Irrig Sci (2012) 30:275–286
DOI 10.1007/s00271-011-0280-6

ORIGINAL PAPER

Water savings, nutrient leaching, and fruit yield in a young avocado orchard as affected by irrigation and nutrient management

**Nicholas Kiggundu · Kati W. Migliaccio ·
Bruce Schaffer · Yuncong Li · Jonathan H. Crane**

Received: 21 September 2010 / Accepted: 6 March 2011 / Published online: 27 March 2011

Abstract This project was designed to determine the effect of fertilizer rate and irrigation scheduling on water use, nutrient leaching, and fruit yield of young avocado trees (*Persea americana Mill.* cv. Simmonds). Seven nutrient and irrigation management practices were evaluated: (1) irrigation based on crop evapotranspiration (ET) with 50% fertilizer at a standard rate (FSR); (2) ET irrigation with FSR (typical for avocado production in the area); (3) ET irrigation with 200% FSR; (4) irrigation based on exceedance of 15-kPa (SW) soil water suction with 50% FSR; (5) SW with FSR; (6) SW with 200% FSR; and (7) irrigation at a set schedule (based on timing and frequency typically used in local avocado production) with FSR. The SW with FSR treatment saved 87% of the water volume applied and reduced total phosphorus leached by 74% compared to the set schedule irrigation with FSR. The SW with FSR treatment had higher avocado fruit production, tree water-use efficiency, and fertilizer-use efficiency than the other six treatments. Thus, the use of soil water monitoring for irrigation management can substantially increase sustainability of young avocado orchards in southern Florida.

Introduction

Leaching of nitrogen (N) and phosphorus (P) from agricultural fields is a water quality concern worldwide due to increased nitrate (NO_3^-) concentrations and eutrophication of water supplies (Quiñones et al. 2007). Nutrient leaching, or the downward movement of dissolved nutrients in the soil profile with percolating water, is influenced by hydrologic and soil characteristics such as rainfall patterns (frequency, intensity, duration, and amount) and infiltration characteristics (Havlin et al. 2004; He et al. 2000; Muñoz-Carpena et al. 2002). Nutrient leaching is also effected by fertilization and irrigation practices, crop characteristics, and production system management. The residual amount of N and P in the soil after crop harvest and the rate of N and P mineralization of the decomposing plant residue also affect nutrient leaching (Jiao et al. 2004). In subtropical and tropical fruit orchards in southern Florida, heavy rainfall and over-irrigation may result in leaching of N and P into the groundwater (Schaffer 1998), even when these nutrients are applied at recommended rates.

Irrigation and fertilizer best management practices (BMPs) have been reported to minimize nutrient leaching (Yates et al. 1992; Paramasivam et al. 2000) and reduce water volumes applied without affecting yields (Migliaccio et al. 2010). Practices that enhance fertilizer utilization efficiency include appropriate timing of fertilizer applications, formulation of the fertilizer material, amount and rate of fertilizer applied, and methods used to apply fertilizers. Efficient irrigation methods such as irrigating based on

Communicated by E. Fereres.

N. Kiggundu (✉) · K. W. Migliaccio
Agricultural and Biological Engineering Department,
Tropical Research and Education Center, University of Florida,
18905 SW 280th Street, Homestead, FL 33031, USA
e-mail: kiggundu@ufl.edu

B. Schaffer · J. H. Crane
Horticultural Sciences Department, Tropical Research
and Education Center, University of Florida,
18905 SW 280th Street, Homestead, FL 33031, USA

Y. Li
Soil and Water Science Department, Tropical Research
and Education Center, University of Florida,
18905 SW 280th Street, Homestead, FL 33031, USA

crop evapotranspiration (ET) or soil water sensors minimize over-irrigation while not affecting yields (Silva et al. 2009; Migliaccio et al. 2010) and subsequently reducing nutrient leaching.

The ET estimation method involves computing the reference evapotranspiration (ET_o) using weather data (e.g., temperature, solar radiation, relative humidity, and wind speed). Two widely accepted equations for estimating ET_o are the Food and Agricultural Organization of the United Nations (FAO) Penman-Monteith (Allen et al. 1998) and the American Society of Civil Engineers-Environmental and Water Resources Institute (ASCE-EWRI 2005). Crop coefficients (k_c) relate evapotranspiration from the reference crop (ET_o) to evapotranspiration rates (ET_a) of a crop of interest (i.e., ET_a is the product of ET_o and k_c) (Allen et al. 1998). The availability of k_c values is the one limitation of using ET-based irrigation scheduling because time and financial resources are required to develop k_c values, and once developed, they remain site, stage of crop growth, plant size, and cultivar specific. Even so, water savings (13–46%) and increased yields (6–11%) have resulted from scheduling irrigation based on ET as opposed to set schedule irrigation for mango (Silva et al. 2009; Spreer et al. 2009) and potato (Meyer and Marcum 1998).

Soil water sensors estimate the soil water content in the root zone and can be integrated with irrigation control equipment to automate irrigation scheduling. In a field nursery in southern Florida, Migliaccio et al. (2008) found that automating irrigation of royal palms (*Roystonea elata*), at soil suctions of 5 and 15 kPa, reduced water volumes applied by 75 and 96% compared to standard irrigation scheduling without sacrificing tree crop quality. In Israel, Meron et al. (2001) reported that irrigating apple (*Malus domestica*) at a soil suction of 15–25 kPa resulted in annual water saving of 500–650 mm compared with ET-based irrigation scheduling. For papaya in calcareous soil of southern Florida, Migliaccio et al. (2010) reported water savings of 64–69% using automated tensiometers set at 10, 15, or 25 kPa compared with irrigating based on a set schedule.

Nutrient BMPs in combination with irrigation BMPs, based either on ET (Yates et al. 1992) or on soil water content (Paramasivam et al. 2000; Alva et al. 2006), have been evaluated for decreased nutrient leaching and increased water savings. Yates et al. (1992) reported that splitting applications of granular fertilizers in avocado (*Persea americana Mill*) orchards to eight times a year reduced nutrient leaching as opposed to applying fertilizers twice a year. The authors did not detect a significant difference in nutrient load leached by irrigating at 80, 100, or 120% of ET.

The effects of combined irrigation and nutrient management practices on nutrient leaching, volume of water applied, leaf nutrient concentrations, and fruit yield of avocado trees grown in gravelly loam soils of southern Florida have not been documented so that irrigation- and nutrient-use efficiencies may be optimized. The overall objective of our study was to determine whether a combined irrigation and fertilization BMP could be established for young avocado trees that would increase water savings and reduce nutrient leaching while maintaining crop yield in the environmentally sensitive ecosystems of southern Florida. The specific objectives of the study were to determine the effect of nutrient load and irrigation scheduling in an avocado orchard in southern Florida on (1) nutrient leaching of N and P; (2) leaf nutrient content, tree growth, and fruit yield; and (3) soil nutrient indicators such as organic carbon, C:N and C:P ratios, and inorganic N.

