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Sweet Orange Orchard Architecture Design, Fertilizer, and Irrigation Management Strategies under Huanglongbing-endemic Conditions in the Indian River Citrus District

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***Abstract*. The prevalence of Huanglongbing (HLB) in Florida has forced growers to search for new management strategies to optimize fruit yield in young orchards and enable earlier economic returns given the likelihood of HLB-induced yield reductions during later years. There has been considerable interest in modifying orchard architecture design and fertilizer and irrigation management practices as strategies for increasing profitability. Our objectives were to evaluate how different combinations of horticultural practices including tree density, fertilization methods, and irrigation systems affect growth, foliar nutrient content, fruit yield, and fruit quality of young 'Valencia' sweet orange [*Citrus sinensis* (L.) Osbeck] trees during the early years of production under HLB-endemic conditions. The study was conducted in Fort Pierce, FL, from 2014 to 2020 on a 1- to 7-year-old orchard and evaluated the following treatments: standard tree density (358 trees/ha) and controlled-release fertilizer with microsprinkler irrigation (STD_dry_MS), high tree density (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high tree density with fertigation and double-line drip irrigation (HDS_fert_DD). Annual foliar nutrient concentrations were usually within or higher than the recommended ranges throughout the study, with a tendency for decreases in several nutrients over time regardless of treatment, suggesting all fertilization strategies adequately met the tree nutrient demand. During fruit-bearing years, canopy volume, on a per-tree basis, was higher under STD_dry_MS (6.2–7.2 m^3) than HDS_fert_MS (4.3–5.3 m^3) or HDS_fert_DD (4.9–5.9 m^3); however, high tree density resulted in greater canopy volume on an area basis, which explained the 86% to 300% increase in fruit yield per ha that resulted in moving from standard to high tree density. Although fruit yields per ha were generally greatest under HDS_fert_MS and HDS_fert_DD, they were lower than the 10-year Florida state average (26.5 $Mg \cdot ha^{-1}$) for standard tree density orchards, possibly due to the HLB incidence and the rootstock chosen. Although tree growth parameters and foliar nutrient concentrations varied in response to treatments, management practices that included high tree density and fertigation irrespective of irrigation systems produced the highest fruit yields and highest yield of solids. Soluble solids content (SSC) and titratable acidity (TA) were lower, and the SSC-to-TA ratio was highest under STD_dry_MS in 2016–17, with no treatment effects on quality parameters detected in other years. Both drip and microsprinkler fertigation methods sufficiently met tree nutrient demand at high tree density, but additional research is needed to determine optimal fertilization rates and better rootstock cultivars in young high-density sweet orange orchards under HLB-endemic conditions in the Indian River Citrus District.**

Sweet orange [*Citrus sinensis* (L.) Osbeck] and grapefruit (*Citrus paradisi* Macf.) production have declined by ≈52% and 65%, respectively, since HLB was first confirmed in Florida in 2005 (USDA, 2020). The bacteria associated with HLB, *Candidatus* Liberibacter asiaticus (*C*Las), are inoculated in the phloem of citrus leaves by the Asian citrus psyllid (*Diaphorina citri* Kuwayama) and block carbon translocation, eventually resulting in phloem clogging and possibly tree death (Bové, 2006; Deng et al., 2019; Gottwald, 2010). Although sweet orange and grapefruit are both highly susceptible to HLB, research performed in Central Florida showed that HLB-induced fruit yield losses of sweet orange can be minimized with appropriate rootstock selection (Bowman et al., 2016). Similar research focusing on grapefruit has only recently begun in the Indian River Citrus District, a region historically dominated by grapefruit but that is well-suited for sweet orange production (USDA, 2020). Given the uncertain future of grapefruit in the Indian River, some grapefruit growers in the region are considering sweet orange as an alternative citrus crop. However, this region is characterized by poorly drained soils, and grapefruit orchards are designed in beds with a narrow width, which makes changes in orchard architecture design difficult and expensive. Management strategies that aim to improve early fruit yields and enable earlier economic returns considering the possibility of HLB-induced yield reductions during later years are needed for Indian River Citrus District growers (Alvarez et al., 2016).

Among the different management strategies available in the Indian River, planting new sweet orange orchards at higher tree densities on narrow beds to achieve earlier returns on investment has drawn considerable interest. Singerman et al. (2018) reported that establishing new orchards at conventional tree densities (≈339 trees/ha) in Florida is no longer profitable under the current market conditions, but that planting at higher densities (544–749 trees/ha) can be profitable despite the greater initial investment required. Studies conducted before the arrival of HLB in Florida showed that higher sweet orange tree densities (667–889 trees/ha) resulted in greater fruit yields during early years of production compared with lower densities (370 trees/ha) (Wheaton et al., 1995; Whitney et al., 1991). Preliminary research conducted during the HLB era has shown that increasing the sweet orange tree density from 538 to 747 trees/ha did not reduce tree height or leaf chlorophyll content in a 2-year-old orchard in Central Florida (Schumann et al., 2009). Although a positive relationship between sweet orange tree density and fruit yields in young orchards has been established, it is necessary to evaluate high-density orchards within the broader context of nutrient-efficient fertilization practices, like fertigation, to provide growers in the Indian River Citrus District with a set of recommended production practices that can be used to optimize productivity of young sweet orange orchards in the HLB era.

Nutrient acquisition by citrus roots is determined by several factors, including rootstock selection, root distribution, soil water status, and fertilizer source, timing, and delivery method (Morgan and Kadyampakeni, 2012; Scholberg and Morgan, 2012). Weinert et al. (2002) reported that 2-year-old sweet orange trees planted at 555 trees/ha in Arizona recovered only 24% of microsprinkler-applied nitrogen (N). However, Menino et al. (2007) found that 3- and 4-year-old sweet orange trees planted at 571 trees/ha in Portugal recovered 20% and 30% of granular N, respectively. Although research focused on nutrient recovery in young sweet orange orchards is lacking in Florida, Mattos et al. (2003) showed that 6-year-old sweet orange trees planted at 285 trees/ha in Central Florida recovered up to 39% of granular-applied N in a study conducted before the HLB era. However, in all these studies, tree densities were considerably lower than the recommendations (725 trees/ha) for optimizing fruit yield during the early years of production under HLB-endemic conditions in Florida (Morgan and Kadyampakeni, 2012). Considering the positive relationship between tree and root density previously reported for sweet orange in Florida (Whitney et al., 1991), the possibility exists for greater fertilizer nutrient recovery and higher fruit yields in young orchards planted at higher densities.

