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Citrus Production Systems to Survive Greening: Horticultural Practices

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Fruit yield is a critical component in the long-term profitability of citrus growers in Florida. Increasingly, two factors outside the control of the growers are forcing Florida citrus growers to re-evaluate the sustainability of their current operations. These factors are: 1) impact of canker and greening diseases on tree health and yields and 2) continued urbanization within the state. A key to increased profitability may be improved early and sustained production on high density groves. Improved early and sustained yields may allow growers to reach earlier return on investment and thus, better deal with potential decreased production due to tree loss from disease. The use of automated irrigation systems and intensive nutrient management may provide critical enhancement to production systems for achieving increased tree growth and yield. A widely discussed approach for maintenance of soil moisture and nutrient concentrations in the tree root zone near optimum levels is known as the Open Hydroponic System (OHS). The system must be adapted for the Florida summer rainy season and sandy soil characteristics so that current fertilizer best management practices (BMPs) are not exceeded and nutrient leaching is not increased. Current OHS management practices utilized in selected citrus producing countries around the world will be reviewed and compared to proposed Advanced Production Systems practices for high density citrus plantings in Florida. Practices considered will be nutrient ratios and application timing, irrigation scheduling and methods, root density distribution, and girdling. Adoption of these intensive citrus management practices has the potential of conserving water, improving nutrient use efficiency, reducing leaching in addition to improving tree growth and yield.

Citrus tree acreage in Florida decreased to 576,577 acres in 2008, the lowest number of citrus producing acres since 1966 (Florida Agricultural Statistics Service, 2009). Cited reasons for lower production acreage were urban development, canker (*Xanthomonas axonopodis*), and hbruanglongbing (*Liberibacter asiaticus*, citrus greening). Acreage decreases were recorded in 25 of the 30 counties included in the annual citrus tree survey. Citrus acreage loss in the Indian River production area was the greatest, with Martin County losing 34% last year alone. Improved tree growth from intensive management practices could reduce the time required from planting to economic break-even production, thus providing potentially valuable management options in light of current devastating diseases such as canker and greening. Florida growers must also adopt Best Management Practices (BMPs) that reduce nutrient leaching by limiting the amount of fertilizer that can be applied, and the time of year when fertilizer can be applied. These BMPs are based on research under low-intensity management systems that apply both water and nutrients at intervals that are less than optimal. However, production systems that combine grove design and irrigation management to increase yield and grove operational efficiency have not been studied in Florida. High density plantings of sweet oranges on low-vigor rootstocks have known advantages, but their long-term behavior and changes in the functional relationship of tree density, growth rate, and yield over time are not well understood.

New production and harvesting concepts have the potential to make the Florida citrus industry more efficient and economically competitive. The two basic grove production components are the Advanced Production System (APS) and the Open Hydroponic System (OHS) (Stover et al., 2008). The fundamental concepts of APS/OHS for citrus are: 1) combining more intensive grove designs with intensive management, and 2) refining tree management through improved manipulation of plant physiology throughout tree and crop development in a production system that optimizes tree performance. These concepts are designed to more fully and efficiently exploit a citrus tree's potential by providing optimal conditions. Those improvements are expressed in maximizing water and nutrient use efficiency and concentrating root within irrigation zones, which should lead to less nutrient leaching. We

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are asking the question "Can we use known principles of plant physiology, but apply them differently?" Also, we are asking whether we can identify critical phenological stages for differential management and culture the trees according to those stages rather than on an annual, less than optimal basis.

The Open Hydroponic System (OHS) is an integrated system of practices including irrigation, nutrition, and horticultural practices that was developed in Spain in the early 1990s (Falivene et al., 2005; Martinez-Valero and Fernandez, 2004) to contend with gravel based soils and the problem of low fertility. OHS provides tight control over water and nutrient-mediated plant growth and development using irrigation to train the root system into a limited area and fertigates with daily requirements of nutrients (Stover et al., 2008). Falivene (2005) defined the OHS as a management practice that aims to increase productivity by continuously applying a balanced nutrient mixture through the irrigation system, limiting the root zone by restricting the number of drippers per tree and maintaining the soil moisture near field capacity in the limited wetted zones. The combination of these practices is claimed to provide a greater control and manipulation of nutrient uptake at specific physiological stages and improved water uptake (Yandilla, 2004). OHS has been successfully used in the production of peaches, almonds, grapes, citrus, avocados, and several vegetable crops in Spain, South Africa, Chile, Argentina, Morocco, and California (USA). In South Africa, commercial growers have adapted the OHS through use of drip fertigation on a daily basis during daylight hours (Pijl, 2001; Schoeman, 2002) resulting in increased citrus yield and fruit size (Kruger et al., 2000a, 2000b; Kuperus et al., 2002). OHS principles were introduced in Australia as an intensive fertigation practice (IFP) in citrus orchards (Falivene et al., 2005; Sluggett et al., unpublished) but is somewhat less intensive than the original OHS developed in Spain to better meet the conditions and needs of the Australian industry. Thus, OHS has been modified to meet local cultural, weather and soil conditions. We present a review of current OHS-related management practices in selected citrus-producing countries with suggestions for adapting the OHS to APS practices for higher density citrus plantings in Florida.

