CITRUS ADVANCED PRODUCTION SYSTEM: UNDERSTANDING WATER AND NPK UPTAKE AND LEACHING IN FLORIDA FLATWOODS AND RIDGE SOILS

By

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To my wife Iness, son Atikonda, dad Simfoliano and mum Ernestina Kadyampakeni and my siblings Dominic, Honoratus, Felicity, Perpetual, Anthony, Auleria and Carnisius

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LIST OF ABBREVIATIONS

AB-DTPA	Ammonium bicarbonate-diethylenetriamine pentaacetic acid
ACPS	Advanced Citrus Production Systems
ANOVA	Analysis of Variance
ARS	Agricultural Research Service
ASWD	Available soil water depletion
BMP	Best Management Practice
CDE	Convection-Dispersion Equation
CEC	Cation Exchange Capacity
CMP	Conventional Microsprinkler Practice
CREC	Citrus Research and Education Center
CWMS	Citrus Water Management System
DM	Dry matter
DMRT	Duncan Multiple Range Test
DOHS	Drip Open Hydroponics System
DSSAT	Decision Support System for Agrotechnology Transfer
DW	Dry weight
ER	Effective rainfall
E_{sap}	Daily sapflow per unit land area
ET	Evapotranspiration
ET_o	Reference evapotranspiration
FRLD	Fibrous root length density
FW	Fresh weight

GLM	General Linear Model
GSA	Global Sensitivity Analysis
HLB	Huanglongbing
ICP	Inductively Coupled Plasma
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometry
IFP	Intensive Fertigation Practice
K_c	Crop coefficient
LAI	Leaf Area Index
LEACHM	Leaching and Chemistry Model
M1K	Mehlich 1 extractable potassium
M1P	Mehlich 1 extractable phosphorus
MOHS	Microsprinkler Open Hydroponics System
NCSWAP	Nitrogen, Carbon, Soil, Water and Plant
OHS	Open Hydroponics System
NPV	Net Present Value
RAW	Readily available water
RLD	Root length density
RZWQM	Root Zone Water Quality Model
SHB	Stem-heat balance
SWASIM	Soil Water Simulation Model
SWATRE	Soil Water and Actual Transpiration, Extended
SWFREC	Southwest Florida Research and Education Center
TAW	Total available water

TCA	Trunk cross-sectional area
TSS	Total Soluble Solids
UF	Upflux
UF/IFAS	University of Florida/Institute of Food and Agricultural Sciences
USA	United States of America
USDA	United States Department of Agriculture

Abstract of Dissertation Presented to the Graduate School
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Florida citrus production is ranked number one in the nation, accounting for 63% of the 371,700 ha production area in the U.S. California, Texas, and Arizona account for 32.5%, 3.3% and 1.6%, respectively. Citrus production in Florida has declined over the past 14 years from 342,077 ha in 1998 to 232,470 ha in 2011 largely due to increased urbanization, hurricanes, citrus canker (*Xanthomonas axonopodis)* and citrus greening (*Liberibacter asiaticus*). The uneven rainfall distribution and sandy soils make water and nutrient management extremely difficult. Thus, novel practices termed advanced citrus production systems (ACPS) using higher tree density, dwarfing rootstocks and a modified open hydroponics system (OHS) were developed to accelerate tree growth and bring young trees into production so growers can break-even within a few years of establishing a grove. Several field and laboratory experiments coupled with computer simulations were conducted to compare the performance of the intensively managed drip and microsprinkler irrigation and fertigation systems with conventional grower practices on the Florida Flatwoods and Ridge soils.

The Ridge and Flatwoods field studies revealed higher but not significantly different water uptake with ACPS/OHS compared with grower practices. However, tissue nutrient concentration was greater for ACPS/OHS than the grower practices. In addition, ACPS/OHS practices, particularly on the Ridge, increased soil nutrient retention in the root zone by 60-90% compared with conventional fertigation or granular fertilization. The soil cores indicated greater root length density for ACPS/OHS than grower practice, in the irrigated zones, and in the 0-15 cm soil layer. HYDRUS-2D model, calibrated with field and laboratory data, showed reasonably good agreements between simulated and measured values suggesting that HYDRUS-2D could successfully be used as a tool for irrigation and nutrient management decision support.

Overall, the results underline the importance of using innovative and carefully managed intensive fertigation practices in promoting tree growth and root length density, increasing nutrient and water uptake, and conserving environmental quality while sustaining high citrus yields on Florida’s sandy soils. The results from the field experiments and computer simulations should allay any fears of potential groundwater contamination associated with proper use of the ACPS/OHS practices.

CHAPTER 1
INTRODUCTION

Citrus is one of the most important crops in Florida with an annual value of $1.1 billion dollars (USDA, 2011). In 2010, Florida ranked number one in the nation for citrus production, accounting for 63% of the 371,700 ha production area in the U.S., while states of Arizona, Texas and California accounted for 6,075 ha, 12,285 ha and 120, 870 ha, respectively. At a global scale, the U.S. produced 12% of the 83 million ton world citrus production in 2010 (USDA, 2011).

Research data from several studies show that increasing water costs and environmental concerns create a need for more efficient management practices for citrus production (Lamb et al., 1999; Alva et al., 2003; Paramasivam et al., 2000a; 2001; Alva et al., 2006a, b). Irrigating to meet crop evapotranspiration (ET) demand and fertigation at optimal nutrient levels have the potential to increase production efficiency. The modifications to current irrigation water and nutrient management recommendations are termed open hydroponics system (OHS) and advanced citrus production systems (ACPS). OHS is an integrated system of irrigation, nutrition and horticultural practices that was developed in Spain to improve production on gravel based soils with low fertility (Martinez-Valero and Fernandez, 2004; Falivene et al., 2005). According to Stover et al. (2008), OHS provides tight control over water and nutrient-mediated plant growth and development using irrigation to train the root system into a limited area and fertigates with daily nutrient requirements. The ACPS is a short- to medium-term approach to citrus water and nutrient management being evaluated in Florida citrus groves for sustainable, profitable citrus production in the presence of greening and canker diseases with the goal of compressing and enhancing the citrus production cycle so economic payback can be reached in fewer years to offset some of the disease losses (Schumann et al., 2009). Elements of OHS that have been incorporated into an Advanced Citrus Production System (ACPS) include a) intensive daily fertigation with complete balanced nutrient formula for early high yields and control of shoot and root growth; 2) high density planting to enable early high yields and early return to investment, and 3) a suitable rootstock adaptable to close spacing and intensive fertigation, capable of promoting vigorous tree growth and high root density in the fertigated zone (Morgan et al., 2009b).

Muraro (2008) described the costs associated with shifting from current production systems to ACPS/OHS. The added costs to establish an ACPS/OHS with 890 trees ha^{-1} are about \$13,541 ha^{-1} more than if a block is replanted to a more typical density of 371 trees ha^{-1} owing to buying 519 additional trees ha^{-1}, planting costs, irrigation/bed preparation and young tree management (Muraro, 2008; Roka et al., 2009). However, net present value (NPV) analysis performed by Roka et al. (2009) over a 15-year horizon and a constant delivered-in price of \$1.20 per pound-solids, showed a cumulative NPV of \$7,949 ha^{-1} for 890 trees ha^{-1} planting and a negative (\$833) ha^{-1} for a 371 trees ha^{-1} planting. The higher returns from ACPS affords a grower a greater cushion against low market prices than a 371 trees ha^{-1} planting. Thus enhancing production from young trees carries two benefits: 1) sustained higher fruit yield over time, and 2) increasing net returns earlier in the cashflow stream when discount rates are relatively higher (Roka et al., 2009).

Despite these postulated notions, research studies on the effect of irrigating at various ET levels and specific NPK levels using OHS on the productivity of young citrus trees have not been adequately conducted on Florida Flatwoods and Ridge soils. This is key to understanding, in detail, interacting factors and processes that govern citrus water and nutrient uptake and movement of nutrients such as N, P and K in the citrus root zone. Also, use of the OHS for fertilizer management in citrus production on Florida soils with high percentage of sand (>85%) and low organic matter content (<2%) may further reduce nutrient leaching and subsequent pollution of groundwater.

This study hypothesizes that proper scheduling of irrigation water by drip or microsprinkler using OHS will improve water and nutrient use efficiency thus helping farmers more efficiently manage inputs in an ecologically sound manner, and attain high citrus growth and/or yields.

For optimum citrus tree growth and yield, fertilization rate and timing must be accompanied by efficient water management to avoid leaching of nutrients below the root zone thus increasing nutrient use efficiency. The research objectives of the studies in the following chapters focus on 1) improved crop growth and fertilizer use efficiency, 2) irrigation management optimization, and 3) modeling of soil-fertigation interactions with the goals of (1) realizing lower water and fertilizer use, (2) ensuring sustainable citrus yields and (3) avoiding environmental pollution associated with nutrient leaching from the citrus root-zone (Morgan and Hanlon, 2006).

Justification for Research on Citrus Irrigation and Nutrient Management in Florida

Soil Types in Florida’s Citrus Growing Regions

Most Florida citrus is grown on sandy soils that are unable to retain more than a minimal amount of soluble plant nutrients against leaching by rainfall or excessive irrigation (Obreza and Collins, 2008). Typical soil orders in the Florida citrus producing regions are Entisols on the Florida Ridge and Spodosols and Alfisols in the Flatwoods

(Figure 1-1). Entisols, found mostly in central Florida, are characterized by excessive drainage, good aeration and a deep root zone (Alva et al., 1998; Fares and Alva, 1999; 2000a, b; Morgan et al., 2006b; Fares et al., 2008; Obreza and Collins, 2008). These soils are ascribed to high hydraulic conductivity for Entisols ranging from 15-215cm h^{-1} with percentage sand $\geq$95% (Paramasivam et al., 2001; 2002; Obreza and Collins, 2008). In the Flatwoods, the Alfisols (except Winder soil series that has 85% sand) and Spodosols contain about 94-98% sand in the top 45cm making irrigation water and nutrient management extremely difficult (Obreza and Collins, 2008). Generally, these soils have low water holding and nutrient retention capacity due to the sandy soil characteristic and low organic matter and thus require use of intensive and well-managed irrigation and fertigation systems that promote high water- and nutrient-use efficiency for high citrus yields.

Climate

Citrus trees in Florida must be irrigated to reach maximum production owing to uneven rainfall distribution and low soil water-holding capacity (Morgan et al., 2006b). However, citrus irrigation and crop water requirements vary with climatic conditions and variety (Rogers and Barholic, 1976; Boman, 1994; Fares and Alva, 1999). Florida citrus water requirement is reported to range from 820 to 1280 mm yr^{-1} (Rogers et al., 1983) while 60% of the average annual rainfall (approximately 1386 mm) is distributed in the summer months of May through August (Paramasivam et al., 2001; Obreza and Pitts, 2002; Paramasivam et al., 2002). Thus, the rain is not distributed uniformly throughout the year stressing the need for supplementary irrigation.

Citrus Canker and Greening Diseases

According to USDA (2011), citrus production in Florida decreased from 386,137 ha in 1966 to 249,317 ha in 2010, as a result of increased urbanization, hurricanes, citrus canker (*Xanthomonas axonopodis)* and citrus greening (*Liberibacter asiaticus*). The latter two diseases have eliminated 10 to 30% of trees and reduced yields of other trees in some citrus groves in Florida (Gottwald et al., 2002a, b; Irey et al., 2008). In a study on the spread of citrus greening (also called Huanglongbing (HLB)) in Florida, Manjunath et al. (2008) found that 9% of plant samples from 43 different counties tested positive for *Liberibacter asiaticus.*

Citrus bacterial canker disease is a quarantine pest for many citrus growing countries (Gottwald et al., 2002a). Citrus canker occurs primarily in tropical and subtropical climates where considerable rainfall accompanies warm temperatures as is the case with Florida (Polex et al., 2007). The disease is exacerbated when wet conditions occur during periods of shoot emergence and development of young citrus fruit (Halbert and Manjunath, 2004; Polex et al., 2007). Citrus canker is mainly leaf-spotting and rind-blemishing disease characterized by defoliation, shoot dieback and fruit drop (Polex et al., 2007) and currently managed through eradication and exclusion of infected and exposed trees (Gottwald et al., 2002b).

Citrus greening (also called Huanglongbing (HLB)) is a disease caused by several species of *Candidatus* Liberibacter consisting of phloem-limited, uncultured bacteria (Zhao, 1981; da Graca and Korsten, 2004. HLB in Florida, vectored by the Asian psyllid (*Diaphorina citri*) (Zhao, 1981), mostly likely originated in China, where it was given its name because of its characteristic symptom, a yellowing of the new shoots in the green canopy (Polex et al., 2007). There is no cure for the infected trees which decline and die within a few months or years (Chung and Brlansky, 2009). The fruit produced by the infected trees is not suitable for the fresh market or juice processing due to significant increase in acidity and bitter taste (Polex et al., 2007; Chung and Brlansky, 2009). HLB bacteria can infect most citrus cultivars, species, and hybrids as well as some citrus relatives (Halbert and Manjunath, 2004). Chronically infected trees display extensive twig and limb dieback, tend to drop fruit prematurely, and are sparsely foliated with small leaves that point upward (Bove, 2006; Polex et al., 2007). HLB-infected fruits are frequently small, underdeveloped and misshapen (Polex et al., 2007). Management of HLB disease has proven to be very difficult, as a result, there are no cases of a completely successful eradication program to date (da Graca and Korsten, 2004; Halbert and Manjunath, 2004; Chung and Brlansky, 2009). Bove (2006) recommended the elimination of Liberibacteria inoculum by removing infected trees, keeping psyllid populations as low as possible through use of contact and systemic insecticides, the use of healthy material for replanting and introduction of biological control predators. Bove (2006) estimated that an orchard with 30% symptomatic trees, half of the trees are infected and will have to be pulled out sooner or later. Also, surveys conducted over an 8-year period in Reunion Island indicated that 65% of the trees were badly damaged and rendered unproductive within 7 years after planting (Aubert et al., 1996). In Thailand, citrus trees generally decline within 5-8 years after planting due to citrus greening, and yet, groves must be maintained for a minimum of 10 years in order to make a profit (Roistacher, 1996).

The use of ACPS is an attempt to help growers optimize production in the face of the impact of canker and greening diseases on tree health and yields. One strategy being proposed is the use of intensive nutrient management to accelerate tree growth and bring young trees into production so growers can break-even within a few years of establishing a grove (Stover et al., 2008; Morgan et al., 2009b; Schumann et al., 2009).

Planting Densities

In Florida, studies on citrus tree densities have been done over the years and show that high planting density produced higher yields (Castle, 1980; Whitney and Wheaton, 1984; Parsons and Wheaton, 2009) and utilized nutrients and irrigation water more efficiently (Parsons and Wheaton, 2009). However, most of the studies done in Florida used much lower densities (80-200 trees per acre) (Obreza, 1993; Obreza and Rouse, 1991; 1993; Alva and Paramasivam, 1998; Paramasivam et al., 2000b) and standard granular fertilization practice or infrequent fertigation at 112-280 kg N ha^{-1} yr^{-1} (Paramasivam et al., 2000b; 2001; 2002) than the 250 trees or more per acre and very frequent fertilization practices proposed for OHS (Stover et al., 2008; Morgan et al., 2009b; Schumann et al., 2009).

Citrus Root Length Density

Citrus root length density is a critical indicator of the potential for water and nutrient uptake. Studies on root water and nutrient uptake are better described with root length density (Morgan et al., 2006b; 2007). Several researchers observed that roots of trees grown in the Flatwoods display much stronger lateral than vertical development (Reitz and Long, 1955; Calvert et al., 1977; Bauer et al., 2004). Research on root length density (RLD) distribution has never been conducted on OHS/ACPS. The RLD data discussed in subsequent chapters will help define the potential of OHS/ACPS in promoting tree water and nutrient uptake while helping retain nutrients and water in the root zone.

Overview of the Dissertation

In view of the need for research on citrus irrigation and nutrient management to reduce the impact of greening infection in Florida, the author presents literature review on the research done on citrus irrigation water and nutrient management, placing emphasis on the novel practices termed the open hydroponic systems (OHS) and advanced citrus production systems (ACPS) in Chapter 2. The review also details methods for nutrient analysis in soil, water and plant tissue samples. The work done in several countries on irrigation design and scheduling using drip and microsprinkler systems including RLD distribution and nutrient uptake efficiencies is discussed. In the final part of the review, the author discusses the use of different models used in agriculture, specifically in citrus production and compares soil water and hydrologic models. The specific model of interest used in the study was HYDRUS 2D and is described and compared with other models used for studying water and solute transport and water uptake.

In Chapter 3, aspects of nutrient-use efficiency and nutrient distribution *in situ* are addressed using data collected over two seasons on an Entisol and a Spodosol. The soil nutrient forms of interest included 2M KCl extractable NH_4^+-N and NO_3^--N and Mehlich 1 extractable K and P. The plant tissue samples presented relate to N, P and K concentration in above- and below-ground tissues collected in July 2011 and September 2011.

The author compares the effects of irrigation and fertigation practices on citrus tree growth and root length density distribution in Chapter 4. In Chapter 4, the author presented calibration equations for root length density (RLD) estimated with the intercept and scanning methods for both Ridge and Flatwoods sites for two of the four replications at each site and validated the equations using data collected from the remaining two replicates. Detailed results on spatial, temporal and vertical root length density distribution for the trees studied are discussed comparing irrigated and non-irrigated zones for varying root diameters ranging from <0.5 mm to >3mm. Tree growth over time is described using data on trunk cross-sectional areas and canopy volumes collected over the 2 years of the study.

Chapter 5 shows the results on citrus water uptake estimated using the stem-heat balance (SHB) technique for 10 to 21 day periods over two to three seasons and the soil moisture distribution measured using capacitance probes. Critical measurements included in the SHB technique included leaf area, average hourly and daily transpiration and sapflows. The capacitance probes were calibrated gravimetrically to help estimate volumetric water content and soil moisture stress factor.

Results and discussion on the investigation of water uptake and movement and Br movement on a Florida Spodosol and Entisol using HYDRUS 2D are presented in Chapter 6. In Chapter 6, the author also describes the sorption parameters for NH_4^+-N, K and P on the Flatwoods and Ridge soils using three electrolytes: deionized water, 0.005M $CaCl_2$, and 0.01M KCl for calibrating HYDRUS-2D for solute transport. The sorption isotherms were determined for P and fertilizer mixture for NH_4^+-N, K and P for 24 h equilibration times using the selected electrolytes. Further, a discussion and results on soil water retention characteristics and hydraulic functions for representative soils for soils on the Ridge and Flatwoods are presented. The soil physical characteristics presented are critical in determining sorption behavior of the soils and parameter estimation for computer model simulations. The physical characteristics determined in the laboratory experiment included 1) bulk density, 2) saturated and unsaturated hydraulic conductivities, 3) residual and saturated moisture contents, and 4) soil moisture release curves. The HYDRUS 2D model was calibrated for water and nutrient movement with spring 2011data after sensitivity analysis using soil parameters e.g. residual and saturated moisture water content, bulk density (Obreza (unpublished data); Carlisle et al. 1989; and Fares et al. 2008), maximum rooting depth (Mattos, 2000; Bauer et al. 2004) and water stress index (Simunek and Hopmans, 2009) and validated using the results collected in-situ in June 2011 at the Flatwoods site and September 2011 at the Ridge site. The author presents a detailed procedure for sensitivity analysis and parameter estimation and discusses implications of using HYDRUS 2D as a tool for decision support. The model simulations compared the performance of the conventional practices, microsprinkler OHS and drip OHS irrigation and fertigation scenarios to determine the most effective strategy for water and nutrient management. Outputs of interest from the model included soil water content, NH_4^+, NO_3^-, P, K and Br distribution.

General Research Goals and Hypotheses

To address the general research objectives and goals listed above, the following specific research goals were conceptualized:

- Develop optimum irrigation rate, method, and timing for young citrus trees.
- Determine growth and yield effects of fertigation on young citrus trees at selected frequencies.
- Measure effect of irrigation method and frequency on rooting patterns, nutrient retention, and water and nutrient uptake.
- Calibrate HYDRUS for water and nutrient movement using site specific soil hydraulic characteristics and nutrient sorption behavior.

- Characterize HYDRUS as a possible decision support system for predicting soil moisture distribution and solute transport in the vadose zone.

The appropriate general hypotheses formulated to answer the above research goals are as follows:

- Microsprinkler and drip OHS will increase citrus growth rate, above ground biomass, fruit yield and nutrient uptake resulting in higher plant N, P and K content than the conventional practice (Chapters 3 and 4).
- Spatial nutrient and root length density distribution will be significantly greater in irrigated zones of microsprinkler and drip OHS than conventional practice (Chapter 4).
- Citrus water use and K_c increase with canopy volume and root length density in-situ irrespective of the irrigation frequency and fertigation method (Chapters 3 and 5).
- Phosphorus adsorption and NH_4^+-N and K^+ exchange on the Flatwoods and Ridge soils do not adversely affect availability and uptake (Chapters 6).
- Measured soil water content, ET, NH_4^+, NO_3^-, P, K and Br correlate positively with simulated outputs thus helping in decision support in citrus production systems (Chapters 6).

Summary

The first chapter (Chapter 1) highlights the need for further research in citrus production systems to adapt the ACPS/OHS practices in Florida through use of intensive irrigation water and nutrient management practices to improved tree growth and productivity to increase short-term citrus production. More research effort needs to be done to help growers contend with several natural and managerial scenarios outside their control namely 1) citrus canker and greening diseases, 2) uneven monthly rainfall distribution, 3) sandy soil characteristic, and 4) the need for sound environmental nutrient management practices according to USEPA specifications.

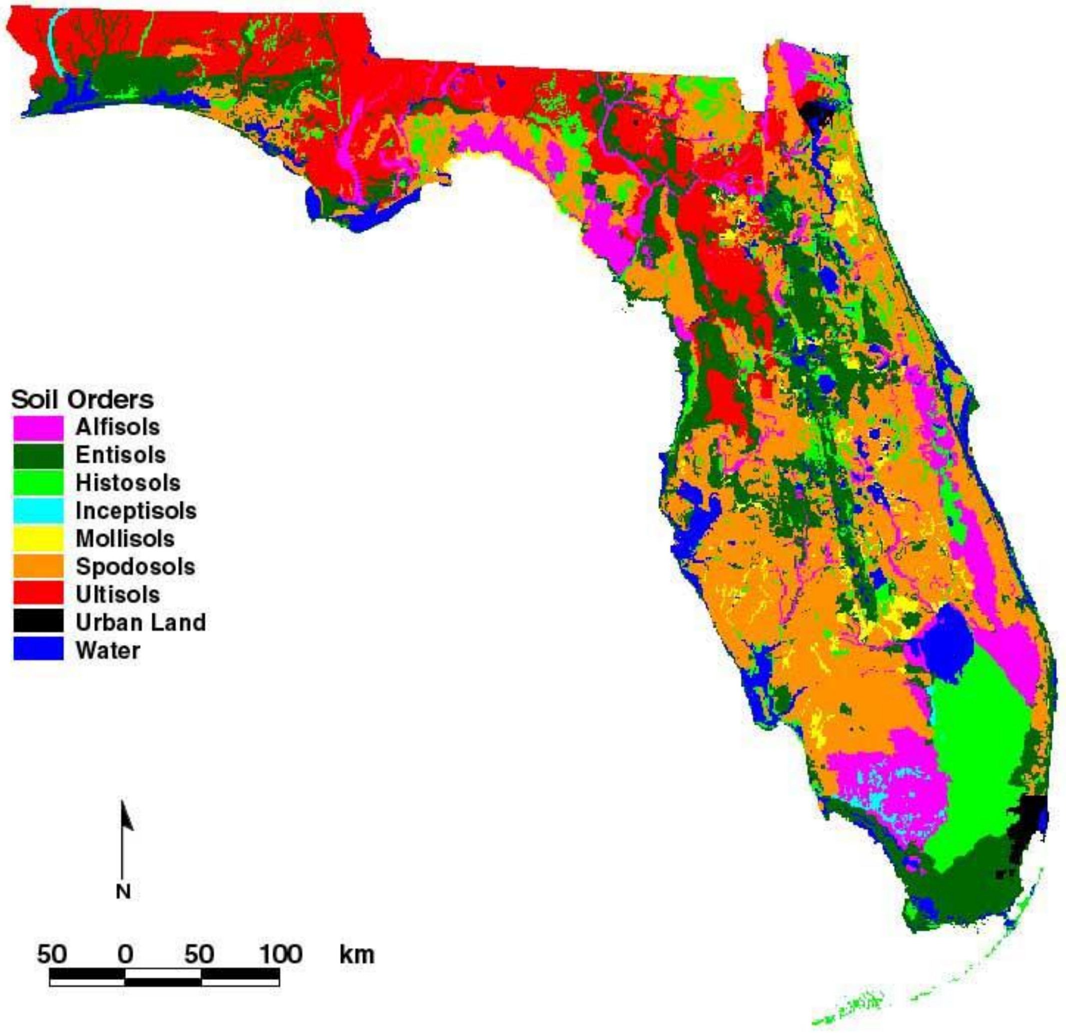


Figure 1-1. Typical soil orders of Florida (Source: K.T. Morgan)

CHAPTER 2
LITERATURE REVIEW

As defined earlier, OHS is an integrated system of irrigation, nutrition and horticultural practices that was developed in Spain to improve crop production on gravelly soils with low fertility (Martinez-Valero and Fernandez, 2004; Yandilla, 2004; Falivene et al., 2005) while ACPS is a short- to medium-term approach to citrus water and nutrient management being evaluated in Florida citrus groves for sustainable, profitable citrus production in the presence of greening and canker diseases with the goal of compressing and enhancing the citrus production cycle so that economic payback can be reached in fewer years to offset some of the disease losses (Schumann et al., 2009). OHS aims to increase productivity by continuously applying a balanced nutrient mixture through the irrigation system, limiting the root zone by restricting the number of drippers per tree and maintaining the soil moisture near field capacity (Falivene, 2005). The combination of these practices is claimed to provide a greater control and manipulation of nutrient uptake at specific crop physiological stages and improved water uptake (Yandilla, 2004). OHS has been successfully used in the production of peaches, almonds, grapes, citrus, avocados and several vegetable crops in Spain, Australia, South Africa, Chile, Argentina, Morocco and California (USA) (Boland et al., 2000; Kruger et al., 2000a, b; Pijl, 2001; Kuperus et al., 2002; Schoeman, 2002; Carrasco et al. 2003; Martinez-Valero and Fernandez, 2004; Falivene et al., 2005; Sluggett et al., unpublished). In South Africa, commercial growers have adapted the OHS through use of drip fertigation on daily basis during daylight hours (Pijl, 2001; Schoeman, 2002) resulting in increased citrus yield and fruit size (Kruger et al., 2000a, b; Kuperus et al., 2002). OHS was introduced in Australia as an intensive fertigation practice (IFP) in citrus orchards (Falivene et al., 2005) that uses similar principles to OHS but is less intensive. Carrasco et al. (2003) in Chile found that cauliflower and cabbage grown in soil-less media with hydroponics resulted in higher growth rate and dry matter yield than those grown in soil with traditional horticultural management. They attributed the lower yields of the cabbage and cauliflower grown in the soil media to reduction in water and nutrient uptake compared with transplants that were grown using traditional hydroponics. Jones (1997) described in detail the use of hydroponics in the USA and early principles applied to this relatively new technology.

This chapter 1) reviews current open hydroponics system (OHS) management practices utilized in selected citrus producing countries around the world, 2) estimates citrus biomass accumulation and fertilizer demand in citrus, 3) describes practices for improved water and fertilizer use efficiency, 4) discusses microsprinkler and drip irrigation system design and scheduling, 5) explains root distribution in response to soil water and 6) describes various types of process-oriented models for solute transport, water and nutrient uptake.

The Open Hydroponic System and Advanced Production Systems

Concepts

Maximize water and nutrient efficiency

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

Concentrate roots in irrigated zone

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

Reduce nutrient leaching

Many researchers have attempted to study nutrient leaching to sustain environmental quality. Paramasivam et al. (2001) found that nitrate-nitrogen leaching losses below the rooting depth increased with increasing rate of N application (112 to 280 N ha^{-1} yr^{-1}) and the amount of water drained, and accounted for 1 to 16% of applied fertilizer N. Paramasivam et al. (2001) noted that the leached nitrate-nitrogen at 240 cm remained well below the maximum contaminant limit of 10 mg L^{-1}. They ascribed their observations to careful irrigation management, split fertilizer applications and proper timing of the application. Thus, it should be possible to reduce nutrient leaching with an OHS and/or IFP because in both scenarios water and nutrients are applied in correct quantities and close to the plant with less waste (Mason, 1990; Jones, 1997) and, at specific physiological stages of the plants (Harris, 1971).

Applications of OHS in view of Florida's soil types and current BMPs

Paramasivam et al. (2002) used the Leaching and Chemistry Model (LEACHM) to show that 50% of water applied through rainfall and irrigation drained beyond the root zone. Thus, Entisols require carefully planned and frequent irrigation scheduling during dry periods (Fares and Alva, 1999; Morgan et al., 2006b; Obreza and Collins, 2008) due to the inherent low water holding capacity of about 0.025 - 0.070cm^3 cm^{-3} (Obreza et al., 1997; Morgan et al., 2006b; Obreza and Collins, 2008), and low organic matter content typically in the range of 0.5 to 1% (Obreza and Collins, 2008). Alfisols and Spodosols are poorly drained due to the presence of restrictive layers below the top and subsoil, respectively called, argillic and spodic horizons that lie at about 30 to 200 cm from the soil surface (Reitz and Long, 1955; Obreza and Admire, 1985; Obreza and Collins, 2008). The Alfisols and Spodosols have higher water holding capacity (particularly the Alfisols, with a water holding capacity ranging from 0.025 to 0.100 $cm^3 cm^{-3}$) and natural fertility (with cation exchange capacity (CEC) ranging from 2-18 cmol(+) kg^{-1}) compared with the Entisols (with CEC ranging from 2-4 cmol(+) kg^{-1}) due to the presence of a high water table (Obreza and Pitts, 2002) and higher organic matter (typically ranging from 0.5-3%) (Obreza and Collins, 2008). In the Flatwoods, the soils require a combination of bedding and collector ditches for drainage (Boman, 1994; Obreza and Admire, 1985; Obreza and Pitts, 2002). However, the Alfisols (except Winder soil series that has 85% sand) and Spodosols contain about 94-98% sand in the top 45cm making irrigation water and nutrient management extremely difficult (Obreza and Collins, 2008). Thus, the use of OHS/ACPS needs to consider the unique soil and ecological characteristics for efficient water and nutrient management for high citrus production.