The use of fertilization methods and irrigation systems that target the root zone of young trees, in conjunction with higher tree densities, may be a strategy for improving the productivity of young citrus orchards during the HLB era in the Indian River Citrus District. Several studies have shown that replacing dry granular fertilizers with fertigation increases tree growth rates and fruit yield in young orchards (Alva et al., 2003, 2008; Morgan et al., 2009), which is likely due to the delivery of readily available nutrients to zones with high root density (Kadyampakeni et al., 2014a). Different fertigation and irrigation methods and application schedules may also affect nutrient and water distribution and uptake by roots. For example, Kadyampakeni et al. (2014b, 2014c) reported that drip and small-pattern microsprinkler fertigation zones had up to 100%, 70%, and 60% more N, phosphorus (P), and potassium (K), respectively, compared with large-pattern microsprinkler fertigation zones in a study in which different fertigation schedules were also used. The use of different fertigation methods and schedules has also resulted in 45% greater N accumulation by trees fertigated daily via drip lines or weekly by small-pattern microsprinklers compared with trees under monthly microsprinkler fertigation (Kadyampakeni et al., 2016). Regarding tree water use, Kadyampakeni et al. (2014d) also found that the use of daily drip irrigation in a young ‘Hamlin’ sweet orange orchard compromised by HLB in Central Florida resulted in greater tree water use than the use of microsprinkler irrigation triggered at specific soil water depletion values.

Because of the urgency to optimize fruit yields during early years of production under current HLB-endemic conditions, research is needed to understand how improved cultural practices affect the productivity of young high-density orchards. In the present study, we aimed to identify a set of feasible management strategies that growers, especially in the Indian River, could use to optimize sweet orange productivity. Our objectives in this study were to evaluate how different combinations of horticultural practices that included tree density, fertilization methods, and irrigation systems affect growth, foliar nutrient content, fruit yield, and fruit quality of young ‘Valencia’ sweet orange trees during the early years of production under HLB-endemic conditions in the Indian River Citrus District.

Materials and Methods

Site description. A study was conducted at the University of Florida (UF)/Institute of Food and Agricultural Sciences (IFAS) Indian River Research and Education Center in Fort Pierce, FL (lat. 27°25′59″ N, long. 80°26′48″ W, 6.7 m elevation) on poorly drained Pineda sand (loamy, siliceous, hyperthermic Arenic Glossaqualfs) typical of the coastal flatwood citrus-growing region. Poor drainage in coastal flatwood soils necessitates construction of ditches followed by the formation of elevated cultivation beds. The site is characterized by a humid subtropical climate with average monthly temperatures ranging from 16 to 27 °C. The annual precipitation is ≈1180 mm and falls mostly between May and October.

Experimental setup and treatments. ‘Valencia’ sweet orange trees budded on Kuharske citrange [*C. sinensis* (L.) × *Poncirus trifoliata* (L.) Raf.] rootstock were planted in Sept. 2013 on raised beds (two rows per bed) 15 m in width using two different planting arrangements. In the first arrangement, a standard tree density consisting of trees planted in single rows spaced 3.8 m × 7.2 m apart (358 trees/ha) was used. In the second arrangement, trees were planted in a high-density configuration. A single row consisted of two staggered sub-rows spaced 1.5 m apart with 2.7 m between trees within the sub-row. Each single row was spaced 6.1 m apart (955 trees/ha) in the bed (Fig. 1). Kuharske citrange rootstock was selected for this study because preliminary data from the same region showed that mandarin (*C. reticulata*) trees budded on this rootstock had faster initial growth rates and a healthier appearance than several other scion/rootstock combinations (Stover et al., 2016).

In June 2014 and May 2015, soil was collected around the tree dripline at a depth of 20 cm using a 2.54-cm-diameter soil probe following the procedures described by Morgan and Kadyampakeni (2020). Samples were randomly collected from each block, homogenized manually, and bulked. A subsample was drawn and evaluated for several soil properties (Table 1). Nutrients were extracted using Mehlich-3 reagent.

An experiment was arranged in a randomized complete block design with eight replications. Each replication was planted on a 15-m × 44-m plot consisting of two rows, from which 8 trees were randomly selected to collect data for all response variables. Treatments consisted of a combination of different management practices: 1) standard tree density with controlled-release fertilizer (CRF) and microsprinkler irrigation

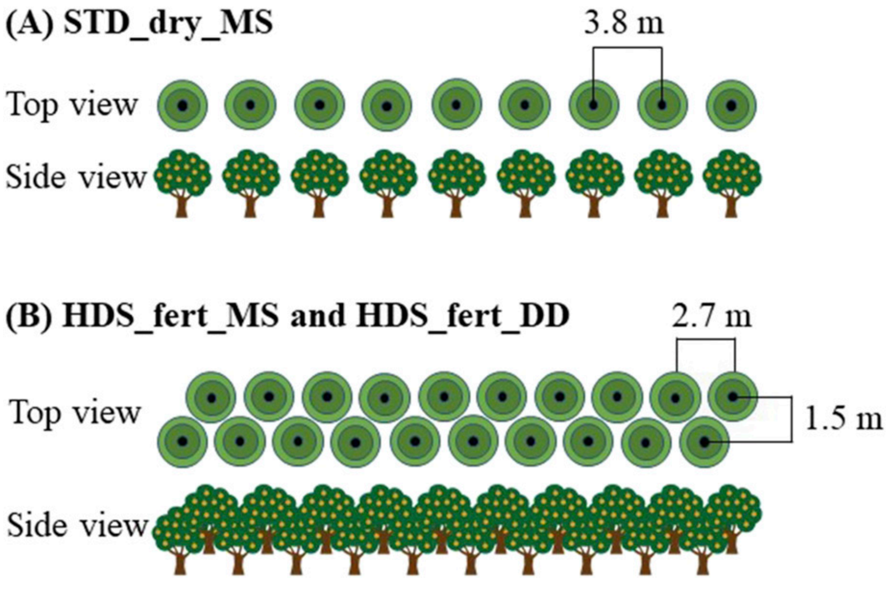

Fig. 1. Orchard architecture design for (**A**) standard tree density in a single row (358 trees/ha) with controlled-release fertilizer and microsprinkler irrigation (STD_dry_MS) and (**B**) high-density staggered planting in a single tree row (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS) or double-line drip irrigation (HDS_fert_DD).

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(STD_dry_MS); 2) high-density staggered planting with fertigation and microsprinkler irrigation (HDS_fert_MS); and 3) high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD).

