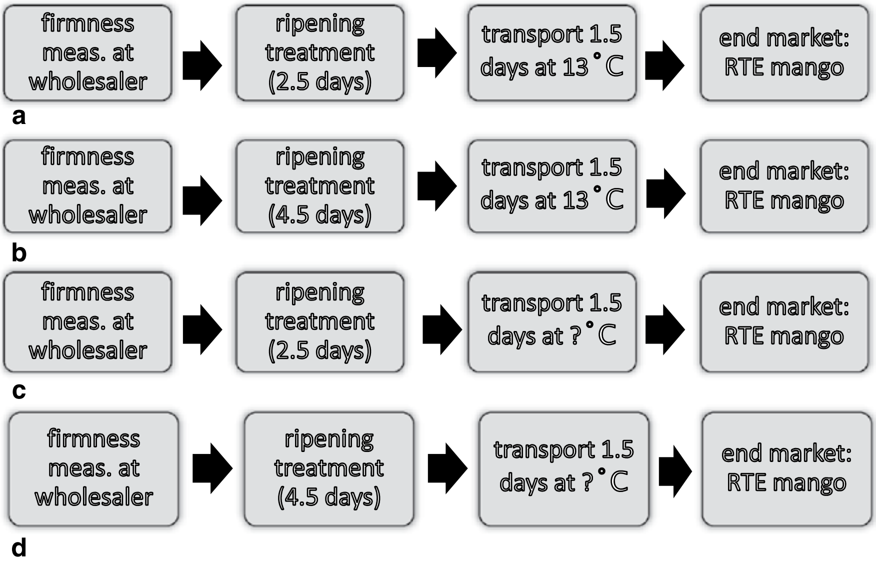


**Fig. 14.5** Four RTE mango scenarios

makes good decision making complex. Temperature is the most important factor regarding softening of the mangoes, but also ethylene as mangoes are classified as being sensitive to this ripening hormone (Mattoo and Modi 1969).

## *QCL Analysis in the Mango Supply Chain*

Consumer acceptance limits were determined by measuring firmness of mangoes and subsequent sensorial scoring of these mangoes into classes such as ‘unripe’, ‘unripe/RTE’, ‘RTE’, and ‘RTE/override’. Based on a kinetic firmness model, calibrated on acoustic firmness measurements gathered at different temperatures, predictions on the development of mango firmness through time at different temperatures could be established. By combining this calibrated model with the acceptance limits it becomes possible to predict the acceptance period, meaning the time it takes to become RTE until overripe.

Four RTE chains (A-D), from wholesaler to supermarket, were simulated as function of ripening time and ripening temperature based on the initial firmness (measured acoustically), consumer acceptance limits and length of the chain (Fig. 14.5). The duration of the chain was based on the time the mangoes will be at the wholesaler and the transportation time. The transportation time was based on a chain from a Dutch wholesaler to a middle-European country and was determined at 1.5 days. Ripening treatment at the retailer was either 2.5 or 4.5 days. Nowadays mangoes are transported under low temperature conditions (10–13 °C). This low temperature transport has several disadvantages: cooling during transport is expen-

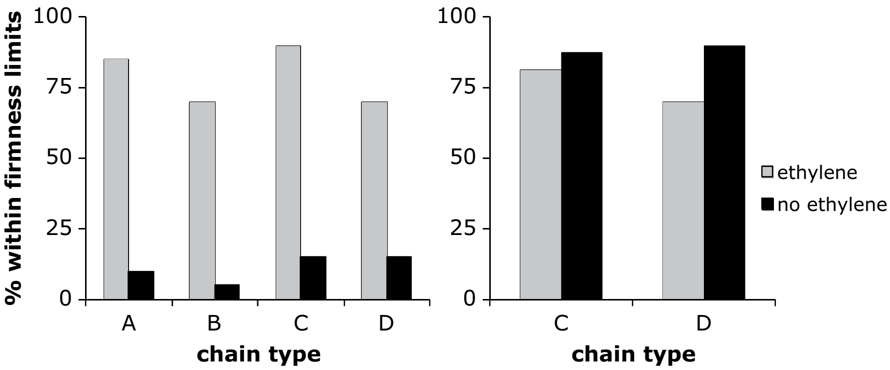


**Fig. 14.6** RTE Performance using four chain scenarios (batch 1, *left hand side* plot) or two chain scenarios (batch 2, *right hand side* plot)

sive, mangoes could be suffering from chilling injury during transport and further ripening during transport is not possible. This last point could be very useful when the transportation time between the wholesaler and the end market is quite long. Ripening rooms could be limiting at the wholesaler by ripening during transport the throughput rate at the wholesaler could be increased. Therefore two of the four chain scenarios have variable transport temperatures, this allows for the mangoes to ripen further during transport.

Mangoes of batch 1 (origin Israel) were sorted on firmness at arrival at the wholesaler and gathered in four sub-batches for batch 1. Mangoes in the sub-batch with the lowest firmness were used for scenario A; mangoes in the sub-batch with the second lowest firmness were used for scenario B etc. Mangoes of batch 2 (origin Brazil) were treated the same, but now only two scenarios were simulated, scenario C and D. Half of the mangoes in every sub-batch were exposed to high levels of ethylene, the other half were not exposed. Ripening (between 17 and 20 °C) and transport temperatures (between 13 and 20 °C) were calculated using the mango acceptance model. Some of the results are depicted in Fig. 14.6, showing the percentage of the fruits within the established consumer acceptance limits at the end of the chain. For all the batches the number of fruits within the acceptance limits is around 80 % when ethylene is used. These are promising results and can be transformed into a ripening protocol.