The current best management practices (BMPs) were developed based on low volume micro-sprinkler irrigation systems (Lamb et al., 1999; Alva et al., 2003) and conventional fertilizer application practices (Obreza and Rouse, 1993; Alva and Paramasivam, 1998; Thompson and White, 2004). Yet, in countries such as Australia and South Africa, the practices have been adapted through use of intensive and advanced fertigation methods using drip irrigation (Slugget, unpublished; Prinsloo,

2007) to conform to the requirements of OHS. Thus, there is need to modify the current BMPs in the light of intensive fertigation practices that go with OHS in order to effectively sustain high yields in citrus groves and prevent nutrient leaching to groundwater. In Florida, citrus groves are established in the Flatwoods on poorly to very poorly drained Spodosols and Alfisols with a shallow water table (Obreza and Collins, 2008) and on the central Ridge on moderately to excessively well drained Entisols (Reitz and Long, 1955; Obreza and Collins, 2008). Thus, BMPs and nutrient management decisions devised for OHS must take into account these ecologically different zones.

Tree density

Martinez-Valero and Fernandez (2004) provide yield results of some orchards using OHS in Spain in which Nova, Marisol and Delite mandarins were planted at high density (405 trees per acre). Yields in the sixth year were about 65 to 75 tons per hectare which is higher than a conventional orchard using low to medium density plantings (150 to 230 trees per acre) (Falivene et al., 2005). Robinson et al. (2007) published results of planting densities ranging from 340 to 2178 trees per acre in New York. They found that the optimum economic density was between 1000-1200 trees per acre which is more than double the planting density proposed by Martinez-Valero and Fernandez (2004). The optimum density achieved improved yield and quality coupled with lower costs of production. Thus, there is a possibility of increasing yield per unit area using ACPS/OHS with densely planted orchards.

Tree size control with rootstocks

Rootstock selection along with tree planting is a key management element in the ACPS/OHS approach to the future. Citrus trees also require a certain amount of space to develop and flourish. When the allocated space is fixed, e.g. 1 acre of land, tree size becomes critical because the productive unit is the canopy and only a certain volume of canopy can be grown on 1 acre. Vigorous, large trees are neither compatible with close spacing nor productive in their younger years. Thus, in a world of economic necessity dictated by early and robust returns, small, closely spaced trees become a required component of the new production concepts. Groves of closely spaced trees on vigorous to size controlling rootstocks have been extensively researched, but have had no commercial implementation in Florida (Morgan et al., 2009b; Schumann et al., 2009). From the research, it is apparent that proper matching of tree size with spacing and site conditions is critical for success. When that combination is achieved, the higher density grove will outperform the more conventional one especially in the early years. In Florida, the conventional grove is spaced about 15 x 25 ft (116 trees/acre), the modern grove is at 10 x 20 ft (218 trees per acre), and the higher density grove would be about 8 x 15 ft (363 trees per acre) (Morgan et al., 2009b).

Fertilizer Demand and Nutrient Uptake in Citrus

Biomass Development with Time

Tree growth and development change with time due to variable distribution of dry matter in both above- and below-ground tree components due to the growth of larger branches and trunks of older trees to support increased tree biomass (Richards, 1992; Morgan et al., 2006b). Mattos et al. (2003a, b), studying the six-year-old Hamlin orange tree [*Citrus sinensis* (L.) Osb.] on Swingle citrumelo rootstock [*Poncirus trifoliata* (L.) Raf. x Citrus paradise Macfad.], showed the following proportions of biomass distribution: fruit=30%, leaf=10%, twig=26%, trunk=6%, and root=28%. The biomass distribution in other citrus cultivars is described in Table 2-1 (Cameron and Appleman, 1935; Cameron and Compton, 1945; Feigenbaum et al., 1987; Quiñones et al., 2003a; 2005; Morgan et al., 2006a). Morgan et al. (2006a), for example, showed that the percent biomass distribution in 14-year-old Hamlin oranges in Florida on Carrizo and Swingle rootstocks, grown on Candler fine sand ranged from 12-13% in leaves, 52-61% in branches, twigs and the trunk, and 27-33% in the roots. In another study in Israel on 20-year-old Shamouti oranges, percent biomass distribution ranged from 6-7% in leaves, 55-56% in branches, twigs and trunk, 8-13% in fruits and 24-31% in roots (Feigenbaum et al., 1987). Quiñones et al. (2003a; 2005), studying eight-year-old Navelina orange trees in Spain under flood and drip irrigation systems on sandy-loamy soil, found similar biomass distribution pattern in roots but noted higher biomass in leaves (13-16%) and fruits (21-27%), and lower biomass in branches (29-34%) compared with values reported by Feigenbaum et al. (1987).

Earlier work on biomass distribution in 3.5- and 10-year-old Valencia oranges was done in California (Cameron and Appleman, 1935; Cameron and Compton, 1945). In these early studies on biomass distribution on 3.5-year-old Valencia oranges, 31% of the biomass was found in both roots and leaves while the remaining biomass was accounted for in bark and woody tissues such as branches and the trunk (Cameron and Appleman, 1935). Contrasting results were noted on bearing 10- and 15-year-old Valencia oranges where percent biomass distribution was approximately 18% in leaves, 61% in trunk and branches while 21% of the biomass was allocated to the below-ground portion (Cameron and Appleman, 1935; Cameron and Compton, 1945).

The accumulation of dry matter (DM) by various components of developing tamarillo (*Cyphomandra betacea*) was investigated by Clark and Richardson (2002).

They found that percent DM accumulation in years 2 and 3 were 21 and 22% in roots, 37 and 33% in the stem, 23 and 15% in branches, 8% in leaves (both years), and, 12 and 13% in fruits. Richards (1992) studied the Cashew (*Anacardium occidentale*) tree nutrition as related to biomass accumulation, nutrient composition and nutrient cycling in sandy soils of Australia at 0-12, 12-40 and 40-70 months after planting. He observed that the tops accounted for 75% of dry weight, with roots <20%, except at 12 months. Cashew apple and nuts account for <10% of tree total DM.

Barnette et al. (1931) studied the biomass and mineral distribution of a 19-year-old Marsh seedless grapefruit tree in Florida. They found that out of 273 kg dry weight per tree, the biomass distribution was as follows: fruits=3%, leaves =6%, roots=34% and, trunk and branches=57%.

Nutrient Requirements for Biomass and Fruit Production

Nutrient application rates for the majority of OHS and intensive fertigation practice (IFP) in citrus can be about 20% to 50% higher than conventional practices (Falivene et al., 2005). OHS and IFP use a more intensive nutrition program with the goal of pushing trees into a higher level of vigor and productivity requiring higher nutrient application rates to maintain production. However, studies on fertilization practices on citrus in Florida have shown mixed results. Previous studies on citrus nutrient management have shown that proper nutrient placement and timing (Koo, 1980; Koo et al., 1984a; Obreza and Rouse, 1993; Obreza et al., 1999; Kusakabe et al., 2006; Obreza and Tucker, 2006), application rate and frequency (Koo, 1980; Tucker et al., 1995; Lamb et al., 1999; Paramasivam et al., 2000b; Mattos et al., 2003a, c; Tucker et al., 2006;) and fertilizer application method (Alva et al. 2003; 2006a, b) can substantially affect nutrient uptake, yield, yield quality and environmental quality in citrus. Obreza and Rouse (1993) showed that an increase in fertilizer rate resulted in a decrease in total soluble solids concentration and total soluble solids to acid ratio. Also, Koo and Smajstra (1984) made similar observations using trickle irrigation and fertigation on 26-year old ‘Valencia’ orange on an Astatula fine sand in Florida. Furthermore, Koo (1980), in trials on sandy soil, found no significant differences due to fertigation frequencies (3 or 10 times a year) on 13-year old ‘Valencia’ orange. Similarly, Syversten and Jifon (2001) studied fertigation in 6-year old ‘Hamlin’ oranges in Florida at 12, 37 and 80 times per year and found that fertigation frequency did not affect leaf nutrient concentration, canopy size, fruit yield or juice quality. Schumann et al. (2003) compared fertilizer application rates and methods for Hamlin oranges on Candler fine sand in central Florida. In the study, Schumann and co-workers showed that fertigation (applied 15 times) was superior to dry granular fertilization (applied in four splits) and control release fertilizer (applied once every fall) where optimal soluble solids concentration was obtained at 145, 180 and 190 kg N ha^{-1} and optimal fruit yields was realized at 138, 160 and 180 kg N ha^{-1} for fertigation, dry granular fertilization and control release fertilizer, respectively. Fertigation resulted in 22-45 kg N ha^{-1} savings per year with leaf concentrations significantly higher per unit of N applied for fertigation>dry granular fertilizer>control release fertilizer, confirming the efficiency of fertigation practice with respect to optimal nutrient placement in the root zone and temporal distribution over the season.

Morgan et al. (2009a) studied the effect of fertigation (4 or 30 times annually), dry granular fertilization (applied in four splits) and control release fertilizer (applied once in February) on 1-5 yr-old ‘Ambersweet’ orange trees. Nitrogen rate by application method data showed that critical values of minimum N rates required to reach canopy volume plateau were 182, 198 and 199 kg ha^{-1} for fertigation (30 times annually), control release fertilizer and fertigation (4 times annually), respectively, representing canopy volumes of 8.4, 7.6, and 7.9 m^3. The more frequent fertigation practice produced larger trees with lower annual rates compared with both control release fertilizer and fertigation (4 times annually). Morgan and colleagues also noted reduced yield and tree size at higher dry granular fertilization rates suggesting improved nutrient use efficiency of trees fertilized by control release fertilizer and fertigation (30 times annually). Root injury observed under dry granular fertilization was ascribed to salt burn from excessive fertilizer distributed over a small area. For maturing trees (6-10 years), Morgan et al. (2009a) observed that citrus root systems were equally effective in capturing available N from frequent small fertilizer application (fertigation 30 times annually) or from 4 much larger applications. They concluded that more frequent applications should result in increased fertilizer-use efficiency and likely promote tree growth, albeit, little increase in fruit yield may be obtained in mature citrus.

Tucker et al. (1995) and Alva et al. (2006c) recommended K rate for optimal production of bearing citrus trees ($\geq$4 years) in the range of 112-186 kg ha^{-1} for orange trees and 112-150 kg ha^{-1} for grapefruit trees. Alva et al. (2006c) observed that there are no consistent research results to make definitive conclusions on potential differences between the dry granular, controlled release, or fertigation methods of K. They also described K concentration in 4- to 6-month-old non-fruiting citrus trees in the range of 12-17 g kg^{-1} as optimal for Florida citrus. A corollary method in some citrus producing parts of the world like South Africa and Brazil, nutritional status of the tree is determined using leaf analysis of fruiting terminals with optimal K status ranging 10-15 g kg^{-1}. Tucker et al. (1995) recommended a minimum of 3 split applications for dry granular fertilizer and 10 times for fertigation practices. Tucker et al. (1995) recommended 120-240 g K $tree^{-1}$ yr^{-1} (year 1), 240-480 (year 2) and 370-740 (year 3) for non-bearing citrus trees. Criteria for selecting a rate within the recommended range include history of fertilization in the tree nursery, soil type, land history, and fertilizer placement.

In other regions such as Arizona, Kusakabe et al. (2006) evaluated the response of 3- to 6-yr-old microsprinkler-irrigated ‘Newhall’ navel orange trees to various N rates and fertigation frequencies on coarse sand. In the study, Kusakabe and colleagues concluded that the maximum fruit yield of the trees occurred at N rates of 113 g N $tree^{-1}$ for the fourth, 105 g N $tree^{-1}$ yr^{-1} for the fifth, and 153 g N $tree^{-1}$ yr^{-1} for the sixth growing season under the maximum fertigation rates (27 fertigations). The effect of timing of fertilizer application and irrigation system on nutrient use- efficiency was investigated in Spain (Quiñones et al., 2005). Quiñones et al. (2005) concluded that drip irrigation together with extensive splitting up of the N dosage may be the appropriate system for the N fertilization management in citrus as it offers greater fertilizer use efficiency, smaller accumulations of residual nitrates in the soil, and 15% reduction in the amount of water applied, without impairing fruit yield and its commercial quality.

Tucker et al. (1995) suggest P reduction or omission in fertilizer if soil test results indicate sufficient residual P. They observed that fertilizer applications in a number of doses generally increase nutrient uptake efficacy by providing available nutrients within the root zone over prolonged growing period and by reducing leaching that occurs due to excess rainfall and/or irrigation. Dry granular fertilizer may be applied in 4-6 doses during annual growing period, while liquid fertilizer could be split in 10-30 applications. Control release fertilizer can be applied at a reduced frequency as preplant treatment, incorporated after planting, or broadcast to insure uniform distribution of nutrients throughout the enlarging root zone of young trees (Tucker et al., 1995).

However, different scion and rootstock combinations respond differently to fertilization. For example, Mattos (2000) and Mattos et al. (2003a, b) showed that response of orange cultivars to P fertilization is great for trees on ‘Cleopatra mandarin’ compared with either ‘Swingle citrumelo’ or ‘Kangpur lime’. Likewise, response of young bearing orange trees to K is more significant for trees grafted on ‘Swingle citrumelo’ rootstock compared with that of trees on ‘Rangpur lime’ root stock. Also, Lea-Cox et al. (2001) demonstrated that same age of grapefruit trees on Volkamer lemon were larger than trees on sour orange rootstock and dry weight distribution of tree parts was affected by N fertilization and soil condition.

From various studies, N, P and K nutrient distribution is mainly concentrated in the leaves or fruits and roots (Cameron and Appleman, 1935; Cameron and Compton, 1945; Legaz et al., 1982; Dasberg, 1987; Feigenbaum et al., 1987; Legaz et al., 1995; Mattos et al., 2003a, b; Quiñones et al., 2003a, b; 2005; Morgan et al., 2006a) (Table 2-2). Earlier work of Alva and Paramasivam (1998) and Paramasivam et al. (2000c) also showed predominance of N, P and K in fruits and leaves. In fruits, Alva and Paramasivam (1998) reported nutrient ranges for N (0.08-1.22%), P (0.14-0.15%) and K (1.17-1.23%) for four citrus varieties namely: Hamlin, Parson Brown, Valencia, and Sunburst. Also Paramasivam and colleagues (2000c) showed leaf concentrations of N

(27.4-29.3 g kg^{-1}), P (1.3-1.4g kg^{-1}) and K (8.5-15.1 g kg^{-1}) for the same varieties presented by Alva and Paramasivam (1998). Recent research showed nutrient concentrations in leaves and fruits of >4-year-old Tahiti acid lime in Brazil (Mattos et al. 2010). Leaf N ranged from 14.7-23.1 g kg^{-1}, while K varied from 11.2-17.1 g kg^{-1}. Mattos and colleagues found N and K values in the range of 7.5-14.5 g kg^{-1} and 12.0-17.2 g kg^{-1} in fruits. Legaz et al. (1995) studied the mobilization of N from reserve organs (leaves, roots, branches and trunk) to developing organs at different moments of the growing cycle in three-year-old Valencia Late orange trees on siliceous sand in Spain. Legaz and colleagues found highest amounts of N in leaves and roots (33-42% and 30-38%), respectively.

Alva et al. (2003) proposed a combined use of foliar fertilizer application and fertigation as the best management practice (BMP) for N because these were effective in reducing nitrate leaching to surficial groundwater. Nevertheless, the practices in the studies above are less intensive than a typical OHS in which 3 or more irrigations per day can be achieved (Falivene et al., 2005).

More recently, novel, intensive fertigation methods termed Advanced Citrus Production Systems (ACPS), are being tested in citrus production systems on Florida’s sandy soil soils (Stover et al., 2008; Morgan et al., 2009b; Roka et al., 2009; Schumann et al., 2009). Preliminary results by Schumann et al. (2009) showed the benefits of ACPS on <1-yr-old Hamlin oranges on swingle and C-35 rootstock grown on a Candler fine sand. Leaf nutrient concentrations for leaves sampled in 2009 had high, non-limiting N concentrations (>3%). Additionally, N fertilizer applications were lower per tree relative to the benchmark N fertilizer applied, lower for drip (13%) and microsprinkler

(20%) fertigation treatments than conventional grower practice (100%). They concluded that the high nutrient and water-use efficiencies possible with an ACPS in young planted citrus could improve overall profitability by reducing production costs and sustaining environmental quality. However, Schumann et al. (2009) noted that the possible limitation to successful implementation of ACPS/OHS in Florida include a unique combination of sandy soils and the distribution of more than half the high annual rainfall in the summer months, consequently, resulting in root growth in the nonirrigated zone.

Nutrient Uptake and Nutrient Use Efficiency

Citrus Nutrient Management

In a study on Best Management Practices (BMPs) for N and P, Thompson and White (2004) noted that adequate supplies of N are necessary to optimize yields of young citrus trees. They reported higher nutrient-use efficiency with micro-irrigated citrus resulting in leaf N above the critical concentration of 2.5% when using surface irrigation. Thompson and White (2004) called for optimal levels of N and irrigation for optimal growth and yield. In a study on the growth response of young 'Hamlin' orange trees to N-P-K fertilizer rates under field conditions in southwestern Florida, Obreza and Rouse (1993) found that an increase in fertilizer rate resulted in a decrease in total soluble solids (TSS) concentration in juice and the TSS : acid ratio, but weight per fruit and TSS per tree increased. Several citrus fertilization experiments from other parts of the world indicate that an annual application of about 200 kg N ha^{-1} is sufficient to sustain optimal tree growth, and maintain high production (Dasberg, 1987). One of the options for improved citrus growth and yield is improved management of water and nutrient systems. Maximization of nutrient uptake efficiency and minimization of nutrient losses is a function of the rate, placement and timing of nutrient application (Saka, 1984; Alva and Paramasivam, 1998; Quiñones et al., 2007). Zekri and Obreza (2003) observed that fertilization represents a relatively small percentage of the total costs of citrus production, but it has a large effect on potential profitability. Analyses of leaves and soil can be used to evaluate nutritional status of trees and nutrient availability in the soil to supply the trees nutrient requirement (Embleton et al., 1956; Alva and Paramasivam, 1998; Obreza et al., 1999). N is the key component in mineral fertilizers applied to citrus groves and has more influence on tree growth and appearance than any other element. N affects the absorption and distribution of all essential nutrients (Zekri and Obreza, 2003).

Quiñones et al. (2003a) found that N uptake efficiency of the whole citrus tree was higher with drip irrigation (75%) than with flooding system (64%) showing that drip irrigation system was more efficient for improving water use and N uptake from fertilizer. This suggests that optimum nutrient management must take into account baseline information on the initial or residual soil nutrient composition of key elements such as N, P and K. For citrus, K is important to yield, fruit size, and juice quality (Obreza and Morgan, 2008) such that its deficiency reduces fruit number, increases fruit creasing, plugging and drop and decreases juice soluble solids, acids and vitamin C content.

Extraction Methods for N-Forms, P, and K from Soils and Plant Tissue

Soil analysis is useful in formulating and improving a fertilization program over several consecutive years so that trends can be observed. Soil testing is particularly useful for P (as shown in Table 2-3 and has no practical value for readily leached like N and K (Obreza et al., 2008a) because in many humid regions where annual precipitation exceeds evapotranspiration, leaching and denitrification reduce profile NO_3^--N and K to levels often unreliable in fertilizer recommendation (Havlin et al., 2005; Obreza et al., 2008b). Most recommendations call for soil testing about 3 years, with more frequent testing on sandy soils to determine whether the nutrient management program is adequate for optimum productivity. For instance, if soil test P is decreasing P application rate can be increased. If soil test P has risen to satisfactory level, application may be reduced to maintenance rates (Havlin et al., 2005).

Havlin et al. (2005) recommends the use of Bray-1 and 2 P and Mehlich-3 P extraction on acid and neutral pH soils. A Mehlich-1 soil test is useful in regions with more highly weathered, low- cation exchange capacity (CEC) soils. The Olsen-P soil test is used in neutral and calcareous soils (Havlin et al., 2005). Bray-1 and Mehlich P tests extract similar quantities of P while the Olsen P test extract about half as much P. The quantity of P dissolved by the extractants is calibrated with crop response. Sato et al. (2009c) collected soils from southwest Florida and compared available P levels by five different soil testing methods (Mehlich-1, Mehlich-3, Olsen, Bray-1, and ammonium bicarbonate-DTPA). They observed that within a surface soil pH range of 6.4 and 8.6, correlation coefficients between available P by Mehlich-1 and those by other 4 methods ranged from 0.61 and 0.73 ($p < 0.001$). Compared with Mehlich-1 method, all other 4 methods extracted less amounts of available P (59%, 22%, 51%, and 25% with Mehlich-3, Olsen, Bray-1, and AB-DTPA, respectively).

Alva (1993) compared methods for extraction of nutrient elements including P and K from the soil. He found that K extractable by Mehlich-3 was significantly correlated to extractions by either Mehlich-1 (r^2=0.95), ammonium acetate (AA) (r^2=0.95), ammonium chloride (r^2=0.97) or ammonium bicarbonate-DTPA (AB-DTPA) (r^2=0.96) extractants. In the study, Mehlich-3 P significantly correlated with Mehlich-1 only (r^2=0.65). Extractable

P correlation between Mehlich-3 versus AB-DTPA was weak (r^2=0.18), non-significant for Mehlich-3 vs AA and Mehlich-3 vs ammonium chloride. This was corroborated by earlier findings by Sartain (1978) who suggested that Mehlich-1 extractant solubilizes some of the calcium phosphate compounds which are not solubilized by ammonium acetate. The work by Elrashidi et al. (2001) also showed that Mehlich-3, Bray-1, or Mehlich-1 (double-acid) were a good test for P concentration in water and soil.

BarYosef and Akirir (1978) found that $NaHCO_3$ extraction is capable of providing simultaneously availability indices for NO_3-N, P, and K. The caveat for K with this extraction method is that it applies only when exchangeable K in the soil is greater than a given fraction of CEC of the soil. In a comparison of mechanical vacuum extraction with batch extraction method for estimation of CEC in soils, Huntington et al. (1990) found that the precision of the two methods was equivalent. The two extraction methods can be used for CEC estimation with consistently similar results.

Obreza et al. (2008b) explained the value of leaf tissue and soil analysis in determining fertilizer programs that increase fertilizer efficiency while maintaining maximum yields and desirable fruit quality in citrus. Leaf tissue analysis is used for quantitative determination of the total mineral nutrient concentrations in the leaf. It is very useful in testing for N, P and K sufficiency. Guidelines for interpretation of tree leaf analysis are described by Koo et al. (1984b), Obreza et al. (1999) and Obreza and Morgan (2008) in Table 2-4.

Anderson and Henderson (1986; 1988) compared four methods for elemental analysis of plant tissues. The methods included sealed chamber digestion method, dry ash combustion, nitric/perchloric acid wet ash digestion, and sulfuric acid/hydrogen peroxide wet ash digestion. They recommended the use of the former three methods whose use is dependent upon the preference of the user and availability of equipment. Sulfuric acid/hydrogen peroxide wet ash digestion appeared to give the poorest overall chemical analyses. Plank (1992) also indicated that nutrient content in the digests could be determined by Inductively Coupled Plasma (ICP). The plant nutrient uptake values (expressed as kg ha^{-1}) could be obtained as the product of concentration (mg kg^{-1} plant) and dry matter yields (kg plant ha^{-1}).

Irrigation Design and Scheduling-Drip and Microsprinkler Irrigation

Evapotranspiration Calculations

Citrus evapotranspiration (ET), like for any particular crop, is limited by atmospheric demand, crop development stage, and available soil water content (Morgan et al., 2006b; Fares et al., 2008). It is estimated from daily reference evapotranspiration (ET_o) using the following equation:

$$ET_c = ET_o * K_c * K_s \tag{2-1}$$

Where ET_c is crop evapotranspiration (mm d^{-1}); ET_o is potential evapotranspiration (mm d^{-1}); K_c is the crop coefficient and K_s is the soil water depletion coefficient, which is also called the water stress function (Allen et al., 1998; Obreza and Pitts, 2002; Morgan et al., 2006b; Fares et al., 2008). The crop coefficient is defined as the ratio of ET_c to ET_o when soil water availability is nonlimiting, and thus, is proportional to atmospheric demand and plant development stage (Morgan et al., 2006b; Fares et al., 2008). Accurate estimation of citrus ET is important in determining irrigation requirement (IRR, mm) calculations. Irrigation requirements for a particular crop are calculated as follows:

$$IRR = ET_c + \Delta S - (UF+ER) \tag{2-2}$$

Where IRR (mm) is the irrigation requirement, ER (mm) is effective rainfall, ΔS (mm) is change in root zone soil water storage and UF (mm) is upward flux from the water table (if present) due to capillary rise. In the deep, well-drained sandy soils of central Florida, UF is negligible (Fares et al., 2008) but is a critical factor in the poorly drained Flatwoods of southwest Florida (Obreza and Pitts, 2002).

Allen et al. (1998) explained that for most soils, a value of soil moisture content (θ) less than field capacity (θ_{FC}) exists where water uptake is not limited by soil water potential (Φ). The range of θ above a critical threshold value (θ_t) is referred to as readily available water (RAW), and used it to estimate K_s as the ratio of remaining available soil water to soil water that is not readily available (Allen et al., 1998; Morgan et al., 2006b):

$$K_s = \frac{(\theta - \theta_{WP})}{(\theta_t - \theta_{WP})} \tag{2-3}$$

where K_s is soil water depletion coefficient ($K_s \leq 1$); θ_{FC} - θ_{WP} is total available water (TAW) ($cm^3\ cm^{-3}$); θ_{WP} is permanent wilting point soil water content ($cm^3\ cm^{-3}$); θ is soil water content ($cm^3\ cm^{-3}$); θ_{FC} is field capacity soil water content ($cm^3\ cm^{-3}$); θ_{FC} - θ_t is readily available water (RAW) ($cm^3\ cm^{-3}$) (Allen et al., 1998; Morgan et al., 2006a).

Daily ET_c of young citrus trees measured during the 1996 and 1997 cropping seasons were from 1.9 to 2.0 mm (Fares and Alva, 1999) and from 1.87 to 3.13 mm (Fares and Alva, 2000), respectively. For mature citrus, daily ET_c ranged from 2.25 to

3.52 mm (Rogers et al., 1983). However, reference ET_c for mature citrus was found to vary from 1.4 mm day^{-1} in December to 4.9 mm day^{-1} in May (Morgan et al., 2006b; Fares et al., 2008). Based on the studies conducted over the years in Florida, ET appears to be low from November to March and peaks from April to October.

Citrus Crop Coefficients

K_c is defined as the ratio of crop evapotranspiration (ET_c) to potential evapotranspiration (ET_o) when soil water availability is non-limiting and is a function of crop type, climate, soil evaporation and crop growth stage (Allen et al., 1998; Morgan et al., 2006b; Fares et al., 2008). Several studies estimated that K_c values of citrus trees range from 0.6 in the fall and winter to 1.2 in the summer (Boman, 1994; Martin et al., 1997; Fares and Alva, 1999; Morgan et al., 2006b). Jia et al. (2007) found that K_c values may vary from location to location. For example, they found that annual average K_c values were higher for the citrus grown in the Ridge regions (K_c =0.88) than for the Flatwoods (K_c = 0.72) in Florida, with monthly recommended values ranging from 0.70 to 1.05 for the ridge and from 0.65 to 0.85 for the Flatwoods citrus, respectively. They attributed the differences to water logging in the root zone of the Flatwoods citrus owing to water table due to the presence of the spodic and/or argillic horizon.

Water Use Efficiency

Michelakis et al. (1993), studying avocado water use in a Mediterranean climate in Greece under drip irrigation, found that root percentage was generally higher in the upper 50cm soil layers and within 2 m from the drip line, where about 70-72% of the roots were located. They attributed the higher root percentage in the upper soil layers to biological factors and to the higher oxygen diffusion rate. In the study Michelakis et al. (1993) applied irrigation water to each treatment using one drip lateral per row of trees with drippers of 4 l h^{-1} discharge rate placed 70cm apart. Coleman (2007) also observed that root length density in cottonwood, American sycamore, sweetgum and loblolly pine was dependent upon depth and position relative to drip emitter when fertilizers were applied and is greatest at the surface and in proximity to the drip line. The factors controlling root length density in the woody species studied included age, depth and proximity to the drip emitter. Partial soil wetting under drip irrigation generally leads to many agronomic benefits such as water and labor saving (Keller and Karmeli, 1974). However, the extent of the wetted soil volume is a function of the emitter discharge and spacing but depends mainly on the soil type and the total water added (Warrick, 1986). High water use-efficiency and water savings using high frequency drip and microsprinkler irrigation systems have also been reported in recent studies in Spain (Quiñones et al. 2003; 2005), California, USA (Bryla et al., 2003; 2005), Florida, USA (Zotarelli et al., 2008a, b; 2009a, b; Kiggundu et al., 2011), Malawi (Fandika et al., 2012) and Australia (Phogat et al., 2011). The principles underlying the restriction of the roots to the wetted zone using drip irrigation are also applicable to OHS.

Bromide as a Tracer for Water Movement in the Soil

Bromide is one of the conservative anions generally applied to soils to trace water and solute movement in the soil. Köhne and Gerke (2005) studied preferential Br^- movement in the soil. They found that Br^- was transported during physical equilibrium conditions, except for conditions of heavy rainfall that triggered preferential flow involving physical non-equilibrium. Afyuni and Wagger (2006) also conducted an experiment on Br^- movement as a function of soil physical properties. They found that preferential flow via macropores appears to play a significant role in Br^- movement. Afyuni and Wagger (2006) postulated that under similar soil and environmental conditions, movement of mobile nonreactive anions such as NO^-_3 will occur if applied in concentrations exceeding those taken up by plants.