Considerations for Successful OHS

Several fundamental aspects of citrus physiology and cultural management must be taken into consideration when implementing OHS. Elements to be considered include fertilizer requirements and irrigation scheduling, and have been researched using many tree sizes and soil conditions. The following section reviews reports on Florida citrus to help guide us in interpreting likely responses of citrus to OHS in Florida conditions and most obvious needs for further research and possible modifications.

Fertilizer requirements. OHS and IFP use a more intensive nutrition program with the goal of pushing trees into a higher level of vigor and productivity requiring higher nutrient application rates to maintain production. Considering current best management practices (BMPs) and potential improvements in nutrient use efficiency, a goal for successful adoption of OHS in Florida will have to be more efficient use of applied nutrients and less associated leaching. To determine whether this is feasible, we must review studies on fertilization practices on citrus in Florida, which sometimes appear confusing and contradictory, due to different tree ages, soil types and application practices compared. Obreza and Rouse (1993) showed that an increase in fertilizer rate from 0.32 to 0.64 kg N per tree in the third year after planting resulted in a decrease in total soluble solids concentration and soluble solids to acid ratio. Also, Koo and Smajstra (1984) made similar observations with annual N rates greater than 200 lb per acre using trickle irrigation and fertigation on 26-year-old 'Valencia' orange on an Astatula fine sand in Florida. Furthermore, in trials on sandy soil, Koo (1980) found no significant differences due to fertigation frequencies (3 or 10 times a year) on 13-year-old 'Valencia' orange. Similarly, Syversten and Jifon (2001) studied fertigation frequencies of 12, 37, and 80 times per year in 6-year-old 'Hamlin' oranges in Florida and found that fertigation frequency did not affect leaf nutrient concentration, canopy size, fruit yield, or juice quality. Morgan et al. (2009b) examined the effect of N fertilizer rates and methods of applying N on growth and productivity of young (3 to 5 years old) and maturing (8 to 10 years old) citrus trees on well drained sandy Entisols of central Florida. In young trees, controlled release fertilizer applied once a year and fertigation done 30 times annually produced higher yields and larger trees compared with fertigation or dry granular fertilizer applied four times annually. In the maturing trees, however, the dry granular fertilizer applied four times a year and fertigation done 30 times annually produced similar yields and total soluble solids. Canopy volumes for the same trees were significantly greater with fertigation treatment compared with the dry granular fertilizer. They observed that increased number of split applications will likely promote tree growth in mature citrus, albeit with little increase in fruit yield.

Alva et al. (2003) proposed a combined use of foliar fertilizer application and fertigation as the BMP for N because these were effective in reducing nitrate leaching to surficial groundwater. Nevertheless, even the most intensive practices in the studies reviewed provide many fewer seasonal applications of fertilizer than a typical OHS in which three or more fertigations per day are standard (Falivene et al., 2005).

Irrigation design and scheduling. Proper irrigation system design is important in APS such as OHS and IFP to ensure that the system does not leak and/or fail at some point. There are two main types of irrigation scheduling programs in OHS: pulsing irrigation and continuous (Falivene et al., 2005). A pulsing irrigation management program involves short pulses of irrigation provided to the trees at a number of times throughout the day while a continuous irrigation management program uses low output rates to match water use conditions in summer. The number and timings of pulses are based on a calculation of readily available water (RAW) and average tree water use along with monitoring of irrigation scheduling devices like tensiometers, capacitance probes and trunk diameter measuring devices. In a restricted root zone situation up to nine or more pulses of irrigation could be scheduled throughout the day in summer (Falivene et al., 2005).

