Chapter 6

Citrus rootstocks

Kim D. Bowman[a], **Johan Joubert**[b]

[a]*U.S. Horticultural Research Laboratory, USDA-ARS, Fort Pierce, FL, United States,* [b]*Citrus Research International, Nelspruit, South Africa*

6.1 Introduction

In present day citriculture, trees are almost always propagated by grafting the fruiting cultivar, or the scion, onto a second cultivar that will form the lower trunk and root system. The second cultivar is termed the rootstock, and in most cases, the rootstock cultivar has been created or selected, and evaluated over time for the specific purpose of being used as a rootstock. The current repertoire of citrus rootstocks includes many that appeared naturally, in the distant past or more recently, as well as others that were the result of specialized citrus rootstock breeding programs over the past 100 years. There are some exceptions to the use of rootstocks in growing citrus. But in most cases, trees will be healthier, grow better, fruit at a younger age, and produce more and better quality fruit if they are grafted on a suitable rootstock.

6.2 Reasons for a rootstock

Probably the most important reason to use a rootstock (rather than growing a seedling) for citrus, is that grafting a branch or bud from a fruiting citrus tree onto a rootstock gives the opportunity to quickly produce an unlimited quantity of the original fruiting tree, each one of which will be genetically identical and have essentially the same fruit characteristics. For some types of citrus, including many mandarins, use of grafting (or cuttings) is the only way the trees of a particular desired fruiting type can be propagated, since they do not grow true to type from seed. In theory, the replication of the fruiting variety by grafting the scion onto a separate plant (to be used as the rootstock) can make use of any healthy growing citrus plant as the rootstock. The rootstock can be nearly any age, or any type of citrus, even a seedling of the same variety as the scion. In practice, this rootstock plant is typically a young seedling 4–8 months old of a variety that is known to have good characteristics for use as a rootstock.

Of additional importance, the use of grafting to replicate trees of the fruiting variety will substantially shorten the time to fruiting of the propagated plants, as compared with planting seeds of that fruiting variety. Although cultivars like sweet orange and grapefruit can usually be propagated through seed, and more or less recover the same fruit traits, seedlings of sweet orange and grapefruit typically must reach at least 5 years of age before they begin to fruit, while grafted trees with a scion of that mature fruiting variety on a suitable rootstock will begin to bear good fruit of that variety within 1–3 years. This extended time period that seedlings require to begin fruiting is termed "juvenility," while varieties that have begun to fruit are considered "mature." The importance of this shortening of time to fruiting (avoiding juvenility) cannot be understated in commercial application, as growers can rarely afford to wait many years to obtain the fruit needed to recover a return on their investment. One variant of propagation that may be used to recover the particular fruiting variety with good fidelity, avoid the long juvenile period, and not require a rootstock, is to propagate the scion variety by making stem cuttings. Procedures for the successful use of stem cuttings in citrus have been described (Bowman and Albrecht, 2017), but with only a few exceptions (such as in lime production), graft propagation onto a rootstock is preferred to cutting propagation.

Most citrus trees are grown for the fruit they produce, and the scion variety to be planted is chosen on the basis of the particular combination of fruit traits that is desired for consumption or profit. Most of the fruiting cultivars in high demand do not have the best combination of traits affecting root health, such as tolerance to salinity, high pH, or flooding, and resistance to biotic threats like *Phytophthora* spp. diseases, nematodes, and *Candidatus* Liberibacter asiaticus (*C*Las). Extremes of heat, cold, and wind can also severely damage citrus trees, and choosing the cultivar of the root system separately from the cultivar of the fruiting variety gives the opportunity to optimize the durability and health of the tree root system independently of the characteristics of the fruit. Planting many of the common scion varieties on their own roots often produces a tree with inferior health and durability, as compared with the same scion grafted onto a good rootstock cultivar.

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For example, sweet orange (*Citrus sinensis*) is notably susceptible to *Phytophthora* spp. damage to the lower trunk and root system, often resulting in consequent early tree death when a sweet orange tree is grown on its own roots.

6.3 Important rootstock attributes

The potential benefit of using a cultivar that has been specifically selected for outstanding lower trunk and root traits can be of major importance for the successful growth and production of the resulting trees. The particular traits that are most useful for the rootstock will vary greatly by environmental factors, pest and disease threats, and the management systems that will be employed during the lifetime of the tree. All of these may change over time, even at the same location. In this section, we will briefly discuss some of the more important of the rootstock attributes.

Anchorage. Good physical anchorage of the tree to the ground is a critical trait for good citrus tree health and survival. This may be an especially important rootstock trait in growing areas affected by regular or periodic strong winds (Fig. 6.1). The length, number, and strength of both scaffold and fibrous roots contribute to this physical anchorage, and the root development of all rootstock cultivars is strongly influenced by soil characteristics, tree health (pests and disease effects), as well as the irrigation and fertilization patterns. Even in deep soils and with minimal disease pressure, root systems will develop primarily in the top soil layers, if irrigation water does not penetrate more deeply. Limited information is available that compares root development and anchorage of different rootstock cultivars under a range of biotic and abiotic conditions (Albrecht et al., 2017; Eissenstat, 1991; Eissenstat and Achor, 1999), and typically most rootstocks are considered to provide adequate anchorage if growing conditions provide for good tree health. In the absence of other compromising factors, rootstocks that support more vigorous growth of the scion will typically make the largest and strongest root systems.

Flood/drought. Citrus is grown in a diverse range of environmental conditions, including the extremes of low and high rainfall and soil moisture. In many growing areas, management systems include drainage structures and irrigation systems

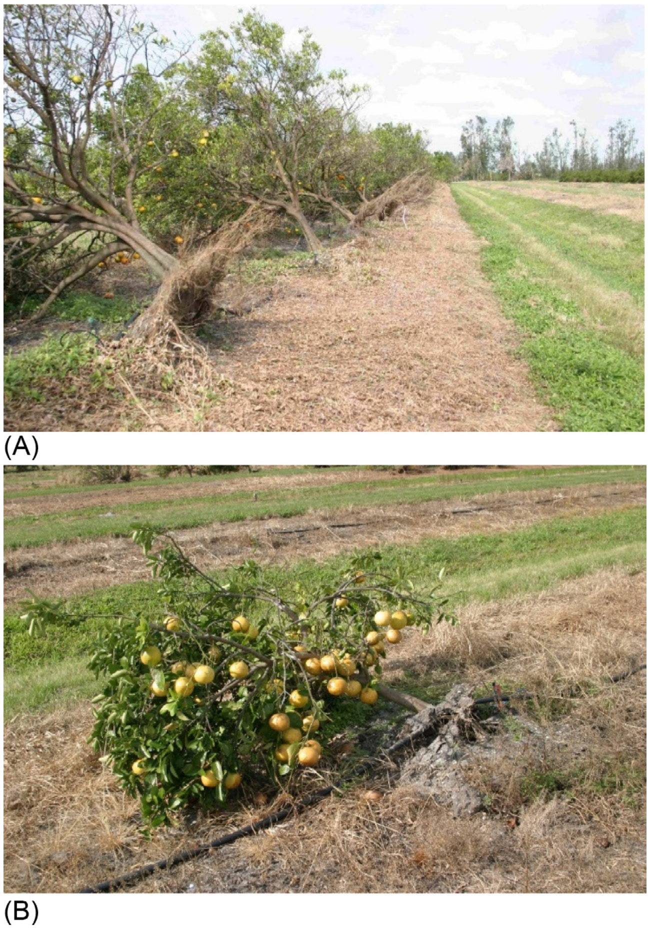

FIG. 6.1 Trees blown over by hurricane Jeanne in Vero Beach, Florida: (A) fourteen-year-old Nova mandarin trees on Cleopatra rootstock; and (B) two-year-old flame red grapefruit tree on Cleopatra rootstock.

to moderate and shorten the duration of flood and drought stress. However, even in areas with drainage and irrigation systems in place, flood or drought may sometimes affect trees. Field observations and studies of the impacts of flooding and drought stress on rootstocks have provided some information about relative rootstock tolerance to these factors (Bhusal et al., 2002; Garcıa-Sanchez et al., 2007; Vu and Yelenosky, 1991). Based on long-term field performance, sour oranges (*Citrus aurantium*) and selections of *Poncirus trifoliata* are typically considered to have good tolerance to wet soil and flooding, while Cleopatra has poor tolerance to flooding. In contrast, *P. trifoliata* and Swingle have relatively poor drought tolerance, while Rangpur and Sunki have good tolerance, and Carrizo is intermediate. Although reliable information on tolerance to flood and drought may be concluded from nonexperimental but long-term field observations, methods for specialized study have been developed and employed to study tree responses and more rapidly evaluate rootstock tolerance under controlled conditions (Romero et al., 2006). The different drought survival strategies of Rangpur and Sunki, two drought-tolerant rootstocks (Santana-Vieira et al., 2016; Dutra de Souza et al., 2017), were contrasted individually and in graft combinations with scions. The rootstock Forner-Alcaide 5 was observed to be more tolerant to drought stress than either of its parents, Cleopatra and *P. trifoliata* (Rodríguez-Gamir et al., 2010).

Temperature extremes. Citrus rootstocks vary in their tolerance of high- and low-temperature extremes, with tolerance of low temperatures having received more research attention (Yelenosky, 1985; Zandalinas et al., 2016). All citrus is sensitive to freeze damage when it is actively growing, and rootstock effects on citrus tolerance of freezing conditions is primarily an influence to increase or reduce active growth of the tree prior to when it is exposed to freezing temperatures (Yelenosky, 1996). It is the different responses of citrus rootstocks to temperature patterns and other conditions in the days and weeks preceding the freeze event (preconditioning) that primarily determine whether a rootstock will induce more or less freeze tolerance in the tree. Because of this large effect of conditions in the weeks preceding a freeze, damage from low temperatures (and relative rootstock effects) can differ significantly between regions and freeze events. However, rootstock often has a significant effect on tree tolerance of freezes, with the rootstocks rough lemon and Volkamer lemon considered to yield trees most sensitive to freeze damage, Carrizo and sour orange intermediate, while trifoliate orange, Swingle, and some of the other trifoliate hybrid rootstocks provide the best resistance to freeze damage. Under conditions likely to have the most freeze risk and good cool temperature preconditioning, trifoliate orange rootstock is typically observed to provide the best freeze tolerance (Ben Yahmed et al., 2016; Ebel et al., 2008; Kawase et al., 1987; Yelenosky, 1985).