Irrigation Methods

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

Partial soil wetting under drip irrigation generally leads to many agronomic benefits such as water and labor saving (Keller and Karmeli, 1974). However, the extent of the wetted soil volume is a function of the emitter discharge and spacing but depends mainly on the soil type and the total water added (Warrick, 1986). Increasing the irrigation rate enhanced NO_3^--N movement to deep layers under wheat (Charanjeet and Das, 1985; Recous et al., 1992). Quiñones et al. (2007) reported similar observations in citrus. Several researchers have recommended the use of frequent fertigation combined with improved irrigation scheduling to improve fertilizer uptake efficiency, to increase residence time of nutrients in the root zone and to reduce the potential for groundwater pollution (Graser and Allen, 1987; Ferguson et al., 1988; Obreza et al., 1999; Alva et al., 2003; Schumann et al., 2003). Also Bryla et al. (2003; 2005) showed that surface and subsurface drip scheduled daily increased fruit size and improved marketable yields of peach and reduced the number of nonmarketable fruit by 9% to 22% over more traditional furrow or microspray irrigation methods.

Irrigation Control Methods

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

Citrus Root Density Distribution

In Florida, citrus groves are established in both Flatwoods and Ridge regions. The Flatwoods soils are in the southern and coastal areas of the state, whereas the Ridge soils are in the northern and central citrus production areas of the state (Jia et al., 2007). Flatwoods are found in a flat landscape with low elevation where surface-water drainage is slow. In these areas, citrus is normally grown on raised 2-row beds, and drainage runs in ditches between beds (Boman, 1994). The Flatwoods Alfisols and Spodosols that support citrus are poorly to very poorly drained (Obreza and Collins, 2008). In contrast, Ridge citrus grows in a landscape of low hills, in which individual plots may be level. The Ridge Entisols are fine to coarse sands (Parsons and Morgan, 2004) that are moderately to excessively well drained (Reitz and Long, 1955; Obreza and Collins, 2008). Also, on the Ridge, mature citrus have at least half their roots in the top 90 cm (Reitz and Long, 1955; Fares and Alva, 2000a, b; Parsons and Morgan, 2004), while in the Flatwoods, over 95% of the roots are in the top 30 to 45 cm (Parsons and Morgan, 2004). Flatwoods citrus roots may be limited to the top 30 to 45 cm because of the high water table and the presence of argillic or spodic horizons (Obreza and Admire, 1985; Boman, 1994). For young citrus trees, most roots are in the top 30 to 60 cm (Parsons and Morgan, 2004). Kalmar and Lahav (1977) irrigated avocados with sprinklers at 7, 14, 21 and 28-day intervals and found that most water was absorbed from upper 60 cm soil layer suggesting that this was where most roots were concentrated. In a study on citrus water uptake dynamics on a sandy Florida Entisol, Morgan et al. (2006b) reported that roots were concentrated in the top 15 cm of soil under the tree canopy (0.71 to 1.16 cm roots cm^{-3} soil), where maximum soil water uptake was about 1.3 mm^3 mm^{-1} $root^{-1}$ day^{-1} at field capacity, decreasing quadratically as moisture content decreased. Michelakis et al. (1993), studying avocado water use in a Mediterranean climate in Greece under drip irrigation, found that root percentage was generally higher in the upper 50 cm soil layers and within 2 m from the drip line, where about 70-72% of the roots were located. They attributed the higher root percentage in the upper soil layers to biological factors and to the higher oxygen diffusion rate. Coleman (2007) also observed that root length density was dependent upon depth and position relative to drip emitter when fertilizers were applied and is greatest at the surface and in proximity to the drip line. The factors controlling root length density included age, and depth and proximity to the drip emitter.

Process-Oriented Models for Solute Transport, Water and Nutrient Uptake

Types and Use of Models in Agriculture

Several simulation models for predicting water and nutrient uptake and movement have been developed in recent years in recognition of the need to develop solutions for various agricultural and environmental management problems such as irrigation scheduling, design of drainage systems, crop management and pollution of surface and groundwater resources (Clemente et al., 1994; Šimůnek et al., 1999; Jones et al., 2003). The models may have some deficiencies in representing the soil-water-plant-atmosphere interaction and processes (Clemente et al., 1994) owing to the biases of their developers (Hutson, 2005) and simplifications associated with input data and variability in field data (Hornsby et al., 1990; De Jong et al., 1992; Clemente et al., 1994). Nevertheless, the models help us examine and gain an understanding of the processes that cannot be subjected to experimentation.

Most models have been developed in the past 20 years to help offer decision support in different cropping systems (Jones et al., 2003), hydrologic systems (Hutson and Wagenet, 1991; Šimůnek et al., 1999; 2007) and soil water management (Ahuja et al. 1993). The decision support system for agrotechnology transfer (DSSAT) model simulates growth, development and yield of a crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time (Jones et al. 2003). The ARS Root Zone Water Quality Model (RZWQM) is used for predicting pesticides reactions and degradation, nutrient transformations, plant growth, and management-practice effects (Decoursey and Rojas, 1990; Ahuja et al., 1993)

Šimůnek et al. (1999; 2007) developed HYDRUS-2D and 3D models to simulate the two-and three-dimensional movement of water, heat, and multiple solutes in variably saturated media. The HYDRUS program numerically solves the Richards's equation for variably-saturated water flow and convection-dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by roots (Šimůnek et al., 1999; Fares et al., 2001; Šimůnek et al., 2007). Soil hydraulic parameters of this model can be represented analytically using different hydraulic models such as the van Genuchten (1980) and Brooks and Corey (1964) equations. Several researchers have used HYDRUS model in irrigated systems (Fares et al. 2001; Gärnenäs et al., 2005; Boivin et al., 2006; Fernández-Gálvez and Simmonds, 2006; Hanson et al., 2006; Zhou et al., 2007; Šimůnek and Hopmans, 2009; Li and Liu, 2011; Bufon et al., 2011; Phogat et al., 2011). Fares et al. (2001) simulated solute movement within the soil profile of Ridge and Flatwood soil types using the HYDRUS-2D model. In the simulations, they found that 25% more water drained under the Flatwoods soil than the Ridge soil. Also, solute leaching was 2.5 greater under the Ridge soil type than Flatwood soil type. The results obtained by Fares et al. (2001), however, require further investigation and validation by statistically correlating the measured outputs in-situ versus the simulated outputs. Despite problems associated with identification of the actual physical processes when conducting simulation, Pang et al. (2000) found that HYDRUS model accurately described soil water contents with minor discrepancies. Studies by Gärnenäs et al. (2005) and Hanson et al. (2006) assessed fertigation strategies using HYDRUS-2D for nitrogen fertilizers. They found that HYDRUS-2D model described the movement of urea, ammonium, and nitrate during irrigation and accounted for the reactions of hydrolysis, nitrification and ammonium adsorption.

The HYDRUS-2D model was used in the study because it is appropriate for use in microsprinkler and drip fertigated systems.

Comparing Soil Water and Hydrologic Models

Skaggs (1980) developed the DRAINMOD water management /drainage model for use in areas with high water tables. Using this model, Obreza and Boman (undated) simulated water table fluctuation, upward flux and citrus ET on 12 citrus groves in the Flatwoods soils. They observed that a water table depth of 50-70 cm was sufficient to maintain a root zone soil moisture that did not limit citrus ET in the Flatwoods.

Clemente et al. (1994) compared three models: SWATRE (Soil Water and Actual Transpiration, Extended), LEACHW and SWASIM (Soil Water Simulation Model). They concluded that model predictions and measured water content profiles were within the limits of acceptance and none of the models consistently outperformed the others. They recommended the use of any of these models for prediction of water content in unsaturated soils.

Several researchers have attempted to use LEACHM to simulate nutrient and water uptake and movement in various conditions. Jabro et al. (1993) found that LEACHM (version 3.0) overestimates leached NO_3^- due to its inability to estimate macropore flow effects. They also deemed the use of the water retention function fitted by Campbell's equation (Campbell, 1974) inappropriate for LEACHM because it tends to overestimate soil water content. However, Jabro et al. (1993) concluded that NO_3^- leaching was better simulated by LEACHM than by NCSWAP (Nitrogen, Carbon, Soil, Water and Plant). A study by Paramasivam et al. (2000b; 2002) also found a good agreement between the measured concentrations of NH_4-N and NO_3-N and the respective concentrations simulated by LEACHM. Soulsby and Reynolds (1992) also used LEACHM to model soil water flux in Al leaching study and found good agreement between model predictions and simulated data.

Models Used for Citrus Production

The Citrus Water Management System (CWMS) is a new soil water and nitrogen balance model that was developed to help citrus growers in irrigation scheduling and nutrient management (Morgan et al., 2006c) basing on earlier work on the citrus growing regions in Florida (Fares and Alva, 2000; Obreza and Pitts, 2002; Scholberg et al., 2002; Morgan et al., 2006b; Wheaton et al., 2006; Fares et al., 2008). The model estimates soil water and nitrogen balances in multiple soil compartments under a mature citrus tree utilizing empirical relationships for water and nitrogen uptake and movement in sandy soils. According to Morgan et al.(2006c), CWMS requires initial setup information such as daily reference evapotranspiration (ET_o), rainfall amounts, irrigation duration (hours:min), nitrogen inputs, and fertilizer application rates. Also, the user of the model is required to provide information on irrigation system output characteristics (spray diameter, inch; wetting pattern and flow rate, gal h^{-1}), soil series, tree spacing parameters (the in-row and between-row tree distances), tree age (for estimation of canopy volume and calculation of root distribution). The Candler and

Immokalee soil series that are found at the Ridge and Flatwoods sites, respectively, are included in the model.

The CWMS model postulates two assumptions: (1) that all trees in a given planting area are of the same average size and have the same growth activities such that water and nutrients taken from one area is the average of all other areas of similar size in the planting; (2) that runoff and lateral water movement are negligible in the very sandy and well drained Florida Ridge soil (Morgan et al., 2006c). The model was designed for mature citrus under microsprinkler irrigation and needs to be calibrated for young citrus under both drip and microsprinkler irrigation. Equations governing water movement, water uptake, nitrogen movement and uptake in the model were based on earlier research work (Williams and Kissel, 1991; Allen et al., 1998; Scholberg et al., 2002; Morgan, 2004; Morgan et al., 2006a).

Other models developed for citrus production have been used in insect pest management to predict population and crop damage caused by citrus pathogens (Timmer and Zitko, 1996), scale insects (Arias-Reveron and Browning, 1995), and in water management for irrigation scheduling (Xin et al., 1997).

Summary

The chapter reviewed the work regarding 1) management options for use under ACPS/OHS, 2) biomass and nutrient distribution in citrus, 3) water and fertilizer use efficiency, 4) microsprinkler and drip irrigation system design and scheduling, 5) root distribution in response to soil water, and, 6) models used in agricultural management systems. As discussed above, options for optimizing nutrient and water uptake and yield on Florida's sandy soils include carefully planned and split fertigation practices and use of weather based irrigation scheduling methods. Use of computer models has been reviewed as one option for aiding the decision making process in citrus nutrient and water management practices.

Table 2-1. Typical percent biomass distribution (dry weight basis) in oranges from different parts of the world

[¶¶]Study area	FL[§]	FL[¶a]	FL[¶b]	SP[†a]	SP[†b]	IS[‡a]	IS[‡b]	CA[‡‡a]	CA[‡‡b]	CA[§§]	SP[††a]	SP[††b]	SP[§§§a]	SP[§§§b]
Age (years)	6	14	14	8	8	22	22	3.5	10	15	8	8	8	8
Plant tissue								%						
Leaves	10	12	13	16	13	6	7	31	18	17	13	12	12	14
Branches, Twigs, and Trunk	32	61	52	32	30	55	56	38	61	61	33	34	29	32
Fruits	30	-[†††]	-	21	26	8	13	-	-	-	23	27	27	22
Roots	28	27	33	31	31	31	24	31	21	22	31	27	32	32

[§] Hamlin-Swingle (25.0 kg tree^{-1}) using microsprinkler irrigation (Mattos et al., 2003a, b)

[¶] Hamlin on Carrizo (104.3 kg tree^{-1}) (a) and Swingle (82.6 kg tree^{-1}) rootstocks (b) using microsprinkler irrigation (Morgan et al., 2006a)

[†] Navelina-Carrizo (0.034 kg tree^{-1}) using low frequency of N application combined with flood irrigation (a) and Navelina-Carrizo (0.041 kg tree^{-1}) using high frequency of N application combined with drip irrigation (b) (Quiñones et al., 2003a, b)

[‡] Shamouti (319.5 kg tree^{-1}) with 223 g N tree^{-1} (a) and Shamouti (319.7 kg tree^{-1}) with 763 g N tree^{-1} (b) using microsprinkler irrigation (Feigenbaum et al., 1987)

[‡‡] Valencia (3.1 kg tree^{-1}) (a) and (80.1 kg tree^{-1}) (b)- Cameron and Appleman (1935)

[§§] Valencia (94.6 kg tree^{-1}) -Cameron and Appleman (1945)

[††] Navelina-Carrizo (39.15 kg tree^{-1}) using two (a) and Navelina-Carrizo (36.08 kg tree^{-1}) using five (b) equal split applications of N with flood irrigation (Quiñones et al., 2005)

[§§§] Navelina-Carrizo (41.03 kg tree^{-1}) using drip irrigation by N demand (a) and Navelina-Carrizo (37.49 kg tree^{-1}) using drip irrigation by evapotranspiration (ET) demand (b) (Quiñones et al., 2005)

[¶¶] FL-Florida, SP-Spain, IS-Israel, CA-California

[†††] – = no data available

Table 2-2. Typical nutrient uptake rates in oranges

Plant tissue	N[†]	K[†]	P[†]	N[††]a	N[††]b	N[§a]	N[§b]	N[‡a]	N[‡b]	N[‡‡]	N[§§a]	N[§§b]	N[¶]	N[¶b]	N[¶a]	N[¶b]	N[¶¶¶]	N[§§§]
										%								
Leaves	46	35	32	36	38	38	30	62	47	45	20	23	42	44	36	35	31	39
Branches, twigs, trunk	15	15	24	39	32	20	25	21	39	35	44	42	18	15	25	23	22	24
Fruits	8	16	13	-[†††]	-	18	21	-	-	-	11	20	26	29	24	22	6	-
Roots	31	34	31	25	30	24	24	17	14	20	25	15	14	12	13	20	41	37
Tree age	6	6	6	14	14	8	8	3.5	10	15	22	22	8	8	8	8	5	3

[†] Hamlin-Swingle in Florida, % of total N **-** Mattos et al. (2003a, b) using microsprinkler irrigation

[††] Hamlin-Carrizo (a) and Hamlin-Swingle (b) in Florida, % of total N - Morgan et al. (2006a) using microsprinkler irrigation

[§] Navelina-Carrizo in Spain, % of total N - Quiñones et al. (2003) using low frequency N application with flood irrigation (a) and high frequency N application with drip irrigation (b)

[‡] Valencia in California, % of total N - Cameron and Appleman (1935) for 3.5-year-old (a) and 10-year-old (b)

[‡‡] Valencia in California, % of total N - Cameron and Compton (1945)

[§§] Shamouti in Israel, % of total N - Feigenbaum et al. (1987) using microsprinkler irrigation with 223 g N tree^{-1} (a) and 763 g N tree^{-1} (b)

[¶] Navelina-Carrizo in Spain, % of total N - Quiñones et al. (2005) using flood irrigation schedules with two (a) and five (b) equal N splits

[¶¶] Navelina-Carrizo in Spain, % of total N - Quiñones et al. (2005) using drip irrigation by N demand (a) and ET demand (b)

[¶¶¶] Calamondin in Spain, % of total N - Legaz et al. (1982)

[§§§] Valencia in Spain, % of total N - Legaz et al. (1995)

[†††] - = No data available

Table 2-3. Soil test interpretation for soil P extraction methods compared with Mehlich 1 extractant[§]

Extractant	Soil test interpretation				
	Very low	Low	Medium	High	Very high
	mg kg^{-1}				
	Less than sufficient			Sufficient	
Mehlich-1	<10	10-15	16-30	31-60	>60
Mehlich-3	<11	11-16	17-29	30-56	>56
Ammonium acetate pH 4.8	≤11			>11	
Bray 1-P	≤40			>40	
Bray 2-P	≤65			>65	

[§] Koo et al., 1984b; Obreza et al., 1999; 2008b

Table 2-4. Guidelines for interpretations of orange tree leaf analysis based on 4 to 6-month-old spring flush leaves from non-fruiting twigs[¶]

Element	Deficient	Low	Optimum	High	Excess
	%				
N	<2.20	2.20-2.40	2.50-2.70	2.80-3.00	>3.00
P	<0.09	0.09-0.11	0.12-0.16	0.17-0.30	>0.30
K	<0.70	0.70-1.10	1.20-1.70	1.80-2.40	>2.40

[¶] Koo et al. 1984b; Obreza et al. 1999; Obreza and Morgan, 2008.

CHAPTER 3
NUTRIENT UPTAKE EFFICIENCY AND DISTRIBUTION IN-SITU FROM THE CITRUS ROOT ZONE

Intimately tied to water management in citrus production systems is the need for efficient nutrient management strategies that enhance nutrient-use efficiency while minimizing leaching losses in the root zone and sustain environmental quality. Several guidelines and criteria are being and/or have been developed for managing water in concert with major nutrients in citrus production systems (Alva et al., 2003; Schumann et al., 2003; Alva et al., 2005; 2006a, b, c; Obreza et al., 2008a, b; 2010). Faced with the devastating citrus greening disease in Florida, researchers are attempting to explore ways of maximizing water and nutrient use efficiency by concentrating roots in the irrigated zones of microsprinklers or drip emitters, which should lead to high citrus yields and less nutrient leaching (Morgan et al., 2009b). The concepts being promoted are termed Advanced Production Systems (APS) and Open Hydroponic Systems (OHS) (Stover et al., 2008, Morgan et al., 2009b). These two concepts are known to combine high density plantings with intensive water and nutrient management thereby optimizing tree performance.

An understanding of soil NH_4^+-N, NO_3^--N, P and K distribution patterns in the citrus root zone will help in devising ways of managing these critical nutrients for better horticultural, irrigation and environmental management. Leaching of NO_3^--N, P and K are the greatest concern in all agricultural practices. Several researchers have shown the importance of applying recommended N rates to manage NO_3^--N levels in groundwater and soil (Lamb et al., 1999; Paramasivam et al., 2001; 2002; Alva et al., 2003; 2006a, b; Sato et al., 2009a) through use of carefully split N fertilizer applications (Quiñones et al., 2003a, b; 2005; 2007) and well scheduled irrigation management (Alva et al., 2003; 2005; 2006b; Morgan et al., 2009b). Phosphorus (P) leaching has been identified recently as a threat to environmental quality (Sims et al., 1998; Boesch et al., 2001; Agyin-Birikorang et al., 2008). One strategy proposed by Obreza et al. (2008a) is for citrus producers to refrain from applying P fertilizer to young trees on Florida sandy soils if soil test P ranges from medium to very high levels according to University of Florida/Institute of Food and Agricultural Sciences recommendations. Obreza et al. (2008a) observed that applying P fertilizer when it is not needed is wasteful and may cause undesirable enrichment of adjacent water bodies. K is also considered a major nutrient in citrus production subject to leaching losses in the root zone. The extent of K leaching and distribution is mainly determined by drainage (Munson and Nelson, 1963), soil texture (Ylaranta et al., 1996) and irrigation practice (Sato et al., 2009b). Increasing nutrient availability in the irrigated zone will probably lead to better water, N, P and K uptake and less nutrient leaching.

This experiment was conducted to:

- 1) determine nutrient (NH_4-N, NO_3-N, Mehlich 1 P (M1P) and Mehlich 1 K (M1K)) and Br distribution patterns in the irrigated and non-irrigated zones as a function of depth and fertigation method;
- 2) determine N, P and K concentration in below and above-ground tissues.

Using the OHS concept, we hypothesized that:

- 1) ammonium nitrogen (NH_4^+-N), NO_3^--N, Br, M1P and M1K distribution will vary with depth, distance from the tree and fertigation method;
- 2) ammonium nitrogen (NH_4^+-N), NO_3^--N, M1P and M1K will be higher in irrigated zones than nonirrigated zones and,
- 3) plant N, P and K accumulation will be greater for OHS applied using microsprinklers or drip than grower practice.

Materials and Methods

Site Conditions

The study was conducted at two locations: 1) University of Florida, Southwest Florida Research and Education Center, near Immokalee, Florida (Latitude 26.42°N and Longitude 81.43°W, at 10.41 m above sea level) and 2) a commercial grove near the University of Florida, Citrus Research and Education Center (SWFREC), near Lake Alfred, Florida (Latitude 28.09^{o}N, Longitude 81.75^{o}W, at 45.50 m above sea level). The soil at the Immokalee site was Immokalee fine sand and consists of nearly level, poorly drained soils on the Flatwoods formed in sandy marine sediments with slopes less than 2 percent (Obreza and Collins, 2008). These soils are classified as sandy, siliceous, hyperthemic Arenic Haplaquods with the spodic horizon lying within 1m from the ground surface (USDA, 1990a). The soils at the research site near Lake Alfred was Candler fine sand and consists of excessively drained soils that formed in sandy marine or eolian deposits found on broad undulating upland ridges and knolls on flatwoods with slopes ranging from 0-8 percent. They are classified as hyperthermic, coated Typic Quartzipsamments (USDA, 1990b; Schumann et al., 2009).

Study Treatments and Experimental Design

At Immokalee, 3 year-old citrus trees on Swingle rootstock were planted at 3.05 m between trees in a row and 6.71 m between tree rows. Irrigation treatments at the Immokalee site were as follows: (1) Conventional practice (CMP) irrigated weekly and fertigated monthly; (2) Drip OHS (DOHS) – irrigated and fertigated daily in small pulses; (3) Microsprinkler OHS (MOHS) – irrigated daily and fertigated weekly. All the treatments were laid in a randomized complete block design replicated four times.

At the Lake Alfred site, Hamlin oranges were planted on Swingle rootstocks at 3.05 x 6.10m (~218 trees/acre) and on C35 rootstock at 2.44 x 5.49m (~302 trees/acre). The treatments imposed at the Lake Alfred site were similar to the set-up at Immokalee except for the modification to the conventional practice where the use of dry granular fertilizer applied under the canopy four times a year acted as a control for the experiment and also drip open hydroponic system was imposed on both Swingle and C35 rootstock. The lay-out of the treatments are described in schematic diagrams (Appendix D).

Plant Tissue and Soil Sampling Design and Analytical Methods

Soil sampling

In 2009 at Immokalee, twelve soil samples per replicate per treatment were collected in June and August for determination of NH_4^+-N, NO_3^--N, P and K concentration in each plot within a 30 cm x 45 cm grid in one quadrant of a given tree in a plot (Total number of soil cores = 3 treatments x 4 replicates x 12 cores samples per replicate x 2 profiles x 1 core per profile= 288 cores at Immokalee). Soil samples were collected at 0 to 15 cm and 15 to 30 cm depths because this is where most roots of young citrus trees ($\leq$3 years old) are concentrated (Fares and Alva, 2000; Paramasivam et al., 2000c; Parsons and Morgan, 2004). In 2010, at Immokalee, soil samples were taken up to the 45 cm depth. Soil samples were also taken at 0-15, 15-30, 30-60 and 60-90 cm (June, 2010) from locations in the irrigated zones to analyze for NH_4^+-N, NO_3^--N, P and K. In June 2011, at Immokalee, soil samples were taken in duplicates every two to three days at 0-15, 15-30, 30-45 and 45-60 cm at 15 cm and 45 cm from the tree to quantify nutrient movement in the irrigated and non-irrigated zone using Br tracer.

At the Lake Alfred site samples were collected in December 2009 at 4 locations per tree in a 15 cm x 15 cm grid (Total number of cores = 4 treatments x 4 replicates x 4 cores samples per replicate x 2 profiles x 1 core per profile= 128). In July 2010, at the Lake Alfred site, nine (9) samples were collected in a 30 cm x 30 cm grid per sampled tree in one replicate within the 0-30cm depth resulting in a total of 432 samples. Soil samples were also taken at 0-15, 15-30, 30-60 and 60-90 cm (July, 2010) in the irrigated zones to analyze for NH_4^+-N, NO_3^--N, P and K. In August-September 2011, at Lake Alfred, soil samples were taken in duplicates every two to three days at 0-15, 15-30, 30-45 and 45-60 cm at 15- and 45 cm from the tree to quantify nutrient movement in the irrigated and non-irrigated zone using Br tracer.

Nitrate-N was compared with the maximum contaminant limit for drinking water standards (10 mg L^{-1}) set by the U.S. Department of Health, Education and Welfare (1962) while P will be compared with numeric nutrient water quality criteria explained by Obreza et al. (2010) and IFAS recommendations (Obreza and Morgan, 2008).

Water sample collection and processing

Water samples were collected every two days using suction lysimeters (Irrometer Co., Riverside, CA 92516) in July and August, 2009 at Immokalee for determination of NO_3^--N leaching beyond the root zone ~50 cm at about 15 cm from the tree (irrigated zone) and 1 m away from the tree (non-irrigated zone). The lysimeters were installed with a vacuum pressure pump for 5 minutes to set a zone of lower pressure in the suction access tube to let soil solution flow into the lysimeter. The samples collected were filtered and later stored in a freezer at <4 ^{o}C until analysis.

Extraction of NH_4-N, NO_3-N, P, Br and K

To determine ammonium-N and nitrate-N concentration, 2 M KCl extraction procedure was used (Hanlon et al., 1997). Two wet subsamples per sample, one weighing approximately 4.5 g used for 2 M KCl extraction (in a ratio of 1 to 10 soil:solution ratio) and the other weighing 25 g for determination of oven-dry soil weight (after drying for 24 h at 105 ^oC) to determine soil ammonium-N and nitrate-N content on dry soil basis. A 40 ml solution of 2 M KCl was added to the soil in each test tube, capped and shaken for 30 minutes. After shaking, all the sample solutions were allowed to settle for 30 minutes and filtered using Whatman filter paper #42 into labeled vials, capped and stored in a freezer at $<4^oC$ until analysis.

Mehlich-1 extraction, a procedure recommended for soils with low organic matter and $pH \leq 6.5$, was used for determination of P and K (Mehlich, 1953). Air-dried soil samples weighing 5.0 g (2 mm screened) were placed into extraction bottles and 20 ml of Mehlich-1 extracting solution was added to each sample and shaken at high speed for 5 minutes at room temperature (25±2 °C) and allowed to settle for 15 minutes. The extracts were filtered (Whatman filter paper #42) and the supernatant was collected in labeled plastic vials and refrigerated.

Bromide was extracted using deionized water (soil:solution ratio of 1:2) by weighing about 5 g of dry soil and adding 10 ml of deionized water, shaking for 30 minutes and centrifuging at 5500 rpm. The suspension was filtered with Whatman filter paper # 42, capped and stored in plastic vials until analysis according to the method described by Bogren and Smith (2003).

Analysis of soil extracts and water samples

Ammonium nitrogen (NH_4-N) and NO_3-N for soil samples were determined using a Flow Analyzer (Quich Chem 8500, Lachat Co.) at 660 nm and 520 nm, respectively (Harbridge, 2007a, b) for samples collected in 2009, 2010 and 2011 at both sites. Bromide was also analyzed using the Flow Analyzer (Quich Chem 8500, Lachat Co.) method (Bogren and Smith, 2003). Nitate nitrogen in water samples was also analyzed using the flow injection analysis method described by Harbridge (2007a).

Analysis for Mehlich-1 extractable P on samples collected in June 2009 at Immokalee was done by a DR/4000U Spectrophotometer (HACH INC.) at 880nm using a blank and four standards (4ppm, 8ppm, 12ppm and 16ppm) prepared in the Mehlich-1 extracting solution. Mehlich-1 extractable K for samples taken June 2009 at Immokalee was determined by a 5100PC Atomic Absorption Spectrophotometer (Perkin Elmer Co.) at 766.5 nm prepared in the Mehlich-1 extraction solution using a blank and three standards (2 ppm, 6 ppm and 12 ppm). Samples collected at the Immokalee site in June 2010 and 2011 and those collected from the Lake Alfred site in December 2009, July 2010 and August-September 2011 were analyzed for M1P and M1K using Inductively Coupled Plasma (ICP) method (Hanlon et al., 1997) on a PerkinElmer Optical Emission Spectrometer Optima 7000DV at 213.6 nm and 766.5 nm, for P and K, respectively. All results were expressed on oven dry soil mass basis.

Plant tissue sampling and analysis

Leaf sampling

Leaf samples (a total of 20 leaves in four randomly sampled middle trees) were collected quarterly to determine nutrient uptake using the procedures outlined in Obreza and Morgan (2008). Moist leaf samples were dried at 60°C for 72 h and then passed through a stainless steel grinder with 20- and 60-mesh sieve and mixed thoroughly. Ground samples were stored at room temperature, but were redried at 60°C for 2 h before weighing for analysis (Jones and Case, 1990; Plank, 1992; Hanlon et al., 1997).

Destructive tree sampling and tissue processing

Trees were destructively sampled in July 2011 at Immokalee (Figure 3-1) and August 2011 at the Lake Alfred site using methods adapted from Mattos (2000) and Morgan (2004). Before destroying the trees at Immokalee, one representative tree per fertigation method was sampled and an area of 3.05 m x 3.05 m around each sampled tree was marked with a shovel to 30 cm depth. All trees were defoliated and the leaves were categorized into two: young or fully expanded, placed into separate plastic bags containing ice and taken to the laboratory. Twigs, fruits, small, medium and large branches were cut from each tree using clippers or manually, and placed in separate plastic bags. When all other tissues were collected from a particular tree, the trunk and roots were removed using an excavator. Thereafter, the soil was sifted and any remaining roots were collected. The roots were washed to remove any soil and debris before determining the fresh weight. All the tissues and tree parts were weighed for fresh weight determination. Thereafter, leaf tissues were dried for 72 h at 60^{o}C while larger tissue samples like the trunk, branches, fruits (fruits were cut into quarters after determining the fresh weight) and roots were dried at 60^{o}C for more than 14 days to constant weight. All the large tissues were cut into much smaller 1-cm wide pieces using a machete and an electric saw before passing them into a larger grinder and then, the small ground tissues were passed through a stainless steel grinder with 20- and 60-mesh sieve and mixed thoroughly. At the Lake Alfred site, because this was in a commercial grove and the trees could not be removed, selected tissues were sampled (twigs, leaves, fruits and roots) from one tree per irrigation method. Collected tissues samples were handled as explained above.