Open Hydroponic System Concepts

The goals of OHS are to 1) increase initial tree growth rate, 2) establish early sustained fruit production, 3) maximize efficiency of production inputs, and 4) improve return on investment to achieve profits in as short a period of time as possible. To accomplish these goals within the framework of Florida environmental needs, three fertigation concepts have been developed: 1) maximization of water and nutrient use efficiency, 2) concentration of roots in the irrigated zone, and 3) reduction of nutrient leaching. These goals and concepts have been incorporated in the APS that utilizes OHS along with tree planting density, tree size control and horticultural manipulation (pruning and girdling).

Maximize water and nutrient use efficiency. Several studies conducted over many years have revealed that it is possible to increase yield, and efficiency of water-use and nutrient-use through water-saving irrigation methods. In a study on water use efficiency and nutrient uptake on low volume irrigated citrus in New South Wales in Australia on Tiltao sand, Grieve (1989) found that water uptake was limited by water availability rather than root density. Also, fertilizer injection with the microsprinkler system significantly increased the efficiency of N and P uptake compared with surface application, whereas leaf K levels were lower under low volume irrigation (Grieve, 1989). Multiple applications of N in relatively small amounts with drip irrigation resulted in lower soil residual mineral-N concentrations and enhanced N-uptake efficiency by the citrus roots (Alva et al. 1998; Klein and Spieler, 1987; Paramasivan et al. 2001). Xu et al. (2004) found that P and water uptake were also enhanced in lettuce by high fertigation frequency at a low P level. In a 3-year study, Bryla et al. (2003) found that peach trees irrigated by surface and subsurface drip produced higher yields and had higher water-use efficiency than those irrigated by microjets and furrow irrigation on a Hanford fine sandy loam in California. Drip irrigation systems, in particular, are known to improve irrigation and fertilizer use efficiency because water and nutrients are applied directly to the root zone (Camp, 1998). The benefits of frequent fertigation and/or irrigations in achieving high water and nutrient use efficiency offered by drip irrigation can be negated by improper water placement as shown by the findings of Zekri and Parsons (1988) in grapefruits. Therefore, careful placement of water in the root zone is important in fruit production to ensure that water and nutrient uptake are optimized.

Concentrate roots in irrigated zone. Studies on tree root density distribution have been in done in Florida and other parts of the world. Morgan et al. (2007) found that fibrous root length density (FRLD) distribution increased with soil depth and lateral distance as trees grew, resulting in mature trees with bimodal root systems. Also, the FRLD varied as a function of rootstock in which trees on Swingle citrumelo developed higher FRLD near the soil surface and lower FRLD below 0.3 m than trees on Carrizo citrange. Abrisqueta et al. (2007) studied root dynamics of young peach subjected to partial root zone drying and continuous deficit irrigation in Spain. In the study, higher root length densities were recorded in non-limiting irrigation conditions than under deficit irrigation where root growth was reduced.

The use of OHS can limit root growth to within the irrigated zone. Research studies into restricted root zones using physical constraints have shown a reduction in yield in fruit and vegetables (Bar-Yosef et al., 1988; Boland et al., 2000; Ismail and Noor, 1996). These studies attributed the yield reduction to reduced canopy growth. Reduced canopy growth or a reduction in yield per tree has not been observed to date in OHS (Boland et al., 2000; Falivene, 2005). The wetted soil volume in OHS is considerably greater than the restricted root zone studies mentioned above where significant reductions in vegetative growth and yield have been reported (Falivene, 2005). The study by Boland et al. (2000) on peach in Australia showed a significant reduction in growth and yield when the root zone was restricted to 3% of its potential. In contrast, the wetted soil volume in OHS is approximately 8% to 15% of the potential root volume (Falivene, 2005). These studies envisage that in an OHS situation, the roots are redirected to grow more densely in a smaller volume of soil, but the soil volume is sufficiently large enough to support active root growth and a productive tree.