Salinity. Citrus is considered highly sensitive to salinity in the soil and irrigation water (Maas, 1993), although there are large differences in tolerance of salinity among rootstocks. Salinity sensitivity in citrus is thought to be primarily a response to the uptake by the rootstock of large amounts of chloride, but excessive sodium and boron can also be problems (Ruiz et al., 1999; Simón-Grao et al., 2018). Selection of rootstocks for salinity tolerance has received considerable research effort (Forner-Giner and Ancillo, 2013; Gallasch and Dalton, 1989; Raga et al., 2014), and among the new major rootstocks, FA-5 is a hybrid rootstock reported to have useful levels of salinity tolerance (Forner-Giner et al., 2009). Clonal selections of *P. trifoliata* introduced to Australia from China were also identified as having good salt-excluding ability (Sykes, 2011a), in contrast to the sensitivity of other trifoliate orange clones that have been studied. There is some variability in the results from assessment of rootstock tolerance to salinity, depending on scion and other factors (Levy and Syvertsen, 2004; Ream and Furr, 1976). In general, Cleopatra, Sunki, and Rangpur are considered the most tolerant, sour orange and rough lemon are intermediate, and the most sensitive are trifoliate orange, Carrizo, and Swingle (Castle, 1987; Castle et al., 2015).

pH. High pH conditions and calcareous soils are a problem in many citrus areas, and use of rootstocks that are tolerant is critical for successful production (Al-Jaleel et al., 2005; Castle et al., 2004; Louzada et al., 2008; Wutscher, 1979). *P. trifoliata* and many of its hybrids (such as Carrizo and Swingle) have been noted to be especially sensitive to high carbonate soils, and suffer from resultant micronutrient deficiencies, especially iron (Castle and Manthey, 1998; Manthey et al., 1994). Significant effort has been devoted to the study of citrus rootstock tolerance of high pH conditions, and methods to evaluate rootstocks for this trait (Castle et al., 2009; Licciardello et al., 2013; Llosá et al., 2009). In general, sour orange and rough lemon are considered most tolerant of high pH, Cleopatra and US-812 intermediate, and *P. trifoliata* and many of its hybrids intolerant (Castle et al., 2015)

Phytophthora. Three species of *Phytophthora* [*P. nicotianae* (*P. parasitica*), *P. citrophthora*, and *P. palmivora*] cause damage to citrus root systems, young trees, and the lower trunk. A key component of minimizing disease damage is the use of a rootstock which is resistant or tolerant to infection. Many evaluations of resistance have focused on individual *Phytophthora* species, especially *P. nicotianae* (Boava et al., 2011; Carpenter and Furr, 1962; Graham, 1995), but it is known that rootstock resistance to one species of the pathogen often differs markedly from its response to the other species (Graham et al., 2003; Graham and Feichtenberger, 2015; Widmer et al., 1998). For example, Swingle and most clones of *Poncirus trifoliata* are considered highly tolerant of *P. nicotianae*, but are susceptible to damage from *P. palmivora* (Fig. 6.2) (Albrecht and Bowman, 2004; Bowman et al., 2002). Since the species of Phytophthora that most affect trees differ by climate and region, identifying which of the pathogens is found locally will be key to identifying the appropriate

FIG. 6.2 Young Swingle seedlings grown in pots in the greenhouse. (A) Swingle grown in clean soil; (B) Swingle grown in soil inoculated with *Phytophthora palmivora* and developing severe root damage; (C) close up of root system of Swingle seedling shown in (B).

rootstock (Bowman et al., 2007). Soil type, irrigation, and drainage conditions can also have a large effect on potential for damage from *Phytophthora*, as excessive moisture and reduced aeration can exacerbate disease development. Physical damage to roots, such as from feeding of nematodes and insects (including Diaprepes weevil), can also circumvent resistance mechanisms and significantly increase *Phytophthora* problems.

Diaprepes weevil. The root weevil *Diaprepes abbreviatus* is a serious pest of citrus, currently found in many parts of Florida, as well as much of the Northern and Eastern Caribbean region. Adults lay eggs on the leaves of citrus and other plant species, but it is the larval stage that drops to the ground after hatching, which causes the most damage to citrus. As the larvae feed on citrus roots, they cause severe fibrous root loss, as well as tissue wounding, which often results in invasion by *Phytophthora* spp. The combination of *Diaprepes* and *Phytophthora* damage has been termed the Phytophthora-Diaprepes Complex (PDC; Graham et al., 2003, 2007) because of the extensive tree decline and death that results in trees on sensitive rootstocks. Although all sexually and graft-compatible citrus relatives have found to be susceptible to damage by the *Diaprepes* weevil (Bowman et al., 2001; Lapointe and Bowman, 2002; Lapointe et al., 1999), large differences are observed between rootstocks in tolerance to *Diaprepes* under field conditions (Bowman et al., 2003). Soil type can significantly affect rootstock reaction to *Diaprepes* infestation, especially because of the consequent effects from *Phytophthora*. In poorly drained soils, Swingle and Carrizo were found to be severely affected by PDC, while other rootstocks such as US-802, US-897, and US-942 were found to be more tolerant (Fig. 6.3). The UF-CREC rootstock breeding program has used a two-phase assay (damage assay/recovery assay) to screen several hundred diploid and tetraploid rootstock candidates for the Phytophthora-Diaprepes Complex (Grosser et al., 2003, 2007).

CTV. Citrus tristeza virus (CTV) is considered a major disease threat to citrus. Although some strains of the virus can cause severe stem pitting and other damage to scions, the most significant rootstock-specific effect of the virus is the stunting or quick decline reaction suffered by sweet orange trees grafted on sour orange rootstock. It is estimated that CTV led to the death of about 16 million trees on sour orange rootstock in Argentina in the 1940s, and smaller but significant number of trees on sour orange were also destroyed by CTV in Brazil and California (Wallace, 1968). In addition to being spread in infected

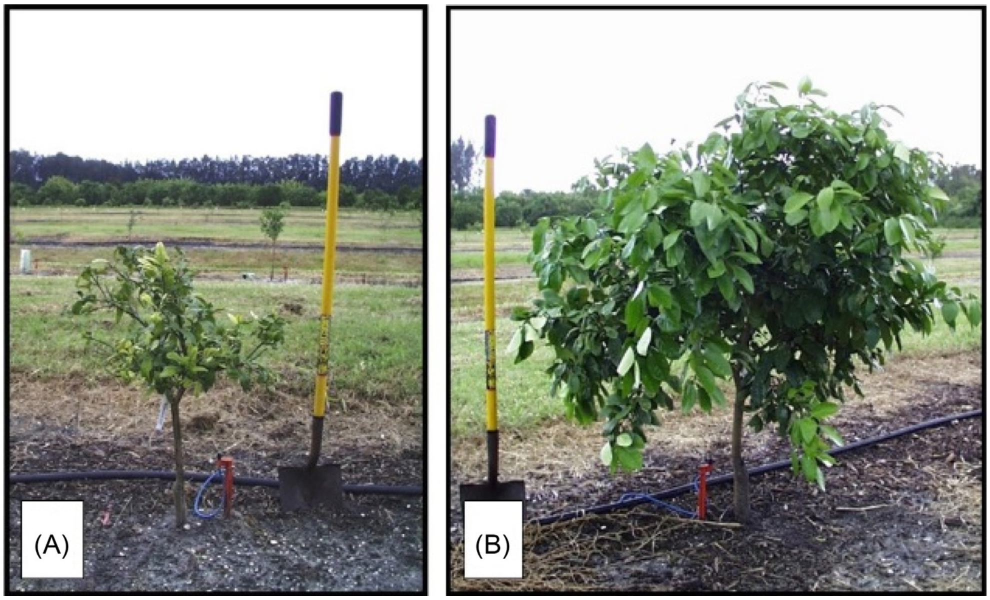

FIG. 6.3 One-year-old red grapefruit trees in area severely damaged by Phytophthora-Diaprepes weevil complex. (A) Red grapefruit/Swingle rootstock; (B) Red grapefruit/US-802 rootstock.

budwood, CTV is readily spread from tree to tree by several species of aphids. Because of this sensitivity to CTV and difficulty in controlling spread, sour orange is currently a relatively minor rootstock in much of the world, despite many otherwise excellent rootstock traits. Among common rootstocks, *Citrus macrophylla* is the other rootstock besides sour orange that suffers from a CTV quick decline-type reaction. In the development and testing of new rootstocks, determining resistance or tolerance to CTV is desired and often relies on natural infection in field trials where sour orange can be an effective susceptible experimental control (Wutscher and Bowman, 1999). Although methods have been described to evaluate CTV tolerance of rootstocks more rapidly and under controlled conditions (Bowman and Garnsey, 2001), a large portion of citrus germplasm and hybrids typically show field tolerance and little tendency toward a quick decline-type reaction. Resistance to CTV has been described from *P. trifoliata* and that trait is transmitted to many hybrids (Garnsey et al., 1987). Significant progress has been made in mapping the locus for CTV resistance from *P. trifoliata* (Gmitter Jr. et al., 1996; Deng et al., 1997, 2001).