Tissue analysis

Tissue N concentration (%) was determined using the NA2500 C/N Analyzer (Thermoquest CE Instruments). To accomplish this, 5.0 mg of dry, ground tissue sample was weighed and compared to standards and blanks basing on calibration curve developed upon weighing and running approximately 2.5 mg, 5.0 mg and 10 mg of standard samples and two blanks on the analyzer. Tissue P and K concentration were determined using the dry ash combustion digestion method recommended by Anderson and Henderson (1988) for plant tissue analyses. Tissue K and P concentration were determined simultaneously by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). A 1.5 g sample of dried plant material was weighed and dry ashed at 500°C for 16 h. The ash was equilibrated with 15 ml of 0.5 M HCl at room temperature for ½ h. Then the contents were gently swirled and allowed to settle for 1 h. The solution was decanted into 15 ml plastic disposable tubes for direct determination by ICP-AES (Munter and Grande, 1981; Munter et al., 1984**;** Fassel, and Kniseley, 1974). All samples were placed in a refrigerator at $\leq 4^{o}$C until extractions and analyses could be done (Plank, 1992; Morgan, 2004). Leaf N, P, K concentration were compared with critical NPK levels for Florida Citrus (Obreza et al., 1999; Obreza and Morgan, 2008) and the concentration in all tissues was used to quantify the nutrient accumulation per tree.

Quality Control of Plant Tissue and Soil Sample Analysis

All sample collection/handling/chemical analysis was done according to standard procedures. A standard curve for certified standards ($R^2 \geq 0.999$) was developed for each set of samples. Method reagent blanks and duplicate samples were included for each 10th and 20th sample for soil samples while blanks, standards and duplicates were also included for each 10th, 20th and 40th sample of the tissue samples, respectively. Samples where blanks did not read as blank and/or where duplicates did not match with a relative standard deviation $\leq$10% were re-extracted and/or rerun until reasonably accurate results were obtained.

Data Analysis

All data were analyzed using PROC GLM Mixed model procedures using SAS 9.2. Means were separated using Duncan Multiple Range Test (DMRT).

Results and Discussion

Leaf NPK Concentration as a Function of Irrigation System

Leaf N concentration using MOHS was similar to the other two treatments at Immokalee site (Figure 3-2). However, leaf N concentration using DOHS was significantly higher (p=0.03) than that observed under CMP. Thus, DOHS was effective in enhancing N content compared with the other two irrigation methods studied. Leaf P and K concentrations were similar across the treatments. Typical critical values for nutrient concentration in orange trees were suggested by Obreza and Morgan (2008). Most of the leaf N values observed in DOHS were either within the optimum (2.5-2.7%) or high (2.8-3.0%) ranges of nutrient concentration suggesting that nutritional requirements of the citrus tree were met by the irrigation and fertigation system. However, most leaf N values for MOHS and CMP were less than 2.5% showing that the two systems did not meet the critical N requirement of the tree. Leaf P concentration was high (0.17-0.30%) in all treatments while as leaf K concentration was within optimum and high (1.2-2.4%) ranges suggesting that all the treatments met the P and K requirements (Figure 3-2). However, adjustments on fertilization programs proposed by Obreza et al. (2008b) need to be done on total N applied in the microsprinkler based systems so as to meet the N requirement of the trees either by applying more fertilizer per unit time or increasing the fertigation frequency. It is apparent that the DOHS promoted more N concentration owing to the more frequent and localized fertigation. Another reason for the increased N concentration is ascribed to high root length density below the dripper (reported in the following chapters). It can be inferred that high root length density enhanced nutrient concentration. The leaf N, P and K concentration at the Lake Alfred site were all in the optimum or high ranges greater than 2.5%, 0.12% and 1.2%, respectively. All the treatments , grower practice and OHS fertigation practices met the tree nutrient requirements at the time of sampling (Figure 3-3). The fertilization practices at the Lake Alfred site did not show any significant differences in leaf concentrations between the four treatments showing that the fertilization rate was adequate in all the four methods used.

NPK Distribution in the Citrus Root Zone as a Function of Time, Depth and Lateral Distance

In June 2009 at Immokalee, 2M KCl extractable ammonium-N ($p<0.001$), M1P ($p=0.0024$) and M1K ($p=0.001$) were significantly different while 2 M KCl extractable nitrate N ($p=0.27$) was not significantly different among the fertigation methods (Table 3-1). Ammonium-N, nitrate-N and M1K were 9 to 34% higher using MOHS than CMP in the irrigated zone. Yet, using the same MOHS, M1P was 25% lower than conventional practice. DOHS significantly increased M1K, ammonium-N, nitrate-N and M1P in the root zone by 44 to 133% over CMP. Ammonium-N, nitrate-N, M1P and M1K were significantly lower under MOHS by 4 to 73% compared with CMP in the non-irrigated zone. In the non-irrigated zone under DOHS, ammonium-N and M1P were 3 to 6% lower than CMP while nitrate-N and M1K were 4 to 48% higher than CMP (Table 3-1).

Concentrations of 2M KCl extractable NH_4^+-N and NO_3^--N, M1 extractable K and P in soil samples decreased with depth in all treatments at SWFREC. This is beneficial because root length density of citrus trees tends to be highest near the soil surface and increase with depth as trees grow (Morgan et al., 2007). Thus, greater nutrient uptake has been found in the 0-30 cm horizon where, according to Paramasivam et al. (2000c), where 80% of the roots are concentrated. Except for ammonium-N, it was observed that all the other forms of available nutrients decreased ($p<0.05$) with distance away from the tree (Figures 3-4 and 3-5).

In August 2009 as shown in Table 3-2, no significant differences in NH_4^+-N and M1K were observed between fertigation methods, by depth and distance from the tree. Nitrate-N (NO_3^--N) decreased with depth in all treatments but was similar between fertigation methods. Mehlich 1 P (M1P) decreased with depth and distance from the tree, resulting in higher M1P distribution in the irrigated zone for MOHS and DOHS. Thus M1P concentration in the top soil (0-15 cm) of the irrigated zones was sufficient and was low or medium at soil depth (15-30 cm) in all fertigation methods at Immokalee. Results obtained from the soil samples collected in June 2010 are shown in Table 3-3. Ammonium-N (NH_4^+-N), NO_3^--N and M1K differed by fertigation method ($p<0.001$), decreased with depth ($p<0.001$), and varied between irrigated vs. non-irrigated zones. Mehlich 1P (M1P) decreased with depth and distance from the tree ($p<0.001$) and was very high in the 0-15 cm depth of irrigated zones of DOHS and MOHS ~80 mg kg^{-1} which was about twofold the M1P for CMP=48 mg kg^{-1}. Significant interaction between fertigation method x distance ($p<0.05$), depth x distance ($p<0.001$) for M1P, M1K and NH_4^+-N suggests the importance of careful placement of the nutrients in the irrigated zones, proximal to the tree for better root uptake. The irrigated zones, as shown in Chapter 4, showed high root length density, a tree characteristic that explains the potential for tree water and nutrient uptake.

The 2M KCl extractable NH_4^+-N and NO_3^--N, M1P and M1K were significantly different among irrigation methods at the Lake Alfred site in December 2009 (Table 3-4) and July 2010 (Table 3-5). Ammonium-N (NH_4^+-N) and M1K were higher at 0-15 cm than 15-30 cm in December 2009. In December 2009, NO_3^--N was similar between DOHS-Swingle, MOHS and DOHS-C35 but all these were approximately one-half of CMP~4 mg kg^{-1}. The NO_3^--N and NH_4^+-N concentration was similar between irrigated and non-irrigated zones of DOHS-Swingle and DOHS-C35 while the M1P was very high (>60 mg kg^{-1}) in all treatments.

In July 2010 at the Lake Alfred site, NO_3^--N and M1K decreased ($p<0.001$) with depth across all irrigation methods. Worth noting was the total NH_4^+-N and NO_3^--N that resulted in high total inorganic N concentration >25 ppm under conventional microsprinkler practice (CMP) in the 0-30 cm top soil that could pose an N leaching threat. The M1P concentration at the Lake Alfred site at both sampling times were very high (>60 mg kg^{-1}) across all the irrigation methods (Table 3-5). This suggests the need for lowering and/or adjusting the P application rate in all irrigation methods, and also lowering the N application rate or changing the application method using CMP to minimize the risk of nutrient leaching beyond the root zone. There was significant interaction between irrigation method x distance from the tree for NO_3^--N and M1K in December 2009 and July 2010, and M1P in December 2009 only.

At the Immokalee site, NH_4^+-N and NO_3^--N remained below 10 mg kg^{-1} in all fertigation methods in irrigated and nonirrigated zones in June 2009 and June 2010 (Fig. 3-4 and 3-5). The M1P concentration was sufficient except in the irrigated zones of DOHS and MOHS where concentrations of 78 and 65 mg kg^{-1} were observed in 2009 and 2010, respectively (Fig. 3-10). The threat of P leaching was negated by high root length density associated with the irrigated zones of MOHS and DOHS as explained later in Chapter 4. Mehlich 1 K (M1K) concentrations were <20 mg kg^{-1} in all fertigation methods in both years suggesting increased K use and availability in the root zone. The lateral NH_4^+-N and NO_3^--N distribution remained below 2 mg kg^{-1} in all fertigation methods in 2009. The NH_4^+-N and NO_3^--N was uniformly distributed in the irrigated zone using CMP, and between the narrow north-south irrigated stretch from 10 to 30 cm from the tree under MOHS and just within 20 cm from dripper using DOHS. In 2010, the NH_4^+-N and NO_3^--N distribution pattern was similar to that of 2009 with concentrations <6 mg kg^{-1}, but changed for DOHS due to the addition of another drip line and movement of the drippers to positions approximately 30 cm from the tree on the east and west of the tree. Nevertheless, nutrient concentrations using DOHS remained within 20 cm from the tree and below 3.5 mg kg^{-1}.

At the Lake Alfred site, concentrations of NH_4^+-N and NO_3^--N were below 7 mg kg^{-1} and uniformly distributed across the irrigated and nonirrigated zones of all the irrigation methods in December 2009 (Table 3-4). In July 2010 at the same site, all NH_4^+-N and NO_3^--N concentrations were below 10 mg kg^{-1} in all irrigation methods but CMP where

NH_4^+-N and NO_3^--N concentrations as high as 17 and 29 mg kg^{-1} were observed due to granular fertilization compared with the fertigated methods. We noted fairly high concentrations of nutrients within 10 to 20 cm from the drip emitter in the DOHS-Swingle and DOHS-C35 irrigation methods. Also M1P concentrations were very high (>60 mg kg^{-1}) in December 2009 (Table 3-4) and July 2010 (Fig. 3-4) in both irrigated and nonirrigated zones suggesting the need for adjusting the P application rate to maintain the P concentration in the sufficiency range (<60 mg kg^{-1}). The M1K concentration for CMP was >50 mg kg^{-1} while the M1K remained below 40 mg kg^{-1} for the fertigated methods decreasing in the order CMP>MOHS>DOHS-C35>DOHS-Swingle in December 2009 (Table 3-4). In July 2010, M1K was <35 mg kg^{-1} in all irrigation methods but CMP (Fig. 3-4) with concentration in the order CMP>DOHS-Swingle>MOHS>DOHS-C35. CMP showed M1K as high as 70 mg kg^{-1}.

Our results on drip irrigation also agree with those of Li et al. (2003) who found high nitrate concentrations within 15 cm from the dripper. However, Li et al. (2003) found that ammonium was concentrated just within 2.5 and 7.5 cm from the drip emitter suggesting that ammonium distribution was restricted in a small volume, about 10 cm around the point source, probably due to adsorption and transformation to nitrate (Clothier et al., 1988; Clothier and Sauer, 1988) for an unsaturated soil. Earlier on, BarYosef and Sheikholslami (1976) found that NO_3^--N was distributed to 16 cm radial distance within 21 h after first irrigation while phosphate movement was not directly proportional to water movement due to phosphate adsorption. Wang and Alva (1996) found that N leaching in microsprinkler-irrigated citrus was a function of solubility of the fertilizer, soil type and duration of the leaching mechanisms. In their experiment, N leaching by N sources followed the order NH_4NO_3>Isobutylidene diurea>polyolefin resin-coated urea, Meister. They also showed cumulative N leached from Wabasso sand (a Spodosol) was 58% of that from Candler sand. The proportion of N not found in the lower soil depth 45-60 cm can be attributed to tree root uptake, microbial immobilization, denitrification, soil N retention or ammonia volatilization (Wang and Alva, 1996; Mattos et al. 2003c, Sato and Morgan, 2008; Morgan et al., 2009a). Our field experimental results somewhat contradict those of Wang and Alva (1996) who found NH_4^+-N to be the dominant form of total N leached compared with NO_3^--N in a greenhouse at 25 ± 3^oC under intermittent leaching-incubation conditions. Probably under the greenhouse conditions, the transformation of NH_4^+ to NO_3^- was somewhat limited by lack of air during saturated flow. Zvomuya et al. (2003) found that use of polylefin-coated urea reduces N leaching but can also increase residual soil N on a loamy sand because NO_3-N leaching is associated with high rainfall and irrigation episodes.

N, P, Br and K Leaching in the Irrigated and Nonirrigated Zones

Leaching of NH_4^+-N, NO_3^--N, M1P, M1K at the Lake Alfred and Immokalee sites in 2010 in irrigated zones is described in Figures 3-16, 3-17 and 3-18. The results show that at SWFREC, soil ammonium N and NO_3^--N (Figures 3-16 A and B) concentrations decreased with depth while remaining below 10 mg kg^{-1} that should lead to NO_3^--N lower than the USEPA (2005) maximum contaminant limit of 10 mg L^{-1}.

At the Lake Alfred site, NH_4^+-N and NO_3^--N was also below 10 mg kg^{-1} except for CMP where NO_3^--N was >10 mg kg^{-1} throughout the 0-90 soil depth (Figures 3-16C and D). This underlined the gains of using fertigation compared with granular fertilization because residual NO_3^--N was substantially increased nutrient retention with either drip or microsprinkler fertigation by 60 to 90%. These results support earlier findings in young and mature citrus (Alva et al., 1998; Scholberg et al., 2002; Morgan et al., 2009a) and other horticultural crops (Zotarelli et al., 2006; 2008a, b; 2009a, b; Scholberg et al., 2009). Muñoz-Carpena et al. (2005) also noted that more frequent fertigation may be beneficial to sustain adequately high N concentrations and soil moisture content in a relatively small spherical soil volume surrounding the plants. According to Havlin et al. (2005) the problem of NO_3^- leaching with CMP is explained by the fact that it is very soluble in water and is not strongly absorbed to the anion exchange capacity (AEC). Consequently, it is highly mobile and subject to leaching losses when both soil NO_3^- content and water movement are high. Thus, it is essential to minimize No_3^- leaching by applying N synchronous with high crop N demand and peak N mineralization.

Increasing N leaching potential occurs when inorganic profile N is present during periods of low evapontranspiration that coincides with periods of high precipitation, soil water content and drainage water. Timing N application to avoid periods of high water transport through the profile reduces leaching potential. Zotarelli et al. showed in their studies on pepper (2006; 2007), tomato (2006; 2007 and 2009a, b) and sweet corn (2008a) that the fertigation systems help the root system to explore the entire soil volume efficiently and thus boost crop N uptake and growth culminating in potentially much more efficient utilization of N fertilizer. Zotarelli et al. (2008b) demonstrated that N leaching increased when irrigation and N-rates increased, with values ranging from 2 to 45 kg ha^{-1} of N. Thus, Zotarelli et al. (2008b; 2009a, b) showed that soil moisture based systems greatly improved irrigation water use efficiency thereby reducing irrigation water use and N leaching potential (NO_3-N leaching was reduced by 5 and 35 kg ha^{-1})

in tomato surface and subsurface irrigation systems. Also, Kiggundu et al. (2011) observed that NO_3-N leaching in a young avocado orchard appeared to be more influenced by the amount of water applied than the fertilizer rate suggesting that efficient irrigation methods have a greater potential to reduce nitrate leaching than reduced fertilizer applications. This speculation holds because under saturated flow, Havlin et al. (2005) contend that NO_3^- ions move at similar speed as water molecules. Thus carefully managed irrigation schedules are critical in retaining nutrients in the root zone.

Mehlich 1 P was high in the top 0-15 cm and decreased to <15 mg kg^{-1} at 60-90 cm depth (Figure 3-17A). It can be speculated that most of the P was available for uptake because most roots were concentrated in the top 0-15 cm and in the irrigated zones. Mehlich 1 P at SWFREC remained largely within the recommended levels (16-60 mg kg^{-1}) in all treatments at 0-30 cm depth and was low (10-15 mg kg^{-1}) or very low (<10 mg kg^{-1}) in the 30-90 cm soil depth layer (Fig 3-17A).

At the Lake Alfred site, CMP showed high M1P in the range 31-60 mg kg^{-1} while OHS fertigation showed very high M1P (>60 mg kg^{-1}) falling between 65 – 160 mg kg^{-1}. Mehlich 1 P was very high in all the irrigation methods at the Lake Alfred site decreasing with depth ($p<0.0001$) suggesting the need for adjusting the annual P application rate with tree age. The very high M1P concentrations will eventually affect P retention, precipitation and adsorption mechanisms on the Ridge site with coated Candler fine sand. With low solution P concentration, adsorption dominates while precipitation reactions proceed when solution P exceeds the solubility product (K_{sp}) of the specific P–containing mineral. Thus, where water–soluble fertilizers are applied, as was the case with grower practice, soil solution P concentration increases greatly depending on P rate and method of application (Havlin et al., 2005). Nelson et al. (2005) attributed excessive P leaching on a loamy soil to over-application of P, low P sorption capacity of the soil and rainfall exceeding evaporation. Soil solution P levels are buffered by adsorbed P on mineral surfaces (labile P), organic P mineralization and P mineral dissolution (Havlin et al., 2005). The P leaching in this study might be due to residual P, such that even with standard P application rates and irrigation, excess P dissolves and becomes available for uptake and leaching as observed by several researchers (He et al., 2000; Nelson et al., 2005; Kiggundu et al., 2011). Thus understanding P–fixation processes is important for optimum P nutrition and efficient fertilizer management.

At Immokalee, M1K decreased with depth and was <15 mg kg^{-1} throughout the 0-90 cm in all the treatments (Figure 3-18A) varying between 10-20 mg kg^{-1} in the 0-30 cm depth in all treatments. In the 30-90 cm soil depth, K was ~15 mg kg^{-1} for CMP while that for MOHS and DOHS was lower than 10 mg kg^{-1} (Figure 3-18A). In July 2010, soil K at Lake Alfred site M1K remained between 15 and 45 mg kg^{-1} (Figure 3-18B).
How ever, Havlin et al. (2005) observed that K leaching losses may be significant in coarse-textured or organic soils in humid regions or under irrigation, as is the case with Florida. Thus carefully split applications rather than a buildup of soil K should be emphasized. Potassium (K) source can influence the amount K leached e.g. compared with KCl, the SO_4^{-2} and PO_4^{-2} sources exhibit greater anion adsorption to (+) exchange sites. Thus with fewer anions in solution available for leaching, fewer K^+ would be leached. Therefore, the efficient irrigation practices through ACPS/OHS practices would significantly reduce fertilizer lost through leaching by promoting uptake and reducing the occurrence of saturated flow and drainage as discussed later in Chapter 5.

Measured soil Br distribution increased over time with depth on Immokalee sand accumulating in the bottom 30-60 cm layers in the irrigated zone. The soil Br spiked to 6 mg kg^{-1} in the irrigated and nonirrigated zones on June 10, 2011 (Appendix A, Figures A1 and A2). However, the initial soil Br was negligibly low ~0-1 mg kg^{-1}, and started increasing immediately after Br application on June 8. A similar trend was observed within the non-irrigated zone probably due to the rains in June 2011. At the Lake Alfred site, soil Br was low (~0-1.5 mg kg^{-1}), initially increasing to about 4.5 and 16 mg kg^{-1} after first application on August 23, 2011, and thereafter decreasing substantially due to heavy rains around the same time (Appendix A, Figures A3 and A4). Thus most of the Br was washed away 6 to 10 days after application from the 0-60 cm soil profile.

The inorganic N (NH_4) remained between 0.5 and 14.0 mg kg^{-1} in the irrigated and nonirrigated zone at 0-30 cm depth of Immokalee site (Appendix A, Figures A5 and A6). Nitrate-N was consistently higher for DOHS ~ 6 – 12 mg kg^{-1} while CMP and MOHS remained between 1 and 6 mg kg^{-1} in the top 0-30 cm in both irrigated and nonirrigated zones on Immokalee sand (Appendix A, Figures A7 and A8). The NH_4-N and NO_3-N concentration were similar in both irrigated and nonirrigated zones at 45- and 60 cm soil depths on Immokalee sand for CMP and MOHS while nitrate-N was significantly higher in the irrigated than non-irrigated zones of DOHS. At the Lake Alfred site NH_4-N ranged between 0.5 and 25 mg kg^{-1} in the top 0-30 cm depth in both irrigated and nonirrigated zones, with significantly higher values observed using CMP compared with ACPS/OHS treatments (Appendix A, Figures A9 and A10). The NH_4-N concentration at the Lake Alfred site varied between 0.5 and 9.0 mg kg^{-1} in the irrigated zone and between 0.2 and 3.0 mg kg^{-1} in the nonirrigated zone of the 30-60 cm soil depth (Appendix A, Figure

A10). As shown in Figures A11 and A12, the nitrate N values varied between 0.5 and 20 mg kg^{-1} in both irrigated and nonirrigated zones of the 0-30 cm soil depth layer for all treatments, except CMP where concentration as high as 30 mg kg^{-1} was noted in the irrigated zone. At 30-60 cm depth (Appendix A, Figures A11 and A12), all treatments but CMP, showed nitrate N varying between 0 and 8 mg kg^{-1} while CMP nitrate N peaked to about 40 mg kg^{-1} at 30-45 cm depth(Appendix A, Figure A11) in the irrigated zone vs. 12 mg kg^{-1} in the nonirrigated zone at 45-60 cm soil depth using CMP.

At the Immokalee site, Mehlich 1 P (M1P) varied between 25 and 160 mg kg^{-1} in the top 0-30 cm of the irrigated zone (Appendix A, Figure A13), with very high M1P values decreasing in the order DOHS>CMP>MOHS in the 0-15 cm depth layer in the irrigated zone throughout the sampling period. The M1P in the nonirrigated zone was either high or very high for CMP and MOHS in the 0-30 cm soil depth and medium or low for DOHS (Appendix A, Figure A14). The M1P values remained between 0.1 and 50 mg kg^{-1} in the 30-60 cm depth of the nonirrigated zones suggesting that most P might have been subjected to root uptake in the top 0-30 cm layer. Comparatively lower M1P values were noted in the 0-15 cm, 15-30 cm, and 30-45 cm and 45-60 cm soil depth layers of the nonirrigated zones. M1P peaked to ~145 mg kg^{-1} using DOHS, MOHS and CMP in the 0-45 cm segment in the irrigated zone and remained below 25 mg kg^{-1} in the lower 45-60 cm depth layer. This is a clear indication that P application rate ~50-70 kg P ha^{-1} for Immokalee sand is adequate for trees <5 yr-old grown on the Flatwoods using either conventional or ACPS/OHS practices without any serious P leaching threat. The M1P at the Lake Alfred site was very high with averages ranging from 100 to 250 mg kg^{-1} in the irrigated (Appendix A, Figure A15) and nonirrigated zones of all treatments (Appendix A, Figure A16). The high values point to the need to lower the P application rate for the Lake Alfred site due to high residual P or the young tree age that might culminate in luxurious P consumption with no economic yield advantage.

The irrigated zone of Immokalee sand (Appendix A, Figure A17) showed Mehlich 1 K (M1K) values in the range of 18-80 mg kg^{-1} in the 0-30 cm soil depth and between 12-40 mg kg^{-1} in the 30-45 cm soil depth suggesting a significant decrease in M1K with depth. Except for CMP at 0-15 cm soil depth where M1K~100 mg kg^{-1} was noted, most of the M1K values in the nonirrigated zones were <60 mg kg^{-1} (Appendix A, Figure A18). As explained earlier in Chapter 3, all the fertigated zones of CMP were irrigated implying a fairly uniform nutrient distribution around the tree using this system. At the Lake Alfred site, significantly higher values of M1K (~75-175 mg kg^{-1}) were noted using CMP in all the sampled depths in the irrigated zones while DOHS-Swingle, MOHS and DOHS-C35 showed values varying between 30 and 140 mg kg^{-1} in the 0-45 cm soil depth (Appendix A, Figure A19). Only in the 45-60 cm soil depth did M1K under MOHS vary between 25 and 110 mg kg^{-1} while DOHS- Swingle and DOHS-C35 remained between 25 and 55 mg kg^{-1}. The M1K was also high in the ‘nonirrigated’ zone of CMP varying between 50 - 250 mg kg^{-1} at 0-15 cm, 60 - 100 mg kg^{-1} at 15-30 cm, 40 - 85 mg kg^{-1} at 30-45 cm, and 40 – 70 mg kg^{-1} at 45-60 cm soil depth layers. The MOHS, DOHS-Swingle and DOHS-C35 had values ranging between 20-75 mg kg^{-1} in all sampling depths except on August 24, 2011 when MOHS showed M1K~90 mg kg^{-1} (Figure Appendix A, A20).

Water Quality Analysis

Nitrate N leaching was very low at Immokalee with nitrate-N <1.7 mg L^{-1} in the irrigated zone of all treatments (Appendix A, Figure A21), much lower than the maximum contaminant limit suggested by USEPA of 10 mg NO_3^--N L^{-1}. At the Lake Alfred site, Schumann et al (2010) showed that CMP had nitrate concentration >10 ppm in July, August and September 2009 and March 2010 while MOHS had nitrate >10ppm in July 2009 and January 2010, and for DOHS <10 ppm was observed between July 2009 and January 2010. The results at the Lake Alfred site show that DOHS and carefully managed fertigated treatments should minimize N leaching, as also demonstrated at the Immokalee site.

Biomass and Nutrient Distribution as a Function of Irrigation Practice

Total above-ground biomass (dry weight-basis) contributed 69.4%, 75.4% and 76.0% while total below-ground biomass (dry weight-basis) accounted for 30.6%, 24.6% and 24.0% of total tree biomass using DOHS, MOHS and CMP at Immokalee, respectively, as shown in Table 3-6. The biomass under DOHS was distributed as follows: young leaves = 6.7%, fully expanded leaves = 12.8%, fruits = 11.6%, twigs = 11.2%, small branches = 4.3%, medium branches = 5.6%, large branches = 4.3%, trunk = 12.8%, small roots (<0.5 mm) = 1.0%, medium roots (0.5-1.0 mm) = 1.8 %, large roots (1.0-3.0 mm) = 3.6%, largest roots (>3 mm) = 24.2%. The biomass under MOHS was distributed as follows: young leaves = 8.0%, fully expanded leaves = 8.0%, fruits = 20.6%, twigs = 11.9%, small branches = 4.4%, medium branches = 3.6%, large branches = 6.6%, trunk = 12.3%, small roots (<0.5 mm) = 2.2%, medium roots (0.5-1.0 mm) = 0.6 %, large roots (1.0-3.0 mm) = 2.1%, largest roots (>3 mm) = 19.7%. The biomass under CMP was apportioned as follows: young leaves = 10.3%, fully expanded leaves = 2.2%, fruits = 23.5%, twigs = 9.5%, small branches = 4.3%, medium branches = 4.1%, large branches = 8.3%, trunk = 13.8%, small roots (<0.5 mm) = 1.6%, medium roots (0.5-1.0 mm) = 0.4 %, large roots (1.0-3.0 mm) = 1.6%, largest roots (>3 mm) =

20.3%. The subsamples of tissue samples for the Lake Alfred site are described in Table 3-7. Above-ground tissues accounted for slightly above 90% of the total dry and fresh weight of subsamples while roots were <10% of total weight.

The nutrient concentrations for the two research sites are presented in Tables 3-8 and 3-9. With reference to guidelines of orange tree analysis in Table 2-4, N (%) was adequate for all treatments at sampling time. P and K were sufficient in all treatments. From the results, P was uniformly distributed among the various tissues in the treatments studied at Immokalee (Table 3-8). However, at the Lake Alfred site a fairly large amount of P was allocated to the roots for the Swingle rootstock (regardless of the fertigation method) and in the leaves for the C35 rootstock (Table 3-9). Generally, the N concentration was highest in the leaves followed by roots, fruits, twigs and branches. Potassium was distributed uniformly across all tissues using Swingle rootstock but significantly low K (%) was noted in the roots of C35 rootstock (<0.75%). Overall, the study notes that most of the OHS treatments, including the conventional grower practices, meet orange tree nutrition requirements.

As shown in the tree nutrient accumulation (Table 3-10) at Immokalee site, DOHS and MOHS accumulated about 44% more N than CMP. Thus, the nutrient accumulation showed lower N accumulation (~79 kg N ha^{-1}) at Immokalee than DOHS (115 kg N ha^{-1}) or MOHS (114 kg N ha^{-1}) (Table 3-10). However, CMP accumulated more P and K than DOHS and MOHS suggesting that even the grower practice was just as good in prompting nutrient accumulation. Nutrient accumulation at both sites analyzed in the leaves, fruits, twigs and roots showed that CMP at Immokalee had the lowest N accumulation in roots (5.6-13.8 g kg^{-1}) while the ACPS/OHS practices on Swingle rootstock at both sites and CMP at the Lake Alfred site had N contents ranging from 7.8-22.6 g kg^{-1} while the DOHS-C35 had N content of ~22 g kg^{-1} in fibrous roots (<0.5 mm in diameter) and 5.8-9.9 g kg^{-1} in roots >0.5 mm in diameter. The N accumulation in twigs at Immokalee was 56 to 132% greater using ACPS than CMP. At the Lake Alfred site, N content in twigs was similar 10.6-13.6 g kg^{-1} in all the four fertilization methods, which was about 1.24 to 3.4 times greater than the Immokalee site. The limited N accumulation in twigs might be ascribed to citrus greening in the Immokalee citrus trees in the third year of the study which might have limited N uptake. Nitrogen for C35 rootstock was largely allocated in the fruits (24.2 g kg^{-1}) compared with trees in the other fertilization methods. The leaf N accumulation at both sites was between 25.2 and 37.7 g kg^{-1}. At the Lake Alfred site, nutrient accumulation for N followed the order MOHS>DOHS-C35>CMP>DOHS-Swingle while P was DOHS-C35>MOHS> DOHS-Swingle >CMP and K was DOHS-C35>MOHS> DOHS-Swingle >CMP (Table 3-11).The P accumulation was similar among the fertilization methods at both sites, falling between 1.1 and 2.3 g kg^{-1}. The K distribution in tissue shows fairly equal allocations to various plant parts using Swingle rootstocks while for C35, the K was largely allocated to the above-ground parts (13.2-15.2 g kg^{-1}) and lower portions (3.3-7.5 g kg^{-1}) were allocated to the roots. The only plausible explanation for high N, P and K accumulation of CMP would be the use of the granular fertilization (4 to 6 times annually) and controlled-release fertilizer at the Lake Alfred site which might have promoted more N, P and K absorption over time compared with monthly fertigated CMP at Immokalee.