Materials and methods

Study area

The study was conducted in Homestead, FL, USA, at the University of Florida's Tropical Research and Education Center (TREC) (25°20′21″ N, 80°20′01″ W). The elevation of TREC is about 4 m above sea level. The annual rainfall is 1.44 m with maximum and minimum daily annual average temperatures of 31.5 and 11.6°C, respectively (considering available data from 1998 to 2007) for Homestead, FL (Florida Automatic Weather Network [FAWN], http://fawn.ifas.ufl.edu/data/reports). Homestead has a humid subtropical climate. The rainy season in Florida spans from May to October, and 80% of the rainfall occurs during this period (Mulholland et al. 1997). The soils at the site are gravelly, loamy-skeletal, carbonatic, hyperthermic lithic udorthents and are classified as Krome very gravelly loam (Noble et al. 1996). Krome soils are very shallow (up to 20 cm deep), well drained, moderately permeable and underline by limestone. Krome soils are characterized as 51% coarse material, 36% sand, 40% silt, and 24% clay with a bulk density of 1.42 g cm^{-3} (Muñoz-Carpena et al. 2002) and a pH of 7.4–8.4 (Zhou and Li 2001). To provide space for root development in this mechanically rock-plowed soil, tropical fruit trees are often planted 0.5 m deep at the intersection of perpendicular trenches (Núñez-Elisea et al. 2001).

Experimental design

An avocado orchard of 84 'Simmonds' trees planted on February 26, 2006, was established for this study. The rootstock used was open-pollinated seedlings of the cultivar 'Waldin'. Trees were planted in four rows at spacing of 6 m between rows and 4.5 m within each row. To establish the orchard, trees were irrigated with similar water volumes for 2 months after planting. Seven irrigation and nutrient management practices were implemented in August 2006: (1) irrigation based on crop evapotranspiration (ET) with 50% fertilizer at a standard rate (FSR); (2) ET irrigation with FSR (typical for avocado production in the area); (3) ET irrigation with 200% FSR; (4) irrigation based on exceedance of 15 kPa (SW) soil water suction with 50% FSR; (5) SW with FSR; (6) SW with 200% FSR; and (7) irrigation at a set schedule (based on timing and frequency typically used in local avocado production [J.H. Crane, personal communication]) with FSR. The experiment was conducted from August 2006 to October 2009. Avocado has a shallow root system, and in this area, 90% of the roots are located with the top 0.3-m soil depth (J.H. Crane, personal communication). Each treatment was replicated four times, and each replicate included 3 trees in a completely randomized design (Fig. 1). For each treatment replicate, a tensiometer (Irrometer, Riverside, CA, USA) was installed on the first tree and a bucket lysimeter was installed on the second tree (Fig. 1).

Irrigation management practices

Evapotranspiration (ET)-based irrigation volumes (m^3) were computed as follows:

1. The average monthly daily reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith (Allen et al. 1998) equation and historical weather data from the FAWN website (http://fawn.ifas.ufl.edu/data/reports) for Homestead, FL, USA.
2. Actual crop evapotranspiration (ET_a) [mm day^{-1}] was calculated as

$$\mathrm{ET_a} = \mathrm{ET_o} \times k_c \quad (1)$$

where k_c is the crop coefficient (unitless).

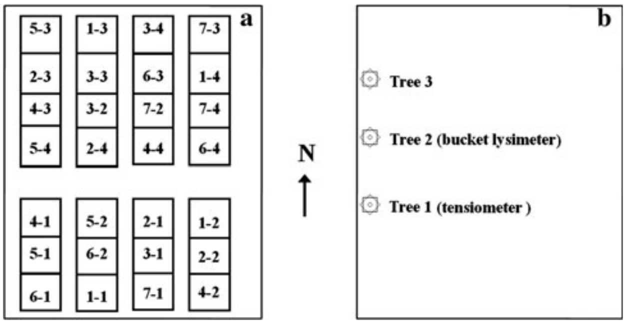

Fig. 1 Orchard layout. **a** treatments and their replicates where the first number is the treatment and second number is the replicate and **b** example replicate: tree and number and type of device installed beside the tree

3. The length of irrigation per day (I_{td}) was calculated in hours as

$$I_{td} = \frac{\mathrm{ET_a} \times A_s \times 10^{-3}}{D_r} \quad (2)$$

where ET_a represents actual evapotranspiration (mm), A_s is the micro-sprinkler delivery area (m^2), and D_r is the irrigation delivery rate of the micro-sprinkler ($m^3\ h^{-1}$).

4. Water volume applied per tree per day (W_{vd}) was calculated in cubic meters as

$$W_{vd} = I_{td} \times D_r \quad (3)$$

To allow for proper root development, the trees receiving ET-based irrigation were irrigated three times each week at 8:05 a.m. EST (Monday, Wednesday, and Friday) using ET_o and crop coefficients (k_c) provided in Table 1.

For soil water (SW)-based irrigation, switching tensiometers (Irrometer, Riverside, CA, USA) were used to monitor soil suction in the orchard (Fig. 1). The tensiometers were installed 0.2 m on the north side of the trees at a depth of 0.15 m. The volumetric water content of Krome soil is considered to have depleted to half of the plant available soil water when the soil water suction is about 15 kPa (Muñoz-Carpena et al. 2002). Irrigation was scheduled at 8:30 a.m. EST and 1:00 p.m. EST each day, and trees were irrigated when the soil water suction exceeded 15 kPa. A second scheduling at 1:00 p.m. was needed to irrigate the trees on days when morning tensiometer readings would be below 15 kPa and soil water content would decrease in the afternoon.

Trees irrigated on a set schedule were irrigated twice a week for 2 h during each irrigation event. Trees were

Table 1 The ET_o and k_c values used to compute water application rates for the ET-based irrigation management method and average monthly rainfall during leachate sampling

Month	ET_o (mm day^{-1})	Crop coefficient (k_c)[a]	Average monthly rainfall from Nov 2007 to Oct 2009 (mm)
Jan	1.85	0.50	25
Feb	2.46	0.50	41
Mar	3.53	0.80	64
Apr	3.99	0.80	60
May	4.55	0.68	196
Jun	4.52	0.68	202
Jul	3.89	0.68	119
Aug	3.51	0.68	277
Sep	3.51	0.68	159
Oct	3.07	0.68	103
Nov	2.49	0.50	16
Dec	1.93	0.50	11

[a] J.H. Crane, Homestead, FL, USA, 2006, personal communication

irrigated every Tuesday and Friday starting at 6:00 a.m. EST. The irrigation times and duration were kept constant for the entire study period.

For all treatments, irrigation was delivered through a micro-sprinkler (Maxijet, Inc. Dundee, FL, USA). Each tree had one micro-sprinkler with an application rate of 0.079 $m^3{-}h^{-1}$. The micro-sprinklers were placed 0.12 m from the tree trunks (on the east side), and the irrigated area per sprinkler had a diameter of 1.57 m during the production year 2009. Each treatment replicate was monitored using a water meter (Daniel L. Jerman Co., Hackensack, NJ, USA) to record the volume of water applied. Irrigation was controlled with solenoids (Nelson Co., Forth Worth, TX, USA) and a Toro controller (Ecxtra, Model 53768, Riverside, CA, USA). The electrical conductivity of irrigation water used was 0.55 dS m^{-1}. Groundwater was used to irrigate the trees. The water table in the area fluctuates between 1.0 and 2.2 m.