Huanglongbing. In many citrus production areas, Huanglongbing or citrus greening disease, is considered to be the most serious disease affecting citrus production, and is potentially the most serious looming threat that could devastate the global citrus industries. Huanglongbing is believed to be caused by several bacterial pathogens identified as *Candidatus* Liberibacter spp., although Koch's postulates have not been fulfilled because the bacteria has not been cultured successfully (Wang and Trivedi, 2013) (see Chapter 18). Generally, three species of *Candidatus* Liberibacter (differentiated by 16S rDNA sequence) are recognized as causing Huanglongbing disease, *Candidatus* L. *asiaticus*, *Candidatus* L. *africanus*, and *Candidatus* L. *americanus*, although *Candidatus* L. *asiaticus* (*C*Las) is by far the most widespread among citrus production areas. All citrus species and near relatives are susceptible to infection by *C*Las (Bové, 2006), but significant differences in tolerance can be found, with sweet orange and grapefruit being severely damaged by infection (Folimonova et al., 2009), while other material including *P. trifoliata* and some hybrids with citrus (Albrecht and Bowman, 2011, 2012) are highly tolerant and virtually free of symptoms. Although some rootstocks are tolerant to *C*Las infection as seedlings, generally this tolerance to infection does not result in a large improvement in the *C*Las tolerance of trees, when the rootstock is grafted with a *C*Las-sensitive scion. Consequently, using a *C*Las-tolerant rootstock will only partially improve the overall tree tolerance to *C*Las in the field (Albrecht et al., 2012; Bowman et al., 2016a,b), possibly the result of only a significantly healthier root system and the consequential direct improvements those healthier roots provide for overall tree health. Delaying infection with *C*Las until field trees are established and a larger size will usually result in better tree tolerance to the infection than when trees become infected at a very young age. Although controversial, there is some indication that enhanced nutrition can improve field performance of trees infected with *C*Las (Morgan et al., 2016; Stansly et al., 2014), and this nutritional effect may be somewhat modulated by rootstock. Numerous field trials in Florida have been conducted with trees naturally infected by *C*Las over multiple years. Generally, under Florida conditions and in field plantings infected by *C*Las, US-942 is one rootstock that has provided field performance superior to many other rootstocks, including Swingle, Carrizo, Kuharske, Ridge sweet orange, sour orange, and Cleopatra (Bowman et al., 2016a,b).

Other diseases. Many other pathogens affect citrus, including those caused by viruses, viroids, fungi, and bacteria (Timmer et al., 2000). In some cases, devastating unidentified diseases are believed to be caused by pathogens, but research has yet to elucidate the cause, such as with citrus blight (Young et al., 1984; Derrick and Timmer, 2000). Often, rootstocks differ significantly in resistance or tolerance to pathogens, but limited information is available, or only applicable to local biotypes or isolates of the pathogen where the research was conducted. Some information is available on rootstock tolerance or sensitivity to viroids and other diseases (Vernière et al., 2004; Timmer et al., 2000). Several publications have provided ratings of all available rootstocks for the most widespread and important pathogens (Bitters, 1986; Castle et al., 2015; Lacey, 2017; Lee et al., 2009; Roose, 2014), and these provide a good resource for broad comparisons.

Nematodes. Numerous species of nematodes affect citrus roots, although many of these are mainly of regional or local importance, rather than having worldwide significance. The 'citrus nematode' *Tylenchulus semipenetrans*, is one nematode that has an impact on citrus production in all regions of the world (Duncan and Cohn, 2005). Rootstocks differ in their tolerance to *T. semipenetrans*, although there are known to be some differences by regional biotypes of the nematode. For most biotypes, *P. trifoliata*, Swingle, and some other hybrids of *P. trifoliata* with citrus have good resistance or tolerance, while Cleopatra, sour orange, and rough lemon are susceptible (Duncan et al., 1994; Verdejo-Lucas and Kaplan, 2002; Verdejo-Lucas et al., 1997, 2000).

Tree size. Citrus tree size is strongly influenced by rootstock, with rough lemon rootstock typically producing very large trees with most scions, and Flying Dragon trifoliate orange producing very small (dwarf) trees (Mademba-Sy et al., 2012; Reforgiato Recupero et al., 1992; Roose, 1986; Stuchi et al., 2003). Terminology for rootstock influence on tree size varies, but we suggest useful categories are very vigorous (rough lemon), standard (Carrizo or Swingle), semidwarf, and dwarf (Flying Dragon). In addition to rootstock, many other factors influence tree size, including scion, soil, management practices, and diseases that affect the tree. In the absence of compatibility issues, a group of rootstocks usually have the same relative size effects on a common scion; so, for example, all scions on rough lemon will make larger trees than all scions on Flying Dragon. In one sweet orange field trial in central Florida (Wutscher and Hill, 1995) with good management and in the absence of any severe disease pressure, sweet orange trees at 18 years old and on US-802 rootstock (very vigorous) were about 6.1 m tall, on Swingle (standard) were about 4.5 m tall, and on US-897 (semidwarf to dwarfing) were about 2.7 m tall (Fig. 6.4). Some rootstocks are particularly responsive to extremes of fertilization, so that rootstock effect on tree size may

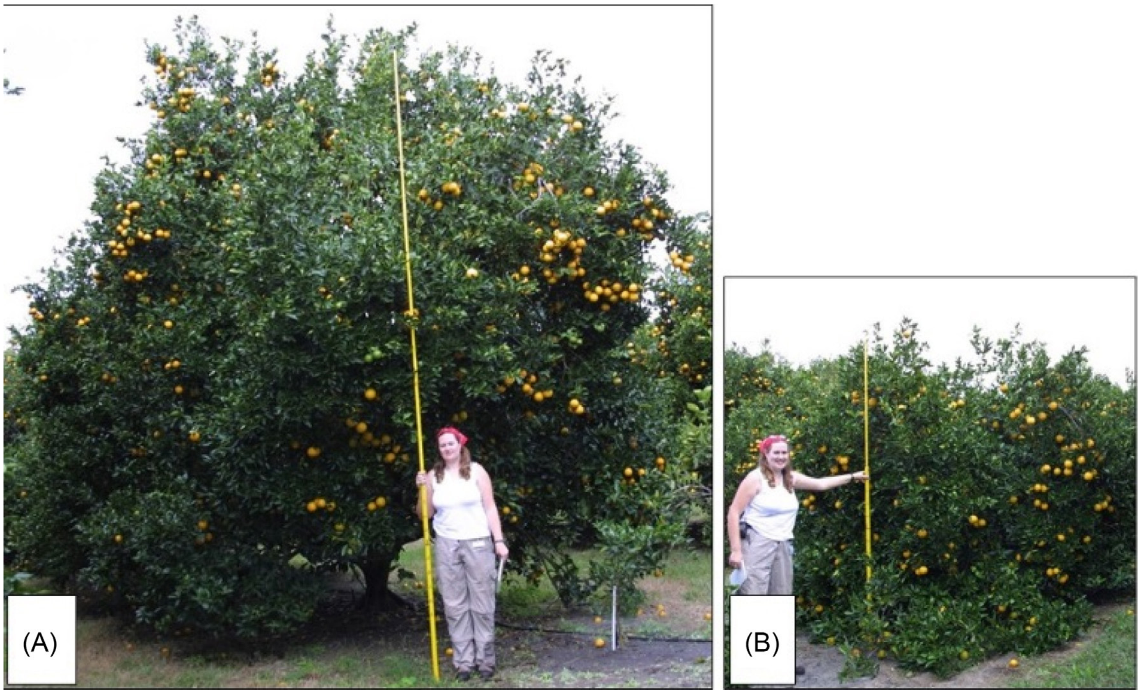

FIG. 6.4 Hamlin sweet orange on two rootstocks with a large difference in effect on tree size. (A) Hamlin/US-802 rootstock at 6.1 m tall; (B) Hamlin/US-897 rootstock at 2.7 m tall. Trees with both rootstocks are 18 years old, and representative of the size for all trees on that rootstock in the trial. The field trial is located in Osceola County, Florida, and did not have prominent disease effects at the time the photos were taken.

be altered significantly by management practices. The rootstock effect on tree size may also be modulated by disease. For example, some strains of CTV may severely reduce the size of sweet orange trees on sour orange, as compared with trees on other rootstocks more tolerant of the infection (Wutscher and Bowman, 1999), and Huanglongbing has been noted to reduce the size of trees with sweet orange scion on all rootstocks (Bowman et al., 2016b). Some viroids have been proposed for use as size-controlling agents for citrus (Hutton et al., 2000; Vidalakis et al., 2011). It should be noted that the rootstocks which promote the highest yield per tree will often not provide the highest yield per hectare if tree densities are not adjusted to optimize yield per area. In addition, optimum spacing to maximize yields per hectare will be different if based on tree size and yield at 5 years or at 15 years.

Yield and fruit quality. Numerous studies have identified large rootstock effects on fruit yield and quality (Barry et al., 2004; Bowman et al., 2016a,b; Castle et al., 2011; Wutscher and Bistline, 1988; Wutscher and Bowman, 1999). Effects of rootstock on yield are strongly associated with rootstock adaptation to growing conditions, and tolerance to any biotic diseases or abiotic challenges that are present. In the field, there are often many different factors interacting in a complex fashion to determine rootstock effects on yield. In the absence of strong biotic or abiotic factors that limit tree health, trees that grow the strongest may often be those that yield the most fruit on a per tree basis. There is a strong association between tree size and yield per tree, so it is important to consider tree size in assessing potential for good yield per unit area; however, as mentioned above, yield efficiency and planting density should be optimized for maximum yield potential per unit area. Fruit quality is a combination of many different fruit traits, including size, shape, external and internal color, Brix, and acid, that may have differing importance, depending on the scion cultivar and the commercial use (Wutscher, 1988). For sweet orange used in the juice trade, Brix is probably the most important fruit quality trait. But with other scions, like grapefruit and mandarins, fruit size, shape, flavor, and color can be equally important (McCollum and Bowman, 2017). Generally, *P. trifoliata* and many of its hybrids, as well as sour orange, are considered to have strong favorable influences on fruit quality, while the effects of rough lemon and Rangpur are less favorable.