Reduced nutrient leaching. Many researchers have attempted to study nutrient leaching to sustain environmental quality. Paramasivam et al. (2001) found that nitrate-nitrogen leaching losses below the rooting depth accounted for 1% to 16% of applied fertilizer N and increased with increasing rate of N application (112 to 280 N/ha per year) and the amount of water drained. Paramasivam et al. (2001) also noted that the leached nitrate-nitrogen at 240 cm remained well below the maximum contaminant limit of 10 $mg \cdot L^{-1}$. They ascribed their observations to careful irrigation management, split fertilizer applications and proper timing of the application. Thus, it should be possible to reduce nutrient leaching with an OHS and/or IFP because in both scenarios water and nutrients are applied in quantities approximating plant needs and close to the plant with less waste and, at specific physiological stages of the plants (Mason, 1990).

Principles Used in Advanced Production Systems

Certain principles of irrigation, nutrient, and horticultural management must be followed in a systematic approach to achieve the goals of OHS. The principles of production used in APS are currently being followed by most citrus Florida growers, but require some modifications and more intensive management. Methods of implementing APS principles in current management practices follow.

Higher tree density (>250 trees/acre). The ideal grove is one in which there is rapid development of trees to bearing volume with sufficient bearing volume to support high levels of cropping. Such groves provide certain known advantages related to production, harvesting and returns, but to be successful, smaller-sized, closely planted trees are essential. The practices and concepts that constitute the OHS are an excellent match with higher planting densities.

Changes in orchard design have occurred primarily in the deciduous fruit industries. Robinson et al. (2007) published results of planting densities ranging from 340 to 2178 trees per acre for apple orchards in New York. They found that the optimum economic density was between 1000 and 1200 trees per acre. The optimum density achieved improved yield and quality coupled with lower costs of production.

New designs have been investigated in citriculture, but largely not adopted commercially. With the advent of the OHS for citrus, some data have demonstrated the performance of groves of closely spaced trees managed with the OHS. Yields of 'Nova', 'Marisol', and 'Delite' mandarins in Spain, planted at higher density (405 trees per acre) and grown using the OHS were about 65 to 75 tons per hectare in the sixth year, which is higher than for a conventional orchard using low to medium density plantings (150 to 230 trees per acre) (Falivene et al., 2005; Martinez-Valero and Fernandez, 2004). In Florida citrus studies involving tree density, higher planting density produced higher early production (Castle, 1980; Parsons and Wheaton, 2009; Whitney and Wheaton, 1984) and utilized nutrients and irrigation water more efficiently (Parsons and Wheaton, 2009). Those studies demonstrated the feasibility of higher density plantings for Florida citrus, but the trials were conducted under lower trees planting densities than proposed for the future with OHS and under less intensive management. Thus, there is a possibility of further increasing yield per unit area using OHS with densely planted citrus trees.

Rootstock selection. Rootstock selection along with tree planting density is a key element in the APS/OHS approach to the future. Citrus trees, like humans, need a certain amount of space to develop and flourish. When the allocated space is fixed, e.g., 1 acre of land, tree size becomes critical because the productive unit is the canopy and only a certain volume of canopy can be grown on 1 acre. Vigorous, large trees are neither compatible with close spacing nor productive in their younger years. Thus, in a world of economic necessity dictated by early and robust returns, small, closely spaced trees become a required component of the new production concepts.

Groves of closely spaced trees on vigorous to size controlling rootstocks have been extensively researched, but have had virtually no commercial implementation in Florida. From the research, it is apparent that proper matching of tree size with spacing and site conditions is critical for success. When that combination is achieved, the higher density grove will outperform the more conventional one especially in the early years. In Florida, the conventional grove is spaced about 15 × 25 ft (116 trees/acre), the modern grove is at 10 × 20 ft (218 trees/acre), and the higher density grove would be about 8 × 15 ft (363 trees/acre). There are modern groves in Florida being cultured and harvested with conventional equipment, which is the key factor. New concept groves are likely to require different and probably less expensive equipment and the application of new harvesting concepts. Also, size-controlling rootstocks are needed and the absence of choices has been a limiting factor to date. However, in addition to Flying Dragon trifoliate orange, there are new options available for testing from the University of Florida and U.S. Department of Agriculture Florida breeding programs.

Horticultural manipulation. Growing citrus trees in a grove usually means that the trees are forced into somewhat unnatural shapes. Therefore, they are mechanically hedged in Florida to contain them and provide equipment access. Often when citrus fruit are grown for the fresh market, the trees are manually manipulated using various horticultural techniques such as pruning and girdling to improve fruit set, yield, and quality. These techniques have perhaps even greater potential to enhance fruit quality and also increase yield when applied to more easily managed small trees planted close together (APS) and intensively managed using the OHS approach.