Fertilizer management practices

The fertilizer at a standard rate (FSR) application rate was modified during the experiment based on tree size (Table 2). It is a standard practice for avocado growers in southern Florida to increase the fertilizer amount as the trees develop (J.H. Crane, personal communication). The standard strategy of the fertilizer program during the first 2 years (2006–2007) is to remove all fruits immediately after fruit set to favor vegetative growth during early tree development. Thus, fruits were removed during the first 2 years, and trees were allowed to produce fruit during the following 2 years (2008–2009). Trees were fertilized by broadcasting the fertilizer under the tree canopy, and the fertilized area was about 5.1 m^2 during the fruiting years.

Nutrient load analysis

Bucket lysimeters described by Migliaccio et al. (2006) were installed in the avocado orchard on the second tree of each treatment replicate. Each lysimeter was composed of a collection container (20 l) and two flexible tubes. The bucket lysimeters were installed 0.3 m from the tree trunk and 0.3 m below the ground surface to prevent interference with tree root development. The 20-l bucket lysimeter occupied an area of 0.067 m^2 implying that the leachate collected represented a fraction of 3.5% of the irrigated area. The flexible tubes on the lysimeters were left protruding above the ground after installation. The tubes provided the ability to collect the water samples from the collection container; one tube served as an air vent, while the other tube was connected to a peristaltic pump to draw the leachate. Leachate samples were collected monthly from November 2007 to October 2009. The amount of water collected from each lysimeter was measured, and a leachate sample was collected in a 270-ml plastic bottle for chemical analysis.

Water samples were analyzed for nitrogen in the form of nitrate (NO_3-N) and total phosphorus (TP). Water samples were prepared for NO_3-N analysis by filtering a portion of each sample through Whatman No. 42 filter paper into a 20-ml vial that was stored at −4°C until the determination of NO_3-N. Nitrate was determined spectrophotometrically by first reducing NO_3^- to NO_2^- using a cadmium coil, and the resulting NO_2^- concentration was then determined by EPA method 353.2 (http://www.caslab.com/EPA-Method-353_2/). Water samples were prepared for TP analysis using 30 ml of unfiltered sample. About 0.6 ml of 5 N H_2SO_4 (sulfuric acid) and about 0.24 g of $(NH_4)_2S_2O_8$ (ammonium persulfate) were added to each sample to convert particulate organic and condensed phosphates into orthophosphates (Li et al. 2005). Samples were covered and shaken to allow $(NH_4)_2S_2O_8$ to dissolve in the water. The samples were digested in an autoclave (Consolidated Stills & Sterilizers, Boston, MA, USA) for 30 min at a pressure of about 103.4 kPa. After digestion, the samples were stored at room temperature until they were analyzed for TP. Total phosphorus was determined by EPA method 365.1 (http://www.caslab.com/EPA-Method-365_1/). All

Table 2 Fertilizer at a standard rate management scheme used for ‘Simmonds’ avocado trees

Development stage	Year	Amount applied (kg ha^{-1})	Nutrient element content (%)			
			N	P	K	Mg
Orchard establishment[a]	2006–2007	98	6	2.6	5	2
Fruit bearing trees (production)[b]	2008	341	8	1.3	7.5	3
	2009	1,950	8	1.3	7.5	3

[a] The compounds used in the fertilizer during production were nitrate nitrogen 0.6%, ammonical nitrogen 2.4%, urea nitrogen 0.7%, water insoluble nitrogen 2.3%; available phosphate 2.6%; soluble potash 5%; chlorine 2%; magnesium 2%; manganese 0.77%, copper 0.03%; zinc 0.07%; iron 2%; boron 0.03%; sulfur 4%

[b] The compounds used in the fertilizer during production were nitrate nitrogen 1%, ammonical nitrogen 4.6%, urea nitrogen 0.8%, water insoluble nitrogen 1.6%; available phosphate 1.3%; soluble potash 7.5%; chlorine 2%; magnesium 3%; manganese 0.11%, zinc 0.11%; iron 1.42%; boron 0.05%

sample analyses were completed using a SEAL AQ2 discrete analyzer (SEAL Analytical, Inc. Mequon, WI, USA). The amount of nutrient load leached for NO_3-N and TP was computed using Eq. 4.

$$N_L = V_T \times C_e \qquad (4)$$

where C_e is the concentration (mg L^{-1}) of any of the four nutrient leached elements, V_T the total volume of water leached in a month (L), and N_L the load of nutrient element leached (mg). The total volume of water leached V_T was determined using Eq. 5.

$$V_T = V_B \times A_S / A_C \qquad (5)$$

where V_B is the volume of water pumped from the bucket lysimeter (L), A_S is the micro-sprinkler delivery area (m^2), and A_C is the area of the bucket lysimeter's catch pan (m^2). In computing nutrient load leached, the irrigated area was considered since it contributes more to the amount of water collected from each lysimeter than the entire fertilized area.

Plant analysis

Tree diameters were measured 0.15 m above the soil surface annually in August on the third tree of each treatment replicate. Tree heights were not collected because trees were pruned at 2 m for protection against wind damage. Three to five fully expanded, recently mature (hardened off) leaves were picked from the third tree of each treatment replicate for nutrient analysis. The leaves were first washed with deionized water (DI) and then washed in a detergent prepared using 30 ml of soap (Liqui-nox, Alconox Inc., White Plains, NY, USA) and 2,500 ml of DI. The leaves were then washed in acid prepared with 60 ml of 6 N HCl and 2,500 ml of DI. The acid was washed off with DI water and the leaves oven-dried at 75°C until they reached a constant weight. The dried leaves were ground in a Wiley mill (Thomas-Wiley Co. Philadelphia, PA, USA) with a 1-mm mesh screen. The ground samples were analyzed for total nitrogen (TN), total carbon (TC), and total P (TP). Both TN and TC in the tissue were measured by the combustion method using a Vario Max Elemental CNS Analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Solutions used to analyze TP were extracted using the ashing and ignition method (Davies 1974; Ben-Dor and Banin 1989). Samples were then analyzed for TP (EPA method 365.1). Tissue samples were collected in April, August, and December.