Compatibility. Although most citrus rootstocks are graft compatible with most citrus scions, there are exceptions. For example, incompatibilities have been observed with Roble, Pera, and Shamouti sweet oranges, Murcott tangor, and Eureka lemon with Swingle and some other trifoliate hybrid rootstocks (Garnsey et al., 2001; Weathers et al., 1955), and sometimes the incompatibility takes many years to become apparent. Consequently, caution should be used in choosing new scion-rootstock combinations until a longer history of use is developed. Citrus rootstock and scion cultivars vary in relative growth rate and metabolism, and this often results in different trunk diameter and bark texture which is apparent at the graft union (Fig. 6.5). The difference in trunk diameter is sometimes termed overgrowth or undergrowth. In particular, overgrowth of rootstocks with *P. trifoliata* parentage is often observed when they are grafted with other citrus species or cultivars as scions. It can be noted that the relative growth difference of two cultivars is often similar, regardless of which is in the scion and rootstock position. For example, US-802 will grow to a much larger trunk diameter than Valencia grafted to it, whether it is Valencia scion on US-802 rootstock, or US-802 scion on Valencia rootstock. In extreme cases, overgrowth of the rootstock can result in a weakened graft union or other physiological problems. However, the moderate rootstock overgrowth typically seen with sweet orange on Carrizo or Swingle normally does not seem to present any hazard for trunk strength or tree physiology.

Nutritional utilization and deficiency. Rootstocks can differ markedly in the ability to uptake and use nutrients from the soil. Focused studies have been conducted on several nutrients, including iron (Albano et al., 2005, 2013; Martinez-Cuenca et al., 2017) and boron (Zhou et al., 2014). Differences in nutrient use efficiency and toxicity may have important effects on rootstock use and performance under differing climatic, soil, and management conditions, but are poorly understood (Lea-Cox and Syvertsen, 1993; Zambrosi et al., 2011).

Nursery characteristics. Propagation of citrus rootstocks in the nursery is traditionally accomplished using genetically uniform nucellar seedlings (Anderson et al., 1991; Kepiro and Roose, 2007; Moore and Castle, 1988). The most widely used rootstocks usually produce a high proportion of uniform seedlings, and consequently, seedling uniformity has generally been an important selective factor in efforts to develop promising new rootstocks (Bowman et al., 2016a; Albrecht et al., 2017). Notably, a few rootstocks with a relatively high frequency of off-types from seed have been used commercially (Bowman et al., 1995; Castle et al., 1993; Stover and Castle, 2002), but up until now, none of these have become of wide importance. Over the past 20 years, propagation of citrus rootstocks by cuttings has become common in research efforts (Bowman and Albrecht, 2017; Bowman and McCollum, 2015) and used somewhat in commercial nurseries. Micropropagation of citrus rootstocks has also become common in some regions, to make up for seed deficiencies (Albrecht et al., 2017), and provides the potential to allow mass propagation of new rootstock clones lacking nucellar seed, which would previously have been impractical (Bowman, 1995). In Florida, about 600,000 nursery trees were produced on micropropagated US-942 rootstock between July 2018 and June 2019 (Fig. 6.6).

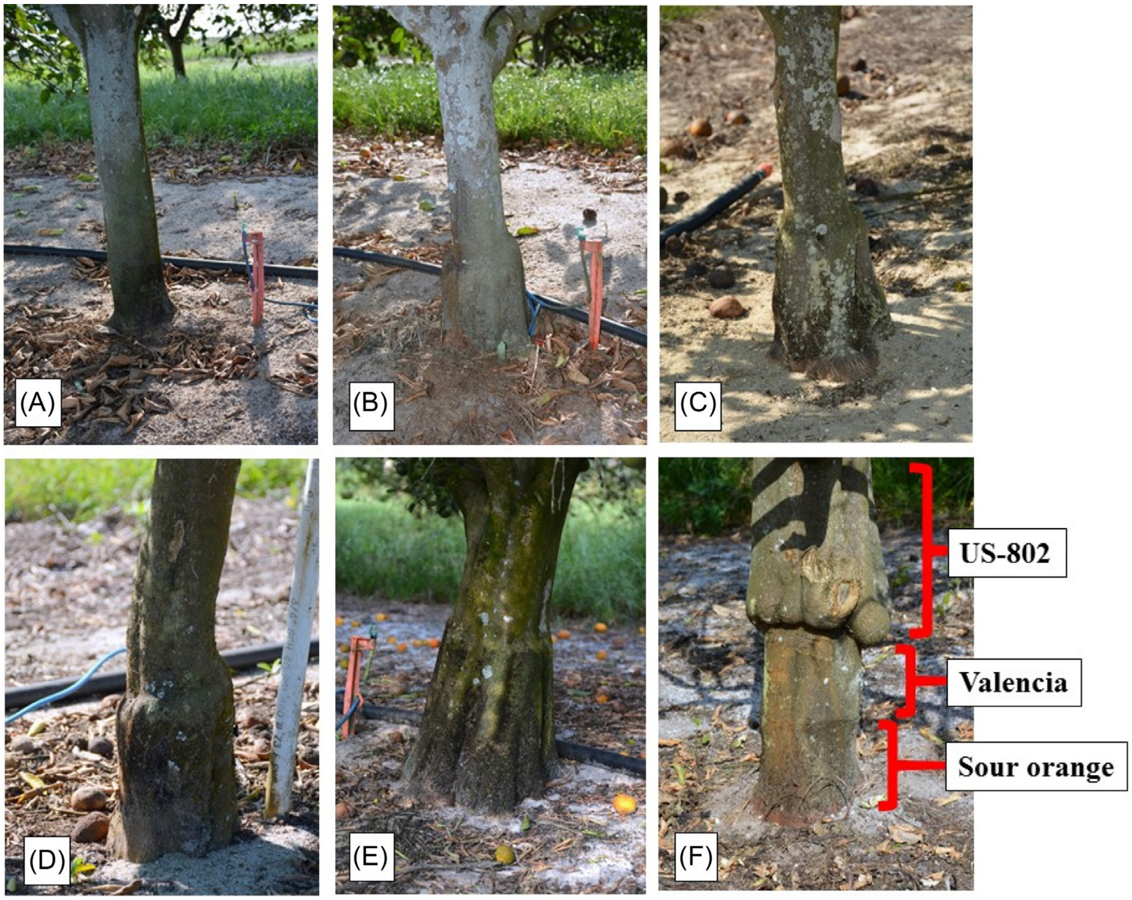

FIG. 6.5 Trees illustrating different types of natural rootstock overgrowth and undergrowth relative to the scion. (A) Minneola scion/sour orange rootstock; (B) Minneola scion/Swingle rootstock; (C) Valencia scion/Swingle rootstock; (D) Clementina Fina scion/US-897 rootstock; (E) US-897 scion/US-802 rootstock; (F) = US-802 scion/Valencia interstock/sour orange rootstock. All trees are 13–14 years old and canopies appear healthy.

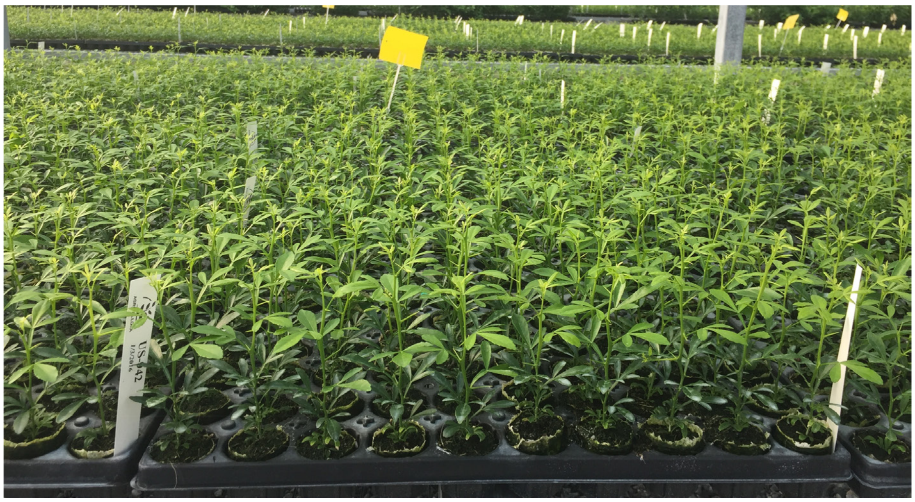

FIG. 6.6 Nursery plants of US-942 rootstock produced by micropropagation. *(Photo courtesy of Mireia Bordas, Agromillora.)*

6.4 Rootstock use by region

Rootstock use varies greatly from one country to another, and sometimes differs dramatically between production regions in the same country. Most citrus production regions do not have good data available to quantify the number of trees propagated on different rootstocks. In addition, there are sometimes rather large shifts in rootstocks used for new propagations over a period of 5 years. Consequently, we have summarized the citrus rootstock usage in new plantings based (for most countries) on the authors' professional opinions, and the insight of regional citrus experts who were willing to provide their estimates in response to an email survey. Rootstocks were only identified in Tables 6.1 and 6.2, when there was data or expert opinion indicating the rootstock was used for at least 5% of new propagations in at least one country (or large region) during the past 5 years. In the following table, we have identified the frequency of use in new propagations, from 2012 to 2017, for the major rootstocks in each of the countries for which good information was available. When there were data or expert opinions that assigned a percentage by rootstock, those numeric values were included in the table. When data were not available and the best expert opinion could not assign a percentage value, rootstocks were ranked by frequency of use, with A = the rootstock that was used for the most propagations. The authors apologize for countries not included, and accept the likelihood of some inaccuracies in the table, but believe that it is broadly a reasonable estimation of worldwide use.

There were 21 rootstocks that were determined to be used for at least 5% of propagations in at least one citrus-producing country. Some major rootstocks, such as Carrizo and sour orange, were used in many countries, while other important rootstocks like Ziyang Xiangcheng are significantly used in only one country. It is apparent that rootstock use in an area is determined by many factors, including tradition, availability of reliable information about the performance of different rootstocks, and the availability of seed. In many areas, probably better rootstocks exist than those currently being used, but there is not enough clear evidence of which rootstocks would be the best or plant material is limited; so, those rootstocks most familiar remain the most used.