An integrated overview of improvement opportunities when implementing the QCL concept in the tomato and mango supply chain is presented in Table 14.2.

## Conclusions

Operations management in FSCN usually takes quality as given; if one approaches product quality as a dynamic issue and uses time dependent quality information more degrees of freedom come to the forefront that will improve supply chain performance significantly. We have introduced a new concept called Quality Controlled Logistics that provides means to optimize product quality and product availability in market outlets concurrently and minimizes shrinkage. Using time dependent quality information and quality change models we can now predict product quality in much more detail enabling us to adaptive control of supply chain processes and direct specific products batches—under specific environmental conditions—to specific market segments. Case studies show that QCL offers new possibilities to improve supply chain performance for fresh products. Future research aims for the further development of the diagnostic instrument and the quantification of costs and performance improvements of QCL scenarios in multiple cases.

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# Chapter 15
# Environmental Impact of Production Horticulture

**Henry Wainwright, Charlotte Jordan and Harry Day**

**Abstract** Horticultural production is primarily involved in the intensive use of resources, such as land, water, labour and inputs such as fertilisers and pesticides. The use of such resources in a concentrated space and time has the potential to negatively impact on the local environment and worker welfare. In addition the transport of horticultural produce over long distances, particularly by air transport is known to have an impact on the global environment. The first part of the chapter outlines these threats to the environment that intensive horticulture presents and how the understanding of wider issues relating to the environment has developed over recent years. Then the methods of analysing the impact of horticulture on the environment are considered including environmental impact assessments and Life Cycle Assessment. In the second part of the chapter, the methods and strategies that are being used to minimise the effect of production on environmental degradation are considered. This includes legislation and Private Voluntary Standards such as GLOBALGAP that have incorporated environmental standards into their remit. The use of technologies that have been used to mitigate the impact of horticultural production on the environment are highlighted including greenhouse technologies, soil protection and conservation, optimal fertiliser use and Integrated Pest Management. The chapter concludes with a case study that examines the production of cut flowers in Kenya and the associated costs of air freight around the globe.

**Keywords** Horticulture · Environment · Integrated pest management · Sustainable resource management · Environmental impact assessment

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## Introduction

Horticultural production is primarily involved in the intensive use of resources, such as land, water, labour and inputs such as fertilisers and pesticides. The use of such resources in a concentrated space and time has the potential to negatively impact on the local environment and worker welfare. In addition the transport of horticultural produce over long distances, particularly by air transport, and reported in term of food miles, is known to have a negative contribution to the global environment.

## Environmental Threats

### *Land*

Land occupied by the horticultural industry is limited and to sustain crop productivity it is essential that it is maintained as a fertile and productive resource. Intensive agricultural and horticultural practices over the twentieth century, coupled with growing greenhouse production, have dramatically impacted on the horticultural landscape. Land and soil degradation caused by erosion (wind and water), organic matter decline, compaction, salinization, reduced fertility and pollution all have the potential of environmental mismanagement within horticulture. This in turn leads to degradation and as a result impede on the biosecurity of future production.

Maintaining and improving fertility is critical to increasing yield; stagnant or decreasing crop yields and per capita food production in Sub-Saharan Africa (SSA) are primarily derived from lack of soil fertility (Henao and Baanante 2006). Fertility, amongst other important soil characteristics, is affected by soil degradation, the most common cause being erosion. It can occur in horticulture if large, open fields are unprotected from wind erosion, or by flood irrigation carrying topsoil off fields with little or no crop cover. Bridges and Van Baren (1997) state that the erosion of 1 cm $ha^{-1}$ of topsoil equates to a loss of between 100–150 t of soil. Every 100 t lost carries with it 2000–2500 kg $ha^{-1}$ of humus, approximately 200 kg $ha^{-1}$ of nitrogen, 100 kg $ha^{-1}$ of phosphate and 500–1000 kg $ha^{-1}$ of potash. Poor soil quality for food producers results in 10 million ha of cropland being abandoned annually due to soil erosion (Pimentel 2006). In addition the replenishment of the soil with lost nutrients and organic matter is a lengthy and complicated process.

### *Water*

Agriculture and horticulture combined is the largest user of freshwater, accounting for 70 % of all bluewater withdrawals (Fischer et al. 2007) worldwide and is mainly used for irrigation. Climate change and population predictions warn of a global reduction in freshwater availability and an increase in demand (Falloon and Betts 2010). By 2030 there is an expected 40 % shortfall between supply and demand for freshwater (Anon 2012a). As the majority of horticultural crops are irrigated, the industry contributes to water scarcity problems and carries a responsibility to reduce water use and causes of contamination.

## *Labour*

An important feature of horticultural enterprises is their intensive use of labour. Economic migration to concentrated areas of horticultural activity benefits communities in terms of high employment rates but simultaneously increases demand on natural resources and social infrastructure. Rapid population growth resulting from expansion of the floriculture industry in Lake Naivasha, Kenya has caused unregulated urbanisation, decreased the quality of peri-urban land, overloaded sewage systems and increased local pollution. Excessive extraction of water from the lake for industrial and residential use has contributed in association with a drought to a decline in water levels. In 2010 the lake receded to its lowest recorded level since the 1940s (Harper et al. 2011). Over-exploitation of the water resource is contributing to reduced biodiversity, threatening future water security and local ecosystems which are already endangered by the introduction of invasive species.