The fertilizer source and application method were based on the recommended N rate because N is usually the limiting nutrient for citrus production in Florida (Mattos et al., 2003). The amount of N applied to trees varied by tree age and was based on the UF/IFAS recommendations (Morgan and Kadyampakeni, 2020). During nonbearing years, each tree received 0.11 kg (2013–14), 0.20 kg (2014–15), and 0.34 kg (2015–16) on an annual basis. During fruit-bearing years (2016–17 to 2019–20), we applied 224 kg·ha^{-1} N. The other nutrients were applied following the UF/IFAS recommendations (Morgan and Kadyampakeni, 2020) to maintain optimal foliar levels. Under standard tree density, a CRF containing 18–3–20 (18N–1.31P–16.53K) (Harrell's LLC, Lakeland, FL) was applied by hand in a circle within a 25-cm radius from the trunk of each tree in three equal split applications during January, May, and September using a 4-month release blend. The 18% N component consisted of nitrate-N (0.78%), ammonium-N (1.22%), and urea-N (16%); almost all of it was polymer-coated and slow-release. The P and K components of the CRF were derived from ammonium phosphate and muriate of potash (63% polymer-coated), respectively. The blend also contained 1.0% calcium (Ca), 1.5% magnesium (Mg), 4.9% sulfur (S), 0.06% boron (B), 0.43% iron (Fe), 0.54% manganese (Mn), and 0.35% zinc (Zn), which were derived from $Ca(NO_3)_2$, water-soluble Mg, K_2SO_4, Fe_2O_3, $FeSO_4$, Fe EDTA, Fe humate, Fe sucrate, $MnSO_4$, $Na_2[B_4O_5(OH)_4]\cdot 8H_2O$, and $ZnSO_4$. Fertigation was used to deliver nutrients to all trees planted under the high-density staggered arrangement, regardless of the irrigation method. Water-soluble fertilizer containing 15–11–31 (15N–4.8P–25.62K) (Agrolution pHLow; ICL, Summerville, SC) was applied weekly to high-density staggered trees. The 15% N component consisted of nitrate-N (8.5%), ammonium-N (0.9%), and urea-N (5.6%). The phosphorus (P) component was derived from ammonium phosphate, monopotassium phosphate, and phosphoric acid. In addition to monopotassium phosphate, potassium nitrate was used to supply potassium (K). This blend also contained 0.8% Mg, 1.0% S, 0.02% B, 0.05% copper (Cu), 0.10% Fe, 0.05% Mn, 0.0005% Mo, and 0.05% Zn. These nutrients were derived from $MgSO_4$, boric acid, EDTA of Cu, Fe, Mn, and Zn, and $(NH_4)_2MoO_4$.

Table 1. Soil properties collected at the study site in June 2014 and May 2015.

Soil property	Units	2014	2015
pH	—	6.2	6.6
Cation exchange capacity	cmol$_c$·kg^{-1}	4.1	4.2
Phosphorus	mg·kg^{-1}	25	48
Potassium	mg·kg^{-1}	23	28
Calcium	mg·kg^{-1}	620	629
Magnesium	mg·kg^{-1}	35	30
Manganese	mg·kg^{-1}	2	2
Zinc	mg·kg^{-1}	3	5

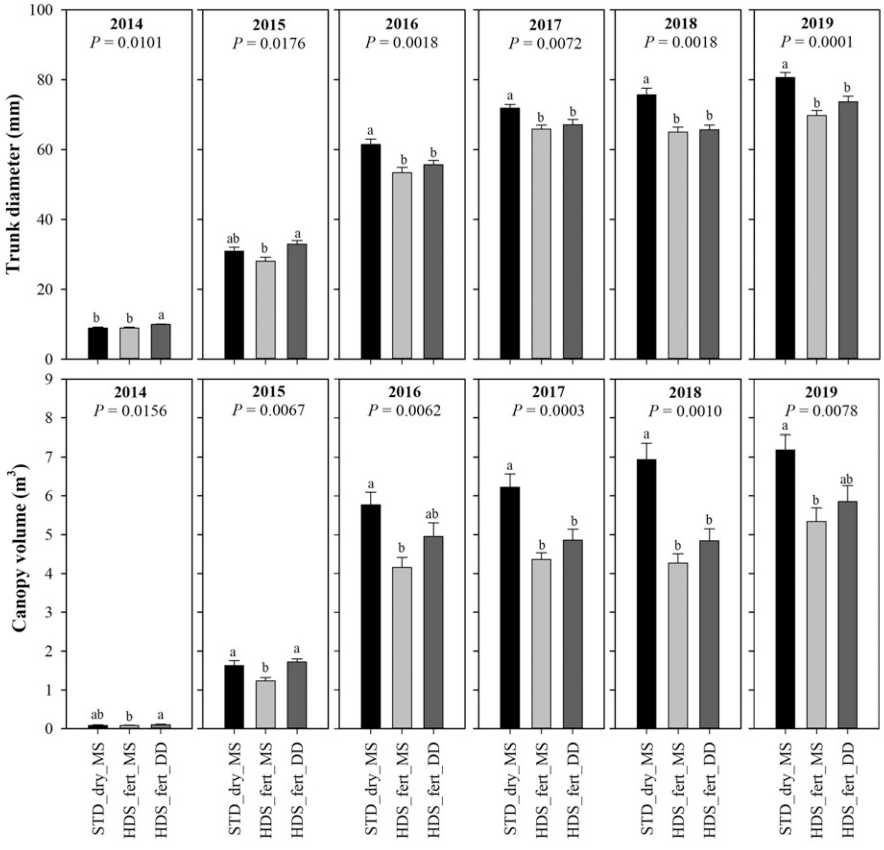

Fig. 2. Trunk diameter (top) and canopy volume (bottom) measured over 6 years at standard tree density (358 trees/ha) with granular and microsprinkler irrigation (STD_dry_MS), high-density staggered planting (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD). Measurements began for 1-year-old trees in 2014. For each growth parameter, bars within the same year sharing the same letter were not significantly different at $\alpha = 0.05$ according to Tukey's honestly significant difference. Mean ± SE of eight replications (n = 8).

The irrigation method depended on the planting arrangement. Under the standard tree density, each tree was irrigated by one microsprinkler emitter (Fan-Jet PLUS; Bowsmith, Exeter, CA) with an output of 64 L·h^{-1} at 138 kPa, a 4.8-m-diameter wetted pattern, and an irrigation efficiency of 79% determined in 2017 by the FDACS Mobile Irrigation Laboratories (MILS, 2020). Microsprinkler irrigation was also applied at the same rate, pressure, and wetted pattern to the high-density staggered trees for the HDS_fert_MS treatment, with one emitter used to irrigate two trees and an irrigation efficiency of 79% determined by MILS (2020). For both planting arrangements, microsprinklers were placed ≈15 cm from the tree. The remaining high-density staggered trees received drip irrigation to form the HDS_fert_DD treatment (Jain Irrigation Inc., Fresno, CA). Two drip lines spaced 30 cm from each row produced 2.2 L·h^{-1} at 69 kPa from emitters spaced 30 cm apart for a total of four emitters per tree and an irrigation efficiency of 91% determined by MILS (2020). Both microsprinkler and drip irrigation were applied daily to match estimated crop evapotranspiration (ET$_c$), and the amount of water applied was adjusted to compensate for the different system irrigation efficiency. Irrigation management followed the recommendations of Morgan and Kadyampakeni (2020) for nonbearing (years 2013–16) and bearing trees (2017 and after). The ETc was monitored from 2013 to 2017 using a local weather station (Mini-Weather Station; Hunter Industries, San Marcos, CA); the ETc from 2017 to 2019 was monitored using the Florida Automated Weather Network (FAWN) station in St. Lucie West, FL. Scouting for pests and diseases occurred monthly, and control measures were implemented in accordance with the UF/IFAS best management practices (Diepenbrock et al., 2019).