Summary

Results over the 2 to 3 year studies showed that NH_4^+-N, NO_3^--N, M1P and M1K was uniformly distributed in the root zone of grower practices but was higher in the irrigated than nonirrigated zones of OHS fertigation practices. Overall, NH_4^+-N, NO_3^--N, M1P and M1K decreased with distance from the irrigated zone and with depth. This confirmed the hypotheses that 'NH_4^+-N, NO_3^--N, M1P and M1K would vary with depth, distance from the tree and fertigation method' and that 'NH_4^+-N, NO_3^--N, M1P and M1K would be higher in irrigated than nonirrigated zones' suggesting the potential for increased nutrient retention and root uptake because the irrigated zone was associated with increased root density as later discussed in Chapter 4. Nitrate-N leaching was more pronounced for CMP at the Lake Alfred site with residual soil nitrate as high as 30 mg kg^{-1} but was largely minimal for all fertigation methods at Immokalee and the OHS fertigation methods at Lake Alfred. The use of Br suggested consistent trends in the movement of NH_4^+-N, NO_3^--N, M1P and M1K in the irrigated and nonirrigated zones, and could be used as an important guideline for making nutrient management decisions with regard to nutrient residence time. M1P was very high at Lake Alfred site, despite applying the recommended rate probably because of the young tree age, coated sands and residual P from previous tree plantings that could have become available from the sorbed or labile phases. M1P application rate at the Lake Alfred site might need to be lowered over time to reduce P loading threat into groundwater.

The citrus biomass distribution patterns were similar between the fertilization methods. All fertilization practices showed that leaf N, P and K concentrations were adequate. However, proportional nutrient accumulation patterns revealed that OHS fertigation increased N accumulation by 45% over grower practice at Immokalee, but P and K accumulation were fairly similar between the three practices, though CMP showed slightly higher P and K accumulation than OHS. Thus, N accumulation confirmed the hypothesis that ‘accumulation would be greater for OHS than grower practices’ but the this hypothesis did not hold for P and K accumulation. The N, P and K concentration using granular fertilization at the Lake Alfred site suggests that grower practices are just as effective in promoting tissue nutrient concentration. However, the grower practices (fertigated or under granular fertilization) might require more fertilizer and water applied per ha to achieve rapid tree development within 1 to 5 years of establishing a grove compared with ACPS practices.

Figure 3-1. Destructive tree sampling in July 2011 at Immokalee with the root zone of the tree marked to 30-cm depth(A), tree after defoliation and fruit removal (B), tree after twig removal (C), fresh twigs (D), plucking the tree trunk and roots (E) and fresh roots (F)

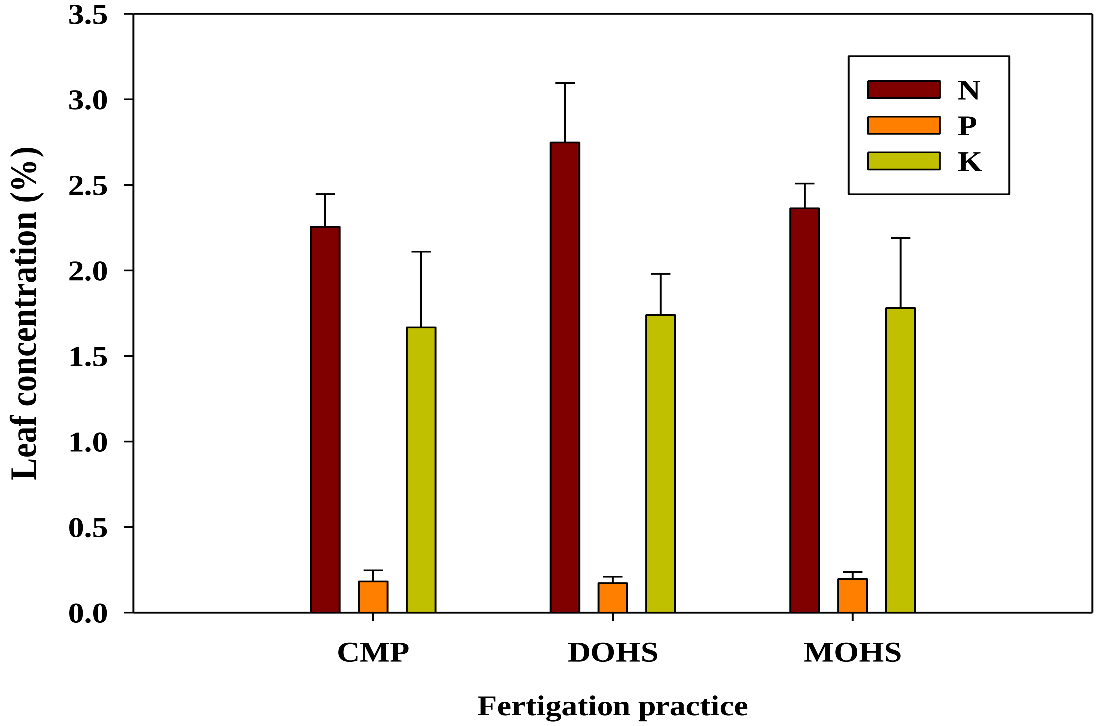


Figure 3-2. Leaf NPK concentration determined in June 2009 at Immokalee. Error bars denote one standard deviation of four replicates

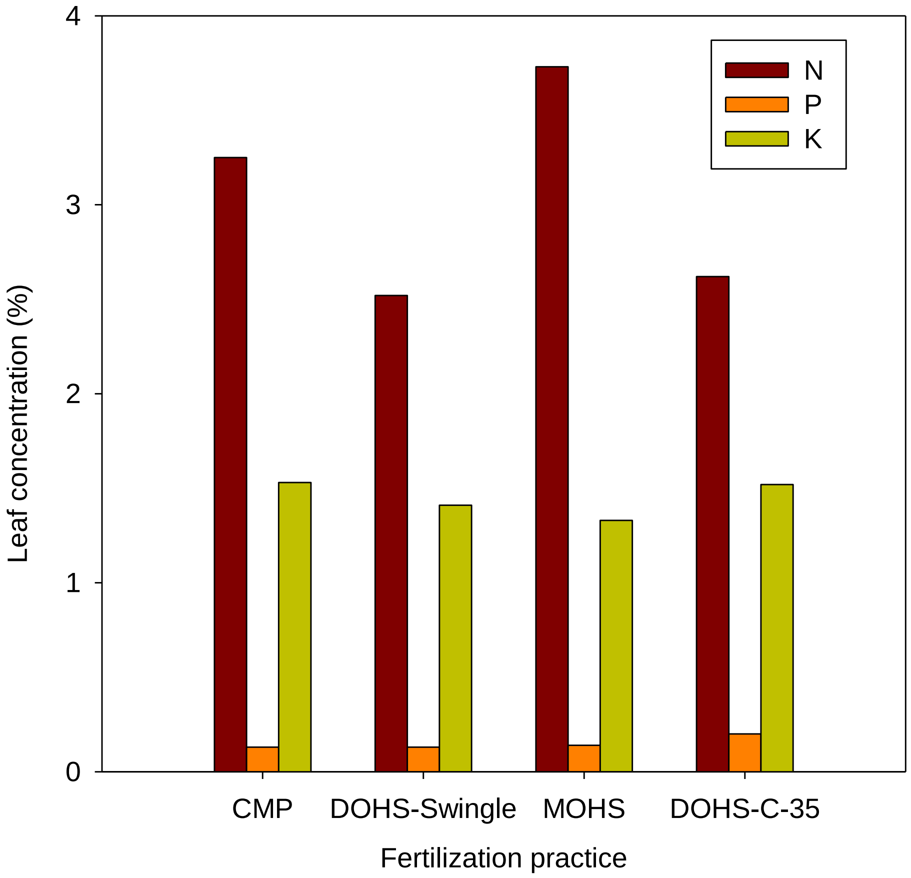


Figure 3-3. Leaf NPK concentration determined in August 2011 at the Lake Alfred site

Table 3-1. 2M KCl extractable $NH4^+$-N and NO_3^--N, M1K and M1P concentrations of soil samples collected in June 2009 at SWFREC

Fertigation method	NH_4^+-N		NO_3^--N		M1P		M1K	
	IRR[‡]	NI	IRR	NI	IRR	NI	IRR	NI
	mg kg^{-1}							
CMP	1.10	-[§]	1.63	-	33.52	-	5.61	-
DOHS	1.65	1.07	2.45	1.69	78.16	31.47	8.06	8.30
MOHS	1.47	1.58	1.78	1.40	25.05	20.67	6.9	5.54
Soil depth (cm)								
0-15	1.26	1.10	2.15	2.01	36.81	35.72	6.55	7.66
15-30	1.18	1.03	1.25	1.31	20.24	17.50	5.01	6.45
Statistics[¶]								
Fertigation method	***		NS		**		***	
Depth	*		NS		**		*	
Distance from the tree	NS		***		***		**	
Fertigation method*Depth	*		NS		NS		NS	
Fertigation method*Distance	NS		NS		NS		NS	
Depth*Distance	NS		NS		NS		NS	
Fertigation method*Depth*Distance	NS		NS		NS		NS	

[‡] IRR-Irrigated, NI-Non-irrigated, [§] For conventional practice, all the sampled locations were irrigated.

[¶] NS-not significant $p>0.05$; *-$p<0.05$, **-$p<0.01$, ***-$p<0.001$

Table 3-2. 2M KCl extractable NH4$^+$-N and NO_3^--N, M1K and M1P concentrations of soil samples collected in August 2009 at SWFREC

Irrigation method		NH_4^+-N		NO_3^-N		M1P		M1K	
	Soil depth	IRR[¶]	NI	IRR	NI	IRR	NI	IRR	NI
	cm				mg kg^{-1}				
CMP	0-15	1.47	-[§]	1.35	-	32.10	-	13.10	-
	15-30	1.12		1.20		12.80		11.27	
DOHS	0-15	1.54	1.30	1.50	1.22	35.78	24.97	13.45	12.72
	15-30	0.74	1.04	1.01	1.38	11.20	22.78	11.11	12.61
MOHS	0-15	2.03	1.81	1.63	1.51	50.62	22.10	13.55	13.19
	15-30	1.54	1.61	1.08	1.23	11.98	9.61	11.67	9.06
Statistics[‡]									
Irrigation method		NS		NS				NS	
Depth		NS		**		***		NS	
Distance from the tree		NS		NS		*		NS	
Irrigation method*Depth		NS		NS		NS		NS	
Irrigation method*Distance		NS		NS		NS		NS	
Depth*Distance		NS		NS		**		NS	
Irrigation method *Depth*Distance		NS		NS		NS		NS	

[¶] IRR-Irrigated, NI-Non-irrigated, [§] For conventional practices, all the sampled locations were irrigated.

[‡] NS-not significant $p>0.05$; *-$p<0.05$, **-$p<0.01$, ***-$p<0.001$

Table 3-3. 2M KCl extractable NH_4^+-N and NO_3^--N, M1K and M1P concentrations of soil samples collected in June 2010 at SWFREC

Fertigation method		NH_4^+-N		NO_3^--N		M1P		M1K	
	Soil depth	IRR[¶]	NI	IRR	NI	IRR	NI	IRR	NI
	cm	mg kg^{-1}							
CMP	0-15	2.07	-[§]	6.44	-	48.04	-	14.88	-
	15-30	1.75	-	4.70	-	27.93	-	15.53	-
	30-45	1.32	-	3.50	-	17.15	-	12.28	-
DOHS	0-15	4.19	3.95	4.34	3.91	81.80	36.73	21.32	15.53
	15-30	2.98	2.02	3.23	2.50	32.78	20.41	14.45	9.67
	30-45	2.03	1.44	2.60	2.15	15.59	11.44	10.61	7.21
MOHS	0-15	3.33	3.69	5.24	4.70	81.24	30.89	14.21	10.23
	15-30	1.89	2.97	3.98	7.40	34.31	28.23	10.61	8.90
	30-45	1.57	2.78	2.77	3.37	23.46	14.05	9.45	7.59
Statistics[‡]									
Fertigation method		***		***		NS		***	
Depth		***		***		***		***	
Distance from the tree		NS		NS		***		NS	
Fertigation method*Depth		NS		NS		NS		*	
Fertigation method*Distance		**		NS		*		*	
Depth*Distance		NS		NS		***		NS	
Fertigation method*Depth*Distance		NS		NS		NS		NS	

[¶] IRR-Irrigated, NI-Non-irrigated, [§] For conventional practices, all the sampled locations were irrigated.

[‡] NS-not significant $p>0.05$; *-$p<0.05$, **-$p<0.01$, ***-$p<0.001$

Table 3-4. 2M KCl extractable NH_4^+-N and NO_3^--N, M1K and M1P concentrations of soil samples collected in December 2009 at the Lake Alfred site

Irrigation method		NH_4^+-N		NO_3^-N		M1P		M1K	
	Soil depth	IRR[¶]	NI	IRR	NI	IRR	NI	IRR	NI
	cm	mg kg^{-1}							
CMP	0-15	1.40	-[§]	4.02		101.29		63.10	
	15-30	1.03		4.39		91.49		56.28	
DOHS-Swingle	0-15	1.18	1.23	1.65	1.74	154.74	104.10	10.70	13.48
	15-30	0.92	0.83	1.48	1.43	136.33	122.42	7.06	8.98
DOHS-C35	0-15	1.59	1.75	1.71	1.49	209.24	104.72	31.75	22.90
	15-30	1.35	1.10	1.38	1.47	167.92	99.45	29.16	12.57
MOHS	0-15	1.12		1.53		147.01		37.97	
	15-30	0.94		1.62		139.35		24.58	
Statistics[‡]									
Irrigation method		*		***		***		***	
Depth		**		NS		NS		**	
Distance from the tree		NS		NS		***		NS	
Irrigation method*Depth		NS		NS		NS		NS	
Irrigation method*Distance		NS		**		***		**	
Depth*Distance		*		NS		NS		NS	
Irrigation method *Depth*Distance		NS		NS		NS		NS	

[¶] IRR-Irrigated, NI-Non-irrigated, [§] For conventional practice and MOHS in December 2009, all the sampled locations were irrigated, [‡] NS-not significant $p>0.05$; *-$p<0.05$, **-$p<0.01$, ***-$p<0.001$

Table 3-5. 2M KCl extractable NH_4^+-N and NO_3^--N, M1K and M1P concentrations of soil samples collected in July 2010 at the Lake Alfred site

Irrigation method		NH_4^+-N		NO_3^-N		M1P		M1K	
	Soil depth	IRR[¶]	NI	IRR	NI	IRR	NI	IRR	NI
	cm					mg kg^{-1}			
CMP	0-15	10.49	-[§]	20.55	-	105.96	-	46.04	-
	15-30	9.51		17.40		98.00		35.00	
DOHS-Swingle	0-15	2.64	2.12	7.59	6.31	105.88	88.52	35.56	24.55
	15-30	2.98	2.77	3.97	2.71	99.08	93.51	27.29	18.13
DOHS-C35	0-15	0.82	0.59	6.83	5.56	158.31	121.55	26.72	24.29
	15-30	0.62	0.60	3.07	2.95	134.61	106.70	17.98	19.97
MOHS	0-15	2.09	1.63	6.64	7.35	114.69	115.87	24.79	25.98
	15-30	2.21	1.48	3.55	3.55	126.04	131.63	21.42	21.39
Statistics[‡]									
Irrigation method		***		***		***		***	
Depth		NS		***		NS		***	
Distance from the tree		NS		NS		NS		NS	
Irrigation method*Depth		NS		NS		NS		NS	
Irrigation method*Distance		NS		**		NS		*	
Depth*Distance		NS		NS		NS		NS	
Irrigation method *Depth*Distance		NS		NS		NS		NS	

[¶] IRR-Irrigated, NI-Non-irrigated, [§] For conventional practices, all the sampled locations were irrigated.
[‡] NS-not significant p>0.05; *-p<0.05, **-p<0.01, ***-p<0.001

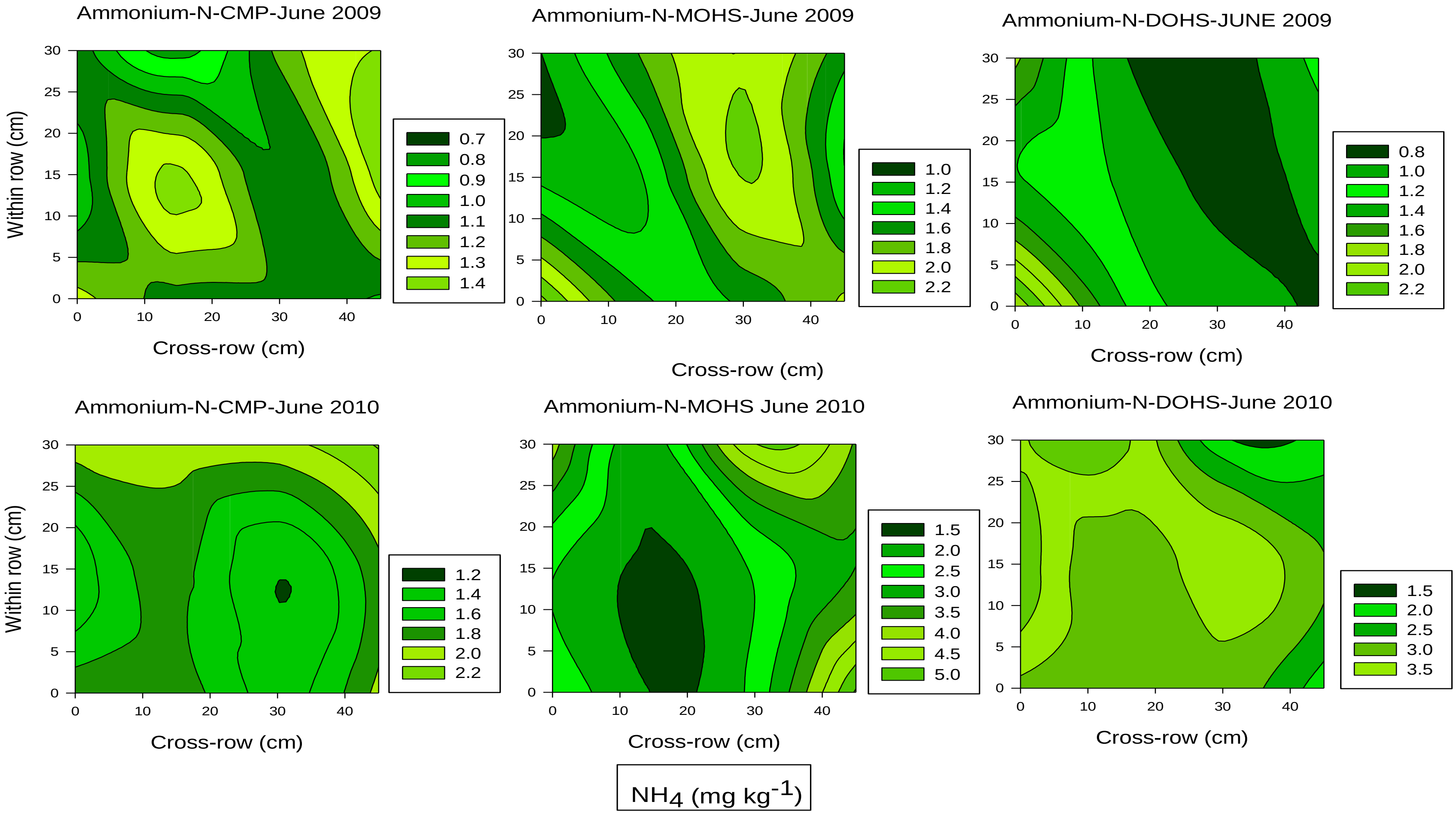


Figure 3-4. Lateral ammonium N distribution at 0-30 cm soil depth in June 2009 and 2010 at the Immokalee site

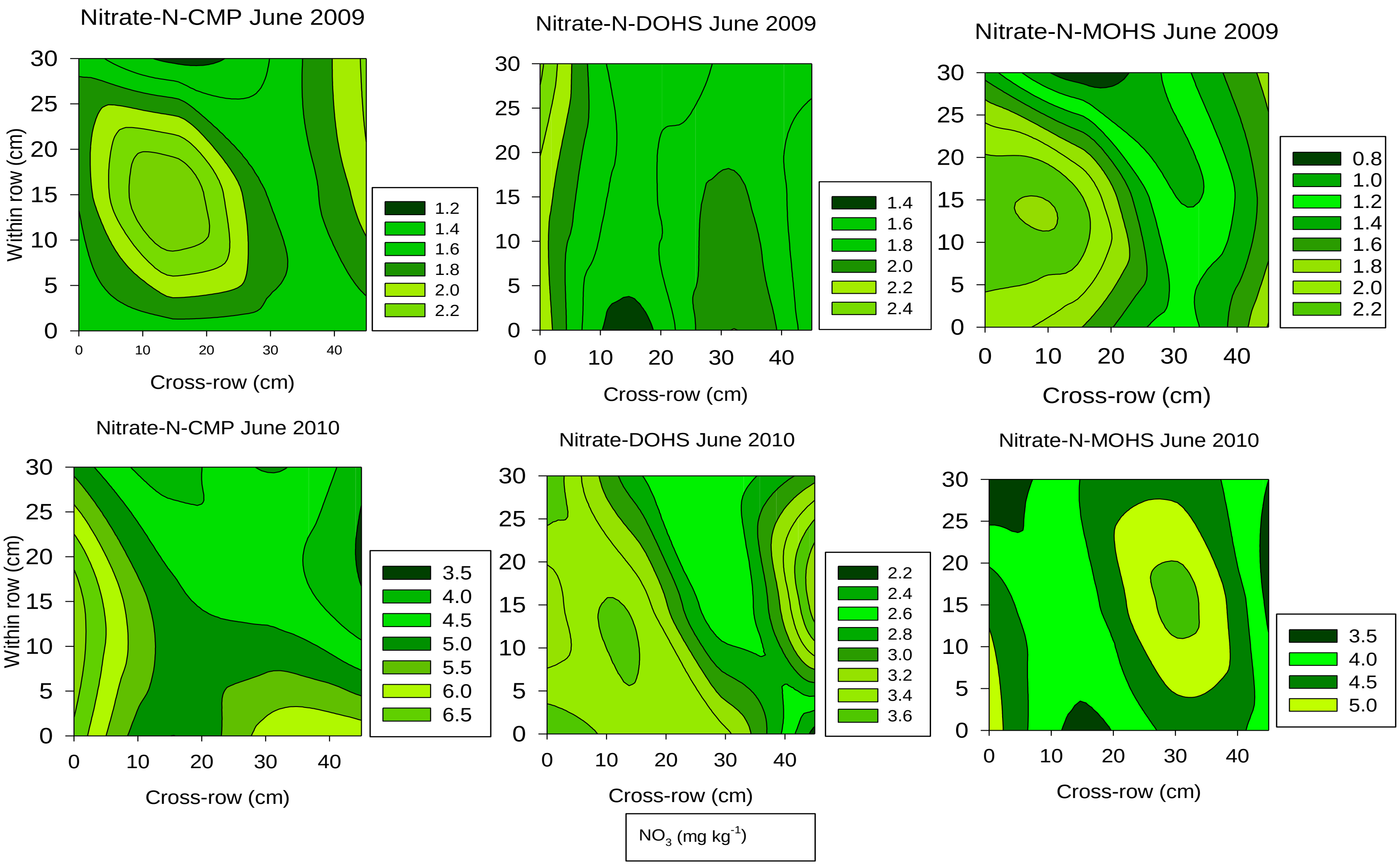


Figure 3-5. Lateral nitrate N distribution in June 2009 and 2010 at Immokalee site

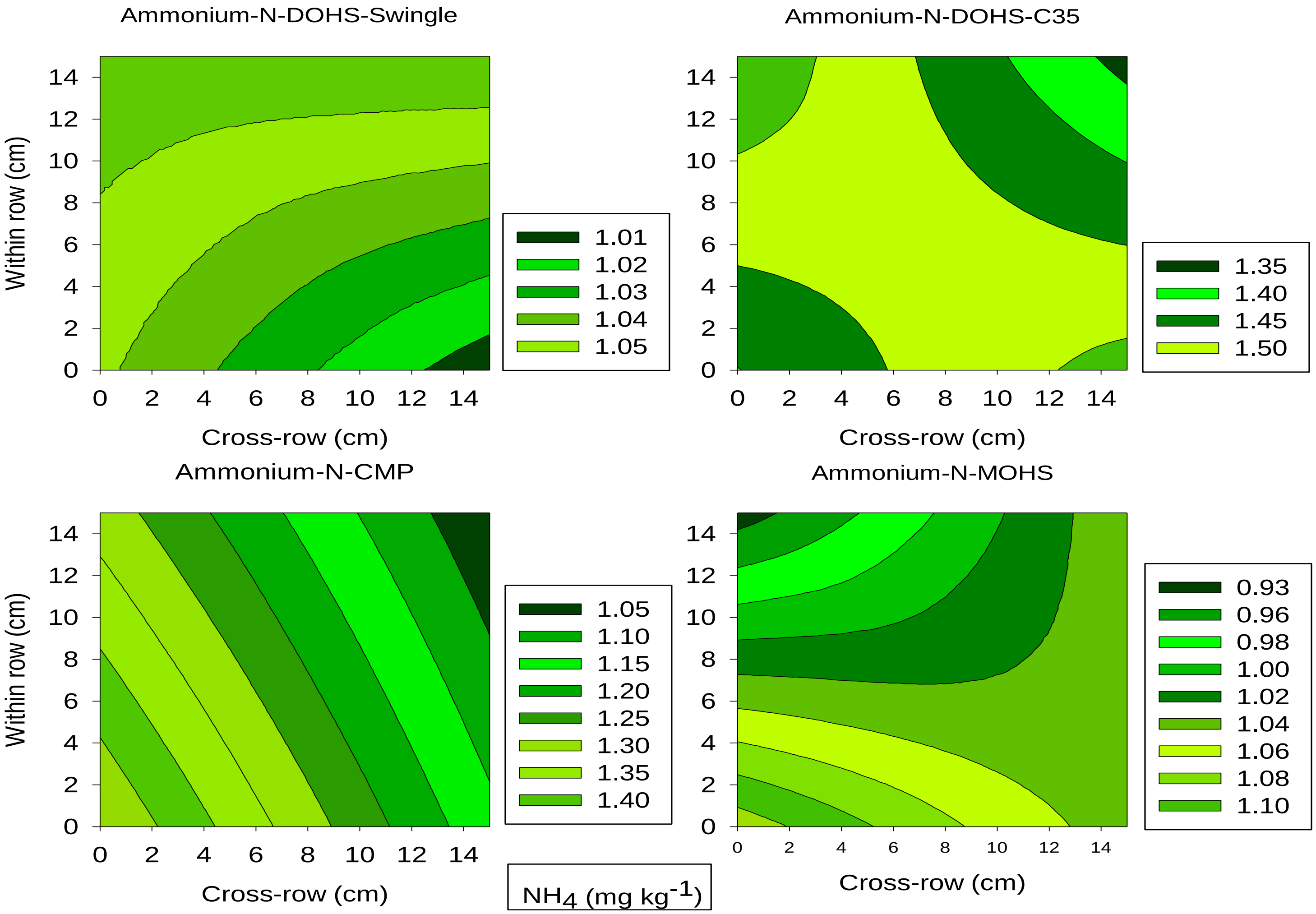


Figure 3-6. Lateral ammonium N distribution in December 2009 on Candler fine sand