6.5 The major rootstocks

Twenty-one rootstocks were identified as major world rootstocks because of their use for at least 5% of recent propagations in at least one significant citrus-producing area. Brief descriptions of these rootstocks are given below, along with references for further information. In some cases, the major rootstocks identified in our list are, in fact, groups of closely related rootstocks rather than individual clones. One example of this is trifoliate orange, which includes many different cultivars (such as Flying Dragon and Rubidoux), some of which may differ in one or more attributes. In other cases, there is controversy about whether named clones that seem to have derived from the same source are, in fact, genetically the same or different. The two similar cultivars, Carrizo and Troyer, are an example of this, and for the purposes of this chapter, we have combined them together. Exploring the diversity of genotypes in these cases was beyond the scope of this chapter, but some references are provided to guide further study. Additional rootstocks that did not meet the criteria we have used for selection as a "major" rootstock now are mentioned in the following section, if we felt they were noteworthy and likely to increase in use during the coming years.

Benton is a citrange (the term applied to hybrids of *C. sinensis* × *P. trifoliata*) rootstock bred in New South Wales, Australia, in an attempt to produce dwarfing rootstocks compatible with Eureka lemon. This rootstock is a hybrid of Ruby Blood orange and trifoliate that has performed well in trials, especially in Australia. Benton has been successfully used for commercial Eureka plantings in Australia since 1990. Benton has also been used successfully as a rootstock for grapefruit, Valencia, navel orange, and mandarins. In South Africa, trees on Benton are more compact than trees on rough lemon, Swingle and Carrizo, resulting in more manageable trees, although trees on Benton have been very large in other areas. When propagating Benton in the nursery, the tree has a "bushy" growth habit with a shrub-like appearance. Consequently, to prepare the rootstock for the budding process, nurserymen plant seeds relatively close together and select the strongest, most upright seedlings. For Valencia types, Benton produces very good quality fruit, with high internal quality early in the season. Medium-to-larger fruit size remains one of the more favorable traits of this rootstock. Midknight Valencia trials were planted on Benton in the Letsitele area of South Africa and produced an average crop of over 80 kg per tree (Lee et al., 2009). The main advantages of Benton are intermediate resistance to *Phytophthora* root rot, nematodes and CTV, good internal fruit quality, and good external color development compared with Swingle. Australia is the only country where Benton is commercially used to a significant extent.

C35 is a semidwarfing rootstock developed by the University of California and is a cross between Ruby sweet orange and *P. trifoliata* (Cameron and Soost, 1986). C35 is tolerant to *Phytophthora*, citrus nematode, and CTV, but sensitive to the citrus exocortis viroid. In South Africa, this rootstock has shown to be sensitive to citrus blight in trials conducted in the Letsitele region (Lee et al., 2009). The growth of trees on C35 is similar to that of trees on Carrizo up to about 6 years

TABLE 6.1 Rootstock use for new plantings in Americas 2012–17.

Country	Benton	Carrizo	Cleopatra	C35	F-A 5	Kuharske	Macrophylla	MXT	*P. trifoliata*	Rangpur	Rough lemon	Sour orange	Sunki	Swingle	US-802	US-812	US-897	US-942	Volkamer	X639	Ziyang X.
USA, Calif.		30	4	24			10		10		4	1		7					9	1	
USA, Fla.			5			18						12		16	8	5	7	7	2	12	
Mexico		E		F			D		G			A		C					B		
Domin. Rep.				B					E	C				D					A		
Costa Rica		15	2	1					20	1				50					10		
Nicaragua		10							30					50					10		
Honduras		10		1					4		1	62		14					7	1	
Panamá		10	2						15					65					8		
Brazil, Parana		1	7							80			5	7							
Brazil, Sao P.			2						1	80			7	10							
Argentina	G	C	F	D					A			E		B							
Colombia		B	C	F					E					A					D		

Estimated percent of trees, or rank for number of trees: A=#1 most used, B=#2, C=#3, D=#4, E=#5, F=#6, G=#7.

TABLE 6.2 Rootstock use for new plantings in Europe, Asia, and Africa 2012–17.

Country	Benton	Carrizo	Cleopatra	C35	F-A 5	Kuharske	Macrophylla	MXT	*P. trifoliata*	Rangpur	Rough lemon	Sour orange	Sunki	Swingle	US-802	US-812	US-897	US-942	Volkamer	X639	Ziyang X.
Spain		21	1	7	29		25					1		15					1		
Italy		60		10	2		5		3			5		10					5		
Greece		C							D			A		B					E		
Turkey		16		25								48							11		
Morocco		B		D			A					E							C		
Tunisia		8		4								80							8		
Egypt		2					2					35							60		
Saudi Arabia			C									A							B		
Israel		25										40				D			30		
Iran		15		8			1		2			63		3					7		
India										B	A										
Pakistan											97	3									
China									80	C		D									10
Japan									99												
Indonesia										90	5										
Thailand		B												A							
Australia	12	34	2	10			1		34					4					1		
New Zealand	2		15						82			1									
South Africa		47		10				5			15			14					1	7	

Estimated percent of trees, or rank for number of trees: A=#1 most used, B=#2, C=#3, D=#4, E=#5, F=#6, G=#7.

of age, at which stage growth is slower with the eventual mature tree size being 15%–25% smaller (mature trees 10 years old). C35 performs well in soils suitable for Carrizo, but it does not adapt well to saline and high pH soils. When planted on very sandy or high clay content soils, C35 performs below average with small and stunted tree size. C35 produces very good quality fruit with high internal quality early in the season and larger fruit size remains one of the better qualities of this rootstock. C35 has performed well in combination with grapefruit, navel orange, Valencia, and mandarin types. There have been reports of tree dieback and incompatibility-like symptoms with Nules Clementine and Fukumoto Navel on C35 (Lee et al., 2009). The main positive attributes for C35 rootstock are intermediate resistance to *Phytophthora* root rot, tolerance to nematodes and CTV, good internal quality fruit, earlier external color compared with Swingle citrumelo, and small-to-medium tree size. C35 is the second-most popular rootstock for new propagations in California, and is widely used to a lesser extent in many other growing regions.

Carrizo (and Troyer) is a hybrid of Washington navel orange and *P. trifoliata*, originating from a cross made at Riverside California in 1909, within the USDA citrus breeding program. Carrizo is often considered identical with Troyer, although separate clones are maintained in many locations, and this is still somewhat controversial (McCarty et al., 1974; Savage and Gardner, 1965). Characteristics of Carrizo and Troyer are very similar; so, for our purposes here, we are considering them the same. With most scions, Carrizo provides excellent early bearing of young trees, internal fruit quality is excellent, and fruit size is usually medium to large. Carrizo is vigorous, and develops medium-to-large tree size (depending on the scion cultivar), or what is often considered "standard" tree size. Carrizo is sensitive to alkaline-induced chlorosis and, in some cases, trees have severely declined as a result of iron and other trace element deficiencies on saline, calcareous, and especially high pH soils. Another major disadvantage of this rootstock in some areas is the tendency to induce a higher incidence of creasing. Carrizo induces higher acid levels than rough lemon, but while this has occasionally created problems with Valencia, Minneola tangelo, and grapefruit in the cooler production areas, it is advantageous in hot areas (Lee et al., 2009). In the absence of limiting disease problems, Carrizo is an excellent rootstock for sweet orange, grapefruit, and most mandarin hybrids. The main advantages of Carrizo citrange are intermediate resistance to *Phytophthora* root rot, nematode and CTV tolerance, good internal quality, earlier external color compared with Swingle citrumelo, and medium tree size. Carrizo is not compatible with Eureka and other Eureka-type lemon selections. Carrizo remains the most-used rootstock in Spain, South Africa, Italy, Australia, and California, and is widely planted in many other countries.

Cleopatra is a small-fruited mandarin that has been often identified as *Citrus reshni*, and is thought to have originated in India where it is known as chota or billi kichili (Hodgson, 1967). The overall field performance of trees on Cleopatra is good in most regions, but trees on this rootstock typically have low yield until the trees are at least 8–10 years old. Cleopatra usually produces a standard to very large tree size with most scions. Fruit of the grafted scion is of high quality, with high sugar content, but sometimes fruit size is somewhat small. Cleopatra induces good cold tolerance and drought tolerance in the scion. Trees are unaffected by CTV and some viroids, as well as having tolerance to some species of *Phytophthora* root rot. It is susceptible to citrus nematode. Cleopatra has been described as having the highest salinity tolerance of all the commercial rootstocks through having the ability to exclude sodium and chloride from being taken up by the root system (Lee et al., 2009). Cleopatra performs well on deep and loamy, well-drained soils but is adversely affected by soils with high water tables. In trials conducted in Florida to compare various rootstocks for blight tolerance, Cleopatra mandarin only began to show decline symptoms after about 12 years. Many years of experience in Florida has shown it to be an excellent rootstock for all mandarin cultivars that are sufficiently large fruited. Cleopatra is used widely as a rootstock in several citrus-production regions, but there are no countries where it is the dominant rootstock. Numerous similar mandarins are sometimes used as rootstocks, and some may have potential advantages over Cleopatra (Castle, 1987; Castle et al., 2004, 2011; Sykes, 2011a,b).

Forner-Alcaide 5 (F-A 5) was the product of a 1978 cross between Cleopatra mandarin and *P. trifoliata* Rubidoux completed in the Instituto Valenciano de Investigaciones Agrarias (IVIA) in Valencia, Spain. Testing in Spain showed that F-A 5 is resistant to CTV, citrus nematode, and *Phytophthora*, and has tolerance to salinity, flooding, and lime-induced chlorosis (Forner et al., 2003; Forner-Giner et al., 2003, 2010, 2011). In trials with Navelina orange and Okitsu satsuma, trees on F-A 5 produced good fruit quality, and higher fruit yields than trees on Carrizo. The rootstock F-A 5 produced a tree that was smaller in size than trees on Carrizo rootstock. F-A 5 has become an important rootstock in Spain, and has begun to gain interest from growers in some of the neighboring countries.