Tree growth parameters. The trunk diameter was measured twice annually at 6-month intervals from 2014 to 2019 using a digital caliper placed 7 cm above the graft union of sampled trees. Using the same annual schedule, canopy volume was determined using Eq. [1], which was initially reported by Obreza and Rouse (1993):

$$\text{Canopy volume} = \left(\frac{4}{3}\right)(\pi)\left(\frac{H}{2}\right)(MCR)^2 \quad [1]$$

where H is the tree height (m) and MCR is the mean canopy radius (m). Tree height was measured from the soil surface to the top of

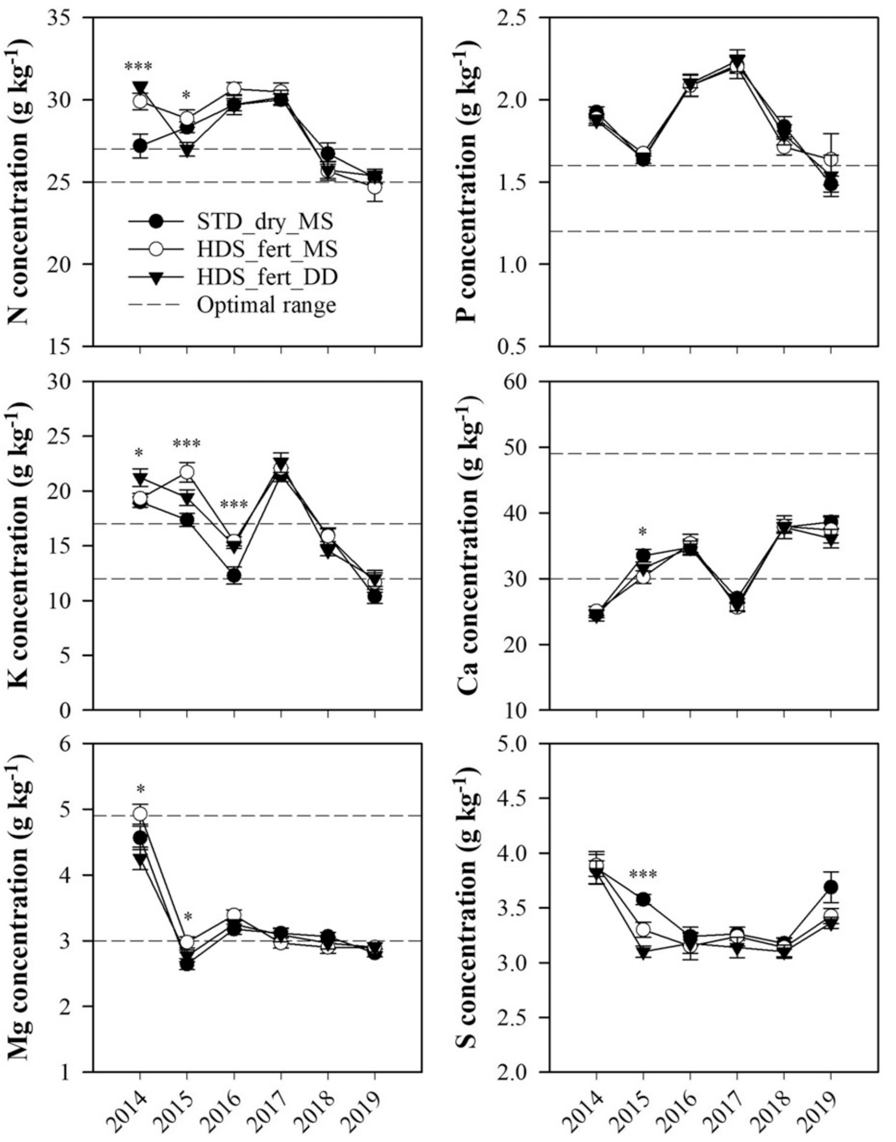

Fig. 3. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) concentrations from leaves sampled each August at standard tree density (358 trees/ha) with granular fertilizer and microsprinkler irrigation (STD_dry_MS), high-density staggered planting (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD). Measurements began for 1-year-old trees in 2014. Dashed horizontal lines represent optimal nutrient concentrations (not available for S) as reported by Morgan et al. (2019). * and *** indicate statistical significance at $P \leq 0.05$ or 0.001, respectively, according to Tukey's honestly significant difference at $\alpha = 0.05$. Mean ± SE of eight replications (n = 8).

the canopy, whereas the canopy diameter, from which the *MCR* was estimated, was measured in north–south and east–west directions. Both trunk diameter and canopy volume are reported on a per-tree basis.

Foliar nutrient concentrations. In August of each year from 2014 to 2019, eight leaves per tree were collected from eight trees per replication and mixed, placed in sealed plastic bags, and sent to a commercial laboratory (Waters Ag Laboratory Inc., Camilla, GA) for nutrient analyses. Leaves were rinsed, dried until a constant weight at 60 °C, and ground to pass a 1-mm mesh screen before being analyzed for N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentrations. Nitrogen was determined by dry combustion, whereas acid digestion followed by inductively coupled plasma spectrometry was used to determine all other nutrient concentrations. Foliar nutrient concentrations were compared to the optimum values for sweet orange defined by Morgan et al. (2019).

Detection and quantification of CLas. In April of each year from 2014 to 2019, one twig containing four or five fully expanded mature leaves was collected from each quadrant of each tree sampled (n = 8). Leaves were removed from twigs and placed in sealed plastic bags separated by plot. Samples were submitted to a diagnostic laboratory (Southern Gardens Diagnostic Laboratory, Clewiston, FL) for the detection of *C*Las by quantitative real-time polymerase chain reaction (PCR) (Li et al., 2006). Trees were considered positive when normalized Ct_{CLas} values were ≤32. For quantification of *C*Las, normalized cycle threshold (Ct_{CLas}) values were converted to copy numbers of *C*Las genomes as described by Albrecht et al. (2014).

Fruit quality and yield. Fruit quality and yield data were collected during the 2016–17 to 2019–20 harvest seasons. 'Valencia' orange is normally harvested in April in the region, but the negative effects of *C*Las infection during fruit-bearing years associated with an increase in Diplodia stem-end rot caused by *Lasiodiplodia theobromae* incidence necessitated a late February harvest in 2019 and 2020 to avoid fruit drop. Representative samples of 20 fruit per plot were collected from the outer and mid canopy of trees just before harvest each year to assess fruit quality. Samples were juiced with a juicer (model 2702; Brown International Corp., Covina, CA), and the juice was weighed. The percentage of juice in fruit was multiplied by the fruit yield to determine the juice weight per ha. The SSC was determined using a temperature-compensated digital refractometer (HI96801; Hannah Instruments, Woonsocket, RI). The yield of solids was determined by multiplying the juice yield by SSC, as described by Wardowski et al. (1995). The TA was measured using an automatic potentiometric titrator (HI931; Hanna Instruments) and expressed as the percentage of anhydrous citric acid. For fruit yield determination, fruit from eight trees per plot, excluding borders, were manually harvested and weighed on a tree basis using a portable scale (D51P60HR1; Ohaus, Los Angeles, CA). Fruit yield per area was calculated by extrapolating the fruit yield per tree to an area basis.

Statistical analysis. An analysis of variance with PROC GLM was used to analyze all response variables (version 9.4; SAS Institute Inc., Cary, NC). Treatments were treated as fixed effects, whereas replication was a random effect. Data were analyzed separately by year. Multiple comparisons between treatment means were made with Tukey-Kramer's honestly significant difference ($\alpha = 0.05$) of least-squared means.