Leaf greenness, an indication of leaf chlorophyll content (Pestana et al. 2004), was determined with a SPAD-502 meter (Minolta, Osaka, Japan) and expressed as SPAD units. Measurements were made three times per year on three fully expanded, recently mature leaves from the third tree of each replicate. The average value for the three leaves was computed and recorded as the SPAD reading for the sampled tree. The relationship between SPAD units and leaf chlorophyll content was determined using the methods described by Abadía and Abadía (1993). The procedure involved collecting 20 leaves of varying maturity and leaf color (ranging from pale yellow to dark green). The SPAD reading for each leaf was recorded after which the leaf was cut from the tree using a razor blade. Once the leaves were removed from the tree, they were wrapped in aluminum bags and stored in a portable cooler with ice before being transported to the laboratory. One ml of 100% acetone was put in a mortar, and a pinch of calcium carbonate was added. A small piece of each leave of 0.283 cm^2 was cut with a borer and dropped in the mortar and ground to extract a chlorophyll solution. The mixture was then poured into a vial, and the mortar was rinsed with 100% acetone that was also poured in the vial to bring the final volume of the extract to 5 ml. The mortar was further washed with acetone before another chlorophyll extraction was performed. Each extract was filtered through a 0.45-μm syringe filter to remove debris and the ascorbate. Total chlorophyll, the sum of chlorophyll a and b, was determined immediately from the filtered extracts at 662 nm and 645 nm using a spectrophotometer (Model DU-640, Beckman Coulter, Inc., Fullerton, CA, USA).

Soil analysis

Soil nutrient concentrations were determined in July in 2006 and 2007 (when trees were too young to bear fruit) and after fruit were harvested (September) in 2008 and 2009. Concentrations of TN, TC, nitrogen in the form of ammonium (NH_4-N), NO_3-N, TP, and inorganic carbon (IC) in the soil were measured. Dry matter and any fertilizer residue covering the soil were removed before collecting soil samples. Samples were collected from four equidistant positions around the third tree from the first three treatment replicates. Each soil sample was dried and sieved to pass through 2-mm mesh screen. TN and TC were analyzed by the combustion method (Vario Max Elemental CNS Analyzer, Elementar Analysensysteme GmbH, Hanau, Germany). For the determination of NH_4-N and NO_3-N, an extraction was made by weighing 2 g of the soil sample in a 50-ml bottle to which 20 ml of 2 N KCl solution was added. The bottles were shaken for 30 min at 180 rpm. A 20-ml sample was filtered through Whatman No. 42 filter paper into vials and stored at 0°C degree until analysis. Nitrate was determined by EPA method 353.2 (http://www.caslab.com/EPA-Method-353_2/), and ammonium was determined by EPA method 350.1 (http://www.caslab.com/EPA-Method-350_1/). Soil inorganic N was determined as the sum of NH_4-N and NO_3-N for each sample. Solutions used to analyze TP were extracted using the ashing and ignition method (Davies 1974; Ben-Dor and Banin 1989). Total phosphorus was analyzed using EPA method 365.1 (http://www.caslab.com/EPA-Method-365_1/). The NH_4-N, NO_3-N, and TP sample analyses were completed using a SEAL AQ2 discrete analyzer (SEAL Analytical, Inc. Mequon, WI, USA). The soil inorganic C was analyzed by the modified pressure-calcimeter method (Sherrod et al. 2002). Soil organic carbon was determined as the difference between TC (from CNS analyzer) and soil inorganic C.

Avocado fruit yield

Avocado fruit were harvested in 2008 and 2009 in accordance with the shipping schedule of the Florida Avocado Administrative Committee (Hatton and Reeder 1965). The fruit harvesting dates were July 7 and 21 and August 4 with the corresponding diameter of fruits to be harvested of 87 mm (3.44 in), 78 mm (3.06 in), and any size (harvesting all remaining fruits). Fruits harvested from each tree were counted and weighed. Average fruit weight for each tree was also computed for the three harvesting dates. The total fruit weight for each treatment was divided by respective treatment total volume of water applied to determine the crop production water-use efficiency (CP-WUE). Likewise, the total fruit weight for each treatment was divided by the total fertilizer amount applied to each treatment to determine the crop production fertilizer-use efficiency (CP-FUE).

Statistical analysis

A one-way analysis of variance (ANOVA) was performed, and treatment means were separated using a Waller-Duncan K-ratio to determine treatment effects. The treatment effects investigated were (1) effects of ET-, SW-, and set schedule-based irrigation methods on volume of water applied per tree per day over the 4 years and (2) the effects of the seven irrigation and nutrient managements on NO_3-N and TP leached; leaf chlorophyll content, TN, TC, tree diameter; soil inorganic N, organic C, TN, TC, and TP; fruit yield, CP-WUE and CP-FWE. Fruit number and weight data were analyzed by date, and also dates were pooled to determine significant differences ($P \leq 0.05$) in yearly total fruit number and weight among treatment means. Total yield data were analyzed for significant differences ($P \leq 0.05$) between the 2 years for each treatment. Before performing statistical analysis, data were checked for normality, and if data were not normally distributed, the Box and Cox (1964) method was used to normalize data distribution.

An additional statistical analysis was done whereby the set schedule irrigation treatment (Treatment 7) was eliminated from the analysis to test statistical interactions between proposed irrigation BMP treatments (SW or ET) and the 3 fertilizer rates (FSR, 50% FSR, or 200% FSR). Those data were then analyzed as a 2 (types of irrigation scheduling) × 3 (fertilizer rate) factorial design by a 2-way ANOVA. The dependent variables for the 2-way ANOVA included leaf nutrient content, soil nutrient indicators, and tree diameter, to explore if there were irrigation × fertilizer interactions. All statistical analyses were done with SAS statistical software (SAS Institute, Cary, NC, USA).

Results and discussion

Water application

Significant differences ($P \leq 0.05$) in volumes of water applied were observed among the irrigation methods (Table 3). The water volumes applied for the ET-based irrigation increased over the study period. This increase was due to tree root growth and thus an increase in the irrigated area over the years, from an area of 0.66 m^2 in 2006 to an area of 1.94 m^2 in 2009. SW-based irrigation also increased during the study period as greater tree water demands resulting in increased soil water depletion triggering a greater number of irrigation events. The historic ET values used to compute irrigation volumes were compared to real-time ET to explore the accuracy of using historical data. The historical ET values computed using weather data from 1998 to 2005 reasonably estimated the real-time ET, with a coefficient of determination (R^2) of 0.91. The data suggest that climate variables such as temperature, radiation, relative humidity, and wind speed that were used to compute historical ET by the FAO Penman-Monteith method were comparable to weather data observed during the study period. For each irrigation practice, there was no significant difference between the volumes of water applied in the wet and dry seasons of

Table 3 Amount of water applied ($\times 10^{-3}$ m^3 $tree^{-1}$ day^{-1}) by the different management practices

Year	Irrigation management[a,b]		
	ET	Soil water	Set schedule
2006	1.55 a	2.24 b	40.61 c
2007	1.70 a	4.49 b	40.36 c
2008	2.12 a	6.13 b	40.56 c
2009	4.33 a	5.73 b	39.85 c

[a] Irrigation managements with different letters within rows are significantly different ($P \leq 0.05$) according to a Waller–Duncan K-ratio test

[b] To get amount of water applied per hectare ($\times 10^{-3}$ m^3 $tree^{-1}$ day^{-1}) multiple value by 358 (trees)

each year, during the 4 years of the study. This was attributed to a dry, cold season (November to April) and a wet, hot season (May–October) (Mulholland et al. 1997). Water savings of 93 and 87% were achieved by using ET- and SW-based irrigation practices, respectively, compared to the set schedule irrigation. The slight difference in water applied based on ET and SW could be attributed to the k_c values. The k_c values were estimated based on avocado k_c values developed from similar climatic conditions elsewhere and not based on measured data for southern Florida. Another likely possibility is that the difference in water savings was due to the functional basis of each irrigation scheduling method; the SW-based method is a function of real-time water demand, and the ET-based irrigation is a function of historical water demand. Similar water savings with SW-based irrigation (69%) and ET-based irrigation (73%) compared to set schedule irrigation were observed by others for other tropical fruit crops (carambola and papaya) in the area where the current avocado study was conducted (Kisekka et al. 2010; Migliaccio et al. 2010).