## *Fertilisers*

Intensive crop production requires higher levels of inorganic fertilisers. As horticultural crops are usually high value, the relative cost of these inputs to producers is less important and as a result they may be applied in excess; consequently increasing the risk of land and water pollution.

A central environmental impact on water quality and human health is excessive nitrate levels. Nitrogen fertilisers which leach into the ground and runoff into water courses contaminate surface water. Excessive nitrate ($NO_3$) in drinking water is associated with an illness of infants under 6 months' old called methemoglobinemia or "blue-baby" syndrome (Knobeloch et al. 2000). However no cases have been reported in the United Kingdom since 1972.

Another process is eutrophication which often takes place when contamination from nitrate and phosphate fertilisers occurs in aquatic ecosystems, both fresh and saltwater. The process derives from increased algal production accelerated by elevated nitrogen deposits (including nitrate and ammonia) within the water. This can cause hypoxia- suffocation- of aquatic life beneath the water surface, disrupting bio diverse ecosystems and promoting the development of nuisance algae (National Research Council 2000).

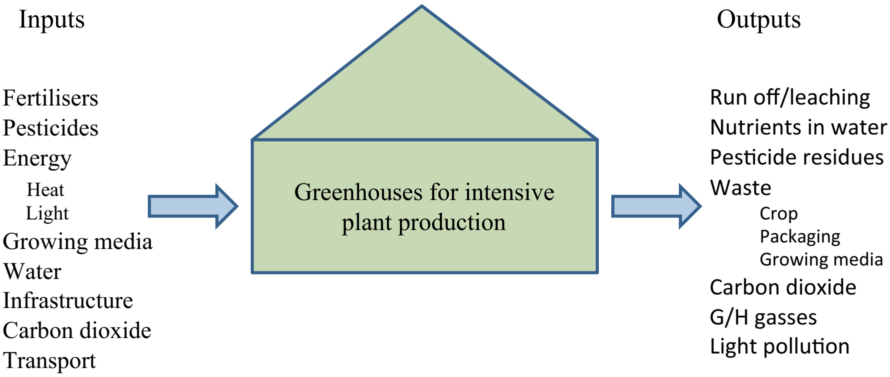


**Fig. 15.1** Schematic representation of the inputs and outputs that have the potential to have an environmental impact from a greenhouse in northern Europe

## *Pesticides*

Of all the resources and inputs used by the horticultural industry the use of pesticides has been perceived as the greatest direct threat to both humans and the environment. This concern dates back to the publication of *Silent Spring* (Carson 1962) which has been widely credited with launching the environmental movement and making people more aware of their environment. However since then there has been an increasing awareness of the impact of relatively small quantities of pesticides can have on food chains and to the complex interactions in the environment.

Chemical pesticides are grouped as either generalists or specialists, providing broad-spectrum or targeted control respectively. Environmental problems, particularly loss of biodiversity, occur from the use of both groups. Generalists threaten the population of non-target species including beneficial predators and parasitoids or important pollinators, whilst specialists often contribute to a population build-up of resistant target pests, and shorten the effective life-span of the chemical active ingredient.

## *Greenhouses*

Whilst horticultural production within greenhouses is highly economically efficient, greenhouses pose particular environmental threats because they are the most intensive users of resources. There are over 800,000 ha of greenhouses globally and can be subdivided into two types; the ‘northern’ type, typically glasshouses with heating and generally a high content of technology, and the ‘southern’ type, plastic-covered houses with simple or no heating systems and a low level of technical complexity (Bergstrand 2010). The type of resources greenhouses use and the threats they pose to the environment are represented diagrammatically in Fig. 15.1.

Northern greenhouses have a significantly higher rate of $CO_2$ emissions than field grown crops or southern greenhouses. This is due to the combustion of natural gas for heating and artificially raising $CO_2$ concentrations within the greenhouse. Dutch greenhouse horticulture for example accounts for 79 % of all energy use in Dutch agriculture (Lansink and Bezlepkin 2003).

Unheated "southern" type greenhouses pose significant environmental threats. Almería province in semi-arid southern Spain is Europe's largest provider of greenhouse-grown fruit and vegetables with approximately 50,000 ha of greenhouses under production. The horticultural industry in the region provides considerable regional economic growth but production in this area has posed extensive local environmental threats. Greenhouse horticulture on this scale has rapidly depleted surface water and freshwater aquifers, subsequently replenished by seawater creating salinization of land and water. Intensive levels of biocide and fertiliser inputs also have also added to the degradation of land and water quality, causing high levels of eutrophication and reducing biodiversity in nearby aquatic ecosystems (Wolosin 2006).

## Global Warming and Climate Change

The contribution made by horticulture to global warming and climate change is through the processes of energy combustion, transportation, refrigerated storage and inorganic inputs. The effects of the environmental impact of horticulture production are entering a cyclical relationship with the impact on horticulture from environmental change.