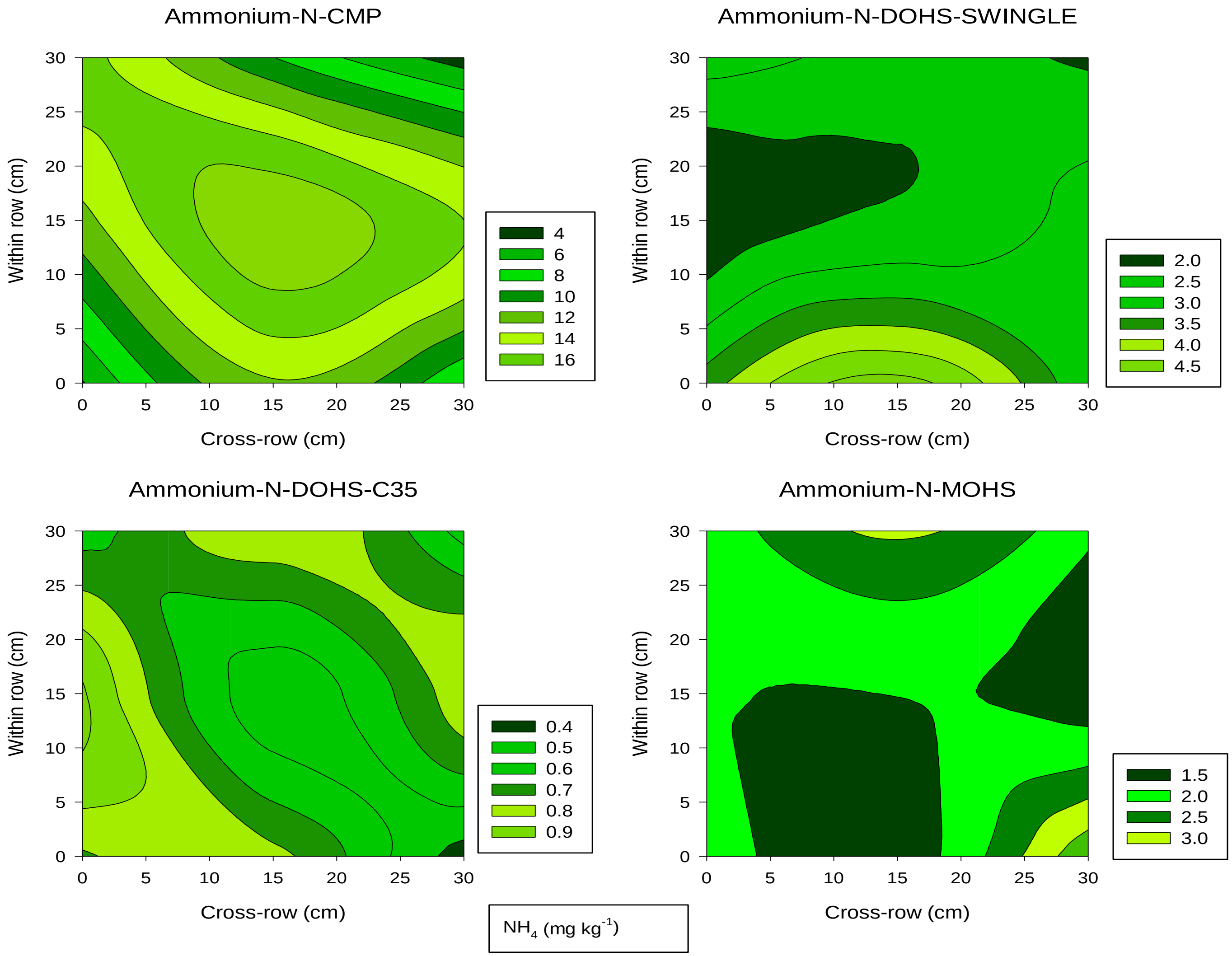


Figure 3-7. Lateral ammonium N distribution in July 2010 at the Lake Alfred site

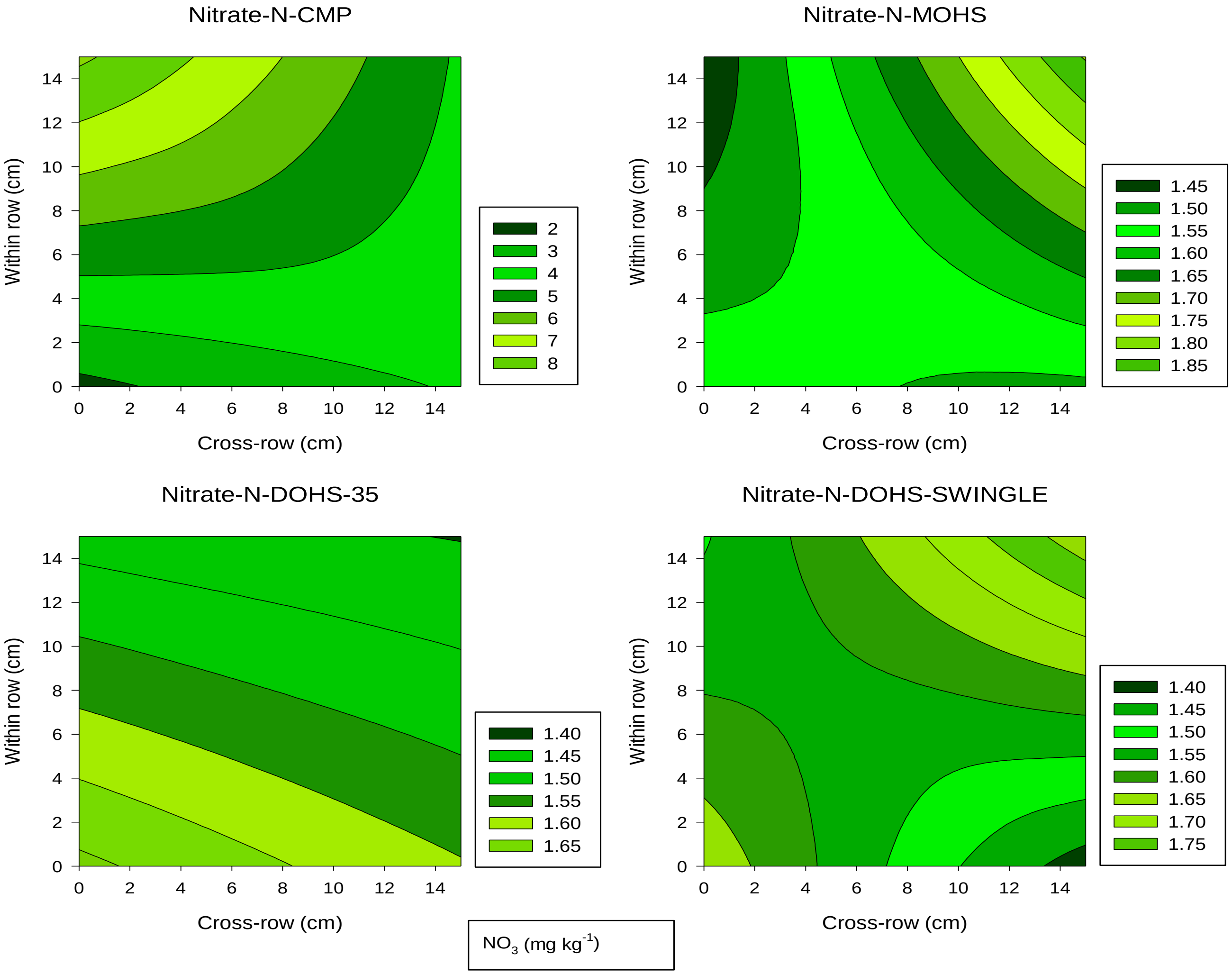


Figure 3-8. Lateral nitrate N distribution in December 2009 at the Lake Alfred site

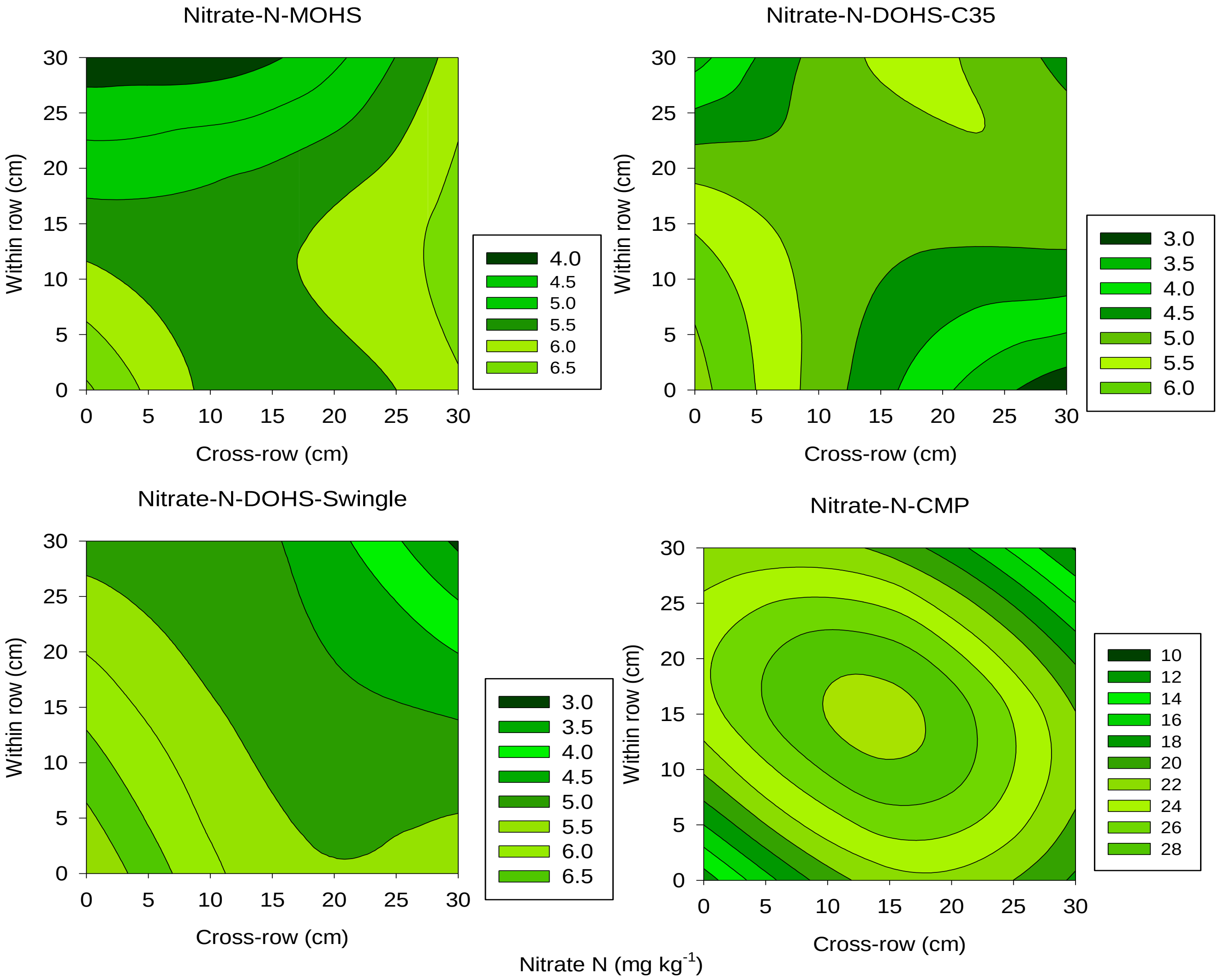


Figure 3-9. Lateral nitrate N distribution in July 2010 at the Lake Alfred site

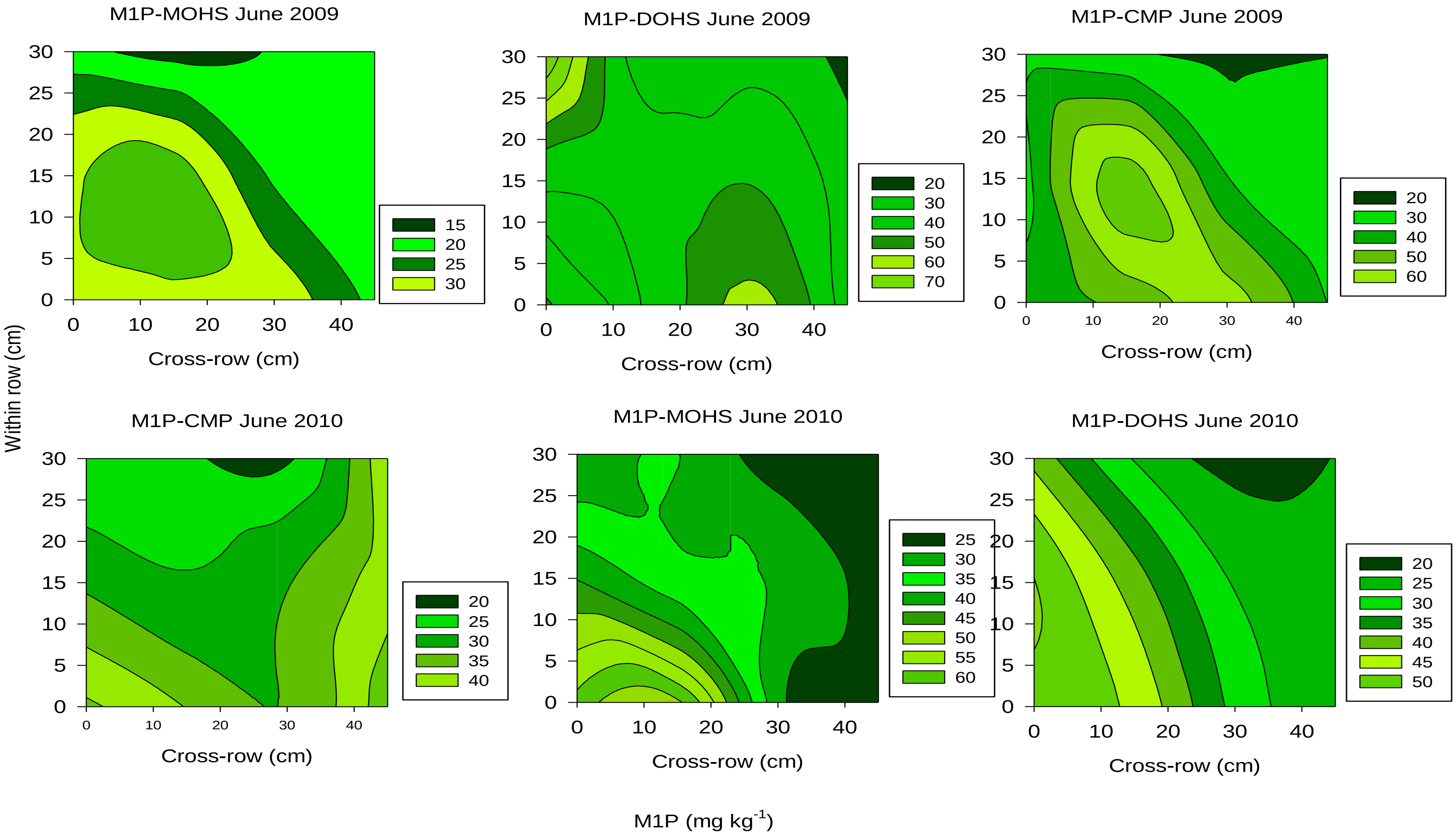


Figure 3-10. Lateral Mehlich 1 P distribution at Immokalee site in June 2009 and 2010

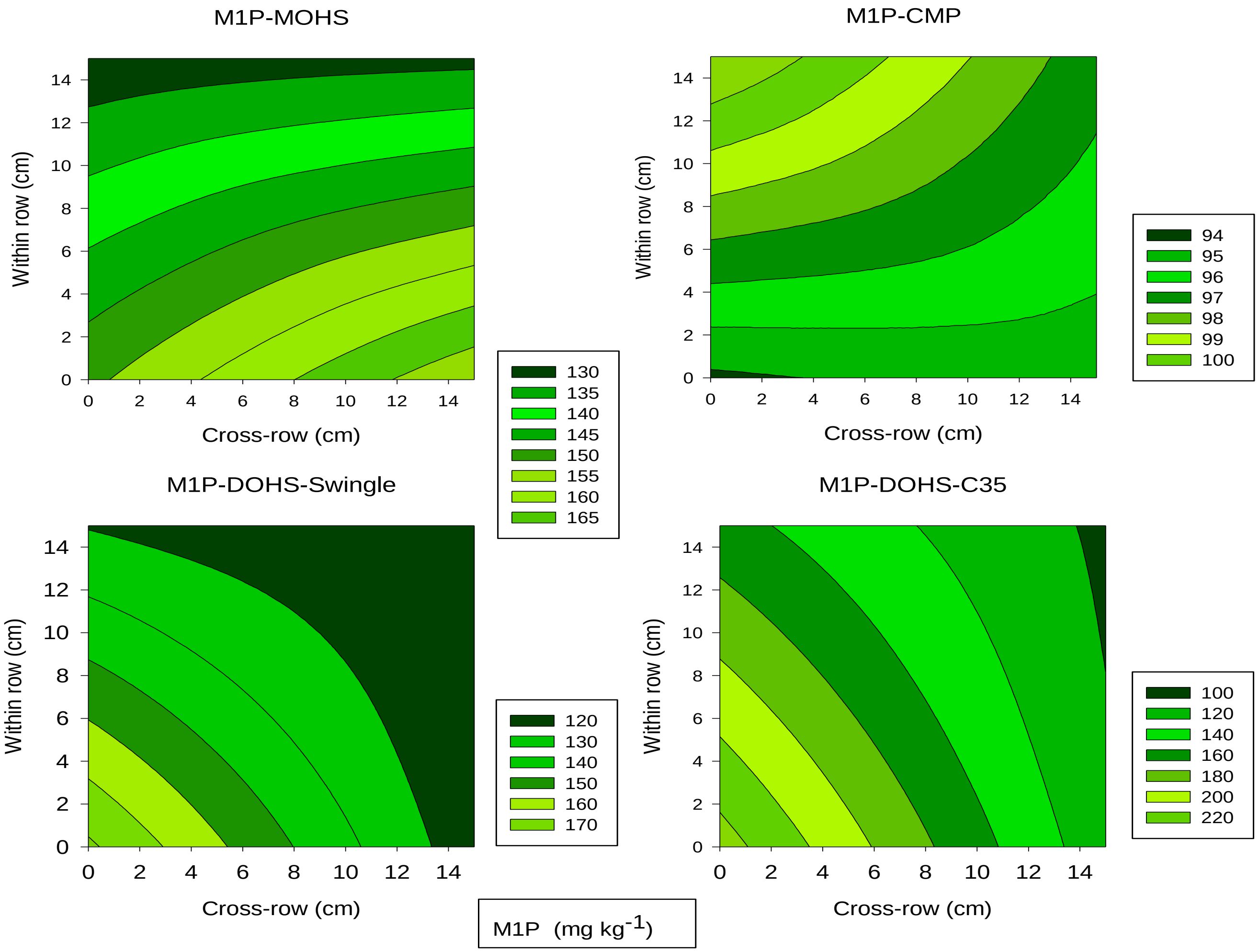


Figure 3-11. Lateral Mehlich 1 P distribution in the 0-30 cm depth layer at the Lake Alfred site in December 2009

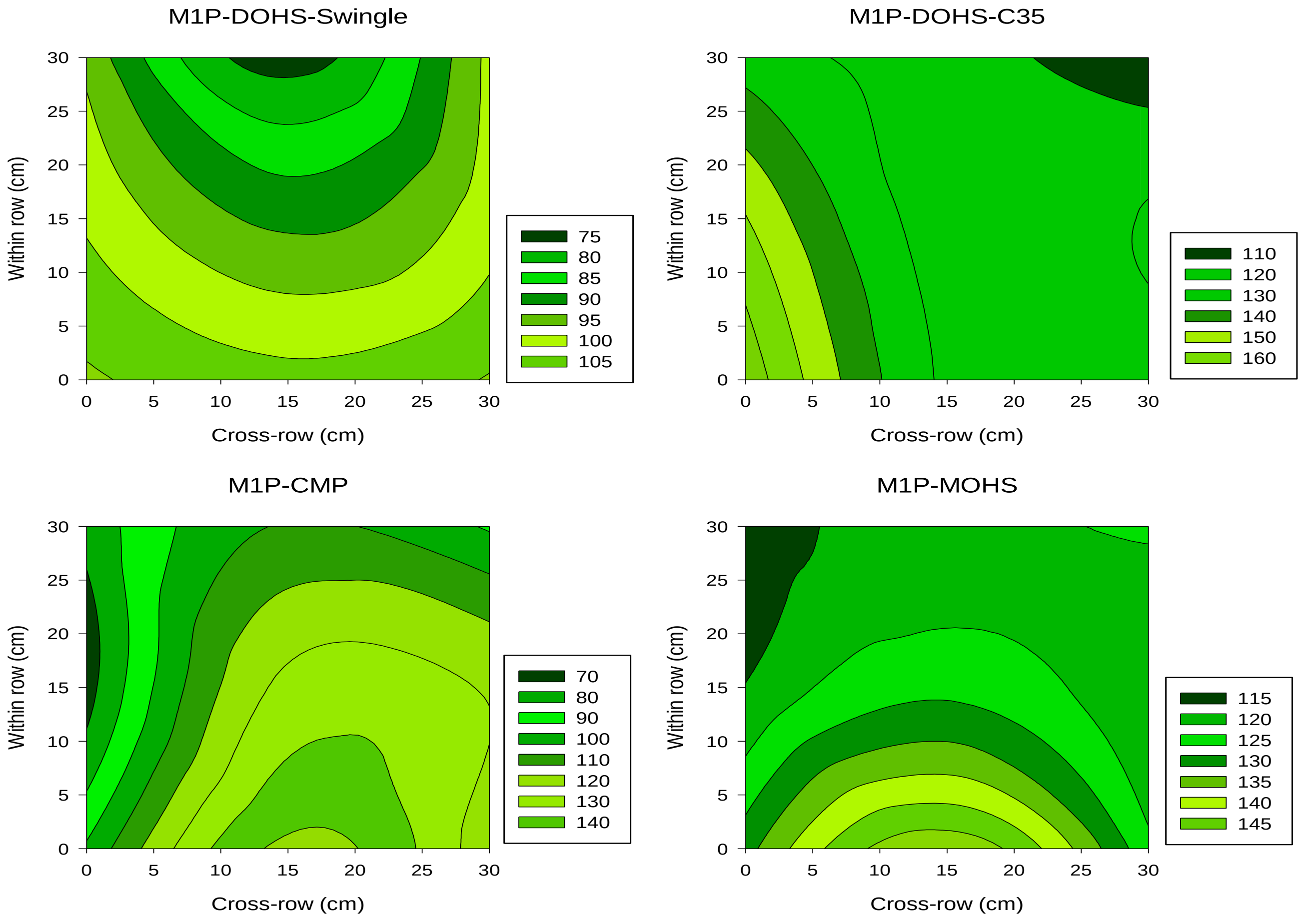


Figure 3-12. Lateral Mehlich 1 P distribution in the 0-30 cm depth layer at the Lake Alfred site in July 2010

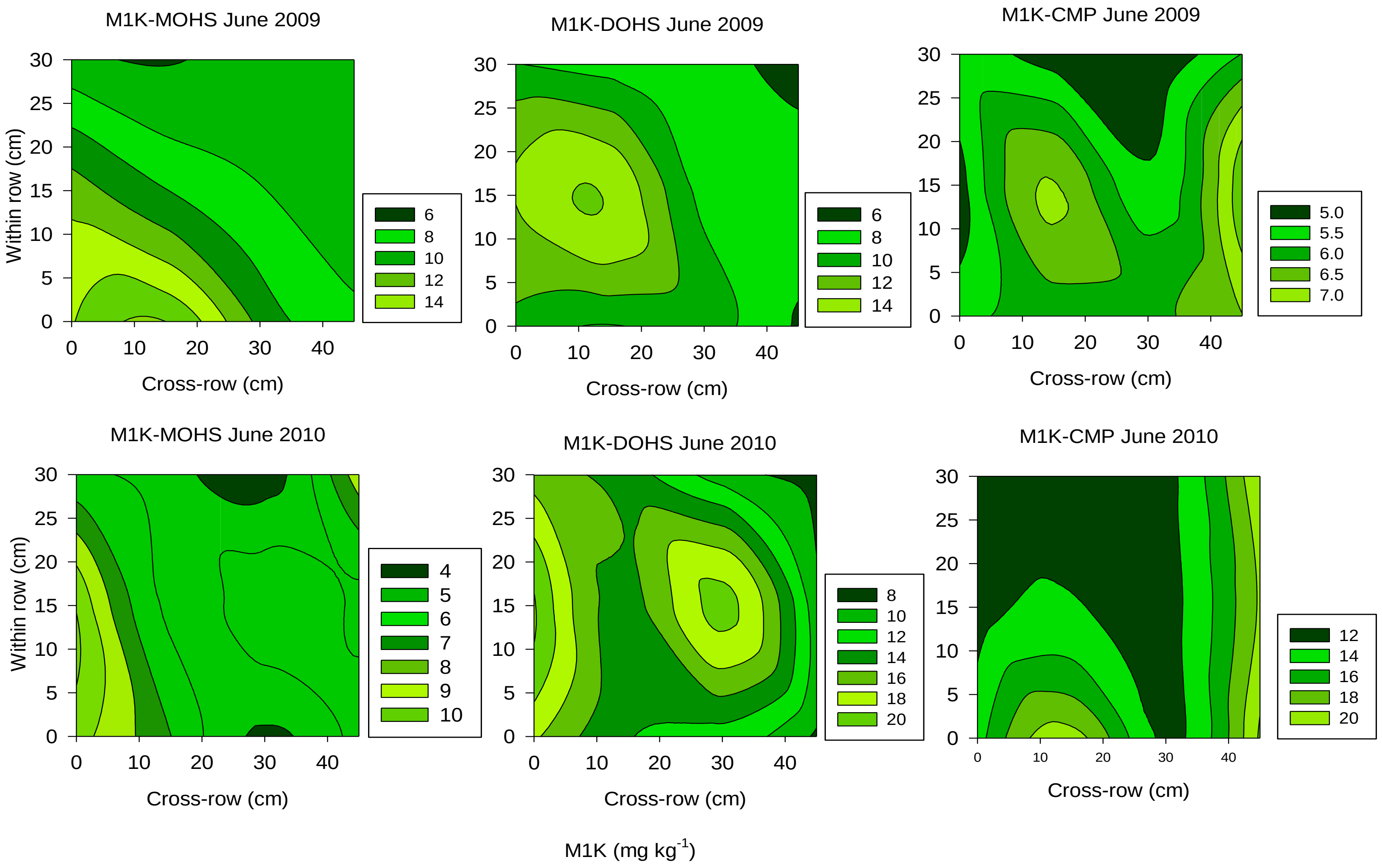


Figure 3-13. Lateral Mehlich 1 K distribution at Immokalee in June 2009 and 2010

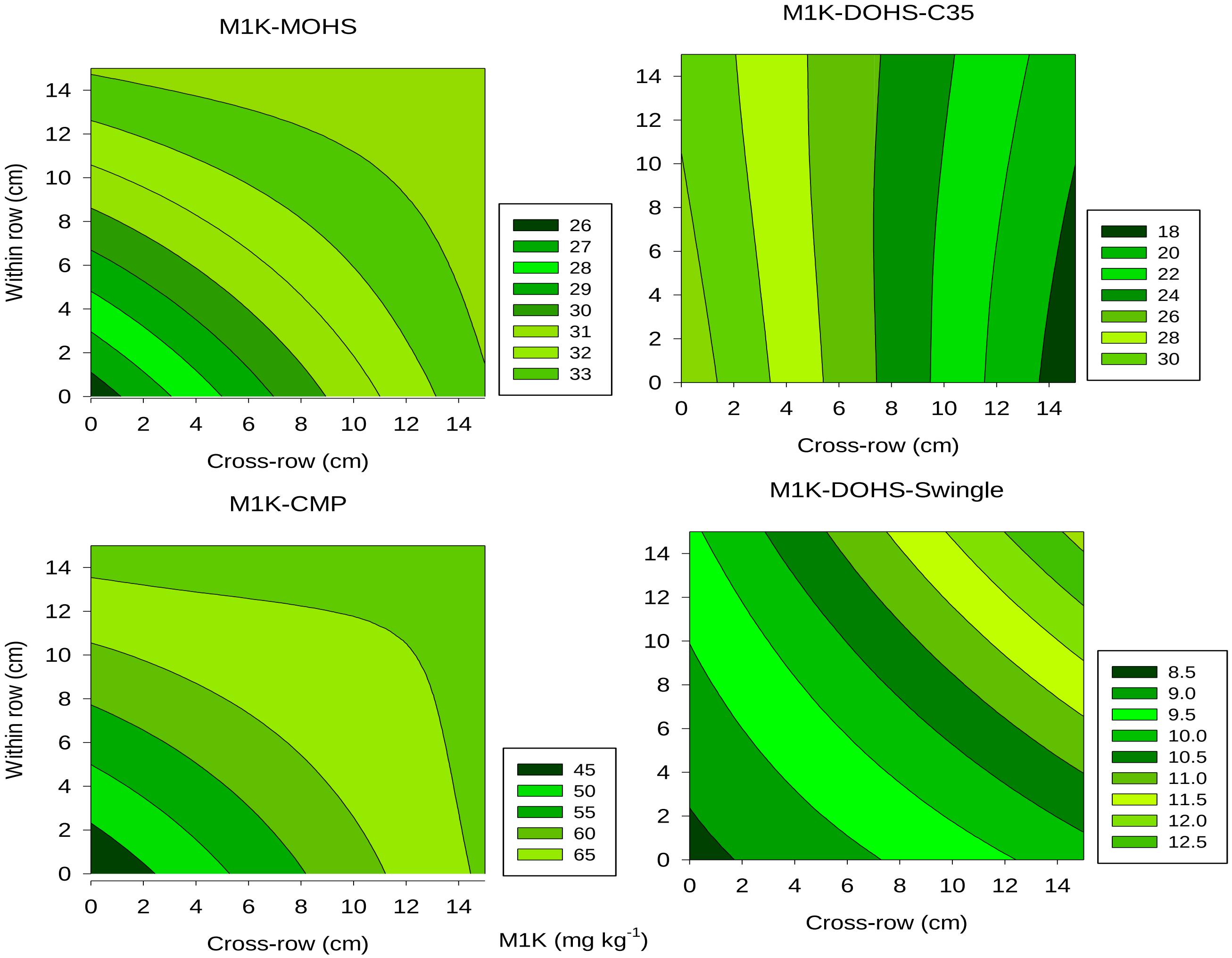


Figure 3-14. Lateral Mehlich 1 K distribution at the Lake Alfred site in December 2009