Nitrogen and phosphorus loads leached

There were no significant differences ($P > 0.05$) among treatments for the NO_3-N load leached over the 2-year period. However, treatments where the fertilizer rate was doubled (i.e., ET with 200% FSR [Treatment 3] and SW with 200% FSR [Treatment 6]) and set schedule with FRS (Treatment 7) leached greater NO_3-N loads than the other treatments (Table 4). The SW with FSR (Treatment 5) and the treatments where the fertilizer rate was halved generally had less NO_3-N leached compared to set schedule irrigation. Thus, the amount of NO_3-N leached appeared to be more influenced by the amount of water applied than the fertilizer rate. The average volume of water collected from the bucket lysimeters for the set schedule irrigation method of 14.1 ± 1.65 l indicates that there was no leachate overflow from the lysimeters. Results from our study (although differences were not statistically significant) suggest that efficient irrigation methods have a greater potential to reduce NO_3-N leaching than reduced fertilizer applications. This is likely because under saturated flow NO_3^- ions move at similar speed as water molecules (Havlin et al. 2004) and the set schedule irrigation treatment likely resulted in saturated flow conditions.

The set schedule with FSR (Treatment 7) leached a significantly ($P \leq 0.05$) greater TP load than the other treatments (Table 4). Both ET and SW-based irrigation methods reduced TP leaching by 75% compared to the set schedule treatment (Table 4). Nelson et al. (2005) reported that excessive P leaching was attributed to over-application of P, low P sorption capacity of the soil, and rainfall exceeding evaporation. The P leaching in our study was attributed to the high P content of Krome soil (3,500 mg kg^{-1}), such that with excess irrigation P dissolves and becomes available for leaching as observed by others (He et al. 2000; Nelson et al. 2005). Thus, efficient water application reduced fertilizer lost through nutrient leaching by reducing the occurrence of saturated flow and drainage.

Leaf nutrient content and tree growth

Generally, there were no significant differences ($P > 0.05$) among treatments for leaf concentrations of TN, TC, or TP observed from 2006 to 2009. The treatment means for the three elements ranged as follows: TN (1.48 to 2.33%), TC (44.8 to 47.7%), and TP (1,090–2,847 mg kg^{-1}). An increase in the FSR amount over the years did not increase TN content in the leaves as observed by Embleton et al. (1958) for 'Hass' avocado trees in California. Analysis of treatment effects as a factorial design with two types of irrigation (SW or ET) with three levels of fertilizers did not reveal information that was contrary to the main treatment

Table 4 Total nutrient load leached and the total amount of nutrient applied from Nov 2007 to Oct 2009, $n = 4$

Treatment	Nutrient leached load (kg ha^{-1})[a]		Total amount of element nutrient applied (kg ha^{-1})	
	NO_3-N[b]	TP	N	P
1. ET + 50% FSR	10 a	0.310 a	92	15
2. ET + FSR	23 a	0.243 a	184	30
3. ET + 200% FSR	44 a	0.256 a	368	60
4. SW + 50% FSR	22 a	0.280 a	92	15
5. SW + FSR	13 a	0.279 a	184	30
6. SW + 200% FSR	35 a	0.269 a	368	60
7. Set schedule + FSR	37 a	1.084 b	184	30

[a] Nutrient leached load with different letters within columns are significantly different ($P \leq 0.05$) according to a Waller–Duncan K-ratio test

[b] Data on NO_3-N leached load were first normalized using the Box–Cox method before performing ANOVA, and results were retransformed to the measurement units after the analysis

effects on TN, TC, and TP. Analysis of chlorophyll by sampling date showed no significant differences ($P > 0.05$) among treatments. The chlorophyll mean (with standard deviation) with all treatment dates pooled was 33 ± 3.9 nmol cm^{-2}.

There were no significant differences ($P > 0.05$) in tree trunk diameter among treatments for any of the 4 years (data not shown). The mean (with standard deviations) pooled for all treatments showed that the tree diameter increased from 1.7 ± 0.5 cm in 2006 to 7.8 ± 1.2 cm in 2009. Factorial analysis of tree diameter as influenced by two types of irrigation and three levels of fertilizer did not show irrigation x fertilizer interactions or treatment differences. The failure to identify the influence of the treatments on tree trunk diameter may be attributed to greater partitioning of the manufactured carbohydrates to the fruits and other vegetative parts of the tree than the tree stem (Liu et al. 1999; McQueen et al. 2004).

Soil analysis

There were no significant differences among treatments ($P > 0.05$) for soil organic C, C:N ratio, C:P ratio, and inorganic N contents, measured over the 4-year period. Generally, set schedule with FSR (Treatment 7), ET with 50% FSR (Treatment 1), and SW with 50% FSR (Treatment 4) had the least soil inorganic N. This implied that applying less fertilizer with optimum irrigation resulted in the same soil inorganic N status as doubling the fertilizer amount with excessive water application. Thus, the excessive water volume in Treatment 7 resulted in nutrient flushing from the root zone. Likewise, set schedule with FSR (Treatment 7) generally had a lower soil organic C and a higher C:N ratio compared to other treatments which was attributed to leaching of organic C as reported by Roose and Barthes (2001). Comparing yearly results after pooling, all treatments together showed a significant decrease ($P \leq 0.05$) in C:N and C:P ratios and inorganic N between the values observed in the first and fourth years (Table 5). This was attributed to a slight increase in soil N and a significant increase in P content (Table 6) over the study period due to inorganic fertilizer input. Analyzing treatment effects as two types of irrigation (SW and ET) and 3 levels of fertilizer in a factorial design resulted in a few significant ($P \leq 0.05$) effects attributed to irrigation method for C:P ratio in 2007 and fertilizer level for C:N ratio in 2009 (Fig. 2). Although the concentration of P in fertilizer applied was reduced by half during fruit production years from the fertilizer rate used during orchard establishment (Table 2), the increase in the P amount applied decreased the C:P ratio over the years. This implies that the P formulation in the fertilizer could be lowered without affecting soil nutrient composition.