Pruning under virtually all conditions is used for two generally recognized and interrelated reasons: 1) to help keep the canopy to a manageable size (containment), and 2) to open the canopy to allow more uniform light penetration, which helps with fruit set and development and improves peel color. Manipulation of the canopy, while not essential, can be helpful because trees often do not assume a form most desirable for best performance. Other less recognized reasons to prune place emphasis on: 1) ensuring that regrowth within a canopy is managed, and 2) maintaining a balance of bearing to non-bearing wood for sustained productivity.

Pruning also encompasses training, an activity mostly reserved for young trees. It is designed to shape the canopy to meet the objectives stated above. In the APS/OHS system, training is important, primarily to encourage early productivity. Pruning and training combined with APS/OHS are also reported to be important in keeping fruit physically close to the tree trunk. There is the view that because the tree's transport system brings water, nutrients and carbohydrates to the fruit, distance becomes a negative factor. Thus, it is most desirable to have the fruit as close as feasible to the sources of food and water while maintaining transport system capacity. For all of these reasons, Stover et al. (2008) suggested that use of APS/OHS systems should help control vegetative growth, keeping trees in check and reducing cost of pruning while also providing earlier cash flow.

The effects of girdling on crop performance depend on when it is done. Girdling in autumn enhances flowering in citrus (Goldschmidt and Colomb, 1982), at full bloom improves fruit set in oranges (Monselise et al., 1972), and in summer, girdling increases grapefruit size (Fishler et al., 1983). In other cases, girdling was reported to limit nitrogen, phosphate and calcium uptake in avocado in South Africa (Davie et al., 1995) and reduce the soluble solids concentration at harvest in grapes in California (Harrell and Williams, 1987). However, Andrews et al. (1978) reported that girdling in peach in Florida increased fruit size, enhanced ripening but resulted in severe necrosis of leaves and gumming on the area of the cut. The pruning and girdling practices need to be carefully considered for use in high planting density Florida citrus plantings because benefits will need to be substantial to justify the high labor costs associated with these practices.

Drip irrigation practices (wetted strips). Michelakis et al. (1993), studying avocado water use in a Mediterranean climate in Greece under drip irrigation, found that root density was generally higher in the upper 50-cm soil layers and within 2 m from the drip line, with about 70% of the roots located in this region. They attributed the higher root percentage in the upper soil layers to biological factors and to the higher oxygen diffusion rate. Michelakis et al. (1993) applied irrigation water to each treatment using one drip lateral per row of trees with drippers of 4 $L \cdot h^{-1}$ discharge rate placed 70 cm apart. Coleman (2007) also observed that root length density in cottonwood, American sycamore, sweetgum, and loblolly pine was dependent on depth and position relative to drip emitter when fertilizers were applied and is greatest at the surface and in proximity to the drip line. The factors controlling root length density in the woody species studied included age, depth and proximity to the drip emitter. Partial soil wetting under drip irrigation generally leads to many agronomic benefits such as water and labor saving (Keller and Karmeli, 1974). However, the extent of the wetted soil volume is a function of the emitter discharge and spacing but depends mainly on the soil type and the total water added (Warrick, 1986). The principles underlying the restriction of the roots to the wetted zone using drip irrigation are also applicable to APS.

Intensive water and nutrient management. Kalmar and Lahar (1997) irrigated avocados with sprinklers at 7-, 14-, 21-, and 28-d intervals on a grumusol with more than 60% clay from the soil surface to a depth of 150 cm and found that most water was absorbed from upper 60-cm soil layer suggesting that this was where most roots were concentrated. Bryla et al. (2005) compared the effect of furrow and microsprinkler irrigation scheduled weekly or bi-weekly and surface and sub-surface drip irrigation scheduled daily on production and fruit quality of peach on a Hanford fine sandy loam in California. They found that daily drip irrigations maintained higher soil water content and prevented soil water stress. As a result of better plant water status, higher marketable yields with larger fruits were produced. Schoeman (2002) also made similar observations in citrus using daily drip fertigation in South Africa.

