Chapter 6
Citrus Production

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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 7.1×10^6 ha. Brazil (20.2×10^6 t) and China (16.2×10^6 t) continue to be the main producing countries, followed by India (8.6×10^6 t), USA (7.5×10^6 t), México (5.9×10^6 t), Spain (5.0×10^6 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.

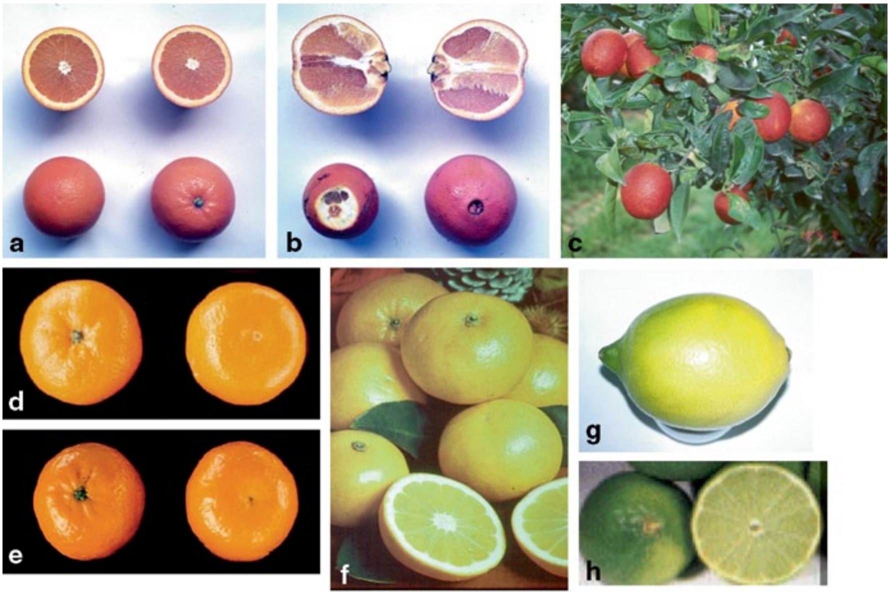

Fig. 6.1 Commercial cultivars of *Citrus* spp. **a** 'Salustina' common sweet orange. **b** 'Washington' navel sweet orange. **c** 'Sanguinelli' blood sweet orange. **d** 'Owari' Satsuma mandarin. **e** 'Clemenules' Clementine mandarin. **f** 'Marsh' grapefruit. **g** 'Eureka' lemon. **h** 'Tahiti' lime

'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

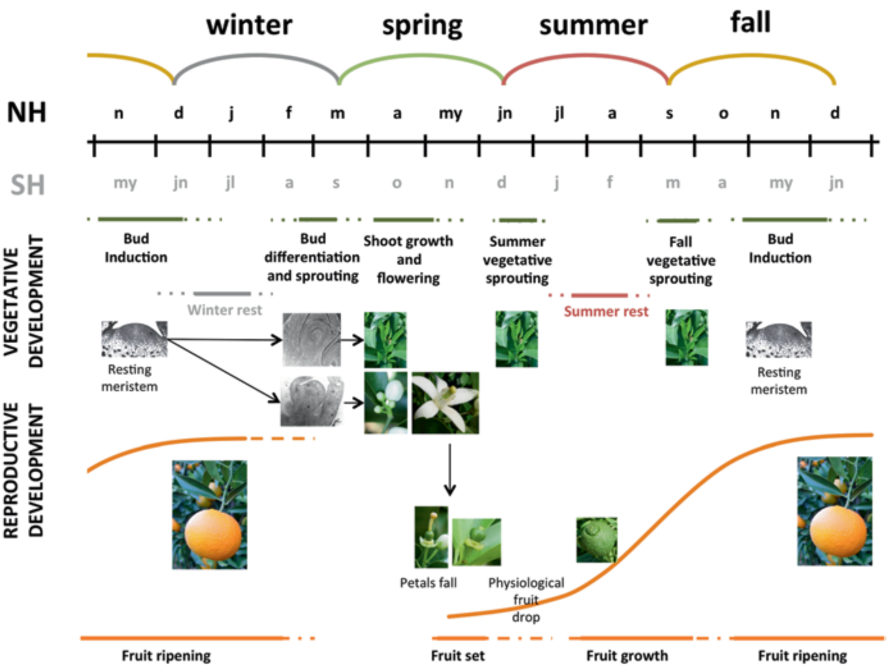

Fig. 6.2 Schematic representation of phenological events occurring during a 1-year developmental period in *Citrus* growing under Mediterranean-type Climate. *NH* northern hemisphere, *SH* southern hemisphere

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.