Results

Tree growth parameters. Tree growth parameters responded similarly to treatments over time, with HDS_fert_DD inducing a trunk diameter and canopy volume growth response early during the study, and STD_dry_MS enhancing growth during later stages compared with other treatments. The trunk diameter under HDS_fert_DD was up to 15% larger than that under other treatments through 2015 (Fig. 2). However, the opposite trend was observed for the remainder of the study. From 2016 to 2019, the trunk diameter was consistently larger under STD_dry_MS compared with other treatments. Like trunk diameter, canopy volume was initially larger under HDS_fert_DD relative to HDS_fert_MS, but it was 16% to 38% larger under STD_dry_MS than under other treatments from 2016 to 2019 (Fig. 2). During this period, both the trunk diameter and canopy volume were similar under HDS_fert_MS and HDS_fert_DD.

Foliar nutrient concentrations. Regardless of treatment, most nutrient concentrations were classified as either optimal or high throughout the study, with a few notable exceptions. There was a trend showing high foliar N, P, and K concentrations from the nonbearing through early fruit-bearing years (Fig. 3). Foliar Ca and Mg concentrations were within the optimal range during four of six sampling times each year. Among the micronutrients, foliar Cu concentrations were excessive throughout the study, which was likely caused by the application of Cu-containing products to control citrus canker disease (Fig. 4). In contrast, foliar Mn and Zn concentrations were at the low end of the optimal range or low for most of the study.

CLas infection. Quantitative real-time PCR first detected *C*Las infection in 2016, at which time HDS_fert_DD had the highest percentage (42%) of trees testing positive for *C*Las (Table 2). Although there were no other instances of treatment effects on *C*Las detection during subsequent years, the percentage of trees testing positive was high during fruit-bearing years for all treatments, ranging from 75% to 100%. There was wide variability in the number of *C*Las genomes from sampled trees within treatments each year, which contributed to the lack of significant differences between treatments despite large numerical differences in copies of *C*Las genomes (Table 2).

Fruit yield and quality. Fruit yield data were collected from the 2016–17 to 2019–20 harvest seasons and were reported on both a tree basis and an area basis. Fruit yield per tree was only affected by treatments for two of four harvest seasons, with no discernible trends observed (Fig. 5). During 2016–17, fruit yield per tree was highest under HDS_fert_DD and lowest under STD_dry_MS. However, in 2018–19, the per-tree yield under STD_dry_MS was higher than that under HDS_fert_MS and HDS_fert_DD. Cumulative per-tree yields from 2016–17 to 2019–20 were similar in all treatments.

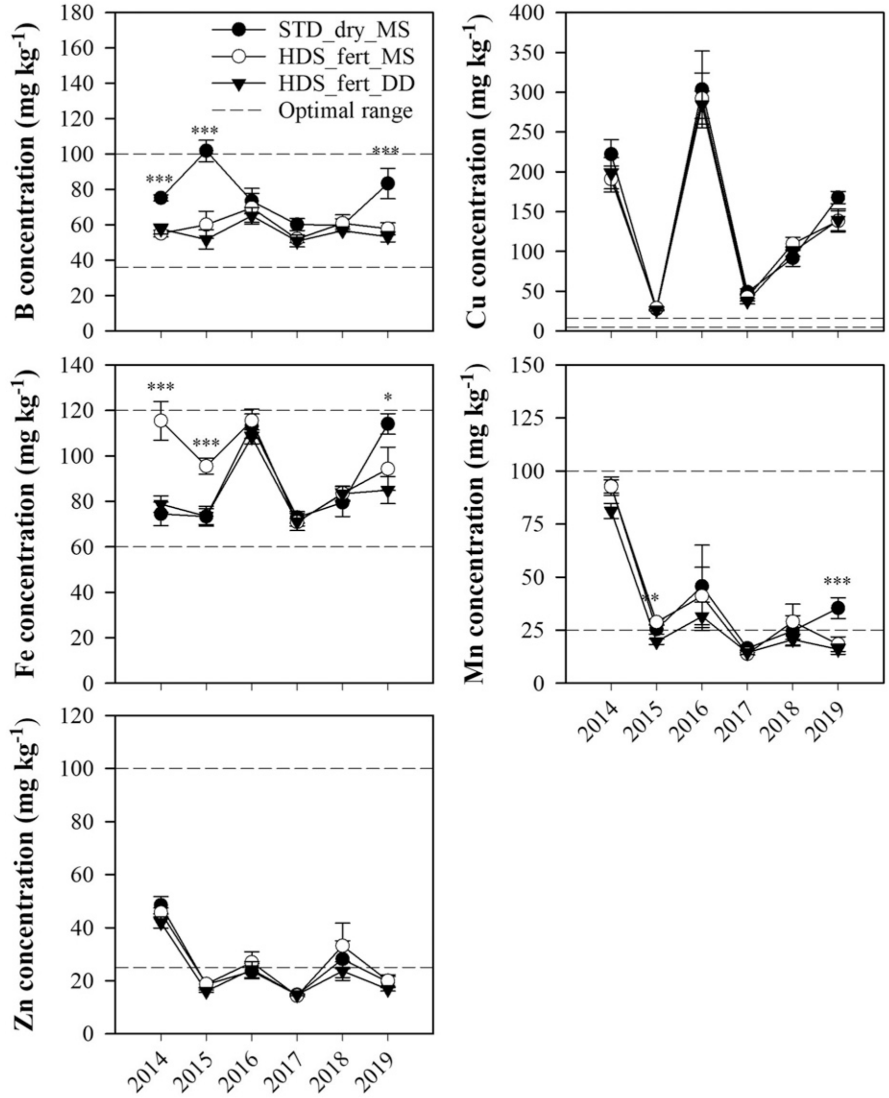

Fig. 4. Boron (B), copper (Cu), iron (Fe), Manganese (Mn), and zinc (Zn) concentrations from leaves sampled each August at standard tree density (358 trees/ha) with granular fertilizer and microsprinkler irrigation (STD_dry_MS), high-density staggered planting (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD). Measurements began for 1-year-old trees in 2014. Dashed horizontal lines represent optimal nutrient concentrations as reported by Morgan et al. (2019). *, **, and *** indicate statistical significance at $P \leq 0.05$, 0.01, or 0.001, respectively, according to Tukey's honestly significant difference at $\alpha = 0.05$. Mean ± SE of eight replications (n = 8).

Table 2. Percentage of trees that tested positive for *Candidatus* Liberibacter asiaticus (*C*Las) and number of *C*Las genomes over 6 years in trees planted at 355 trees/ha with dry granular fertilization and microsprinkler irrigation (STD_dry_MS), 955 trees/ha with fertigation and microsprinkler irrigation (HDS_fert_MS), and 955 trees/ha with fertigation and double-line drip irrigation (HDS_fert_DD).