Schumann et al. (2003) compared fertilizers sources and rates in 'Hamlin' orange on a Candler fine sand in Florida. The results showed that optimal soluble solids production for fertigation was obtained at a N level of 145 $kg \cdot ha^{-1}$ while the N optima for dry granular and controlled release fertilizers were 180 and 190 $kg \cdot ha^{-1}$, respectively. The greater efficiency of fertigation amounted to a N saving of 35 to 45 $kg \cdot ha^{-1}$ per year and approximately 20% more soluble solids yield than the other fertilizer sources. Also, leaf N concentrations were significantly higher per unit of N applied for fertigation > dry granular > controlled release. Thus, Schumann et al. (2003) concluded that fertigation was the most efficient fertilizer source because of optimal placement in the root zone and optimal temporal distribution over the season. Morgan et al. (2009b) made similar observations in young citrus trees on the sandy soils of central Florida. The results from preliminary studies on the ridge indicate that daily irrigation schedules using drip systems and more intensive irrigation programs can help in sustaining high yields compared to conventional practice (Schumann, unpublished data). In theory, the growth and yield of citrus trees should be maximized if the demand for nutrients and water by the roots is always matched with an adequate supply from drip fertigation, thus avoiding even transient deficiencies. The daily timing for both water and nutrient delivery should coincide with the time of maximum transpiration flow, which is during the daylight hours. Uptake of nutrients like calcium which move mainly by mass flow in the transpiration stream, is particularly important during periods of high transpiration. Temporary calcium deficiencies of crops have been recorded during prolonged humid, cloudy periods when transpiration rates are low. Thus, the common strategy in OHS systems worldwide is to pulse-fertigate during daytime hours and hopefully facilitate a high percentage of immediate uptake by the roots instead of temporarily storing the water and nutrients in the soil as with conventional fertilization and irrigation systems. Storage of water and nutrients in the soil before uptake by roots can increase losses and inefficiencies due to evaporation, leaching, adsorption, precipitation, and volatilization mechanisms as well as immobilization by microbes. Since all those processes are kinetically regulated, minimizing the duration of soil contact is one of the underlying principles of OHS.

Issues Specific for Florida Conditions

Irrigation scheduling for sandy soils. Smajstrla et al. (2009) described the main components required in irrigation scheduling as 1) estimating evapotranspiration (ET), 2) soil water storage capacity, and 3) allowable water depletions. They recommended two irrigation scheduling methods for Florida soils and climate 1) a water budget method requiring estimation of daily ET and soil water content, and 2) the use of soil moisture measurement instrumentation. Following the water budget principles, Morgan et al. (2009a) developed an ET-based scheduling tool for Florida that factors in soil characteristics and rooting depth for determining when to irrigate and how much water to apply. Researchers in Florida have also proposed methods of determining when to irrigate and how much water to apply using soil moisture measuring devices in the sandy soils (Alva and Fares, 1998; Migliaccio and Li, 2009; Munoz-Carpena, 2009). Advances in the irrigation scheduling methods using microsprinklers can be adjusted to approximate the intensive irrigation practices used in drip irrigation APS.

Limitations with current BMPs. The current BMPs were developed based on low volume microsprinkler irrigation systems (Alva et al., 2003; Lamb et al., 1999) and conventional fertilizer application practices (Alva and Paramasivam, 1998; Obreza and Rouse, 1993; Thompson and White, 2004). Yet, in countries such as Australia and South Africa, the OHS practices have been adapted through use of intensive and advanced fertigation methods using drip irrigation (Prinsloo, 2007; Slugget, unpublished). Thus, there may be need to modify the current BMPs in the light of intensive fertigation practices that go with APS to effectively sustain high yields in citrus groves and prevent nutrient leaching to groundwater. In Florida, citrus groves are established in the flatwoods on poorly to very poorly drained Spodosols and Alfisols with a shallow water table (Obreza and Collins, 2008) and on the central ridge on moderately to excessively well drained Entisols (Obreza and Collins, 2008; Reitz and Long, 1955). Thus, BMPs and nutrient management decisions devised for APS must take into account these ecologically different zones.

Need for ridges on ridge or flatwood soils? Flatwoods are found in a flat landscape with low elevation where surface-water drainage is slow (Boman, 1994), whereas the ridge Entisols are well drained (Obreza and Collins, 2008; Reitz and Long, 1955). The current practice in the flatwoods is to grow citrus on raised two-row beds with furrows between beds draining into ditches (Boman, 1994). With OHS practice outside Florida, individual row raised ridges are suggested to allow for adequate water drainage and air infiltration in heavy loam or clay soils. In Florida, however, the soils are predominantly sandy (>95% sand) and the need of for additional raised ridges for air infiltration is almost certainly unnecessary for APS on flatwoods Spodosols and Alfisols using two-row beds or in any well-drained ridge grove.