For instance the production methods for inorganic fertilisers are extremely energy intensive. The Harber-Bosch process used to create nitrogen fertiliser has increased the quantity of nitrous oxide ($N_20$) within the nitrogen cycle, contributing to global warming as its global warming potential is 298 carbon dioxide equivalent ($CO_2$e). It has been calculated that this production system, along with other industrial processes, has doubled the supply of reactive nitrogen within the global environment.

Increased globalisation has led to greater travel and increased knowledge and desire of exotic foods; consequently international trade in fresh horticultural commodities and their subsequent consumption has increased. Transporting fresh horticultural produce around the global by air has led to concern about the sustainability of agricultural and food systems. Air freight accounts for 2.1 million t of $CO_2$e emissions in the UK – a mere 0.2 % of total UK $CO_2$e emissions, but the rate of growth accelerated between 1992 and 2002 when air freighted food produce grew by 140 % (Watkiss 2005). The $CO_2$e is a measure of how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide ($CO_2$) as the base reference. This trend has been encouraged by a liberalising international and national regulatory framework, the policies of organisations such as the World Trade Organisation (WTO) and the World Bank.

## Environmental Management and Methods for Analysis

Though limited, the totality of horticulture has an impact on the environment. To control and reduce environmental impacts of a process, service or product, it is important to measure or predict its impact. There are various environmental management tools and methodologies which quantify and control environmental impact.

### *Environmental Management Systems*

Environmental Management Systems (EMS) are intended to control resource management by setting objectives, policy and targets. They have received a considerable amount of attention, between 2003 and 2007, when the Australian government set up a fund of $AUD 8.5 m to encourage a voluntary form of farm-based EMS, which yielded mixed results (Cary and Roberts 2011). However, a more recent Department of Environment, Food and Rural Affairs (DEFRA) study in the UK found that a third of small and medium sized enterprises (SMEs) with certified EMS enjoyed an average value of £ 4,875 per £ 1 m turnover in the year subsequent to accreditation. This implies a payback period of 1 month against the costs of setting up an EMS (Burr and Hillary 2011).

The most popular standard that EMS is tested against is ISO 14001, with 270,000 certifications awarded worldwide. However Gunningham (2007) states that because the standard is process based, it does not guarantee environmental performance outcomes.

## Environmental Impact Assessment

An Environmental Impact Assessment (EIA) is an influential and diverse tool. EIAs are carried out to ascertain the impacts of a proposed process. Typically it is a legislative requirement for projects of a certain size. There are certain properties of a proposed development that would trigger an EIA Schedule 1 or 2 (Anon 2011a).

The assessment enables developers and the local community to inspect the environmental impacts (or aspects) of a proposed development. A project's impact on water, land, wildlife and emissions are quantified and scrutinised by qualified environmental impact assessment practitioners. Other types of development that have significant effects on the environment will have to carry out a study to decide whether a full EIA is required. Any form of development has to show that it has considered alternatives where there is a negative environmental effect.

**Table 15.1** Greenhouse gases' global warming potential when expressed as a factor of carbon dioxide (whose GWP is standardized to 1)

| Green House Gas (GHG) | Global Warming Potential (GWP) |
|---|---|
| $CO_2$ (carbon dioxide) | 1 |
| $CH_4$ (methane) | 25 |
| $N_2O$ (nitrous oxide) | 298 |

## *Life Cycle Assessment*

The International Standards Organisation defines Life Cycle Assessment (LCA) as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (Anon 2006). LCA quantifies the environmental burdens of a product or service during its lifetime. This tool has recently gained significant ground and has been largely accepted by the scientific community (Ingram and Fernandez 2012). Conducting an LCA can aid in the creation of a robust benchmark to reduce Green House Gases (GHG) emissions, whilst employing LCA to identify inputs with large environmental burdens used in a process, for example potential pesticide pollution or the breakdown rate of plastic propagation bags in the environment. LCAs are key to good environmental management and in reducing GHG emissions and its impact on global warming.

There are several aspects to calculating a 'footprint' of a process. Calculating an environmental footprint enables stakeholders, for example, growers, legislative bodies or consumers, to be able to quantify and compare a product's impact with another. Carbon foot printing is one of the principal and most common elements of LCA. It quantifies the GHG emitted by a product or service (Anon 2011). Carbon footprints are expressed in kilograms of $CO_2$e. This allows other GHGs to be compared and measured on the same level (Table 15.1). An inventory analysis is a fundamental element of LCA. Figure 15.2 provides a schematic representation of a Life Cycle Assessment, showing how inputs and outputs impact within a predefined boundary.

Ingram and Fernandez (2012) state that carrying out an LCA on horticultural processes is difficult to access because of the little information regarding the "diverse yet specific set of inputs" associated with horticulture. For example they illustrate that there is a variation of 85 % in the carbon footprint between ammonium nitrate and urea used in horticultural production.

## Environmental Footprint

Additionally, when compared with other food production systems such as livestock and arable agricultural land, there has been limited investigation on the environmental and social impact of production horticulture. A study in the UK by Lillywhite et al. (2007) commissioned by DEFRA, constructed environmental footprints for 12

**Fig. 15.2** Intensive use of resources for the production of roses as a cut flower

commodities on a per hectare, per year basis. The higher the value, the greater the environmental impact (results in brackets, ranked low to high):

winter wheat (11.5)
sugar beet (18.3)
lamb (18.4)
carrot (19.3)
cauliflower (20.3)
onion (20.3)
Narcissus (22.3)
potato (27.1)
apple (29.2)
milk (34.6)
protected strawberry (54.9)
protected lettuce (59.1)

Those crops/commodities which required infrastructure, such as protected lettuce and strawberry production, have large environmental footprints as do those, such as milk, that emit vast quantities of GHGs. Field grown crops on average recorded low scores, although potato tends to have higher footprints due to increased water and storage costs. However because of the size of the horticultural industry the impact of horticulture in total was low in comparison to the total environmental burden.