Table 5 Soil analysis mean and standard deviation values, $n = 21$

Sampling date[a]	C:N ratio[b]	Organic C %	C:P ratio[b]	Inorganic N (mg kg^{-1})[b]
09/05/2006	44 a	4.5 ab	13 ab	27 b
07/06/2007	42 ab	3.7 c	14 a	39 a
09/22/2008	30 c	4.9 a	12 b	22 b
09/07/2009	36 bc	4.0 bc	10 c	42 a

C carbon, *N* nitrogen, *P* phosphorus

[a] Soil nutrient indicator with different letters within columns is significantly different ($P \leq 0.05$) according to a Waller–Duncan K-ratio test

[b] Data were first normalized using the Box–Cox method before performing ANOVA, and results were retransformed to the measurement units after the analysis

Table 6 Soil analysis mean, $n = 21$

Sampling date[a]	TN%[b]	TC%	TP%[b]
09/05/2006	0.24 b	10.1 b	0.34 bc
07/06/2007	0.25 b	10.0 b	0.27 c
09/22/2008	0.38 b	10.6 a	0.41 ab
09/07/2009	0.29 b	10.2 ab	0.45 a

TN total nitrogen, *TC* total carbon, *TP* total phosphorus

[a] Soil nutrient with different letters within columns is significantly different ($P \leq 0.05$) according to a Waller–Duncan K-ratio test

[b] Data were first normalized using the Box–Cox method before performing ANOVA, and results were retransformed to the measurement units after the analysis

Avocado fruit yield

The highest number of fruit was collected on July 21 of each year, while the fewest fruit were collected on August 4 (Table 7). Significant differences ($P \leq 0.05$) in total fruit yields (fruit number and weight) were observed among treatments, with SW with FSR (Treatment 5) and SW with 200% FSR (Treatment 6) having the most fruit in 2008 (Table 8). The SW with FSR (Treatment 5) and SW with 200% FSR (Treatment 6) also had higher yields in 2009 compared to other treatments, although the differences were not significant among treatments. Yield results showed that avocado trees were responsive to both water volume applied and fertilizer rate. Given that SW with FSR and SW with 200% FSR recorder, greater fruit yield in 2008 and 2009 than set schedule with FSR suggests that over-irrigation and nutrient leaching in the set schedule with FSR treatment reduced crop yields. Due to high yield variability within treatment replicates, there was no significant difference ($P > 0.05$) between the 2008 and 2009 yields within each treatment. The high variability within treatment replicates may have led to the failure to achieve the anticipated biennial bearing trend in the 2 years.

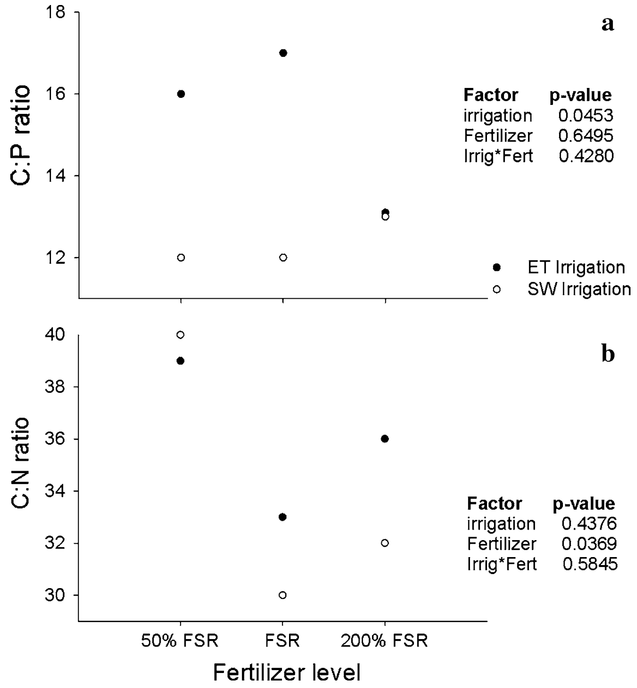

Fig. 2 Soil nutrient indicators analyzed as a factorial design (2-levels of irrigation and 3-levels of fertilizer input) for the 2 years where irrigation or fertilizer rate had an effect. **a** C:P ratio for 2007 and **b** C:N ratio for 2009. Abbreviations were as follows: *C* carbon, *N* nitrogen, *P* phosphorus

Evaluation of crop production water-use efficiency (CP-WUE) as a ratio of fruit weight per volume of water applied resulted in significant differences ($P \leq 0.05$) among treatments in 2008 (Table 8). The set schedule with FSR (Treatment 7) had the lowest CP-WUE compared to other treatments in both 2008 and 2009. Generally, there were no significant differences ($P > 0.05$) in CP-WUE between ET- and SW-based irrigation treatments for year 2008 or 2009. Although SW with FSR (Treatment 5) had the highest yield in 2008, it had a lower CP-WUE compared to the ET-based treatments. This was attributed to a leak in the Treatment 5 water line that resulted in excess water flowing through the water meters unlike in 2009 where no system leaks occurred.

Analysis of crop production fertilizer-use efficiency (CP-FUE) as a ratio of fruit weight per amount of fertilizer applied resulted in significant differences ($P \leq 0.05$) among treatments (Table 9). Treatments where fertilizer rate was halved corresponded to a higher CP-FUE, while treatments where the fertilizer rate was doubled resulted in the lower CP-FUE. The low CP-FUE in 2009 was attributed to a rise in FSR from 340 kg ha^{-1} in 2008 to 1,950 kg ha^{-1} in 2009. Thus, the FSR increased by about 600%, yet the fruit yield did not change significantly. The CP-FUE ratio assisted with identifying the treatments with the greatest yield returns per unit of fertilizer input.

The set schedule with FSR (Treatment 7) had the lowest CP-WUE compared to all other treatments (Table 8). Removing Treatment 7 from the analysis and re-analyzing treatment effects as a factorial design of two types of irrigation (SW or ET) with three levels of fertilizers showed that both irrigation method and fertilizer rate significantly ($P \leq 0.05$) affected fruit yield in 2008 (Fig. 3). However, in 2009, fruit yield was only significantly ($P \leq 0.05$) affected by the irrigation level. SW-based irrigation resulted in greater fruit yield than ET-based irrigation except at half fertilizer rate in 2008 (Table 7). The failure to detect a significant difference due to fertilizer rate in 2009 was attributed to a sharp rise in the FSR of about 600%, suggesting that an effect may have been detected again had a lower FSR been used in 2009. The data imply that doubling the fertilizer rate was not beneficial in influencing fruit yields in both production years.