Methods for enhancing earlier flowering and cropping in citrus. High early production is essential for higher-density, shorter-cycle citrus production to be economically sound in Florida. Early cropping not only front-loads economic returns but also, importantly, competes with vegetative growth and helps keep trees smaller. Several horticultural practices to enhance early cropping have been explored and documented in citrus and other fruit crops and many have been widely used in recent high density citrus plantings in South Africa and likely in other regions where intensive plantings have been utilized. Not all scion/rootstock combinations will require horticultural intervention to accelerate cropping. From initial OHS/APS plantings in Florida, it appears that grapefruit will be sufficiently early-bearing to achieve ideal early yields without the need for additional management. How will we encourage earlier and heavier cropping in slower-to-bear cultivars or where rootstock selection delays cropping? Girdling, control of water (and perhaps nutrients), and gibberellins during flowering may all be used to enhance floral initiation and/or subsequent cropping. These practices are briefly reviewed in the context of high density Florida citrus plantings.

Selection of rootstock and scion. A long period of observation has permitted citriculturists to develop a general understanding of which scions, rootstocks, and specific scion/rootstock combinations are slow to bear. Among commonly grown Florida scion cultivars, most growers would agree that 'Minneola' tangelo trees are particularly low bearing early in grove life, and that non-mandarin scions are slow to bear on Cleopatra rootstock. Detailed observations of early yield for scion/rootstock combinations under OHS may be the most important information for enhancing early cropping through selection of planting material which is most responsive.

Girdling. A widely used horticultural practice to enhance early bearing is girdling or scoring to alter the distribution of growth regulators, carbohydrates, etc., between the root system and canopy. Severe girdling, in which a ring of bark is removed, is seldom used in citrus. Instead, a more transient disruption in phloem transport is produced through making a single ring cut through the bark around all or part of trunks or scaffold branches.

The tree response to girdling varies with the time of year and associated stage in tree/fruit development. The most frequent use of girdling in citrus is to enhance retention of fruit by girdling during or just before the bloom period (Monselise et al., 1972). This is most commonly used to enhance retention of parthenocarpic fruit, and has been shown to enhance numbers of fruit in varieties with varying degrees of parthenocarpy (Rivas et al., 2006). Girdling as harvest approaches is sometimes used to enhance fruit size (Fishler et al., 1983), but would be expected to provide no enhancement of flowering or cropping. A few efforts have been made to enhance flowering by girdling during the period before flower initiation (Erner, 1988; He, 1997; Takahara et al., 1980). Erner (1988) compared fall and spring girdling and found that fall girdling was more effective in very poorly cropping 'Shamouti' while spring girdling was more effective in enhancing yield of trees that already bore substantial crops. In Brazil, Koller et al. (2000) found that a wire constriction (in which a wire is tightened around each scaffold branch) in fall was more effective than fall girdling in enhancing fruiting the next spring.

In an informal survey of South African citrus growers producing citrus at high density with pulse fertigation, it appears that mandarin growers are most likely to use girdling, and only girdling during bloom was reported (Castle, personal communication). Growers varied in girdling annually or biannually. Girdling in year two for a newly planted block was emphasized as important to initiate strong bearing and some growers of sweet oranges reported that no further girdling was practiced after this initial application. Girdling of parthenocarpic cultivars may increase cropping by more than 100% (e.g., Rivas et al., 2006) with reports of 6-fold increases in the literature (Perez-Madrid et al., 2005).

Girdling is among the more finicky horticultural practices with considerable art in achieving desirable outcomes and not weakening trees. The refereed research literature on girdling citrus reports frequent but not routine effectiveness of treatments, and the ideal timings vary greatly between studies. Anecdotally, some practitioners identify a very particular stage of flowering which gives good enhancement of fruit retention. Others emphasize the need to move from trunk girdling to scaffold branch girdling as trees mature. In regions where girdling has become routine, many growers prefer high budded nursery stock, so that initial trunk girdles on the rootstock are easier to make and do not expose low wounds in more phytophthora susceptible scion tissue.