Kuharske was a natural seedling variant of Carrizo identified in a Groveland (Florida) citrus nursery in about 1986, as notably resistant to a locally important problem, burrowing nematode (*Radopholus similis*). Field performance of this rootstock in trials over the past 20 years has generally indicated relatively good influence on tree health and fruit quality, but only average in effects on fruit yield (Bowman et al., 2016b; Castle et al., 2011). Kuharske has been noted to be widely used in Florida because it is similar to Carrizo citrange, but otherwise is exceptional only in having very good tolerance to the burrowing nematode (Castle, 2010). Kuharske is currently of commercial significance only in Florida, where it has been the most widely used rootstock for new propagations over the past 5 years.

Macrophylla, also known as Alemow, was thought to be a hybrid of citron (*Citrus medica*) and pummelo (*Citrus maxima*) originating on the island of Cebu, Philippine Islands (Saunt, 2000), but a recent study revealed that it resulted from an hybridization between *Citrus micrantha* (or a close papeda species) and citron (Curk et al., 2016). Lemon performs well on this rootstock and trees are precocious and produce good-quality fruit, although they are more sensitive to the mal secco disease (*Plenodomus tracheiphilus*). Trees on this rootstock grow vigorously for a few years, with growth thereafter being considerably less vigorous due to heavy fruit loads. Fruit on the trees are large, but the fruit on young trees generally have a low juice and brix content, and tend to dry out early. In rootstock trials, trees on *Macrophylla* typically have the lowest juice quality. Trees on *Macrophylla* are very susceptible to cold damage, CTV (when used with other scions besides lemon), xyloporosis, citrus blight, and citrus blackspot (Castle et al., 1993). *Macrophylla* is resistant to root rot as well as being tolerant to salt and boron. The insensitivity of lemons as a scion to CTV makes this a rootstock option for lemons under South African conditions, and it also appears one of the best options for Tahiti lime in South Florida. *Macrophylla* has been extensively used as a lemon rootstock in California and, in recent years, has become popular in Spain and Morocco, where water with high salinity levels is used for irrigation (Lee et al., 2009).

Minneola × Trifoliate (M×T) is the product of a cross between the parents indicated, within the USDA-Florida breeding program. Although it is not known commercially in Florida, field performance in Florida has been reported as HRS/US-934 (Wutscher and Bowman, 1999). At present, this rootstock is only of commercial significance in South Africa, where it was introduced from Florida in 1992. The rootstock (known as M×T in South Africa) performs very vigorously in the nursery, but once the scion is budded, it induces some size-controlling effect in the scion. In two trials, one in the Eastern Cape and one in Limpopo Province (South Africa), in combination with Palmer navel as the scion, tree volumes were about 55% of trees budded to rough lemon or Troyer citrange. Excellent per tree yields and tree productivity (expressed as yield/unit tree size) were obtained with M×T, significantly higher than that obtained for the standard rootstocks (Lee et al., 2009). The tree size of Clementine on M×T in the Eastern Cape (South Africa) has been slightly smaller, although quality and production have been similar to Swingle and Carrizo. Several scion cultivars budded to this rootstock have performed outstandingly in a planting at Malelane (Lee et al., 2009). No incompatibility problems have been identified with Eureka lemon on M×T, but severe incompatibility signs were visible in combination with kumquat (*Fortunella* spp.). The adaptation of this rootstock to various soil types is not well known, but early indications are that it does not adapt well to soils with a high pH, and MxT is sensitive to some citrus viroids. Trials done to date indicate M×T has good tolerance to CTV, *Phytophthora*, and nematodes (Lee et al., 2009).

Poncirus trifoliata (L.) Raf. (trifoliate orange) is regarded as a separate genus from citrus, and has been grown in China for thousands of years (Swingle and Reece, 1967). Many different selections of this species exist, and have been often categorized either as large-flowered types which grow upright and develop fewer branches (e.g., Pomeroy), or small-flowered types which are less vigorous and with more branches (e.g., Rubidoux and Australian), although it is not clear that these morphological differences have a strong association with horticultural traits when used as a rootstock. Specific selections of this species have been described, which differ from many of the other selections of *P. trifoliata* in one or more important horticultural attributes (Lapointe and Bowman, 2002; Sykes, 2011a,b). In general, trees on trifoliate orange have a low to moderate vigor, but bear a good crop of fruit for the tree size. Fruit quality on trifoliate orange is excellent, generally with high Brix and acid contents, and developing a smooth, thin rind. The fruit size may be smaller compared with other rootstocks, but fruit has been noted to hang well on the trees. For the most common selections of trifoliate orange, they are noted to be resistant or tolerant to citrus nematode, some *Phytophthora* species, CTV, flooding, and cold, but sensitive to high pH, salinity, drought, and exocortis. Trifoliate orange rootstocks seem more favorably suited to areas with cool winter temperatures, and are often regarded as a good choice for cases where significant tree dwarfing is desired, especially the *P. trifoliata* cultivar Flying Dragon (Castle et al., 2005; Mademba-Sy et al., 2012). Trifoliate orange rootstocks may also have utility in some situations because of their particularly strong ability to improve internal fruit quality of the grafted scion. Trifoliate orange is currently heavily favored as a rootstock in Japan, China, Australia, New Zealand, and Argentina, and is significantly used in many other citrus-producing regions.

Rangpur (*Citrus limonia* Osbeck) is a natural selection that probably originated in India, and was previously thought to be a hybrid of acid mandarin (*Citrus reticulata*) with either the rough lemon or sour orange (Hodgson, 1967; Saunt, 2000); a recent study suggested an acidic mandarin as the female parent and citron as the male parent (Curk et al., 2016), and this has more recently been confirmed by genome sequence analysis (Wu et al., 2018; see Chapter 2). Trees on this rootstock are very vigorous and productive, similar to rough lemon. Trees typically bear fruit at an early stage and are tolerant to CTV, but are susceptible to citrus and burrowing nematodes, exocortis, *Phytophthora*, and citrus blight. Rangpur has good tolerance to drought as well as calcareous soils, and for these reasons has popularity in areas with possible drought conditions and lacking supplemental irrigation. Trees on Rangpur rootstock typically produce large-size fruit, with internal quality similar to rough lemon, and notably inferior to the internal fruit quality of fruit on many other rootstocks, such as Carrizo or Swingle. Rangpur is the major rootstock in Brazil and Indonesia, but is relatively little used in most other countries.

Rough lemon (*Citrus jambhiri* Lush) is presumed to be indigenous to north-east India, where it still grows wild (Lee et al., 2009); like Rangpur, it has been shown to be a hybrid of *C. reticulata* × *C. medica* (Wu et al., 2018; see Chapter 2). Many rough lemon selections are known, and clone choice differs between countries. In South Africa, where rough lemon is common and is currently the second-most-used rootstock, the selection that has been favored is Cairn. Rough lemon is one of the most vigorous rootstocks used with citrus, under favorable conditions producing a very large tree, and has seen widespread use around the world. Typically, grafted scions on rough lemon produce large crops and large fruit size. Other advantages of rough lemon are the resistance to high pH and drought, and good growth in deep sandy soils. One of the disadvantages of rough lemon is the internal quality of the fruit is lower in Brix and percent juice than other higher fruit quality-inducing rootstocks. Rough lemon is not tolerant of either citrus or burrowing nematodes, and is not sufficiently tolerant to *Phytophthora* root and foot rot to be used on wet, poorly drained soils, even though it is relatively tolerant to flooding. Trees on rough lemon are more sensitive to cold and frost damage, but young trees planted on rough lemon and damaged by cold recover more rapidly than trees on less vigorous rootstocks that are severely damaged. Rough lemon has additional negative effects in combination with mandarins, as the fruit tend to dry out (granulate), reducing the already naturally short harvest season of most mandarin cultivars, and also tends to increase the alternate-bearing tendency of many mandarin cultivars. Rough lemon is the most used rootstock for new plantings in India and Pakistan, and important in South Africa, but is currently relatively unimportant in most other countries.

Sour orange (*Citrus aurantium* L.) is an F1 hybrid between mandarin and pummelo (Wu et al., 2014; see Chapter 2). The origin of this natural hybrid is speculated as from northeastern India and nearby regions in neighboring countries (Hodgson, 1967), but it had spread to most other citrus-growing areas very early in recorded history. Sour orange is close to the ideal rootstock in many horticultural respects, inducing high yields and superb fruit quality, along with good tolerance to root rot, high pH, salinity, flooding, cold, and blight. However, in many areas and scion combinations, sour orange cannot be used without extreme risk, due to its susceptibility to a tree stunting or quick decline induced by infection of the scion with CTV. At some point in time, sour orange was the most important rootstock in almost every citrus growing region of the world. However, millions of trees of sweet orange, grapefruit, or mandarin were lost on sour orange in South America, Central America, the Caribbean, Florida, Spain, Italy, and South Africa after trees became infected with CTV. At present, virulent forms of CTV and the prevalence of the aphid vector have discouraged use of sour orange as a rootstock for new plantings in many regions. Scions that are less susceptible to CTV, such as lemons, can be successfully used in combination with sour orange. Sour orange is a heavily used rootstock for new propagations in Greece, Turkey, Tunisia, Saudi Arabia, Israel, Iran, Honduras, and Mexico, and sees significant use in many other regions. Many different regional clones of sour orange exist, although all seem to have similar sensitivity to CTV (Bowman and Garnsey, 2001). Efforts to create a sour orange-like rootstock without sensitivity to CTV have received considerable attention in Florida (Bowman, 2007; Bowman and McCollum, 2018a,b,c; Grosser et al., 2004).