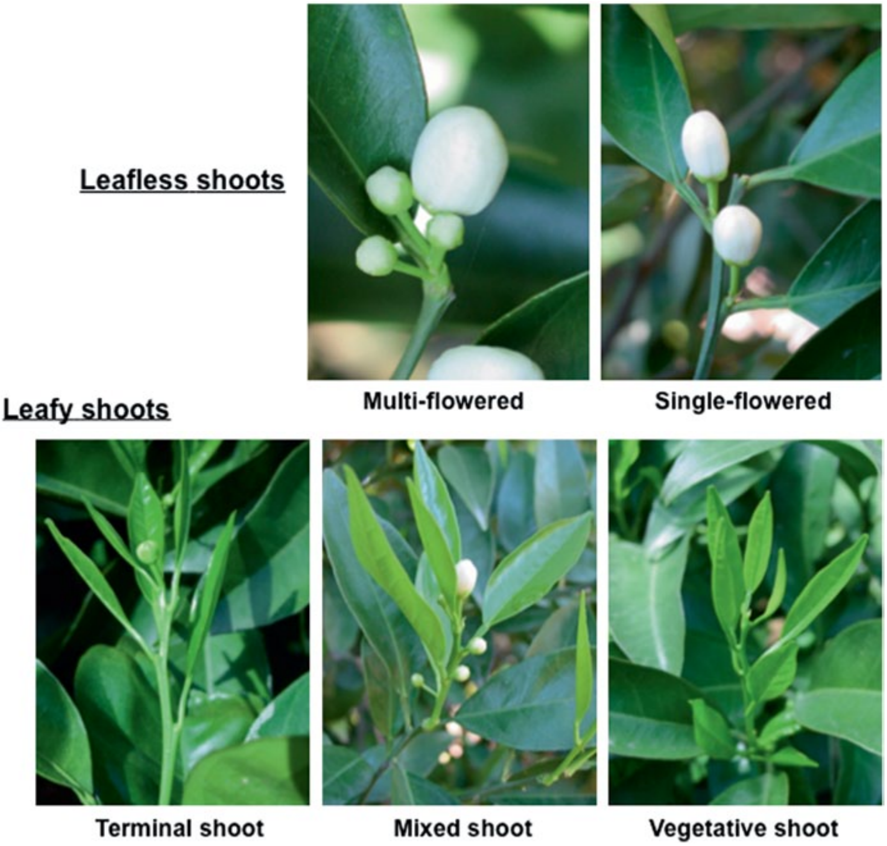

Fig. 6.3 Different type of shoots in *Citrus* according to the number of leaves and flowers

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 ΦPSII. 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

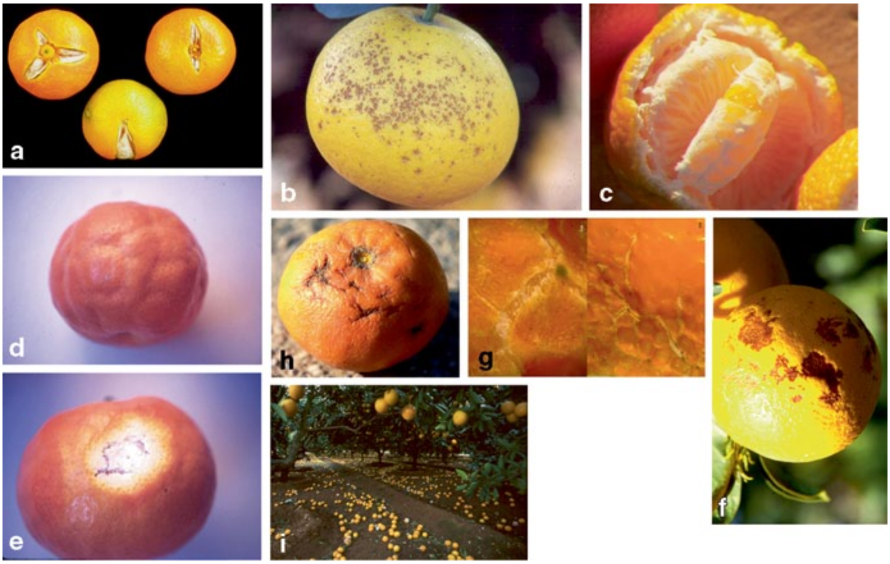

Fig. 6.4 Physiological citrus fruit disorders. **a** *splitting* in 'Nova' mandarin. **b** *peel pitting* in 'Marsh' grapefruit. **c** *Puffing* in Satsuma fruit. **d** *Creasing* in Clementine mandarin. **e** Albedo breakdown in a Clementine fruit showing *creasing*. **f** Navel rind stain. **g** and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