The total environmental burden assessed in this project can be broken by commodity into dairy (44 %), lamb (28 %), winter wheat (21 %), other arable crops (6 %) and horticulture (1 %) based on toxicity and quantity of pesticides used, global warming potential, eutrophication and acidification potential, water and labour as indicators of the ecological footprint.

### *Footprint Analysis*

The term footprint analysis is not dissimilar to LCA. It is widely used term and methodology in relation to $CO^2$ production and water use, e.g. carbon footprint or water footprint. An example of the method used is described in The Water Footprint Assessment Manual: Setting the Global Standard (Hoekstra 2011). This manual sets out the scientific basis for calculating how much freshwater is used in the production of a crop. This allows the user to understand how much water can be used and where savings can be made.

### *Strategies to Minimise Horticulture's Impact on the Environment*

The strategies developed to manage the potential environmental threat from horticultural production and marketing have been determined by two major forces, legislation and private voluntary standards as described below.

### *Legislation*

National and international legislation to protect the environment is now well developed and integral part of the management of horticultural enterprises. To illustrate this positive trend the number of European Union (EU) Directives that relate to the environment and crop production are listed in Table 15.2.

### *Private Voluntary Standards*

Private Voluntary Standards (PVS) are set by the food-producing industry and retailers. These standards require growers to comply with Good Agricultural Practice (G.A.P.), including environmental protection that is independently certified. Examples can be found on GLOBALGAP's web site (www.globalgap.org). Interestingly, the influence of PVS on how horticultural production impacts on the environment have probably had a greater effect than any legislation. There are now nearly 400 private standards governing the food industry in operation in Europe with the complication and financial cost of compliance is of major concern to the horticultural industry (Borot de Battislini et al. 2009). Any single large scale grower, for example in Kenya, may have to comply with over ten different PVS including GLOBALGAP, Fair Trade, Linking the Environment and Farming (LEAF), Rainforest Alliance, Ethical Trade Initiative, Utz Certified, various organic standards, as well as the numerous individual food retailer standards such as Nature's Choice, and Field to Fork when it comes to horticultural food processing.

**Table 15.2** Examples of EU Directives that have an impact on horticultural production and environmental protection. (Source: Anon 2012b)

| EU Directive | Reference | Topic related to Environment |
|---|---|---|
| Birds | 2009/147/EC | The conservation of wild birds |
| Sustainable Use of Pesticides | 2009/128/EC | The approval and application of pesticides |
| Inland transport of dangerous goods | 2008/68/EC | Safe transportation of pesticides |
| Integrated Pollution Prevention and Control | 2008/1/EC | Integrated Pollution Prevention and Control |
| Groundwater | 2006/118/EC | Controlling the pollution of lakes and rivers |
| Maximum levels for pesticide residues | 2000/42/EC | Establishes MRL on food crops |
| Dangerous Preparations | 1999/45/EC | The classification packaging, and labeling of pesticides and hazardous substances |
| The Drinking Water | 98/83/EC | Safe drinking water. E.g. Setting a limit of 1 part per 10,000 million of any pesticide in water |
| Environmental Impact Assessment | 85/337/EEC | Impact assessment of developments |

## *Technologies for Reducing Environmental Impact*

One of the major ways horticultural producers reduce their impact on the environment is through the adoption of technical solutions and the use of best practice. These are many and varied and too extensive to describe fully, however the following are a few examples of how growers have adopted innovative solutions to reduce the environment risk of their operations.

## *Greenhouse technologies*

As greenhouses are responsible for the largest levels of $CO_2$ emissions within horticulture, energy conservation and efficiency must be optimised to reduce current levels. There are significant financial incentives to promote greenhouse energy reduction. One example is a recent report (Anon 2012a) which found that a 20 % reduction in energy cost represents an equivalent bottom line benefit of 5 % increase in sales. The Carbon Trust makes simple recommendations to producers on how to improve energy efficiency for heating greenhouses, which include for example, the insulation of boilers, pipes and hot water tanks, the instalment and regular updating of control systems for heating timers, the use of open external doors only when necessary, and the use of thermal screens and well-sealed greenhouses to reduce air leakage. Bergstrand (2010) found that LED lighting technology within greenhouses is continually improving, resulting in higher light intensity, higher efficiency and lower costs.

Water pollution as a result of inorganic fertiliser contamination remains a considerable impact within greenhouse horticulture. Bergstrand (2010) found that the use of closed irrigation systems with biological filtration can reduce the use of water and fertilisers by between 25 and 40 %. Microflora populations in a filtration system can also produce biosurfactants, providing control for zoosporic pathogens such as Phytophthora species.