Treatment	2014	2015	2016	2017	2018	2019
			*C*Las-positive trees (%)			
STD_dry_MS	0	0	22 b	75	100	100
HDS_fert_MS	0	0	11 b	100	100	88
HDS_fert_DD	0	0	42 a	88	88	88
			P value			
			0.001	0.350	0.385	0.766
			No. of *C*Las genomes (per g plant tissue)			
STD_dry_MS	0	0	4	12,353	31,546	154
HDS_fert_MS	0	0	2	24,570	20,958	346
HDS_fert_DD	0	0	263	8,607	17,066	127
			P value			
			0.136	0.213	0.497	0.407

Means within the same column and separated by response variable with the same letter were not significantly different according to Tukey's honestly significant difference ($\alpha = 0.05$).

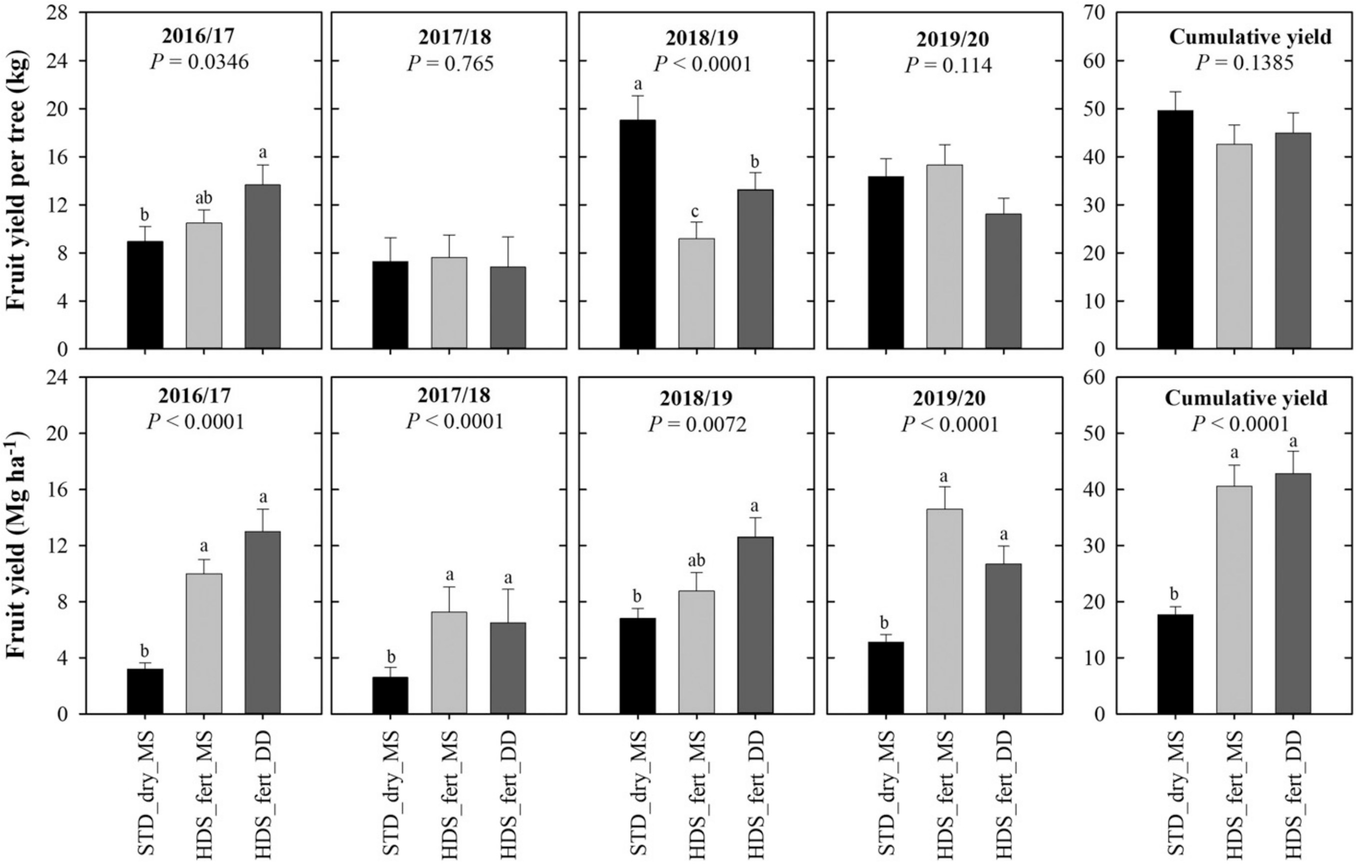

Fig. 5. Fruit yield per tree (top) and per hectare (bottom) under standard tree density (358 trees/ha) with granular fertilizer and microsprinkler irrigation (STD_dry_MS), high-density staggered planting (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD) in an orchard planted in 2013. Bars within the same year sharing the same letter were not significantly different at $\alpha = 0.05$ according to Tukey's honestly significant difference. Mean ± SE of eight replications (n = 8).

Fruit yield on an area basis varied widely by treatment, ranging from 2.6 to 14.6 $\mathrm{Mg{\cdot}ha^{-1}}$ during the study. Trees planted under STD_dry_MS produced lower yields than HDS_fert_MS and HDS_fert_DD for 3 and 4 years, respectively (Fig. 5). The magnitude of treatment effects was substantial when cumulative yields were considered because trees planted under HDS_fert_MS and HDS_fert_DD had ≈136% higher fruit yields than STD_dry_MS. However, there were no yield differences between trees planted under HDS_fert_MS and HDS_fert_DD. The relatively low yields observed for all treatments during the 2017–18 season were due to hurricane damage sustained in 2017.

The yield of solids was also reported on a tree basis and an area basis and followed the same general pattern as fruit yield (Fig. 6). On a tree basis, the yield of solids was highest under HDS_fert_DD and lowest under STD_dry_MS in 2016–17, but it peaked in STD_dry_MS plots in 2018–19. On an area basis during the 2016–17 and 2017–18 harvest seasons, yield of solids were 69% to 75% lower under STD_dry_MS compared with HDS_fert_MS and HDS_fert_DD (Fig. 6). As with fruit yields, the yield of solids was similar under HDS_fert_MS and HDS_fert_DD, peaking at 727 $\mathrm{kg{\cdot}ha^{-1}}$ in the 2016–17 season. The cumulative yield of solids was expectedly highest under HDS_fert_MS and HDS_fert_DD, amounting to ≈2140 $\mathrm{kg{\cdot}ha^{-1}}$. The SSC and TA were lower under STD_dry_MS than under HDS_fert_MS and HDS_fert_DD during the 2017–18 and 2016–17 seasons, respectively (Fig. 7). Additionally, the SSC-to-TA ratio was highest under STD_dry_MS in 2016–17. However, there were no treatment effects on quality parameters detected in other years.

Discussion

This study provided critical information regarding the productivity of a young sweet orange orchard subjected to different sets of management practices that included tree density, fertilization methods, and irrigation systems under HLB-endemic conditions in the Indian River Citrus District. Because 75% to 100% of fruit-bearing trees tested positive for *C*Las, we were able to evaluate the effects of different management practices on orchard productivity under growing conditions reflective of commercial citrus orchards in the Indian River (Singerman and Useche, 2017).