Sunki (*Citrus sunki* hort ex. Tanaka) is small-fruited acidic mandarin that is considered native to China, and has some similarity to Cleopatra (Hodgson, 1967). Sunki was used historically as a rootstock in China, and has been included in rootstock trials in several other areas. Sunki is reported to be tolerant of CTV, xyloporosis, blight, and salinity, but is only moderately tolerant of high pH and cold, and susceptible to *Phytophthora* and exocortis. Fruit yield and fruit quality are probably similar to that of trees on Cleopatra (Castle, 1987; Castle et al., 1993, 2015; Wutscher, 1979). There is interest in replacing Rangpur with Sunki mandarin in Brazil because of good salinity and drought tolerance along with better blight tolerance (Girardi et al., 2017). Brazil is the only country where Sunki is significantly used for new tree propagations.

Swingle citrumelo is a hybrid of Duncan grapefruit (*Citrus paradisi*) and trifoliate orange (*P. trifoliata*) created in 1907 in Eustis (Florida) by the USDA pioneering citrus breeder for which it is named, Walter T. Swingle. The Swingle rootstock was officially released by USDA in 1974 (Hutchison, 1974; Wutscher, 1979). In the field, Swingle rootstock produces large, vigorous, and productive trees with fruit that is similar to or slightly larger than fruit on Carrizo, and good internal quality. It has been noted that trees on Swingle have an average of 3 weeks delayed rind color development and later fruit maturity as compared with Carrizo, due to higher acidity (Lee et al., 2009). Swingle has good tolerance to drought, cold, *P. nicotianae* (but not *P. palmivora*), citrus nematode, blight, and CTV. The rootstock is suitable for most soils except highly calcareous conditions, salinity, and heavy clay soils, with a clay content greater than 25%–30%, or heavy clay layers. Swingle shows trunk overgrowth with most scion cultivars, and this overgrowth has been considered a significant problem in some cases with mandarins and with early slow-growing navel sweet orange selections, when it can result in compression girdling (Garnsey et al., 2001; Lee et al., 2009). Swingle has been observed as not compatible with the scions Eureka lemon, Tomango and Shamouti oranges, and Murcott tangor. Swingle is the dominant rootstock for new propagations in Colombia, Panama, Nicaragua, Costa Rica, and Thailand, and is used for a significant portion of new propagations in Argentina and several other regions. In Florida, Swingle was used for nearly half of all propagations from 1988 to 2010, but since then, it has declined significantly because of better performance from other rootstocks showing broader soil adaptability, better cropping, and improved tolerance to Huanglongbing.

US-802 citrus rootstock was released by the US Department of Agriculture in 2007 (Bowman, 2007a), and has subsequently been widely used in Florida, especially with sweet orange scions. Florida Department of Agriculture Annual Budwood Reports puts the number of propagations on US-802 from 2011 to 2018 at 1,782,501 trees. This rootstock is from a cross of Siamese pummelo (*C. maxima*) × Gotha Road Trifoliate Orange (*P. trifoliata*) and was tested primarily by USDA with industry partners in Florida prior to release, but has subsequently been widely planted and evaluated. The rootstock induces strong vigor in grafted scions, similar to the effects of rough lemon, and in most cases trees will become large. With sweet orange scion in Florida, US-802 was the most productive rootstock in some trials (on a per tree basis) both before *C*Las, and afterwards as well when trees were affected by Huanglongbing. Other positive attributes of US-802 are resistance or tolerance to high pH, CTV, citrus nematode, *P. nicotianae* and *P. palmivora* foot and root rot, Diaprepes root weevil, and citrus blight. Most notable faults with this rootstock are very high vigor, and a corresponding tendency to induce lower Brix in the fruit of grafted scions. Field performance has been described in several publications (Bowman et al., 2003, 2016a,b; Castle et al., 2004; Wutscher and Hill, 1995). US-802 is virtually unknown in other areas outside Florida.

US-812 citrus rootstock was released by the US Department of Agriculture in 2001 (Bowman, 2001), and has subsequently been widely used in Florida. Florida Department of Agriculture Annual Budwood Reports puts the number of propagations on US-812 from 2011 to 2018 at 1,377,171 trees. This rootstock originated from a cross of Sunki mandarin × Benecke trifoliate orange (*P. trifoliata*) and was tested primarily by USDA with industry partners in Florida prior to release, but has subsequently been widely planted and evaluated. Prior to the introduction of Huanglongbing in Florida, US-812 was often among the most productive rootstocks with a range of scions in field trials (Bowman and Rouse, 2006; Castle et al., 2011; Wutscher and Bowman, 1999), and typically induced good fruit quality. Trees on US-812 are similar in vigor to trees on Carrizo and Swingle, and US-812 has good tolerance to CTV, *P. nicotianae*, citrus blight, and high pH. In trials strongly affected by Huanglongbing, field performance of trees on US-812 has generally been about average, but not outstanding (Bowman et al., 2016a,b; McCollum and Bowman, 2017). US-812 is used to a limited extent in other countries outside the US, including Israel and South Africa, where it is often referred to as Sunki-Benecke.

US-897 citrus rootstock was released by the US Department of Agriculture in 2007 (Bowman, 2007b), and has subsequently been widely used in Florida, especially with the goal of achieving tree size control for close set plantings and intensive management. Florida Department of Agriculture Annual Budwood Reports puts the number of propagations on US-897 from 2011 to 2018 at 1,646,569 trees. This rootstock originated from a cross of Cleopatra mandarin × Flying Dragon trifoliate orange (*P. trifoliata*) and was tested primarily by USDA with industry partners in Florida prior to release, but has subsequently been widely planted. Calculated on a per tree basis, fruit productivity of trees on US-897 is typically poor, but because of the small tree size, calculations of potential yield per hectare at predicted optimum spacing may be very high. US-897 usually induces good internal fruit quality on grafted scions, but fruit size may often be smaller than average. In addition to the tendency for US-897 to produce small or semidwarf trees, this rootstock was also noted to be tolerant of CTV, citrus nematodes, the PDC, and high pH. US-897 exhibits a susceptibility to citrus blight that is intermediate, as compared with other rootstock cultivars. Because of its effects to control tree size, US-897 has been a preferred rootstock in many new attempts at very high-density plantings, and plantings in protected structures (Ferrarezi et al., 2017). US-897 has reportedly been introduced to many other countries, but as of yet, commercial use is only of significance in Florida. Field performance has been described in several publications (Bowman et al., 2003, 2016a,b; Castle et al., 2004; McCollum and Bowman, 2017; Wutscher and Hill, 1995).

US-942 citrus rootstock was released by the US Department of Agriculture in 2010 (Bowman and McCollum, 2010), and since then has rapidly gained popularity in Florida. Records from Florida Department of Agriculture Annual Budwood Reports puts the number of propagations on US-942 from 2011 to 2018 at 1,784,729 trees. This rootstock originated from a cross of Sunki mandarin × Flying Dragon trifoliate orange (*P. trifoliata*) and was tested primarily by USDA with industry partners in Florida prior to release, but has subsequently been widely planted and evaluated. Field performance has been studied primarily with sweet orange scion, but trials have also indicated excellent performance with grapefruit, mandarin, pummelo, and Tahiti lime scions. The major positive attributes of US-942 are ease of uniform seed propagation, resistance or tolerance to CTV, citrus blight, *Phytophthora* root diseases, Diaprepes weevil, and high pH soils, as well as a semidwarfing effect on scion tree size, induction of good fruit quality, and induction of good fruit productivity per tree and per canopy volume. Performance has been outstanding in trials on both well-drained deep soils and heavy soils with a high water table. More recently, US-942 has been a top performer in field trials affected by Huanglongbing disease (Bowman et al., 2016a,b), and the nature of its Huanglongbing tolerance has been the subject of detailed greenhouse studies (Albrecht and Bowman, 2012; Albrecht et al., 2016; Bowman and Albrecht, 2015). Major faults are, as yet, unidentified. Although relatively unknown in other citrus production areas, US-942 will likely be the most used rootstock for new propagations in Florida during 2018–19, surging ahead of the previously most used rootstocks Kuharske, Swingle, sour orange, and X639. Characteristics and field performance of US-942 have been described in additional publications (Albrecht and Bowman, 2019; Bowman and Albrecht, 2017; Bowman et al., 2003; Castle et al., 2004, 2011; McCollum and Bowman, 2017; Wutscher and Bowman, 1999).

Volkamer (*Citrus volkameriana*) is likely a mandarin × citron hybrid, and of Italian origin. The Volkamer lemon was named in honor of J.C. Volkamer, the 18th-century German botanist (Saunt, 2000). Volkamer resembles rough lemon in many respects, including the induction of high vigor and poor internal fruit quality on grafted scions. In combination with lemon selections, Volkamer is considered an excellent choice in many areas, including southern Africa. Volkamer is susceptible to *Phytophthora* root rot and cold damage, although slightly less sensitive to both than rough lemon. In South Africa, Volkamer is considered sensitive to CTV and citrus nematodes (Lee et al., 2009), and it is susceptible to citrus blight in Florida. However, the rootstock performs well on a fairly wide range of soil conditions, including sandy, high pH, and areas affected by salinity. Volkamer is not susceptible to some citrus viroids. In some cases, performance of Volkamer is considered superior to rough lemon, but this is not uniformly the case. Volkamer is a major rootstock in Mexico, Dominican Republic, Egypt, and Israel, and has widespread use in many countries with lemon scions.