Mean fruit weight was not significantly different ($P > 0.05$) between 2008 and 2009. The mean (with

Table 7 Fruit weight (kg ha^{-1}) and fruit number (ha^{-1}) of 'Simmonds' avocado by harvest date per treatment for 2008 and 2009, $n = 12$

Treatment[a]	2008[b]					2009[b]				
	July 7	July 21	Aug 4	Total fruit weight	Total fruit number	July 7	July 21	Aug 4	Total fruit weight	Total fruit number
1. ET + 50% FSR	101 d	1,239 a	93 a	1,433 b	3,643 b	370 bc	1,045 a	143 a	1,558 a	3,224 a
2. ET + FSR	463 bc	1,379 a	105 a	1,947 ab	4,598 ab	469 c	997 a	221 a	1,687 a	3,374 a
3. ET + 200% FSR	612 b	1,233 a	21 a	1,866 b	4,061 b	958 ab	875 a	305 a	2,138 a	4,030 a
4. SW + 50% FSR	290 cd	1,141 a	146 a	1,577 b	3,583 b	633 bc	994 a	472 a	2,099 a	4,061 a
5. SW + FSR	654 b	1,789 a	167 a	2,610 a	6,001 a	744 abc	1,326 a	492 a	2,562 a	5,106 a
6. SW + 200% FSR	1,299 a	1,316 a	33 a	2,648 a	5,823 a	1212 a	1,030 a	267 a	2,509 a	4,867 a
7. Set schedule + FSR	579 bc	1,051 a	191 a	1,821 b	3,941 b	890 ab	920 a	382 a	2,192 a	3,971 a

[a] Yield with different letters within columns is significantly different ($P \leq 0.05$) according to a Waller–Duncan K-ratio test

[b] Data for 2008 and 2009 were first normalized using the Box–Cox method before performing ANOVA, and results were retransformed to the measurement units after the analysis

Table 8 Means weight of 'Simmonds' avocado fruit per cubic meter of water applied (kg m^{-3}), $n = 12$

Treatment[a, c]	2008[b]	2009
1. ET + 50% FSR	9.4 b	5.8 a
2. ET + FSR	12.8 a	6.8 a
3. ET + 200% FSR	12.3 ab	7.9 a
4. SW + 50% FSR	3.4 dc	6.3 a
5. SW + FSR	5.0 c	7.3 a
6. SW + 200% FSR	9.8 ab	7.8 a
7. Set schedule + FSR	0.7 e	0.9 b

[a] Fruit yield with different letters within columns is significantly different ($P \leq 0.05$) by column according to a Waller–Duncan K-ratio test

[b] Data for 2008 were first normalized using the Box–Cox method before performing ANOVA, and results were retransformed to the measurement units after the analysis

[c] Calculations were based on yield obtained and volume of water applied on a hectare basis

Table 9 Means weight of 'Simmonds' avocado fruit per kg of fertilize applied (kg kg^{-1}), $n = 12$

Treatment[a, c]	2008[b]	2009[b]
1, ET + 50% FSR	8.4 a	1.6 ab
2, ET + FSR	5.7 bc	0.9 cd
3, ET + 200% FSR	2.7 d	0.5 e
4, SW + 50% FSR	9.3 a	2.2 a
5, SW + FSR	7.6 ab	1.3 bc
6, SW + 200% FSR	3.8 cd	0.6 de
7, Set schedule + FSR	5.8 bc	1.2 bc

[a] Fruit yield with different letters within columns is significantly different ($P \leq 0.05$) according to a Waller–Duncan K-ratio test

[b] Data for 2008 and 2009 were first normalized using the Box–Cox method before performing ANOVA, and results were retransformed to the measurement units after the analysis

[c] Calculations were based on a hectare basis of yield obtained and amount of fertilizer applied

standard deviations) with all treatments pooled showed that the fruit size was 0.44 ± 0.07 kg in 2008 and 0.50 ± 0.09 kg in 2009. However, in 2009, fruit were slightly larger than in 2008, although the total fruit weight was similar in each year (Table 8). This may be attributed to the trees being larger in 2009 and capable of manufacturing and allocating more carbohydrates for fruit development than in 2008 (Liu et al. 1999; McQueen et al. 2004).

Other findings

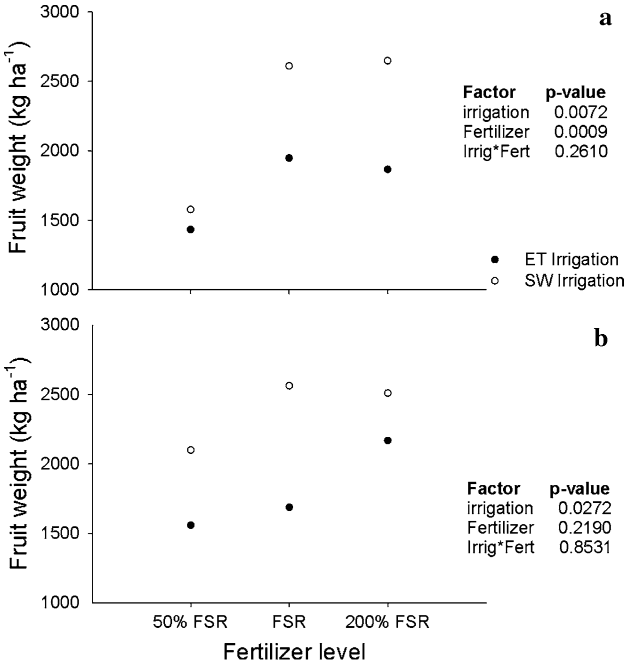

Fig. 3 Fruit weight of 'Simmonds' avocado analyzed as a factorial design with 2-levels of irrigation and 3-levels of fertilizer input for the 2 years of production; **a** 2008 and **b** 2009

Monitoring nutrient leaching with bucket lysimeters allowed for cumulative collection of the leachate between sampling events. However, one of the drawbacks of bucket lysimeters is the failure to collect leachate under unsaturated soil conditions due to by-pass flow. Secondly due to high water percolation rates of Krome soil, by-pass flow could have occurred during high-intensity rainfall events. This is believed to have occurred based on preliminary water balance analyses. These measurement limitations may have resulted in an under estimation of the NO_3-N and TP loads reported in our study. Research is needed to explore modification of the leachate collection device to better capture high rainfall events.

Conclusions

Irrigating young avocado trees based on ET or SW saved 93 and 87% of the water volume applied compared to irrigation based on a set schedule over the 4-year period. Irrigating based on SW with FSR (Treatment 5) resulted in a reduction of 74% in TP leached compared to the set schedule irrigation method. Irrigating based on ET with FSR (Treatment 2) resulted in a reduction of 78% in TP leached compared to the set schedule irrigation method. Such high reductions were attributed to nutrient leaching being more influenced by the irrigation management than fertilizer rate. The SW with FSR treatment resulted in higher avocado fruit production, tree water-use efficiency, and fertilizer-use efficiency than the other six treatments. Thus, the use of soil water monitoring for irrigation management can substantially increase sustainability of young avocado orchards in southern Florida. Yield results suggest that ‘Simmonds’ avocado is responsive to well-maintained soil water regime in the root zone. Generally, no significant differences ($P > 0.05$) were observed among treatments for TN, TC, and TP; trunk diameter; and soil organic carbon, C:N, and C:P ratios, and inorganic N. Considering impacts on water supplies from climatic variability and increasing demand by other uses and the need for more sustainable agriculture, irrigation BMPs should be beneficial for avocado producers and likely other similar production systems. The P concentration in the fertilizer applied was reduced by half during fruit production years, yet the C:P ratio declined over the years. This implies that the P concentration in the fertilizer formulation could be lowered without affecting soil nutrient status.

Acknowledgments The authors thank Tina Dispenza, Harry Trafford, Laura Rosado, Quiqin Yu, Michael Gutierrez, and Wanda Montas for assistance with material preparation and data collection and analysis. We also thank several colleagues who assisted with result interpretations and manuscript review. We would also wish to acknowledge support from the Agricultural and Biological Engineering Department and the College of Agricultural and Life Sciences at the University of Florida, Gainesville, Florida, USA. This project was funded by a USDA-CSREES National Integrated Water Grant.