Although tree growth parameters and foliar nutrient concentrations varied in response to treatments, management practices that included high tree density and fertigation produced the highest fruit yields. Previous studies have established that increasing tree density can lead to higher fruit yield in young citrus orchards in Florida (Wheaton et al., 1995; Whitney et al., 1991); however, our study was the first long-term trial to evaluate how a young sweet orange orchard would respond to different tree density, fertilization methods, and irrigation systems under HLB-endemic conditions in the Indian River Citrus District.

Regarding tree nutrient acquisition, our observations of higher foliar concentrations of nutrients such as K under HDS_fert_MS and HDS_fert_DD relative to STD_dry_MS were likely due to differences in K concentrations in CRF and the fertigation formulation. However, it should be emphasized that foliar nutrient concentrations under all treatments were generally within or higher than recommended ranges for sweet orange (Morgan et al., 2019), with the exception of K and Mg in 2019 and Mn and Zn in 2015 and 2017–19, indicating that fertilization strategies met tree nutrient demand but were potentially influenced by HLB over time. Researchers have recently described the need to adjust fertilizer rates for HLB-affected trees (Vashisth, 2020). Kadyampakeni et al. (2016) also found that sweet orange foliar N, P, and K concentrations were optimal or higher under drip and

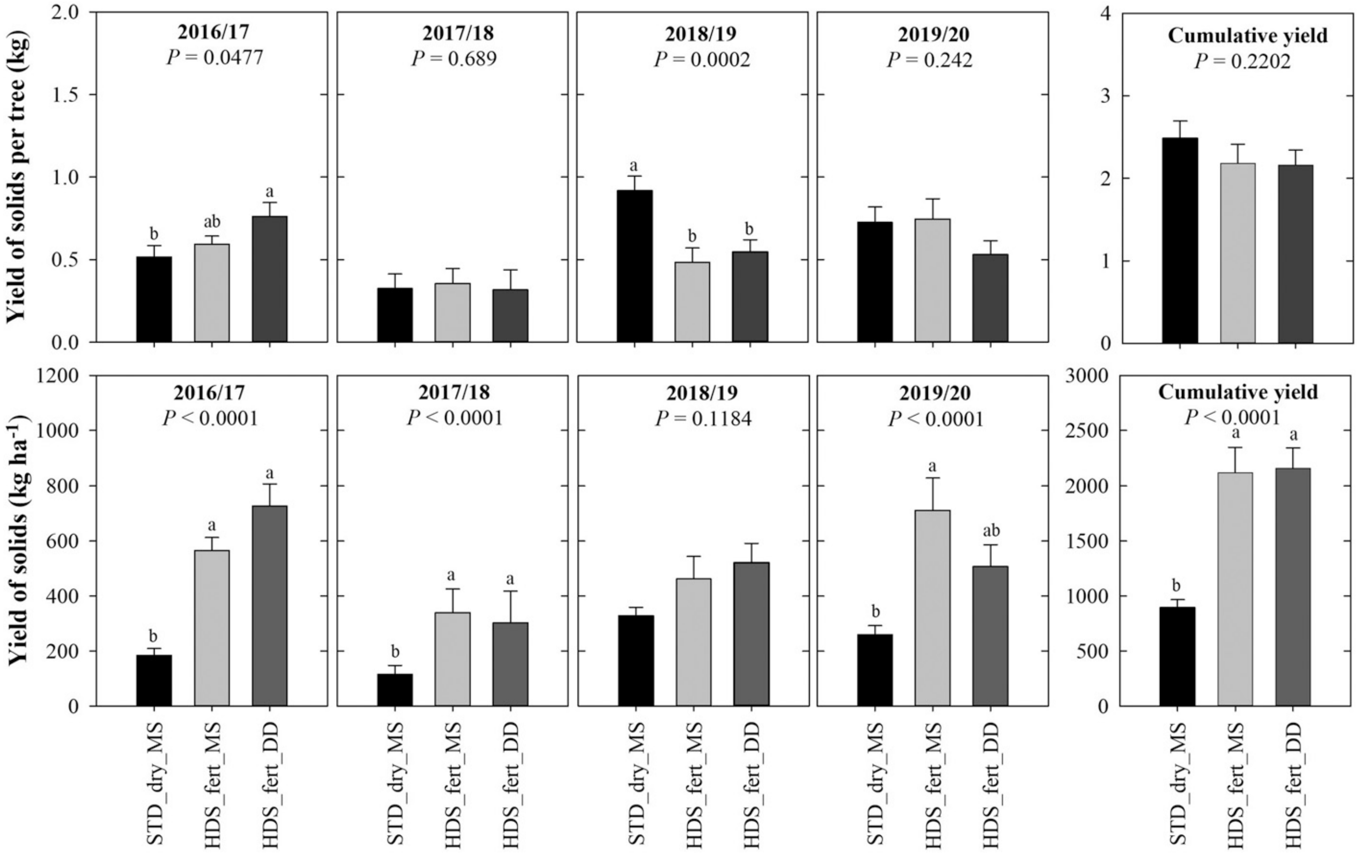

Fig. 6. Yield of solids per tree (top) and per hectare (bottom) under standard tree density (358 trees/ha) with granular fertilizer and microsprinkler irrigation (STD_dry_MS), high-density staggered planting (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD) in an orchard planted in 2013. Bars within the same year sharing the same letter were not significantly different at $\alpha = 0.05$ according to Tukey's honestly significant difference. Mean ± SE of eight replications (n = 8).

microsprinkler fertigation on a Florida coastal Flatwoods soil; however, a study of well-drained soil in Central Florida showed that CRF and microsprinkler fertigation resulted in similar foliar N concentrations in young sweet orange orchards (Morgan et al., 2009). In our study, fertilization rates followed the UF/IFAS recommendation on a per-area basis, but additional research is needed to determine optimal fertilization rates for young high-density orchards under HLB-endemic conditions. Before the arrival of HLB in Florida, Wheaton et al. (1986) reported that increasing tree density from 371 to 891 trees/ha generally did not affect foliar nutrient concentrations but did improve fruit yield in a young orchard in Central Florida. These early findings, along with our own results showing optimal or higher foliar nutrient concentrations at a high tree density for N, K, and Mg earlier in the study, suggest that optimal fertilization rates for high tree density in young sweet orange orchards in the Indian River Citrus District may be lower than the rates used in this study.

Observations of higher fruit yields under HDS_fert_MS and HDS_fert_DD compared with STD_dry_MS may have been due to differences in CO_2 assimilation (A_{CO2}) between orchards with high tree density and standard tree density. Total canopy volume during fruit-bearing years ranged from 4078 to 5587 $m^3 \cdot ha^{-1}$ under HDS_fert_MS and HDS_fert_DD compared with 2227 to 2574 $m^3 \cdot ha^{-1}$ under STD_dry_MS. Modeling sweet orange photosynthesis in Israel, Cohen et al. (1987) reported that A_{CO2} would be greatest when the canopy volume was maximized within a given area. Previous studies have also demonstrated a positive relationship between foliar N concentrations and A_{CO2} in both grapefruit and sweet orange (Bondada and Syvertsen, 2005; Syvertsen et al., 1997). Because foliar N concentrations under HDS_fert_MS and HDS_fert_DD were optimal or higher during fruit-bearing years, the potentially large increase in canopy volume when moving from standard to high tree density would facilitate greater A_{CO2} in orchards with high tree density compared with orchards planted at standard tree density. Based on our canopy data, we speculate that A_{CO2} was greater under HDS_fert_MS and HDS_fert_DD compared with STD_dry_MS, which contributed to higher yields in the former relative to the latter.