## *Land*

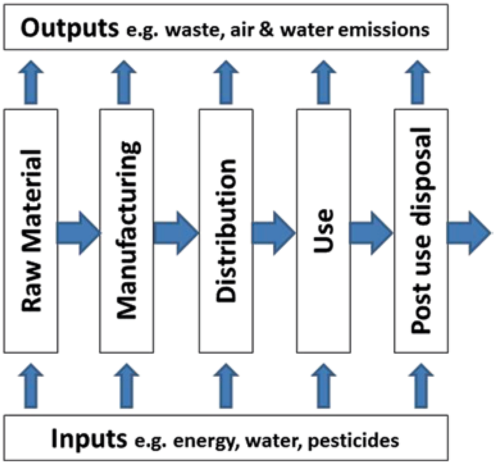
With pressure to increase agricultural land to feed a growing global population and the overall quality of those agricultural lands and soils decreasing, horticultural producers have to strike a delicate balance in coming years. As a large carbon sink, soil has an important role to play in climate mitigation and therefore strategies to support this status are vital. Soil is most at risk from nutrient depletion and erosion when no crop cover exists, therefore a continuous cover crop will go some way to protect soil structure, texture and fertility. The residue of horticultural crops that have been harvested should be left in the ground during a usual fallow period, providing bird habitat, weed and insect control until replanting. Ramos et al. (2010) list a number of benefits to cover cropping which includes holding the soil with root systems, increasing soil organic matter, improving soil aggregation and increased microbial activity. Conservation or low soil tillage is another method that preserves soil nutrients and organic matter from exposure to erosion and depletion.

An important method to protect soil within horticulture is to reduce the dependency on inorganic fertilisers which artificially alter soil composition and contribute to longer-term soil degradation and reduced natural fertility. Another alternative technology includes rotation cropping, in which crops extract differing quantities of macro and micro-nutrients at different stages, allowing natural build-up of important nutrients. An additional advantage is biological pest and disease control, in which the life cycle of certain pests and pathogens are broken and future outbreak problems reduced.

## *Water*

Water is a vital resource to horticultural production and the security of supply across the global is decreasing. Many current irrigation methods are inefficient. It is estimated that only half of total water withdrawal is utilised by the intended crop, the remainder being wasted along the delivery from abstraction to the crop (Knox et al. 2012). Horticulture producers must overcome these challenges to remain profitable in the future (Anon 2003). This can be done by reducing dependence on mains water supply, improving greywater recycling and increasing irrigation efficiency.

**Fig. 15.3** A schematic representation of a Life Cycle Assessment, showing how inputs and outputs interact with the flow of product development



Applying water to crops below their full requirements, or only replacing the equivalent water lost through evapotranspiration, is of increasing interest to the horticultural industry. Known as deficit irrigation, various methods such as Partial Root Drying (PRD) and Regulated Deficit Irrigation (RDI) have been found to encourage both above and below ground biomass through activating water stress survival mechanisms (Wakrim et al. 2005). Sub-optimal water supply can also improve horticultural crop quality (Turner 1990), harden field crops off within the nursery prior to transplantation, reduce dispersal of water-borne diseases and run-off or potential contamination into water courses, and reduce evaporation loss through precision application using drip line irrigation.

## *Wetlands*

Horticultural farms as well as using water for irrigation, also produce significant amount of waste water from their packhouses. Such sources may contain small quantities of detergents, soaps, post-harvest preservatives, dilute pesticides and sterilants. Clearly this water cannot be disposed of directly into water courses yet cleaning such water can be potentially costly. A solution that is increasing in popularity particularly in Kenya is the wetland system. A wetland is a single or series of lagoons that have a gravel base where plants grow. The water passes through the lagoon and is purified by the activity of the bacteria and algae attached to the substrate and the plant roots (Fig. 15.3). The biological processes at work in a wetland are complex and interacting but involve algae, bacteria and plants and the process is also called phytoremediation or bioremediation (Fig. 15.4).

Wetlands come in many shapes and sizes but keys to success are that the water must progress from one end to the other end and not be allowed to “short circuit” the journey through the wetland. Also the water should not be able to pass through

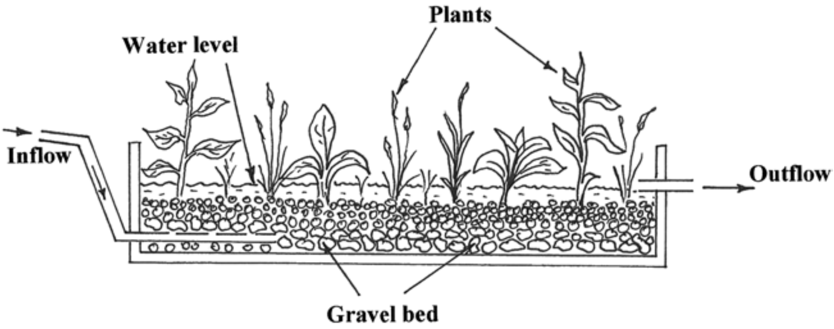


**Fig. 15.4** A schematic representation of a reed bed for the cleaning of waste water (Wainwright 2009)

**Fig. 15.5** A wetland used for cleaning grey water leaving a horticultural pack-house in Kenya

the wetland too quickly. Four days is the minimum period recommended; however this is dependent on many wetland factors such as temperature, type of plants used and degree of pollution in the water. Wetlands are low cost, low maintenance and a natural solution to dirty packhouse water (Wainwright 2009) or other sources of waste water (Fig. 15.5).