X639 rootstock arose from a cross between Cleopatra and *P. trifoliata* made at the CSFRI (now ARC-ITSC) South Africa, by Dr. Hojby in the early 1950s (Lee et al., 2009). The overall characteristics appear similar to those of Carrizo, but it may be more sensitive to *Phytophthora* root rot in replant conditions. X639 develops a fairly vigorous medium-sized tree in combination with most scion cultivars. In susceptibility tests for saline and calcareous conditions conducted in Australia, X639 was found to be similar to or slightly less susceptible than Swingle citrumelo (Lee et al., 2009). X639 has performed well in the higher pH soils of the Tshipise (Limpopo) and Lower Orange River (Northern Cape) areas in South Africa. Trees on this rootstock generally are productive, and the rootstock is considered to induce good internal fruit quality and good-sized fruit in South Africa (Lee et al., 2009), although some studies in Florida have indicated particularly low Brix for grapefruit on X639 (McCollum and Bowman, 2017). X639 is considered to have good promise in South Africa for Valencia, navel, grapefruit, and mandarin scions (Lee et al., 2009). Trials in Florida indicated that X639 behaved similarly to Cleopatra mandarin with regard to citrus blight tolerance, that is, trees were susceptible, but took about 12 years to show decline and die-back. The main advantages of X639 are *Phytophthora* root rot tolerance, nematode and CTV tolerance, good internal quality fruit (under some conditions), medium tree size, good performance on higher pH soils, good cold hardiness, and compatibility with Eureka lemon. X639 been used for a significant number of propagations over the last 5 years in both Florida and southern Africa.

Ziyang Xiangcheng (Fragrant citrus) is a local citrus rootstock that originated in southwest China. It is sometimes identified as *Citrus junos* (Tan et al., 2015), and has been suggested as a putative hybrid of *Citrus ichangensis* and *C. reticulata* (Liu et al., 2008; Zhou et al., 2014); in fact, it is a local selection of what is commonly known outside of China as Yuzu. This appears to be similar to, but not the same as Zhique or *Citrus wilsonii* Tanaka (*C. junos*) (Fu et al., 2016; Hancevic et al., 2013). Ziyang Xiangcheng has been described as having excellent tolerance to biotic and abiotic stresses, including high soil pH. It has been used in Sichuan and Chongqing regions of China, primarily in citrus orchards planted on wet and heavy paddy soils. Although not widely used, it is increasingly being used for new plantings of Orah mandarin trees in Guangxi and Yunnan provinces. Ziyang Xiangcheng is as yet untested in other citrus growing regions, and limited descriptive information is available.

6.6 Rootstock trends and future prospects

The common use of rootstocks in citriculture began in many countries during the mid-1800s (Castle, 2010), and initial rootstocks used included sour orange and other naturally occurring citrus types. A series of disasters affecting the citrus industries in different countries followed, often driven by epidemic spread of CTV strains that destroyed vast areas of trees on sour orange rootstock, and prompting a search for other, better rootstocks. During this phase, rough lemon, Cleopatra mandarin, Rangpur, trifoliate orange, and sweet orange enjoyed popularity for use as rootstocks in some areas, and guided breeding of citrus began in earnest within the USDA in Florida under the leadership of Walter T. Swingle. Although they took many years to reach commercial use, out of those early USDA efforts came the first hybrids from controlled crosses to see worldwide use as citrus rootstocks, Carrizo/Troyer citrange and Swingle citrumelo (Webber et al., 1967). During the 1960s and after, hybrid rootstocks began to increase in popularity through many citrus-producing regions, although the timetable and particular rootstocks involved varied by country. During the 1970s–80s, Carrizo and Swingle displaced sour orange and rough lemon as the dominant rootstocks in Florida (2004 Florida Department of Agriculture Citrus Budwood Annual Report). It can be noted that among the 21 major world rootstocks, 10 are naturally occurring species or hybrids, and 11 are F1 hybrids from breeding programs. Among all the F1 hybrids, *P. trifoliata* is one of the parents. None of the major rootstocks are more advanced hybrids, somatic hybrids, the product of induced mutation, or from any other type of genetic manipulation. As there are many efforts underway to create more complex hybrids and somatic hybrids to broadly improve performance, as well as genetically engineer citrus rootstocks to obtain improved tolerance to disease, it may be anticipated that the future of citrus rootstocks will include more diversity of germplasm and other types of genetic combinations. It should also be recognized that all of the 21 major rootstocks produce a high proportion of nucellar seedlings and are thus easily and uniformly propagated by seed. This ease of seed propagation has been a major selective factor for citrus rootstocks until now, but with the commercialization of citrus rootstock micropropagation, it may become of considerably less importance in the years to come. It is easy to see how a rootstock with outstanding field performance might become a major world rootstock in the future, even if it cannot be propagated by seed.

Numerous citrus rootstock breeding and testing programs exist, and in many cases, these programs have developed and released new or improved rootstocks. In all, 11 of the 21 rootstocks listed as major world rootstocks were the product of past citrus breeding efforts in the United States (7), South Africa (2), Australia (1), and Spain (1). Typically, new citrus rootstocks are only slowly adopted for widespread use because of the many years required to collect reliable field performance information, and the long life of a commercial planting. In the past, reliance on seed for rootstock propagation also slowed the adoption of new rootstocks to an area, and the production of seed often has greatly limited the use of new rootstocks even where they are desired. Sometimes vast regional differences in soils, pests and pathogens, scion cultivars, and management practices contributes to the long delay in determining suitability of new rootstocks for use in multiple regions. Nevertheless, the history of Carrizo and Swingle rootstocks has shown that new rootstocks developed in one region can eventually become widely used throughout citrus production regions of the world. There are many new rootstocks from regional programs that did not make the list of 21 major rootstocks now, but appear to have promising characteristics, and could become major rootstocks in the coming years. In the following is mentioned some of these new rootstocks, poised to possibly move into more significant roles for the future.

The University of Florida citrus breeding program in Lake Alfred, Florida, has developed a series of new rootstocks, many of them tetraploids, and the product of somatic hybridization or the subsequent sexual hybridization of two somatic hybrids (Grosser et al., 2011, 2015). UFR-4 rootstock [(Nova mandarin + Hirado Buntan pummelo seedling) × (Cleopatra mandarin + Argentine trifoliate orange)], UFR-5 rootstock [(Nova + Hirado Buntan pummelo seedling) × (Succari sweet orange + Argentine trifoliate orange)], and UFR-6 rootstock (Changsha mandarin + Trifoliate orange 50-7) are three examples that have evidenced good field performance and are seeing considerable commercial interest. These were reported by Florida Department of Agriculture as having been used for the propagation of 71,231 trees, 16,735 trees, and 28,617 trees, respectively, during the period July 2017 to June 2018. UFR-4 and UFR-5 performed well in the University of Florida two phase assay for PDC, and then have demonstrated good tolerance to PDC and HLB, along with good yield, through 5 years of field testing. UFR-6 is a cold-hardy somatic hybrid rootstock that produces small trees which bear fruit with high soluble solids, thus making it a good candidate for new production systems featuring high-density plantings. Additional new hybrids derived from Flying Dragon maternal parentage are showing promise for tree size control as well as tolerance of Huanglongbing and good yields.

The citrus rootstock breeding program at IVIA in Valencia, Spain, was responsible for development of F-A 5, one of the major world rootstocks from our list. Two other promising rootstocks from this program, Forner-Alcaide 517 and Forner-Alcaide 418, have more recently been described (Forner-Giner et al., 2014). As these two new rootstocks combine tree size control, high yield efficiency, and good fruit quality with good tolerance to high pH, traits of great current interest, it might be expected that at least one of these new rootstocks will also grow in popularity.

The USDA rootstock breeding program in Ft. Pierce, Florida, was responsible for the development of four rootstocks from our major rootstocks list, released between 2001 and 2010, and all having names that begin with "US." Over the past 15 years, the USDA rootstock breeding program has focused efforts on developing an improved sour orange-type rootstock, targeting a rootstock that combines all the best traits of sour orange with good tolerance to CTV and outstanding productivity. This genetically broad group of hybrids created and being evaluated under this effort includes hybrids of sour orange itself, as well as other hybrids that include the two parental species of sour orange, *C. reticulata* and *C. maxima*. The first of these "SuperSour" rootstocks were released in 2018, based on field performance considerably superior to both sour orange and Swingle in tree health and productivity (Bowman and McCollum, 2018a,b,c). The three SuperSour rootstocks released in 2018 are US SuperSour 1 rootstock = *C. maxima* × *C. reticulata,* US SuperSour 2 rootstock = *P. trifoliata* × (sour orange × *C. ichangensis*), and US SuperSour 3 rootstock = Cleopatra mandarin × (*C. maxima* × *P. trifoliata*). There has been considerable commercial interest in these new rootstocks.

The citrus breeding program at the University of California, Riverside, was responsible for testing and releasing of one of the major rootstocks on our list, C35. In addition, several other rootstocks from the University of California program, including C22, C54, C57, and C146 (all of Sunki × Swingle trifoliate orange parentage), show promise for some citrus production areas (Federici et al., 2009; Roose, 2007), especially in areas of high pH soils (Louzada et al., 2008), and seem likely to increase in use over the coming years.

Several other citrus-breeding programs have significant efforts directed toward development of improved rootstocks, including work in Brazil (Fadel et al., 2018), Australia (Smith, 2017; Sykes, 2011a,b), Italy (Reforgiato Recupero et al., 2009), and China (Guo and Deng, 2001; Guo et al., 2002; Liu and Deng, 2007). In addition, numerous programs have invested strongly in genetic transformation or other methods of genetic manipulation, that offer the opportunity to introduce major new types of disease resistance or other important traits to citrus rootstocks. Although most of these efforts are probably more than a decade away from a product that will become a major world rootstock, it seems likely these efforts will eventually yield new rootstocks with commercial impact.

Although creating the best rootstock through sexual hybridization, somatic hybridization, genetic transformation, or mutation is itself a huge challenge, it may be that the greatest difficulty in development of a new rootstock and widespread commercial use, is in the sufficiency and accuracy of field evaluation that can provide clear information about which rootstock is the best choice for each environment, scion, and production system. Probably many excellent rootstocks already exist, but only require thorough multiyear evaluation at multiple sites, to determine which few of the many hundreds of promising rootstocks are truly worthy of widespread commercial use in each area. Through the many efforts underway now, the field of rootstocks will evolve greatly over the coming 10 years, and should provide growers in every citrus region better facts to inform which of the many new and existing rootstocks provide the best opportunity to improve production and profitability.

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