References

Abadía J, Abadía A (1993) Iron and plant pigments. In: Barton LL, Hemming BC (eds) Iron chelation in plants and soil microorganisms. Academic Press, New York, pp 327–343

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56. FAO Rome

Alva AK, Paramasivam S, Obreza TA, Schumann AW (2006) Nitrogen best management practice for citrus trees: I. Fruit yield, quality, and leaf nutritional status. Sci Hortic 107:233–244

ASCE-EWRI (2005) The ASCE Standardized reference evapotranspiration equation. Technical Committee report to the Environmental and Water Resources Institute of the American Society of Civil Engineers from the Task Committee on Standardization of Reference Evapotranspiration. American Society of Civil Engineers, Reston

Ben-Dor E, Banin A (1989) Determination of organic-matter content in arid-zone soils using a simple loss-on-ignition method. Commun Soil Sci Plant Anal 20:1675–1695

Box GEP, Cox DR (1964) An analysis of transformations. J R Stat Soc B 26:211–252

Davies BE (1974) Loss-on-ignition as an estimate of soil organic-matter. Soil Sci Soc Am J 38:150–151

Embleton WT, Garber JM, Jones JW, Richards JS (1958) Effects of irrigation treatments and rates of nitrogen fertilization on young Hass avocado trees. IV. Macronutrient content of leaves. Proc Am Soc Hortic Sci 71:310–314

Hatton TTJ, Reeder FW (1965) Maturity of minor varieties of Florida avocados. Proc Florida State Hortic Soc 78:327–330

Havlin JL, Beaton JD, Tisdale SL, Nelson WL (2004) Soil fertility and fertilizers. An introduction to nutrient management, 7th edn. Prentice Hall, New Delhi

He ZL, Calvert DV, Alva AK, Banks DJ, Li YC (2000) Nutrient leaching potential of mature grapefruit trees in a sandy soil. Soil Sci 165:748–758

Jiao Y, Hendershot WH, Whalen JK (2004) Agricultural practices influence dissolved nutrients leaching through intact soil cores. Soil Sci Soc Am J 68:2058–2068

Kisekka I, Migliaccio KW, Dukes MD, Schaffer B, Crane JH (2010) Evapotranspiration-based irrigation scheduling and physiological response in a carambola (*Averrhoa carambola L.*) orchard. Appl Eng Agric 26:373–380

Li YC, Zhou M, Zhao J (2005) The role of chemical analysis on soil and water characterization. In: Alvarez-Benedi J, Muñoz-Carpena R (eds) Soil-water-solute process characterization: an integrated approach. CRC Press, Boca Raton, pp 503–558

Liu X, Robinson PW, Madore MA, Witney GW, Arpaia ML (1999) ‘Hass’ avocado carbohydrate fluctuations. I. Growth and phenology. J Am Soc Hortic Sci 124:671–675

McQueen JC, Minchin PEH, Silvester WB (2004) Changes in non-structural carbohydrate concentration in 1-year-old shoots of ‘Braeburn’ apple (*Malus domestica*) over two consecutive years. N Z J Crop Hortic 32:319–323

Meron M, Hallel R, Peres M, Bravdo B, Wallach R (2001) Tensiometer actuated automatic micro irrigation of apples. Acta Hortic 562:63–69

Meyer RD, Marcum DB (1998) Potato yield, petiole nitrogen, and soil nitrogen response to water and nitrogen. Agronomy 90:420–429

Migliaccio KW, Li YC, Trafford H, Evans E (2006) A simple lysimeter for soil water sampling in south Florida. http://edis.ifas.ufl.edu/AE387. Accessed 6 September 2006

Migliaccio KW, Schaffer B, Li YC, Evans E, Crane JH, Munoz-Carpena R (2008) Assessing benefits of irrigation and nutrient management practices on a southeast Florida royal palm (*Roystonea elata*) field nursery. Irrig Sci 27:57–66

Migliaccio KW, Schaffer B, Crane JH, Davies FS (2010) Plant response to evapotranspiration and soil water sensor irrigation scheduling methods for papaya production in south Florida. Agric Water Manag 97:1452–1460

Mulholland PJ, Best GR, Coutant CC, Hornberger GM, Meyer JL, Robinson PJ, Stenberg JR, Turner RE, VeraHerrera F, Wetzel RG (1997) Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrol Process 11:949–970

Muñoz-Carpena R, Li YC, Olczyk T (2002) Alternatives of low cost soil moisture monitoring devices for vegetable production in south Miami-Dade County. http://edis.ifas.ufl.edu/AE230. Accessed 13 March 2007

Nelson NO, Parsons JE, Mikkelsen RL (2005) Field-scale evaluation of phosphorus leaching in acid sandy soils receiving swine waste. J Environ Qual 34:2024–2035

Noble CV, Drew RW, Slabaugh JD (1996) Soil survey of dade county area, Florida. U.S. Dep Agric Nat Resour Conservation Serv

Núñez-Elisea R, Schaffer B, Zekri M, O’Hair SK, Crane JH (2001) In situ soil-water characteristic curves for tropical fruit orchards in trenched calcareous soil. HortTechnology 11:65–69

Paramasivam S, Alva AK, Fares A (2000) An evaluation of soil water status using tensiometers in a sandy soil profile under citrus production. Soil Sci 165:343–353

Pestana M, de Varennes A, Goss MJ, Abadía J, Faria EA (2004) Floral analysis as a tool to diagnose iron chlorosis in orange trees. Plant Soil 259:287–295

Quiñones A, Martínez-Alcántara B, Legaz F (2007) Influence of irrigation system and fertilization management on seasonal distribution of N in the soil profile and on N-uptake by citrus trees. Agric Ecosyst Environ 122:399–409

Roose E, Barthes B (2001) Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nutr Cycl Agroecosys 61: 159–170

Schaffer B (1998) Flooding responses and water-use efficiency of subtropical and tropical fruit trees in an environmentally-sensitive wetland. Ann Botany 81:475–481

Sherrod LA, Dunn G, Peterson GA, Kolberg RL (2002) Inorganic carbon analysis by modified pressure-calcimeter method. Soil Sci Soc Am J 66:299–305

Silva VPR, Campos JHBC, Azevedo PV (2009) Water-use efficiency and evapotranspiration of mango orchard grown in northeastern region of Brazil. Sci Hortic 120:467–472

Spreer W, Muller J, Hegele M, Ongprasert S (2009) Effect of deficit irrigation on fruit growth and yield of mango (*Mangifera indica L.*) in Northern Thailand. Acta Hortic 820:357–364

Yates MV, Stottlemyer DE, Meyer JL (1992) Irrigation and fertilizer management to minimize nitrate leaching in avocado production. In: Proceedings of Second World Avocado Congress. Orange, California, pp 331–335

Zhou MF, Li YC (2001) Phosphorus-sorption characteristics of calcareous soils and limestone from the southern Everglades and adjacent farmlands. Soil Sci Soc Am J 65:1404–1412