## *Fertilisers*

Good Nutrient Management (GNM) is an important method of growing crops without harming the environment or health. Over the last two decades UK farmers have succeeded in increasing yields while reducing the use of fertiliser and the associated greenhouse gas emissions. GNM considers nutrients from all sources and these should balance, but not exceed, the crop requirements. Nutrient sources typically include mineralisation of soil organic matter, gaseous deposits from the atmosphere, biological nitrogen fixation, application of organic manures and the application of manufactured fertilisers. There are many agronomic practices that can influence and maximise the supply of nutrients and the grower should be aware of these and their potential to save money and replace the use of inorganic manufactured fertilisers (DEFRA 2010).

## *Pesticides*

Pesticides are a potential threat to the environment. However their production and use are now controlled by legislation and best practice throughout the world that have the aim of minimising any potential negative effect on the environment or human health. For instance a pesticide has the potential to cause harm even if it is kept in an unopened contained locked away in a store. However the risk of the pesticide causing harm, that is the likelihood is increased considerable if used incorrectly. Considerable efforts are taken to ensure that the risk is minimised by both legislation and codes of practice that growers adopt for the safe use of pesticides. A component of this is through training of those involved in using pesticides such as operators, store owners and advisers. The environmental threat from pesticides can originate from a range of sources and the options for their safe disposal on a farm are well laid out for the UK in the Pesticide Code of Practice (DEFRA 2006). Examples of sources of pesticide contamination include drainage and run-off from dedicated mixing and loading bays, damaged pesticide containers containing concentrate pesticide, dilute pesticide waste, empty waste containers and used Personal Protective Equipment. Codes of Practice such as that published by DEFRA clearly lay out good practice that is designed to safeguard the environment.

## *Integrated Pest Management*

Integrated Pest Management (IPM) is often presented as horticulture’s solution to the threat of pesticides to the environment. There is no globally accepted legal definition of IPM in the same way that organic production is defined. Bajwa and Kogan (2003) reported that 67 different definitions of IPM were proposed between 1959 and 2000. Interestingly when a crop is grown under an “organic” label the consumer is clear of the meaning but if an IPM label were used this would not carry the same degree of clarity. Poncet et al. (2012) discuss fully the dilemma facing the use of IPM terminology. There has been a paradigm shift in the understanding of IPM and this might be a probable explanation of why if we look back there are so many definitions. A recent definition presented encapsulates modern horticulture’s understanding of what IPM means:

> Integrated Pest Management (IPM) is an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties. Pesticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism. Pest control materials are selected and applied in a manner that minimizes risks to human health, beneficial and non-target organisms, and the environment. (Flint 2012).

The recurring theme of more recent IPM definitions is minimising the use of pesticides in crop protection. However IPM does not advocate the non-use of pesticides but that their use needs to be fully justified. With the increased understanding and availability of alternative strategies the need to use pesticides has declined. However the perception that all and any pesticides are dangerous and should be avoided is an oversimplification. There are numerous advantages and the benefits from using pesticides, and these have been reviewed by Cooper and Dobson (2007). Pesticides should be viewed as one of an array of tools available to the grower to produce consistent, high yielding, good quality crops and that they should be used judiciously to ensure safety for the operator, consumer and the environment as part of an IPM programme.

An IPM programme in any crop involves five key steps, these being:

1. Anticipation and planning. Many pests and diseases can be anticipated based on the grower’s historical knowledge, the weather, the pest life cycle, the crop being grown and the location. By planning and anticipating the optimum timing in the use of control strategies maximum control at minimum cost can be achieved.
2. Correctly identification of the pest. This will ensure that the appropriate control strategy or strategies are implemented.
3. Monitoring the pest and the damage. Ascertain if the problem is increasing or decreasing.
4. Action thresholds. At what point does corrective action needed to be taken? At what level is there potential economic damage to the crop that justifies control inputs?
5. Implementing control measures. These can be biological, cultural, physical or the use of a pesticide. However many control measures should be considered at the planning stage as many of these controls are slow to act and may not be suitable or effective in a crisis crop protection strategy.

## Case Study: Flowers from Kenya—A Threat to the Environment?

Floriculture forms the main horticultural industry around Lake Naivasha in Kenya. The production and export of flowers, mainly roses, is often proposed as a threat to the environment. Three aspects of the environmental threat will be briefly considered, firstly the adoption of IPM, then the impact the floriculture industry has had

**Table 15.3** The list of biological control agents with full registration as pest control agents in Kenya. (Source: PCPB (2011))

| Source | Biological Organism | Target pest |
|---|---|---|
| Imported | *Ampelomyces quisqualis* | Powdery and Downy mildew |
| Kenya | *Amblyseius cucumeris* | Thrips in carnations |
| Kenya | *Aphidius transcaspinus* | Aphids |
| Kenya | *Bacillus subtilis* | Powdery Mildew |
| Imported | *Bacillus thuringiensis (var israelensis, kurstaki and aizawai available)* | Caterpillars |
| Imported | *Beauveria bassiana* | Aphids, DBM and sucking insects |
| Imported | *Coccidoxenoides peminulus* | Mealy bug |
| Kenya | *Diglyphus isaea* | Leaf miner |
| Kenya | *Encarsia formusa* | White fly |
| Imported | *Eretnocerus eremicus* | White fly |
| Kenya | *Metarhizium anisopliae* | Mealy bugs |
| Kenya and imported | *Neoseilus californicus* | Red spider mite |
| Imported | *Neoseilus swirskii* | White fly |
| Imported | *Paecilomyces lilacinus* | Nematodes in roses |
| Kenya and imported | *Phytoseiulus persimilis* | Spider mite |
| Kenya | *Steinernema feltiae* | Nematode |
| Kenya | *Trichoderma asperellum* | Root diseases |
| Imported | *Trichoderma harzianum* | Root diseases |
| Imported | *Verticillium lecanii* | White fly |