Girdling is potentially a very valuable technique for enhancing early cropping, and typically is reported to be more effective than gibberelic acid sprays (next section). However, it is important to realize that few studies have evaluated the effect of girdling and gibberelic acid on early cropping of new plantings. Expertise and detailed recommendations are probably best developed using a limited number of trees, ideally before there is significant high density acreage in Florida. Various hand tools have been developed which may facilitate uniform and efficient girdling. Growers should be cautioned that there is a very real danger of damaging trees through improper application of girdling.

Gibberelic acid. Bloom applications of gibberelic acid (GA_3) have been labeled for use in citrus for 40 years (Krezdorn and Brown, 1970) to enhance retention of fruitlets. During this period, many growers have used such sprays (primarily on mandarins and mandarin hybrids, though a 15× GA_3-induced increase in 'Valencia' yield was reported by Turnbull in 1989) and mixed results are often reported. Again, the refereed research literature on GA_3 to enhance fruit retention reports frequent but not routine effectiveness of treatments, and the ideal timings vary greatly between studies. As with girdling, GA_3 is most effective in enhancing set of parthenocarpic fruit. While increasing application costs, practitioners often apply 2–3 sprays to cover the bloom period and enhance success. Some growers are committed to routine use of GA_3. There has been considerable experience with bloom GA_3 application in Florida but much of this was in the 1970s when newer cultivars (such as tangelos) known to benefit from cross-pollination were being grown in isolation (Krezdorn and Brown, 1970).

GA biosynthesis inhibitors. It may seem counterintuitive, but although GA applied during bloom can significantly enhance fruit set, primarily of fruit with low seed count, GA is a potent inhibitor of flower initiation and/or development. Application of a single GA spray during the primary period of floral initiation reduced flowering in the Florida citrus varieties tested by ~50% (mostly unpublished, Stover, Ciliento, and Yang, 2000). Aggressive application of several different gibberellin biosynthesis inhibitors has been shown to enhance flowering in citrus seedlings. Lime and kumquat seedlings treated with paclobutrazol flowered within 11 months of germination (Snowball et al., 1994). The GA biosynthesis inhibitor paclobutrazol is not labeled for use in food crops in the US, but has been shown to enhance flowering in many experiments with mature citrus (e.g., Martinez-Fuentes et al., 2004). Related compounds have also been shown to be effective as gibberellin inhibitors in a wide array of citrus genotypes (Stover et al., 2004) and some of these are labeled for use on food crops, though currently not in citrus. The path to registration of GA biosynthesis inhibitors on bearing citrus is likely to be slow and expensive, but may have value in high density production.

Tree training to enhance early cropping. Training vertical branches to a more horizontal position to enhance early bearing and decrease vegetative growth is almost universal in production of stone and pome fruits. High density plantings in these crops almost always use trellises or other tree supports to permit early cropping without damaging tree structure and divert tree resources into fruiting rather than trunk development. Japanese researchers reported that bending of scions to the horizontal significantly shortened time to flowering in citrus seedlings (Soost, 1987). It may make sense that these practices could also enhance early fruiting in young budded trees, but little research has been devoted to these practices in citrus production. Rabe (2000) and colleagues have reported on several initial experiments considering more intensive training in citrus with better early production.

Water stress. Water stress and cool temperatures are well documented as enhancing flower induction in citrus. The more limited root system of pulse-fertigated citrus trees [estimated at 2% of conventionally grown trees in Spain (Schoeman, 2002)] should permit rapid induction of water stress as a tool for horticultural manipulation.

Conclusion

To survive citrus greening and maintain its place as the largest horticultural food crop producer in Florida, the citrus industry may need to adopt more intensive grove design and management practices that have been shown to work in other citrus production areas of the world. Two sets of practices that can be adapted to Florida environmental conditions and sandy soils are high density plantings and the Open Hydroponic System, which are combined in a set of practices described as the Advanced Production System. The production system will involve planting densities of 300 or more trees per acre on rootstocks that match final tree size to soil characteristics and planting density. Tree irrigation and nutrition using this new system will be linked through the use of management systems that will apply the appropriate ratio of nutrients to roots concentrated within the irrigated zone. The production system adopted by the industry should comply to current nutrient and water quality BMPs. Finally, the system will rely on selective horticultural manipulation of tree growth and fruiting through mechanical pruning and girdling or chemical treatments (e.g., gibberelic acid and GA biosynthesis inhibitors) as needed in each block. This combined system of production will result in higher young tree growth rates, earlier fruit production, and may maintain high levels of productivity compared with current cultural practices especially in the presence of tree losses due to citrus greening.

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