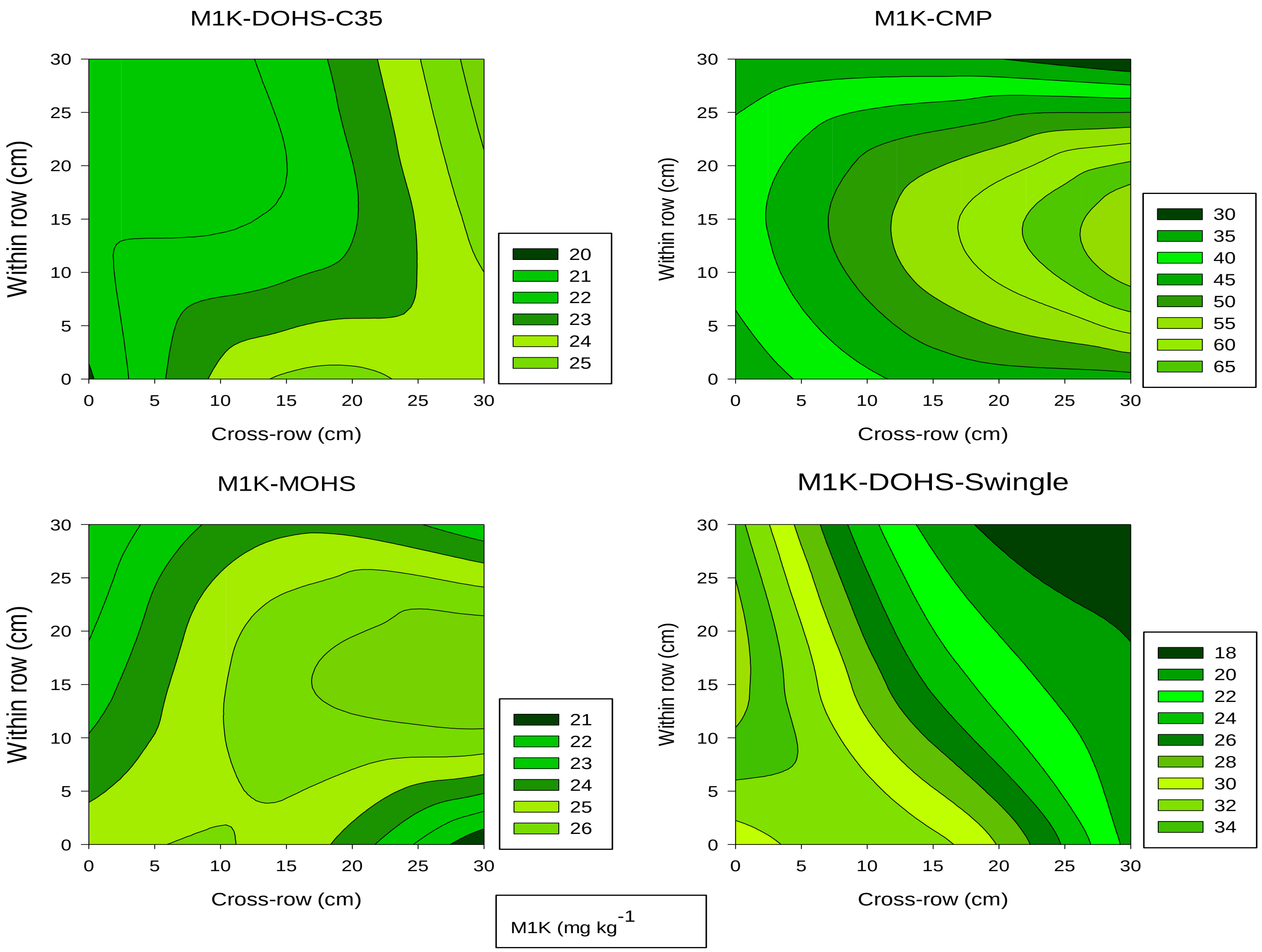


Figure 3-15. Lateral Mehlich 1 K distribution at the Lake Alfred site in July 2010

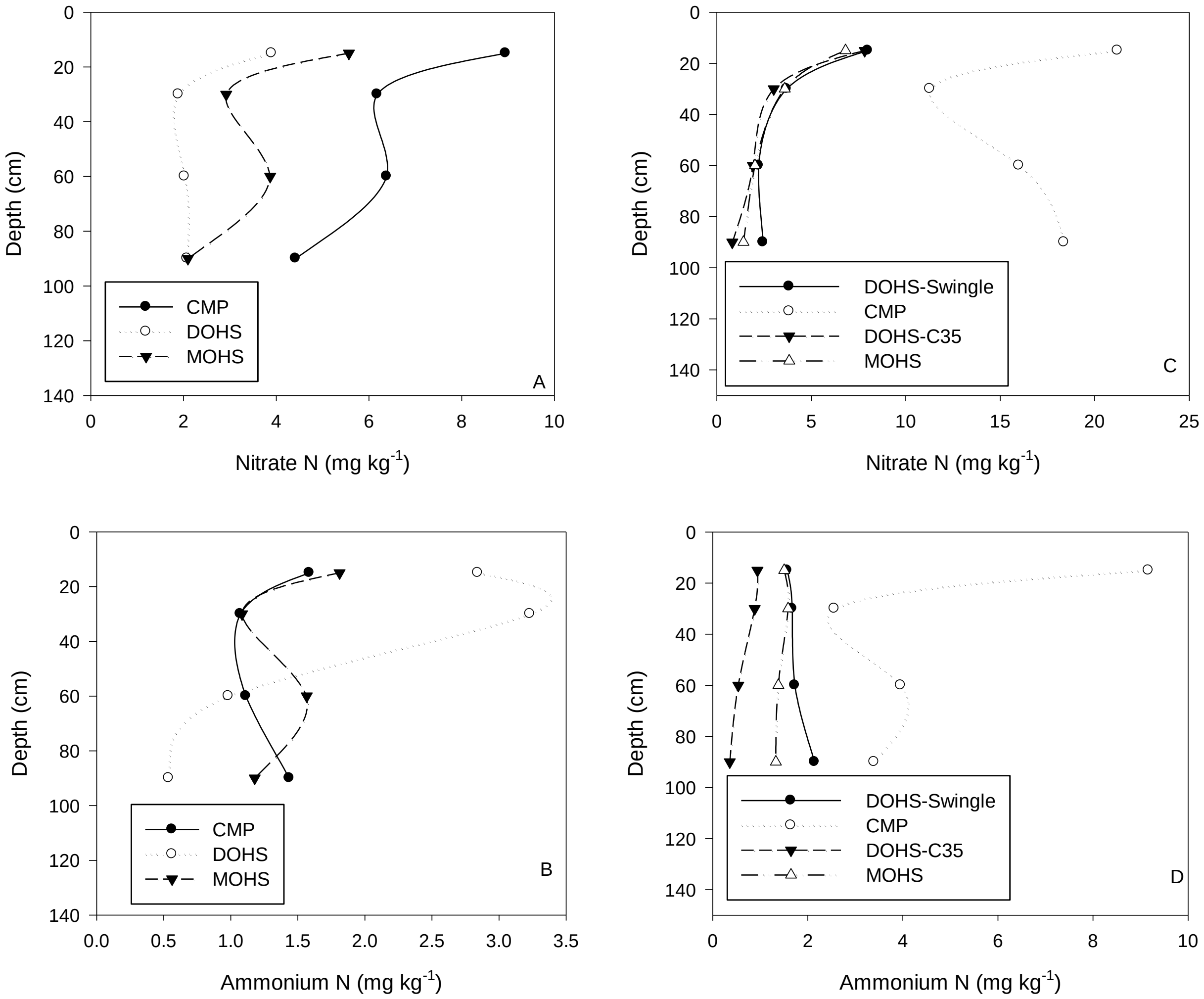


Figure 3-16. Vertical nitrate N and ammonium N distribution in June 2010 at Immokalee site (A and B) and in July 2010 at the Lake Alfred site (C and D)

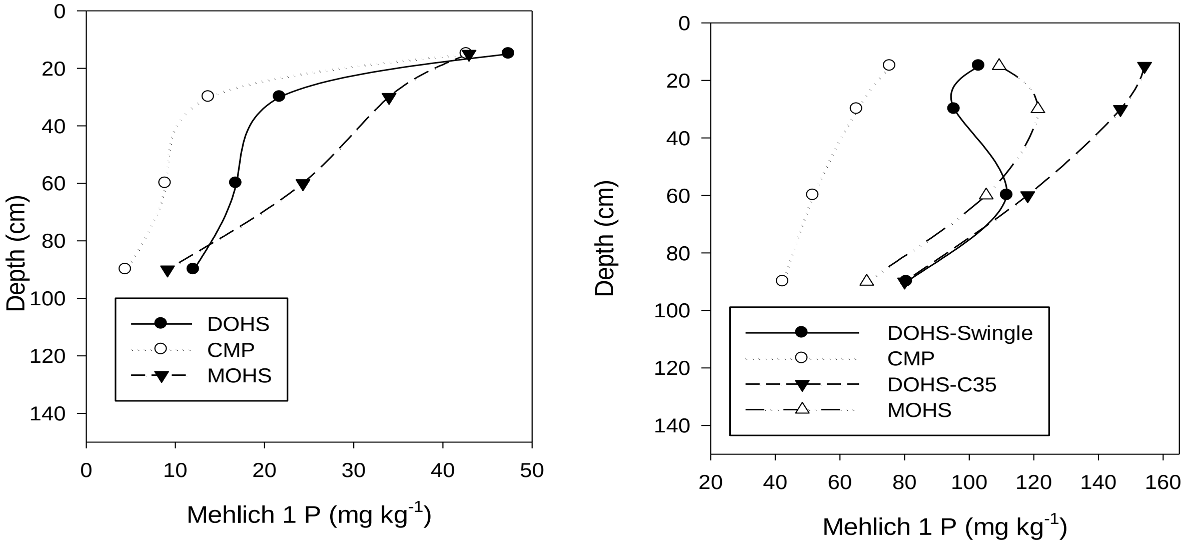


Figure 3-17. Vertical M1P distribution in June 2010 at Immokalee site (A) and in July 2010 at the Lake Alfred site (B)

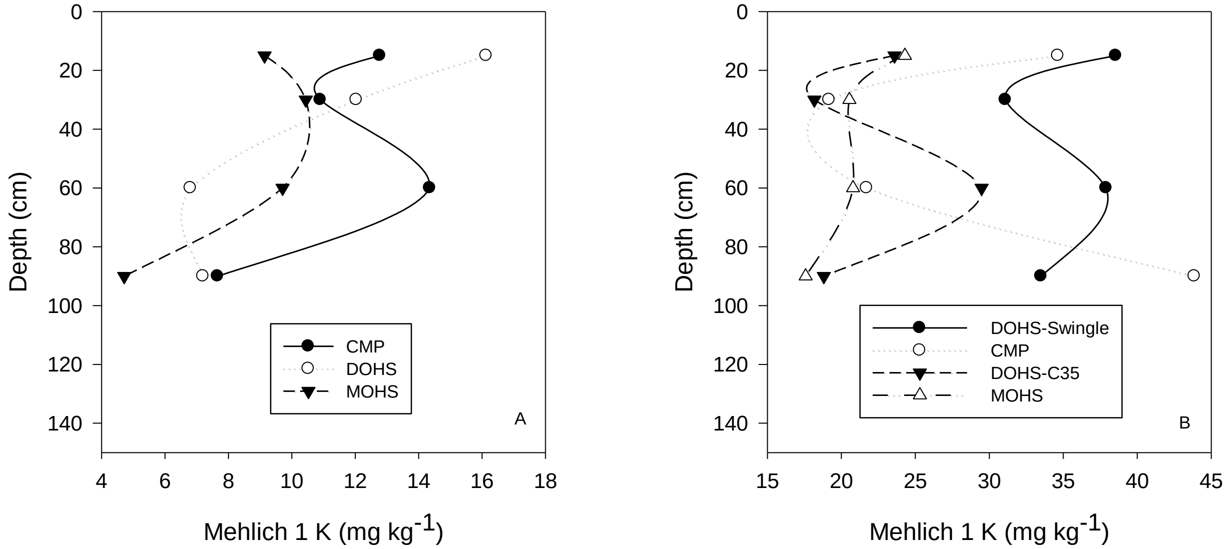


Figure 3-18. Vertical M1K distribution in June 2010 at Immokalee site (A) and in July 2010 at the Lake Alfred site (B)

Table 3-6. Fresh and dry tissue weight for samples collected in July 2011 at Immokalee

Fertigation method	CMP				DOHS				MOHS			
Tissue	FW[¶]	%	DW	%	FW	%	DW	%	FW	%	DW	%
Young leaves	4,391.4	12.8	1,598.2	10.3	2,989.9	8.3	1,017.4	6.7	3,349.0	9.2	1,208.0	8.0
Fully expanded leaves	923.5	2.7	340.9	2.2	5,712.3	15.8	1,947.1	12.8	3,350.9	9.2	1,212.3	8.0
Fruits	12,922.7	37.5	3,657.3	23.5	9,685.8	26.8	1,763.8	11.6	13,557.9	37.2	3,111.9	20.6
Twigs	2,890.0	8.4	1,480.0	9.5	3,394.6	9.4	1,700.0	11.2	3,589.9	9.9	1,800.0	11.9
Small branches	1,187.6	3.5	676.0	4.4	1,186.5	3.3	650.3	4.3	1,124.3	3.1	667.5	4.4
Medium branches	1,065.9	3.1	633.4	4.1	1,474.2	4.1	847.0	5.6	952.5	2.6	542.2	3.6
Large branches	2,156.1	6.3	1,286.2	8.3	1,134.0	3.1	655.7	4.3	1,678.3	4.6	1,006.5	6.7
Trunk	3,447.3	10.0	2,143.9	13.8	3,243.2	9.0	1,934.2	12.8	3,164.4	8.7	1,869.5	12.4
Total above-ground	28,984.5	84.2	11,815.7	76.0	28,820.4	79.7	10,515.5	69.4	30,767.3	84.5	11,418.0	75.4
Roots (<0.5mm)	501.0	1.5	253.6	1.6	298.4	0.8	155.7	1.0	653.0	1.8	329.0	2.2
Roots (0.5-1mm)	84.9	0.3	67.3	0.4	449.2	1.2	273.5	1.8	100.9	0.3	86.0	0.6
Roots (1-3mm)	335.0	1.0	252.9	1.6	1,155.5	3.2	547.1	3.6	383.6	1.1	322.0	2.1
Roots (>3mm)	4,532.8	13.2	3,153.7	20.3	5,432.0	15.0	3,667.5	24.2	4,525.3	12.4	2,979.9	19.7
Total below-ground	5,453.7	15.8	3,727.5	24.0	7,335.1	20.3	4,643.8	30.6	5,662.9	15.5	3,716.9	24.6
Total	34,438.2	100.0	15,543.2	100.0	36,155.5	100.0	15,159.3	100.0	36,430.1	100.0	15,134.9	100.0

[¶] FW-Fresh weight, DW-Dry weight in g

Table 3-7. Fresh and dry tissue weight for samples collected in August 2011 at the Lake Alfred site

Irrigation method	CMP				DOHS-Swingle				MOHS				DOHS-C35			
Tissue	[¶]FW	%	DW	%	FW	%	DW	%	FW	%	DW	%	FW	%	DW	%
Leaves	160.1	12.6	60.2	26.5	199.7	15.8	72.1	31.7	163.4	12.9	56.7	25.0	166.0	13.1	59.3	26.1
Fruits	811.5	64.1	104.7	46.1	1,003.8	79.3	123.8	54.5	850.6	67.2	104.4	45.9	844.4	66.7	103.7	45.6
Twigs	24.6	1.9	10.5	4.6	43.1	3.4	19.8	8.7	32.9	2.6	14.2	6.2	32.8	2.6	14.3	6.3
Total above-ground	996.1	97.1	175.5	90.8	1,246.6	98.4	215.7	94.9	1,046.9	96.0	175.3	94.7	1,043.2	97.8	177.3	91.7
Small roots (<0.5 mm)	4.0	0.3	2.8	1.2	6.1	0.5	4.7	2.1	5.4	0.4	4.5	2.0	4.5	0.4	3.1	1.4
Medium roots (0.5-1 mm)	1.2	0.1	0.6	0.3	1.3	0.1	0.3	0.1	1.3	0.1	0.9	0.4	0.9	0.1	2.0	0.9
Large roots (1-3 mm)	5.0	0.4	2.6	1.1	6.3	0.5	2.9	1.3	4.4	0.3	3.0	1.3	3.1	0.2	1.5	0.7
Largest root (>3 mm)	20.0	1.6	11.8	5.2	6.2	0.5	3.7	1.6	32.5	2.6	1.5	0.7	14.8	1.2	9.4	4.1
Total below-ground	30.1	2.9	17.8	9.2	20.0	1.6	11.6	5.1	43.6	4.0	9.9	5.3	23.2	2.2	16.0	8.3
Total	1,026.3	100.0	193.3	100.0	1,266.6	100.0	227.3	100.0	1,090.5	100.0	185.2	100.0	1,066.5	100.0	193.3	100.0

[¶] FW-Fresh weight, DW-Dry weight in g

Table 3-8. N, P and K concentration in tissues collected in July 2011 at the Immokalee site

Fertigation method	CMP			DOHS			MOHS		
Tissue	N	P	K	N	P	K	N	P	K
					%				
Young leaves	2.58	0.14	1.83	3.25	0.11	1.11	3.33	0.12	1.36
Old, fully expanded leaves	2.31	0.15	1.35	3.53	0.12	1.20	2.94	0.13	1.17
Twigs	1.22	0.13	1.45	1.54	0.14	1.15	1.30	0.17	1.36
Small branches	0.37	0.13	0.88	0.58	0.11	1.13	0.86	0.13	0.89
Medium branches	0.34	0.14	1.29	0.71	0.11	0.92	0.32	0.13	1.12
Large branches	0.53	0.17	1.30	0.45	0.16	1.41	0.54	0.12	1.22
Trunk	0.60	0.18	1.35	0.99	0.14	1.36	0.95	0.15	1.15
Fruits	1.25	0.15	1.41	1.83	0.12	1.55	1.97	0.15	1.26
Small roots (<0.5 mm)	1.38	0.14	1.19	2.26	0.11	1.12	1.91	0.13	1.31
Medium roots (0.5-1 mm)	1.21	0.13	1.21	1.60	0.13	1.15	1.46	0.13	1.37
Large roots (1-3 mm)	0.65	0.14	1.19	1.11	0.15	1.55	2.62	0.14	1.43
Largest root (>3 mm)	0.56	0.16	1.27	0.78	0.13	1.41	0.85	0.17	1.42

Table 3-9. N, P and K concentration in tissues collected in August 2011 at the Lake Alfred site

Irrigation method	CMP			DOHS-Swingle			MOHS			DOHS-C35		
Tissue	N	P	K	N	P	K	N	P	K	N	P	K
						%						
Leaves	3.25	0.13	1.53	2.52	0.13	1.41	3.73	0.14	1.33	2.62	0.20	1.52
Fruits	1.27	0.11	0.93	1.05	0.12	1.01	1.69	0.13	1.33	2.42	0.19	1.47
Twigs	1.26	0.11	1.13	1.06	0.16	1.41	1.36	0.14	1.09	1.07	0.15	1.32
Small roots (<0.5 mm)	2.14	0.18	1.25	2.05	0.15	1.28	1.70	0.13	1.43	2.21	0.18	0.45
Medium roots (0.5-1 mm)	1.78	0.17	1.20	2.09	0.23	2.28	0.99	0.26	2.21	0.58	0.17	0.75
Large roots (1-3 mm)	1.26	0.12	1.09	1.26	0.13	1.24	0.85	0.14	1.47	0.86	0.11	0.33
Largest root (>3 mm)	1.11	0.12	1.01	0.89	0.14	1.53	1.70	0.16	1.49	0.99	0.11	0.33

Table 3-10. Nitrogen, phosphorus and potassium accumulation on Immokalee sand

Fertigation method	CMP	DOHS	MOHS	CMP	DOHS	MOHS	CMP	DOHS	MOHS
Tissue		N			P			K	
					kg ha^{-1}				
Young leaves	20.16	16.17	19.67	1.09	0.55	0.71	14.30	5.52	8.03
Old, fully expanded leaves	3.85	33.61	17.43	0.25	1.14	0.77	2.25	11.43	6.94
Fruits	22.36	15.78	29.98	2.68	1.03	2.28	25.22	13.37	19.17
Twigs	8.83	12.80	11.44	0.94	1.16	1.50	10.49	9.56	11.97
Small branches	1.22	1.84	2.81	0.43	0.35	0.42	2.91	3.59	2.91
Medium branches	1.05	2.94	0.85	0.43	0.46	0.34	4.00	3.81	2.97
Large branches	3.33	1.44	2.66	1.07	0.51	0.59	8.18	4.52	6.00
Trunk	6.29	9.36	8.68	1.89	1.32	1.37	14.15	12.86	10.51
Small roots (<0.5 mm)	1.71	1.72	3.07	0.17	0.08	0.21	1.48	0.85	2.11
Medium roots (0.5-1 mm)	0.40	2.14	0.61	0.04	0.17	0.05	0.40	1.54	0.58
Large roots (1-3 mm)	0.80	2.97	4.13	0.17	0.40	0.22	1.47	4.15	2.25
Largest root (>3 mm)	8.64	13.99	12.39	2.47	2.33	2.48	19.59	25.29	20.69
†Total	78.65	114.78	113.72	11.64	9.52	10.95	104.43	96.49	94.13

†Total NPK accumulation is fairly low compared with accumulation observed in a typical orange grove owing to citrus greening infection

Table 3-11. N, P and K accumulation in 2011 at the Lake Alfred and Immokalee sites

Irrigation method	CMP			DOHS-Swingle			MOHS			DOHS-C35		
Lake Alfred	N	P	K	N	P	K	N	P	K	N	P	K
	g kg^{-1}											
Leaves	32.5	1.3	15.3	25.2	1.3	14.1	37.3	1.4	13.3	26.2	2.0	15.2
Fruits	12.7	1.1	9.3	10.5	1.2	10.1	16.9	1.3	13.3	24.2	1.9	14.7
Twigs	12.6	1.1	11.3	10.6	1.6	14.1	13.6	1.4	10.9	10.7	1.5	13.2
Small roots (<0.5 mm)	21.4	1.8	12.5	20.5	1.5	12.8	17.0	1.3	14.3	22.1	1.8	4.5
Medium roots (0.5-1 mm)	17.8	1.7	12.0	20.9	2.3	22.8	9.9	2.6	22.1	5.8	1.7	7.5
Large roots (1-3 mm)	12.6	1.2	10.9	12.6	1.3	12.4	8.5	1.4	14.7	8.6	1.1	3.3
Largest root (>3 mm)	11.1	1.2	10.1	8.9	1.4	15.3	17.0	1.6	14.9	9.9	1.1	3.3

Fertigation method	CMP			DOHS			MOHS		
Immokalee	N	P	K	N	P	K	N	P	K
Young leaves	25.8	1.4	18.3	32.5	1.1	11.1	33.3	1.2	13.6
Fully expanded leaves	23.1	1.5	13.5	35.3	1.2	12.0	29.4	1.3	11.7
Fruits	12.2	1.3	14.5	15.4	1.4	11.5	13.0	1.7	13.6
Twigs	3.7	1.3	8.8	5.8	1.1	11.3	8.6	1.3	8.9
Small branches	3.4	1.4	12.9	7.1	1.1	9.2	3.2	1.3	11.2
Medium branches	5.3	1.7	13.0	4.5	1.6	14.1	5.4	1.2	12.2
Large branches	6.0	1.8	13.5	9.9	1.4	13.6	9.5	1.5	11.5
Trunk	12.5	1.5	14.1	18.3	1.2	15.5	19.7	1.5	12.6
Roots (<0.5mm)	13.8	1.4	11.9	22.6	1.1	11.2	19.1	1.3	13.1
Roots (0.5-1mm)	12.1	1.3	12.1	16.0	1.3	11.5	14.6	1.3	13.7
Roots (1-3mm)	6.5	1.4	11.9	11.1	1.5	15.5	26.2	1.4	14.3
Roots (>3mm)	5.6	1.6	12.7	7.8	1.3	14.1	8.5	1.7	14.2

CHAPTER 4
EFFECTS OF FERTIGATION AND IRRIGATION RATES ON ROOT LENGTH DISTRIBUTION AND TREE SIZE

The use of automated irrigation systems and intensive nutrient management is critical to citrus production systems for achieving increased tree growth and yield. Maintenance of soil moisture and nutrient concentrations in the tree root zone near optimum levels is known as the open hydroponic system (OHS) (Morgan et al., 2009b). Sound water and nutrient management is required in Florida soils with high sand content (>94%) and low organic matter content because leaching and subsequent pollution of groundwater is a likely threat.

Key to improving citrus nutrient and water uptake is the understanding of the root system dimensions, topological properties and distribution in the soil. Of these root properties, the property of greatest importance is root length density (RLD) distribution because it defines limits to the efficiency of a root system in absorbing water and nutrients (Tinker and Nye, 2000; Himmelbauer et al., 2004). Studies on tree RLD distribution done in Florida by Morgan et al. (2007) found that fibrous root length density (FRLD) distribution increased with soil depth and lateral distance as trees grew, resulting in mature trees with bimodal root systems. In their study, they classified fibrous roots as those roots whose diameter fell between 0-4 mm because such roots determine tree water and nutrient uptake efficiency. Morgan et al. (2007) reported that FRLD varied as a function of rootstock in which trees on Swingle citrumelo developed higher FRLD near the soil surface and lower FRLD below 0.3 m than trees on Carrizo citrange. Abrisqueta et al. (2008) studied root dynamics of young peach subjected to partial root zone drying and continuous deficit irrigation in Spain. In the study, higher root length densities were recorded in non-limiting irrigation conditions than under deficit irrigation where root growth was reduced.

Two methods (plant based or soil based) have been used to estimate and describe root systems. The plant-based method describes the way in which different parts of the root system are interconnected (Rose, 1983; Klepper, 1992). The second method describes root systems in the soil in terms of the distribution of RLD or mass throughout the rooting zone and has been used as a standard way of measuring density in distributions of roots in field soils (Barraclough and Leigh, 1984; Vincent and Gregory, 1989a, b; Masse et al., 1991). Basing on the latter, researchers devised methods of soil coring and root washing to provide the most practicable way of obtaining quantitative data on root system length and distribution in the field (Tinker and Nye, 2000). The main methods that have been used for measuring root length over the years are line intersect method (Newman, 1966); direct measurement and opisometer methods (Reicosky et al., 1970); photocopying and scanning (Collins et al., 1987; Kirchoff, 1992; Himmelbauer et al., 2004) and the stereological procedure (Wulfsohn et al., 2004). Despite its merits, the line intersect method uses a tedious operational procedure which includes insuring uniform root dispersal throughout a finite area and the repetitive use of short line intercepts (Reicosky et al., 1970). The study by Reicosky et al. (1970) showed significant gains in time by using the line intersection method over the direct and opisometer methods. Reicosky and colleagues found that there was little difference in precision between the line intersect, direct and opisometer methods for estimating root length but found more gains on time in using the first method (1.0 h) compared with the latter two where it took 5.0 h and 1.5 h for the direct and opisometer methods, respectively. Thus, through root scanning, the line intersect method can be calibrated and used to predict root length with speed and greater precision (Collins et al., 1987; Bland and Mesarch, 1990).

Studies done in central and south Florida showed that tree size was a function of root density (Castle and Krezdon, 1975; Ford, 1954; 1964; 1972), root stock (Morgan et al., 2006a) and fertilization practice (Obreza and Rouse, 1991; 1993; 2006; Morgan et al., 2009a). Marler and Davies (1990) showed that canopy volume, trunk cross-sectional area and root dry weight can be influenced by irrigation rate. In their study, canopy volume and trunk cross-sectional area were similar at high (20 % of available soil water depletion) and moderate (45 % of available soil water depletion) levels in 2 of 3 years, but were reduced at low (65 % of available soil water depletion). More than 90 % of the roots were within 80 cm of the tree trunk at the end of the growing season. Parsons et al. (2001), in their study on the effect reclaimed water on citrus tree growth, found that tree growth was greatest at high irrigation rate (2500 mm) though fruit production per canopy volume was low compared with lower rates ~400 mm and 1250 mm. However, very little research, if any, has been conducted to determine the effect of irrigation rate and fertilization method on tree size in Florida using the modified ACPS/OHS practices. Documentation of the performance of ACPS/OHS practices with regard to tree size and root density is critical for their adaptation to Florida soil and climatic conditions.

The objectives of the experiment were to:

- (1) calibrate line intersect method for determining RLD in 1- and 3-year old citrus using the digital scanning method on Florida Entisol and Spodosol,

- 2) to determine the effect of fertigation frequency and irrigation method on RLD distribution,
- (3) validate the RLD estimated based on root area using the intercept method,
- (4) determine root distribution patterns in the irrigated and non-irrigated zones as a function of fertigation method and depth, and,
- (5) determine the effect of fertigation frequency and irrigation method on canopy volume and trunk cross-sectional area.

The following hypotheses were postulated:

- (1) root area using a flatbed scanner can be calibrated using the line intersect method and used to predict root length with speed and greater precision,
- 2) spatial root length density distribution will be greater in irrigated zones of microsprinkler and drip OHS than conventional practice, and,
- 3) microsprinkler and drip OHS will increase citrus growth rate resulting in canopy volumes and trunk cross-sectional areas higher than conventional practice.

Materials and Methods

Description of Study Sites and Treatments

Treatments and orchard locations for this study were the same as trees used in the nutrient distribution and accumulation study presented in Chapter 3. At the SWFREC site treatments were: (1) Conventional practice –irrigated weekly and fertigated monthly (CMP); (2) Drip OHS – irrigated daily and fertigated weekly in small pulses (DOHS); (3) Microsprinkler OHS – irrigated daily and fertigated weekly (MOHS). All the treatments were laid in a randomized complete block design replicated four times. The Hamlin oranges (*Citrus sinensis*) on Swingle rootstock were planted on a 3.05 x 6.71 m tree and row spacing. A second study was installed at a 15-acre Ridge site near the Citrus Research and Education Center (CREC), Lake Alfred, with Hamlin oranges on Swingle rootstocks at 3.05 x 6.10m (~218 trees/acre) and C35 rootstock at 2.44 x 5.49m (~302 trees/acre). The treatments imposed at the Lake Alfred site were similar to the set-up at SWFREC except for the modification to the conventional practice where the use of dry granular fertilizer applied under the canopy four times a year acted as a control for the experiment and also DOHS was imposed on both Swingle and C-35 rootstock.

Root Sampling Methods

Roots were sampled for RLD and average root diameter estimations of 3-year old citrus at SWFREC, on June 9 through 17, 2009 in the 0-30 cm depth at 15 cm depth increments because this is where most roots of young citrus trees (<3 years old) are concentrated (Fares and Alva, 2000; Paramasivam et al., 2000c; Parsons and Morgan, 2004). The samples were collected at 0, 15, 30, and 45 cm distance from the tree in the row in 15 cm increments up to 45 cm from the tree perpendicular to the planted row, giving a total of 12 sampling locations in one quadrant for each tree (3 x 4 grid). On June 16 through 24, 2010 root samples at SWFREC were collected up to 45 cm depth using the above sampling scheme. At the Lake Alfred site, fewer samples than those at SWFREC were collected using a 2 x 2 grid on December 22, 2009 and a 3 x 3 grid on July 7 and 8, 2010 at 0-15 cm and 15-30 cm depth.

All the cores were carefully bagged, labeled and stored in a refrigerator at ≤4 C awaiting subsequent analysis. Roots were removed from the soil using a 2 mm diameter sieve. Other debris passing through the sieve was removed manually. The roots were hydrated for 15 minutes and categorized into four groups according to diameter: <0.5 mm, 0.5-1.0 mm, 1-3 mm and >3 mm before using the line intersection method (adapted from Morgan, 2004). Root length for each root category was estimated using the grid system explained by Tennant (1975) by counting the number of horizontal and vertical intersections of roots in a grid system of 1.0 x 1.0 cm which was multiplied by 11/14 and divided by volume of the corer to give root length density in cm cm^{-3} soil (Mattos, 2000).