on Lake Naivasha and its environment, and finally the consideration of air freight of flowers from Kenya to global markets. The adoption of IPM and the reduction in pesticides has been a prominent feature of the Kenyan flower industry (Wainwright and Labuschagne 2009). This is also supported by the number of biological control agents currently approved by government for use in Kenya (Table 15.3). Despite protestations by the popular press there is no scientific evidence that the flower industry has caused pesticide pollution in Lake Naivasha, a freshwater lake in Kenya, lying north-west of Nairobi, outside the town of Naivasha, where the flower industry is based (Fig. 15.6).

The ecology and exploitation of Lake Naivasha in the context of many human activities has been reviewed by Harper et al. (2011). Horticulture is a significant player in the challenges that interface with the lake's ecosystem. There are some 5,000 ha of horticultural production dependant on the fresh water of the lake or surrounding catchment area. Water extraction has increased not only due to horticultural activity but also geothermal power generation, abstraction from rivers in the catchment area, and extraction for several large towns for domestic use. The lake is about a third lower than the predicted level however the nature of the lake has always been considered hydrologically unstable and fluctuated considerable over the last 100 years even before the arrival of the horticulture industry. The success of the horticultural industry has resulted in an increase in human population as a result of employment opportunities.

**Fig. 15.6** *Phytoseiulus persimilis*, a predatory mite for the control of red spider mite that has been a major contribution to the reduction of pesticides in flower production in Kenya

There are many other factors which impact on ecological change that Lake Naivasha has undergone in the last 100 years. The introduction of exotic species, such as the common carp (*Cyprinus carpio*) has resulted in all fish being exotic, the arrival of water hyacinth (*Eichhornia crassipes*) and the oscillating natural flora populations (Harper et al. 2011). The use of geothermal energy generation using the lake water has increased. Introduced in 1981, the first geothermal plant was commissioned and by 1985, a total of 45 megawatt (MW) of electricity was being generated in the area. The increased human activity has also resulted in illegal fishing, cattle access and defecation, and the degradation of the lake shore vegetation. The buffalo population has increased three-fold in the lake zone. Increased small-scale agriculture has contributed to erosion and lake sedimentation. Finally a weakness in the governance of these interacting factors has contributed to the lack of resolution of the challenges facing Lake Naivasha. In 2005 legislation supported the establishment of the Water Resources Management Authority in Kenya and they were charged to form the Lake Naivasha Water Resource Users' Association (LNWRUA). Through the initiative of the LWRUA and others, community based water resource management has led to the successful management of Lake Naivasha water abstraction and pollution. However, the question of alien species has had limited attention (Harper et al 2011). The increased awareness of the lake's challenges with local communities and international organisations is also likely to bring on-going benefit.

The arguments for and against the airfreight of flowers from Kenya are the same irrespective of the country they are being sent to. Airfreight is a contributor to rising levels of GHGs, global warming and climate change. In addition there are arguments that the transport of virtual water from a country such as Kenya may cause drought (Chapagain and Orr 2009). However the position about airfreight and horticultural trade is often misrepresented and over simplified within the environmental debate.

The consumer in Northern Europe who wants to purchase roses as a cut flower has two options. Firstly they can buy those grown locally, which would have been produced in a heated greenhouse, possibly in The Netherlands. Alternatively, they could buy roses grown in Kenya and airfreighted to Europe. Kenya is six times more carbon efficient when it comes to growing roses than The Netherlands, even if the emissions associated with airfreight are included (Edwards-Jones et al. 2008; Wrangler 2006).

To the Kenyan grower, those in Europe who advocate not purchasing Kenyan roses because of airfreight's contribution to global warming seems disingenuous. Firstly the amount of carbon emission that airfreight of fresh fruit and vegetables contributes is as little as 0.1 % of total UK carbon emissions (Garside et al, n.d) and secondly according to the USA Energy Information Administration, the UK emits 8.5 t of $CO_2e$ per person per year whilst the Kenyan emission is 0.3 t of $CO_2e$ per person per year (Anon 2010). However the debate on $CO_2e$ emissions and the "food miles" is important and the comparisons made on the contribution of transporting horticultural produce to global warming is complex, difficult to quantify and needs more research. However there are also wider issues of fair trade, ethical employment, environmental protection and product safety, and through this the consumer can buy with a clear conscience and contribute to the income of many in the developing world (Wainwright 2008).

## Conclusion

The past decade has seen an increasing awareness of man's activities on the planet's environment. The horticultural value chain has affected virtually every aspect of the environment. In addition we have seen greater advances in quantifying the impact of horticultural activity on the environment. By understanding and measuring, then scientists and growers themselves have been able ways to minimise their effect on the environment through the use of technology and management strategies. This is likely to be an on-going scenario. However the climate change we are seeing currently is as a result of practices totally outside horticulture and in future global warming and the environmental impact on horticultural production may be more important than horticulture's impact on the environment.

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