Although fruit yields were generally greatest under high tree density, they were lower than the 10-year Florida state average ($\approx$26.5 $Mg \cdot ha^{-1}$) for standard tree density orchards (USDA, 2020). As discussed previously, Kuharske citrange rootstock was chosen for this study because preliminary data from the study site showed that mandarin trees budded on this rootstock had faster initial growth and a healthier appearance than several other scion/rootstock combinations (Stover et al., 2016). The overall poor fruit yield in this study was likely primarily caused by HLB, which can drastically reduce fruit yields of young trees, depending on disease severity (Bowman et al., 2016). Although trees were not rated for HLB infection, between 75% and 100% of trees were *C*Las-positive by the first harvest season. Our personal observations of the orchard also revealed HLB disease symptoms at this time. Since 2015, the UF/IFAS and U.S. Department of Agriculture/Agricultural Research Service Citrus Improvement teams have released several rootstock cultivars with improved HLB tolerance and broad adaptation to Florida coastal flatwood soils (Albrecht et al., 2019). Moving forward, there is an urgent need for additional field testing in the Indian River Citrus District to evaluate sweet orange tree performance on an array of rootstock cultivars using management strategies that include high tree density, fertilization methods, and irrigation systems.

Conclusion

The devastation caused by HLB throughout citrus production regions in Florida, and especially in the Indian River Citrus District, has led growers to search for alternative citrus crops and management strategies

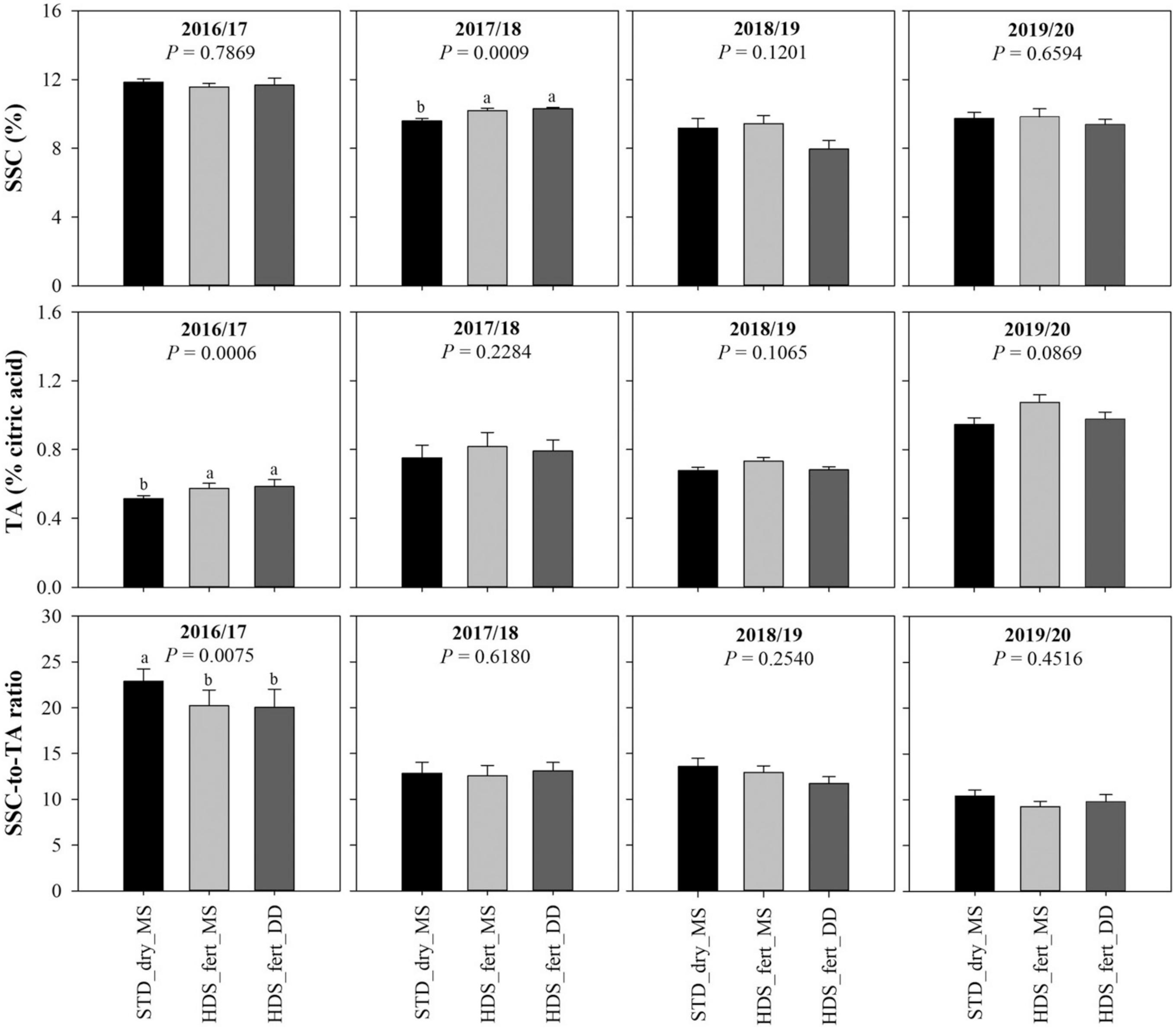

Fig. 7. Soluble solids content (SSC; top), titratable acidity (TA; middle), and SSC-to-TA ratio (bottom) of fruit harvested from trees planted at standard tree density (358 trees/ha) with granular fertilizer and microsprinkler irrigation (STD_dry_MS), high-density staggered planting (955 trees/ha) with fertigation and microsprinkler irrigation (HDS_fert_MS), and high-density staggered planting with fertigation and double-line drip irrigation (HDS_fert_DD) in an orchard planted in 2013. Bars within the same year sharing the same letter were not significantly different at $\alpha = 0.05$ according to Tukey's honestly significant difference. Mean ± SE of eight replications (n = 8).

to improve fruit yields in young orchards, thus enabling earlier economic returns given the likelihood of lower orchard productivity during later years. Our study showed that management practices that included high tree density, fertigation, and drip irrigation led to higher fruit yield than standard tree density and CRF fertilization in a *C*Las-infected sweet orange orchard in the Indian River. Both drip and microsprinkler fertigation methods sufficiently met the tree nutrient demand at high tree density, indicating a more efficient system that saves water could be used for citrus production; however, additional research is needed to determine optimal fertilization rates for young high-density sweet orange orchards under HLB-endemic conditions. Although fruit yields under high tree density were greater than those at standard tree density, they were still relatively low, and there is a need for additional research focusing on fruit yield responses in different rootstock cultivars in young high tree density orchards in the Indian River Citrus District.

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