Estimation of Tree Growth Characteristics

Tree canopy volumes were made by measuring the average canopy diameter using canopy width in the east-west and north-south directions and canopy height. Then, using the formula for a sphere= $\frac{4}{3}\pi r^3$, where r is the canopy radius (where the canopy width in the east-west and north-south directions and canopy height were averaged to give the canopy radius), canopy volume was calculated. Trunk diameter was estimated from averaging the diameter in the east-west and north-south directions and then calculating the area using the formula πr^2, assuming circular shape, where r is the trunk radius.

Statistical Analysis

Roots of selected root diameters from samples collected in two of the four replications at SWFREC were designated the calibration set and roots from the remaining two replications were designated the validation set. The RLD estimate using the intercept method (dependent variable) and mean root area using the scanning method (independent variable) for calibration set roots were correlated resulting in a calibration curve for the root scanning method. To validate the calibration curve, estimated RLD calculated using the mean root areas of the validation set roots were correlated with the RLD estimate of the same roots using the intercept method. After validating the procedure at Immokalee and getting reasonably good calibration curves, a calibration curve was also determined for estimating RLD at Lake Alfred using similar calibration and validation techniques. All correlations were done using SAS 9.2

PROCREG procedures (SAS Inst. 2011) and SIGMA PLOT 10.0. The rest of the data were analyzed using PROC GLM Mixed Model Procedures (SAS Inst. 2011) to determine the effect of the irrigation method and fertilization frequency on vertical and lateral root length density distribution, and tree growth.

Results and Discussion

Correlation of RLD Measured by Intersection Method versus Scanning Method

Root length density measured using the modified Newman method (Tennant, 1975) correlated well with scanned area of the calibration set at both SWFREC and Lake Alfred sites (Appendix F). RLDs predicted by the calibration scanning method also agreed with measured RLDs for the validation set at both SWFREC and the Lake Alfred site (Tables 4-1 and 4-2). The strong positive correlation for all diameters of roots collected at both locations shows the precision of using the scanning method upon calibration with the line intersection method. Only 1.61% of the scanned roots at CREC and 2.25% of the scanned roots at SWFREC were above the normal deviations (relative standard deviation 10%) showing that scanning roots in triplicate represent a fairly accurate and precise way of determining RLD. The equations for the calibration set using scanned root area provided PLD with reasonable agreement to RLD measured using the intercept method (greater than $R^2 \geq 0.79$) at both study sites. There was close agreement in the validation set between RLD estimated using the intercept method and that predicted using the calibration equation developed from root scanning (R^2 ranged from 0.88 to 1.00 at CREC and 0.87 to 0.97 at SWFREC). Lowest coefficient of determination for roots greater than 3 mm in diameter was noted at CREC owing to few roots in this root category ascribed to the young tree age. Examination of equation slopes revealed that of the validation models developed for both sites, only the models for root sizes <0.5. 0.5-1.0, and 1.0-3.0 mm yielded close approximations of predicted RLD with slopes >0.78 thus nearly a 1:1 ratio, adequately explaining the variability in the validation and versus calibration sets. Slopes for root sizes >3 mm explained about 50 to 60% of the variability probably because there were very few roots >3 mm at both sites. The scanning method reduces the time required to measure RLD in samples. In this study for example, it took about 40 to 60 hours to scan root samples compared with the line intercept method that took 140 hours (about 10 hours per day, though not statistically done across different sets of individuals). Considering the importance of accurate root length estimation, the scanning method offers a worthwhile alternative especially when the researcher has a large number of samples. Several researchers approve photocopying (Collins et al., 1987; Kirchoff, 1992) and scanning (Collins et al., 1987; Bland and Mesarch, 1990) in RLD determination to achieve as much accuracy in the shortest time possible.

RLD Distribution as a Function of Irrigation Method, Time and Soil Depth

Root samples collected at SWFREC in June 2009 showed that lateral RLD distribution for CMP decreased from 0.374 cm cm^{-3} near the tree to 0.084 at 45 cm away from the tree row (Table 4-3 and Appendix A, Figure A22). The irrigated zones of DOHS and MOHS showed RLD as high as 0.386 cm cm^{-3} and 0.279 cm cm^{-3} that decreased to 0.139 and 0.053 in the non-irrigated zone respectively (Table 4-1, Appendix A, Figures A23 and A24). Small roots (<0.5 mm and 0.5-1.0mm in diameter) accounted for ≥80% of the RLD at both 0-15- and 15-30 cm depths while largest roots (>3 mm) contributed <3% of the total RLD.

For RLD samples collected at SWFREC in June 2010, fibrous roots (roots <0.5 mm and 0.5-1.0mm in diameter) contributed >77% of RLD while largest roots (>3 mm) accounted for <2 % of total RLD (Table 4-4). For CMP, 49% of the roots were found in the 0-15 cm depth while 36% and 15% of the roots were observed in the 15-30 cm and 30-45 cm soil depth. About 54%, 35% and 10% were found in the 0-15-, 15-30- and 30-45 cm depth using DOHS (Table-4-4). Most of the roots (60%) were found in the 0-15 cm depth using MOHS while 23% and 17% of the roots were distributed in the 15-30 and 30-45 cm depth (Table 4-4). Roots (<0.5 mm in diameter) for CMP were uniformly distributed in the irrigated zones averaging about 0.089 cm cm^{-3} while the roots greater 0.5 mm in diameter were largely found in the irrigated zone at 15 to 30 cm from the tree. The lateral root distribution (0.5 mm) for DOHS averaged 0.33 cm cm^{-3} in the irrigated and non-irrigated zones of 0-15 cm soil depth layer (Table 4-4) probably because drippers were increased from 4 to 8 drippers per tree and due to the rainy season which supplied water even in the nonirrigated zone. However, at 15-30 cm and 30-45 cm soil depths, RLD for (root <0.5 mm in diameter) was approximately 2 times that observed in the non-irrigated zone while for roots greater than 0.5 mm in diameter the RLD was similar between the irrigated and non-irrigated zones (Table 4-4). Root density estimated for MOHS for roots (<0.5 mm in diameter) was two times higher in irrigated than nonirrigated zone at all depths (Table 4-4) decreasing from 0.33 cm cm^{-3} in the irrigated zone to about 0.022 cm cm^{-3} in the nonirrigated zone. In June 2010 at SWFREC, roots were uniformly distributed laterally in the grid around the tree using CMP with RLD ranging from 0.154 cm cm^{-3} to 0.086 cm cm^{-3} (Figure A25). Root length density using DOHS decreased from 0.439 cm cm^{-3} below the dripper to 0.170 cm cm^{-3} at 45 cm from the tree (Figure A26). Similar pattern for MOHS was noted (Figure A27). The root densities under the drip at SWFREC were lower than Lake Alfred because the drippers were moved from near the tree trunk to 30 cm away from the tree, when the number of lines was increased from one to two in March 2010 prior to the June sampling.

In December 2009, at the Lake Alfred site, RLD was high in irrigated zones of DOHS-Swingle and DOHS-C35. For example, positions below the dripper showed RLD of about 0.8 cm cm^{-3} (DOHS-Swingle) (Appendix A, Figure A28) and 0.86 cm cm^{-3} (DOHS-C35) (Appendix A, Figure A29) which, respectively, decreased to 0.41 cm cm^{-3} and 0.091 cm cm^{-3} with distance away from the tree. The microsprinkler irrigation methods, CMP (Appendix A, Figure A30) and MOHS (Appendix A, Figure A31), yielded similar RLD≈0.42 cm cm^{-3} closer to the tree that decreased laterally to 0.074 cm cm^{-3} and 0.27 cm cm^{-3}, respectively (Table 4-5). All irrigation methods but CMP showed that >60% of the roots were concentrated in top 0-15 cm than the 15-30 cm soil depth. However, CMP showed that 65% of the roots dominated the 15-30 cm soil depth. All treatments showed that fibrous roots (<0.5 mm and 0.5-1 mm) contributed to > 80% of the total RLD at both 0-15- and 15-30 cm soil depth suggesting that it is likely that young trees will develop small, fine roots to promote water and nutrient uptake and accelerate tree growth. Largest roots (>3 mm) contributed <1.1% of total RLD. These results are similar to those reported by Morgan et al. (2007) on 2 to 5-year-old Hamlin and Valencia orange trees. In agreement with our findings, they also reported that citrus trees develop a dense root system within the upper 30 cm where fibrous RLD distribution increases with depth and lateral distance as trees grow.

Results suggest that the further away from the tree, the less likely we are to find roots as shown in the significant decrease in RLD with distance from the tree. Thus, irrigation methods such as drip which apply water and fertilizer frequently and in small pulses within a limited root zone offer a viable option for increasing root water and nutrient uptake compared with the microsprinkler based systems when the trees are small. Positions below drippers tended to have high root density as exemplified in the DOHS-C35 and DOHS-Swingle where RLD ~0.8 cm cm^{-3} was close to 2 times that obtained in the irrigated zones of CMP or MOHS at the Lake Alfred site. Thus, this should typify the potential for increasing root density and subsequent tree uptake using drip irrigation.

In July 2010, lateral root distribution showed that RLD decreased gradually with distance from the tree at the Lake Alfred site. For CMP and MOHS, RLD near the tree was about 0.25 cm cm^{-3} and 0.45 cm cm^{-3} and decreased to 0.10 cm cm^{-3} and 0.19 cm cm^{-3}, respectively at 30 cm from the tree (Appendix A, Figures A32 and A35, Table 4-6). The drip fertigated treatments showed high RLD of about 1.0 cm cm^{-3} in the irrigated zone that decreased to 0.20 cm cm^{-3} in the non-irrigated zone (Appendix A, Figures A33 and A34). Also, the high RLD in the non-irrigated zones for the OHS-based fertigation methods was not expected. We ascribe the presence of roots in the non-irrigated zone to the high rainfall in Florida (approximately 1400 mm) which probably increased the amount of available water including in the non-irrigated zone thus promoting root growth and development. Obreza and Pitts (2002) also observed similar phenomena on root density distribution between the irrigated and non-irrigated zones of southwest Florida. The results show RLD $\leq$1.3 cm cm^{-3}, consistent with findings of other researchers in citrus (Mattos et al., 2003), apple (De Silva et al., 1999) and somewhat lower than the RLD reported by Coleman (2007) in other woody species. Positions below the dripper or in irrigated zones, except for CMP (probably due to infrequent irrigation), had very high root length density. Zhang et al. (1996 and1998) also reported that RLD of fibrous roots was significantly greater near the emitter and at 0-15 cm deep layer for grapefruit trees. Similar results were obtained in citrus (Alva and Syvertsen, 1991; Mattos et al., 2003a; Morgan et al., 2007) and in drip-irrigated woody species Coleman (2007). At the Lake Alfred site, small roots (<0.5 mm) accounted for ≥87% of the total RLD at 0-15 cm soil depth using all irrigation methods and ≥64% at 15-30 cm depth while largest roots accounted for the smallest portion (≤2%) of the total RLD. All other treatments but grower practice showed high RLD in the top 0-15 cm where 58%, 67% and 57% of the roots were concentrated using DOHS-Swingle, DOHS-C35 and MOHS, respectively. Only 36% of the roots were found in the 0-15 cm using the grower practice. Nappi et al. (1985) and Bassoi et al. (2003) found that highest grapevine root presence was within the top 40 cm and within 40 cm radius from the trunk for drip and at 0.8-1 m distance from the trunk using microsprinkler irrigation. In their studies, roots with diameter ≤2 mm corresponded to at least 80% of total root length. Overall, root length density found in this study was higher for drip- than microsprinkler-irrigated citrus, which is similar in relation to results from Australia (Stevens and Douglas, 1994) and Brazil (Bassoi et al., 2003). The maximum RLD values reported by Stevens and Douglas (1994) were 1.2 and 0.6 cm cm^{-3} for drip- and microsprinkler-irrigated 8-yr-old vines, respectively. Thus, our values, particularly, on the Ridge site are somewhat greater for the tree age (<3 yr-old) and point to the intensive irrigation and fertigation rates. The study of Stevens and Douglas (1994) also revealed that 47% and 40% of the roots were found in the top 0-40 cm in a 0-160 cm profile of microject and drip irrigation. These observations confirm our postulated hypothesis that RLD would be greater using OHS-based fertigation methods.

Effect of Fertigation Method on Trunk Cross-Sectional Area and Canopy Volume

DOHS treatments using Swingle and C35 rootstocks increased canopy volumes from 0.45 ± 0.05 m^3 to 1.87 ± 0.20 m^3 while MOHS increased canopy volume from 0.40±0.12 m^3 to 1.73±0.19 m^3 beginning 11/12/10 to 07/15/11 at CREC. Thus, compared with grower practice, DOHS-Swingle and DOHS-C35 increased canopy volumes by 47 to 112% for the same sampling period, while MOHS increased canopy volumes by 36 to 87% (Fig. 4-1). Consistent results with DOHS, MOHS and CMP treatments were also observed at SWFREC in July 2010 and August 2011 where canopy volumes were increased by 15, 20 and 9%, respectively (Fig. 4-2). All three fertigation treatments at SWFREC, CMP, DOHS, and MOHS increased TCA by 97, 123 and 122% in year 2 and by 44, 56 and 66% in year 3. All TCA measurements were similar in August 2009, July 2010 and August 2011.

The results revealed that DOHS and MOHS treatments promoted vigorous tree growth across the years of study at the Lake Alfred site probably as a result of increased water uptake and nutrient accumulation as described in Chapters Three and Five. At SWFREC, DOHS and CMP increased tree growth in a similar pattern. Noteworthy in the study is the fertilization practice at the Lake Alfred site where granular fertilizer was applied quarterly in the CMP while at SWFREC it was fertigated monthly suggesting that use of fertigation practice for the CMP will promote tree growth and canopy development as shown in Figures 4-1 through 4-3. The caveat for monthly fertigation is that more fertilizer has to be applied due to a larger irrigated and fertigated area for CMP (360^o) than MOHS and DOHS where there is a limited irrigated and fertigated area and a restricted root zone.

Trunk cross-sectional areas (TCAs) at the Lake Alfred site were similar in 2009 (Table 4-7). In July 2010, MOHS, DOHS-Swingle and DOHS-C35 increased TCA by 31%, 38% and 51% over CMP. In March 2011, MOHS and DOHS-C35 increased TCA by 28% while DOHS-Swingle increased TCA by 44%.

Thus, our hypothesis that 'MOHS and DOHS treatments will increase citrus growth rate resulting in canopy volumes and trunk cross-sectional areas higher than conventional practice' was confirmed at the Lake Alfred site and SWFREC. Our results at SWFREC, while supporting this hypothesis, showed that TCA and canopy volume for CMP were similar to DOHS and better than MOHS probably because it was fertigated. However, the results at SWFREC show that the annual percent increments in TCA and canopy volume were higher using MOHS and DOHS than the grower practice.

Summary

The chapter has shown the importance of root scanning in determining RLD in young citrus trees. There was good agreement between root length density and scanned area and shorter time for measuring root length with a flatbed scanner than using a line-intersect method thus confirming the hypothesis that 'root area using a flatbed scanner can be calibrated using the line intersect method and used to predict root length with speed and greater precision'. Thus, root densities measured using the line intersection method showed strong and positive correlation ($R^2 \geq 0.79$) with those predicted by the calibration equation relating RLD and scanned root area. The results showed that use of the scanning method could be used to increase the accuracy and reduce the time for determination of RLD. Generally, root length density was highest in the 0-15 cm depth and decreased with depth and distance away from the tree. Positions below the dripper of DOHS and in the irrigated zones of MOHS showed root length density twofold higher than non-irrigated zones and even greater RLD than the irrigated zones of grower practices. Despite having irrigated zones around the tree using CMP, the infrequent irrigation probably resulted in lower RLD compared to the irrigated zones of DOHS and MOHS at both study sites. Thus, the hypothesis that spatial root length density distribution would be greater in irrigated zones of MOHS and DOHS than conventional practice holds. However, root densities at Immokalee were three to four times lower than those observed at the Lake Alfred site largely because of citrus greening that infected all trees in the grove during the second year of the study and probably because of the spodic horizon found at 60-70 cm from the soil surface. Also, the number of drippers for drip irrigated trees was increased from four to 8 drippers per trees around March 2010, just two months before the June 2010 sampling at Immokalee such that the roots might have not fully developed below the dripper.

The results further showed that our hypothesis that ‘MOHS and DOHS treatments will increase citrus growth rate resulting in canopy volumes and trunk cross-sectional areas higher than conventional practice’ was true at the Lake Alfred and Immokalee sites. Our results at Immokalee, while supporting this hypothesis, showed that TCA and canopy volume for CMP were similar to DOHS and better than MOHS probably because CMP was fertigated. However, annual increments in TCA respectively by CMP, DOHS, and MOHS were 97, 123 and 122% in year 2, and 44%, 56% and 66% in year 3 at Immokalee suggesting vigorous tree growth with ACPS/OHS.

Table 4-1. Models for RLD estimation at CREC

Regressed variables	Model type	Root size (mm)	[¶]β_0	β_1	n	R^2	RMSE (cm cm^{-3})	P-value
Measured RLD vs. scanned area	Calibration set	<0.5	0.0270	3.78exp(-6)	64	0.88	0.1156	<0.0001
Predicted RLD vs. measured RLD	Validation set	<0.5	-0.0194	1.02	64	0.94	0.0857	<0.0001
Measured RLD vs. scanned area	Calibration set	0.5-1.0	0.0036	3.49exp(-6)	64	0.92	0.0086	<0.0001
Predicted RLD vs. measured RLD	Validation set	0.5-1.0	0.0095	0.78	64	0.88	0.0092	<0.0001
Measured RLD vs. scanned area	Calibration set	1.0-3.0	0.0008	1.76exp(-6)	64	0.90	0.0103	<0.0001
Predicted RLD vs. measured RLD	Validation set	1.0-3.0	0.0003	0.95	64	0.92	0.0080	<0.0001
Measured RLD vs. scanned area	Calibration set	>3.0	0.0003	2.57exp(-7)	64	0.79	0.0021	<0.0001
Predicted RLD vs. measured RLD	Validation set	>3.0	0.0003	0.51	64	1.00	0.0001	<0.0001

[¶]β_0 is the y intercept, β_1 is the slope, n is the number of samples, R^2 is the coefficient of determination, RMSE is the root mean square error

Table 4-2. Models for RLD estimation at SWFREC

Regressed variables	Model type	Root size (mm)	[‡]β_0	β_1	n	R^2	RMSE (cm cm^{-3})	P-value
Measured RLD vs. scanned area	Calibration set	<0.5	0.0116	2.19exp(-6)	144	0.92	0.0350	<0.0001
Predicted RLD vs. measured RLD	Validation set	<0.5	0.0128	0.91	144	0.87	0.0455	<0.0001
Measured RLD vs. scanned area	Calibration set	0.5-1.0	0.0025	1.88exp(-6)	144	0.94	0.0089	<0.0001
Predicted RLD vs. measured RLD	Validation set	0.5-1.0	0.0026	0.98	144	0.93	0.0102	<0.0001
Measured RLD vs. scanned area	Calibration set	1.0-3.0	0.0021	1.03exp(-6)	144	0.81	0.0113	<0.0001
Predicted RLD vs. measured RLD	Validation set	1.0-3.0	0.0023	0.88	144	0.91	0.0095	<0.0001
Measured RLD vs. scanned area	Calibration set	>3.0	0.0005	2.19exp(-7)	144	0.84	0.0028	<0.001
Predicted RLD vs. measured RLD	Validation set	>3.0	0.0005	0.58	144	0.91	0.0013	<0.0001

[‡] β_0 is the y intercept, β_1 is the slope, n is the number of samples, R^2 is the coefficient of determination, RMSE is the root mean square error

Table 4-3. RLD as a function of irrigation method, soil depth and distance from the tree at SWFREC in June 2009

Irrigation method	Soil depth	Root diameter <0.5 mm		Root diameter 0.5-1.0 mm		Root diameter 1.0-3.0 mm		Root diameter >3.0 mm	
	cm	cm cm^{-3}							
		IRR[†]	NI	IRR	NI	IRR	NI	IRR	NI
CMP	0-15	0.154	-[§]	0.045	-	0.018	-	0.002	-
	15-30	0.105	-	0.047	-	0.032	-	0.005	-
DOHS	0-15	0.205	0.170	0.065	0.062	0.017	0.027	0.001	0.002
	15-30	0.203	0.078	0.073	0.058	0.052	0.043	0.011	0.003
MOHS	0-15	0.168	0.136	0.033	0.035	0.008	0.013	0.001	0.001
	15-30	0.155	0.055	0.061	0.033	0.031	0.015	0.006	0.001
Statistics[¶]									
Irrigation method		NS		***		***		NS	
Depth		***		NS		***		***	
Distance from the tree		***		NS		NS		NS	
Irrigation method *Depth		NS		NS		NS		NS	
Irrigation method*Distance		NS		NS		NS		NS	
Depth*Distance		NS		NS		*		NS	
Irrigation method*Depth *Distance		NS		NS		NS		NS	

[†] IRR-Irrigated zone, NI-Non-irrigated zone. We did not observe many roots >3 mm in diameter at CREC in December 2009, [§] for conventional practices, all the sampled positions were irrigated, [¶] Statistics: NS-Non-significant difference, *-p<0.05, **-p<0.01, ***-p<0.001

Table 4-4. RLD as a function of irrigation method, soil depth and distance from the tree at SWFREC in June 2010

Irrigation method	Soil depth	Root diameter <0.5 mm		Root diameter 0.5-1.0 mm		Root diameter 1.0-3.0 mm		Root diameter >3.0 mm	
	cm	cm cm^{-3}							
		IRR[¶]	NI	IRR	NI	IRR	NI	IRR	NI
CMP	0-15	0.148	-[§]	0.025	-	0.010	-	0.002	-
	15-30	0.089	-	0.025	-	0.017	-	0.003	-
	30-45	0.031	-	0.016	-	0.007	-	0.001	-
DOHS	0-15	0.318	0.346	0.036	0.054	0.028	0.039	0.005	0.003
	15-30	0.216	0.104	0.064	0.058	0.054	0.036	0.011	0.009
	30-45	0.039	0.028	0.037	0.028	0.014	0.013	0.001	0.001
MOHS	0-15	0.330	0.206	0.035	0.032	0.024	0.018	0.005	0.001
	15-30	0.103	0.061	0.033	0.022	0.013	0.010	0.005	0.002
	30-45	0.090	0.022	0.032	0.009	0.015	0.005	0.004	0.001
Statistics[†]									
Irrigation method		***		**		***		*	
Depth		***		**		***		***	
Distance from the tree		*		NS		*		***	
Irrigation method *Depth		***		NS		***		*	
Irrigation method*Distance		NS		NS		NS		NS	
Depth*Distance		NS		NS		NS		NS	
Irrigation method*Depth *Distance		NS		NS		NS		*	

[¶] IRR-Irrigated zone, NI-Non-irrigated zone.

[§] For conventional practices, all the sampled positions were irrigated.

[†] Statistics: NS-Not significantly different, *-$p<0.05$, **-$p<0.01$, ***-$p<0.001$

Table 4-5. RLD as a function of irrigation method, soil depth and distance from the tree at the Lake Alfred site in December 2009

Irrigation method	Soil depth	Root diameter <0.5 mm		Root diameter 0.5-1.0 mm		Root diameter 1.0-3.0 mm		Root diameter >3.0 mm	
	cm	cm cm^{-3}							
		IRR[†]	NI	IRR	NI	IRR	NI	IRR	NI
CMP	0-15	0.113	-[§]	0.026	-	0.013	-	0.002	-
	15-30	0.220	-	0.038	-	0.026	-	0.000	-
DOHS-SWINGLE	0-15	0.777	0.404	0.041	0.072	0.029	0.017	0.000	0.000
	15-30	0.407	0.261	0.048	0.061	0.044	0.044	0.003	0.003
DOHS-C-35	0-15	0.811	0.347	0.044	0.060	0.003	0.031	0.002	0.000
	15-30	0.323	0.077	0.019	0.008	0.010	0.005	0.002	0.000
MOHS	0-15	0.428	0.351	0.079	0.054	0.015	0.012	0.000	0.004
	15-30	0.124	0.109	0.037	0.029	0.040	0.013	0.000	0.000
Statistics[¶]									
Irrigation method		NS		***		***		NS	
Depth		***		NS		***		***	
Distance from the tree		***		NS		NS		NS	
Irrigation method *Depth		NS		NS		NS		NS	
Irrigation method*Distance		NS		NS		NS		NS	
Depth*Distance		NS		NS		*		NS	
Irrigation method*Depth *Distance		NS		NS		NS		NS	

[†] IRR-Irrigated zone, NI-Non-irrigated zone. We did not observe many roots >3 mm in diameter at the Lake Alfred site in December 2009, [§] For conventional practices, all the sampled positions were irrigated [¶] Statistics: NS-Not significantly different, *-$p<0.05$, **-$p<0.01$, ***-$p<0.001$

Table 4-6. RLD as a function of irrigation method, soil depth and distance from the tree at the Lake Alfred site in July 2010

Irrigation method	Soil depth	Root diameter <0.5 mm		Root diameter 0.5-1.0 mm		Root diameter 1.0-3.0 mm		Root diameter >3.0 mm	
	cm	$cm\ cm^{-3}$							
		IRR[¶]	NI	IRR	NI	IRR	NI	IRR	NI
CMP	0-15	0.184	NA[§]	0.016	NA	0.011	NA	0.0007	NA
	15-30	0.120	NA	0.043	NA	0.023	NA	0.0021	NA
DOHS-SWINGLE	0-15	1.172	0.885	0.033	0.036	0.026	0.019	0.0098	0.0003
	15-30	0.543	0.185	0.030	0.027	0.040	0.016	0.0069	0.0006
DOHS-C-35	0-15	1.195	0.582	0.008	0.017	0.010	0.017	0.0042	0.0047
	15-30	0.293	0.165	0.012	0.017	0.008	0.016	0.0003	0.0009
MOHS	0-15	0.564	0.487	0.026	0.038	0.023	0.019	0.0037	0.0017
	15-30	0.218	0.083	0.022	0.027	0.018	0.029	0.0062	0.0003
		Statistics[‡]							
Irrigation method		**		***		NS		***	
Depth		***		NS		NS		NS	
Distance from the tree		***		**		NS		**	
Irrigation method *Depth		**		***		NS		***	
Irrigation method*Distance		*		*		NS		*	
Depth*Distance		*		**		NS		**	
Irrigation method*Depth* Distance		NS		*		NS		*	

[¶] IRR-Irrigated zone, NI-Non-irrigated zone. §NA-Not applicable, the whole sampled area was irrigated under CMP

[‡] Statistics: NS-Not significantly different, *-p<0.05, **-p<0.01, ***-p<0.001

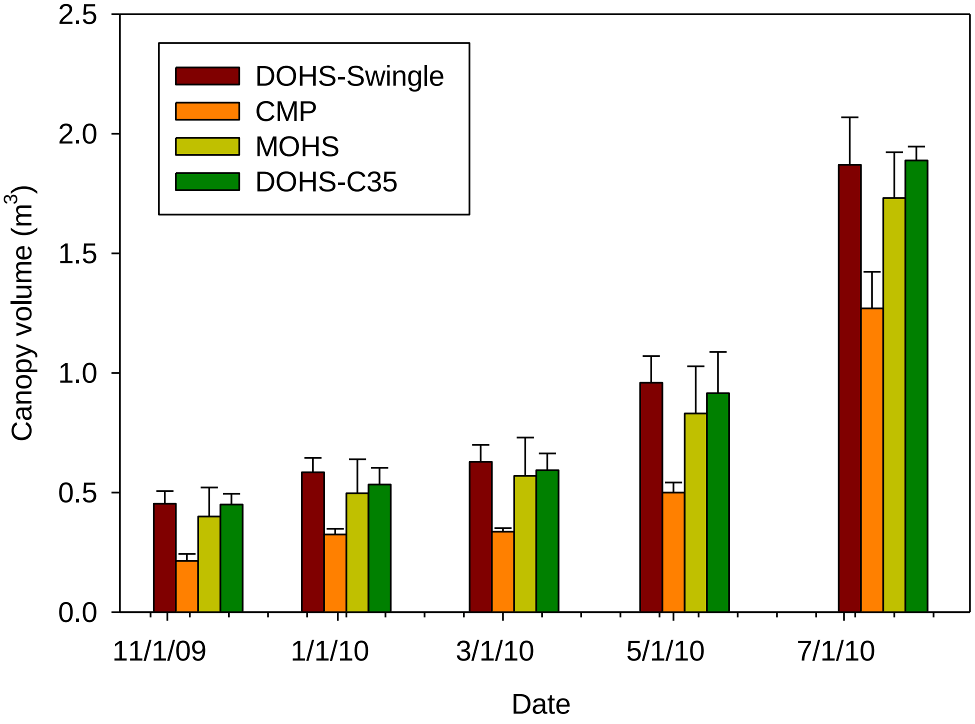
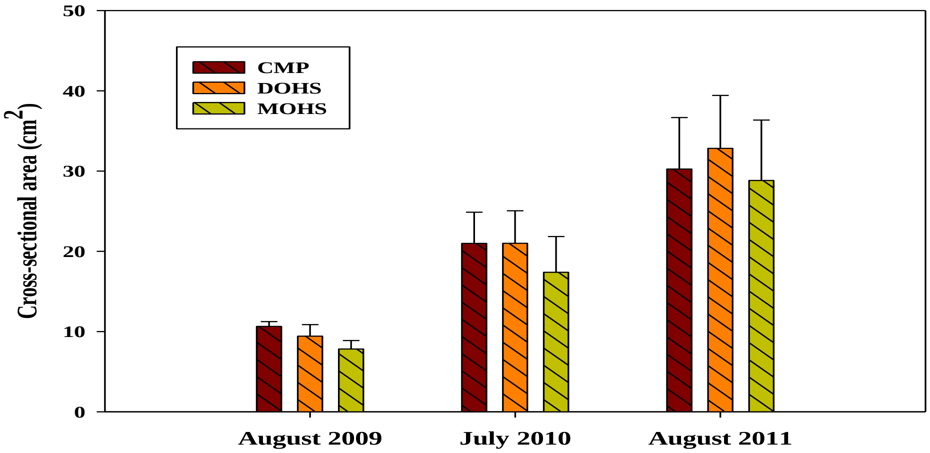


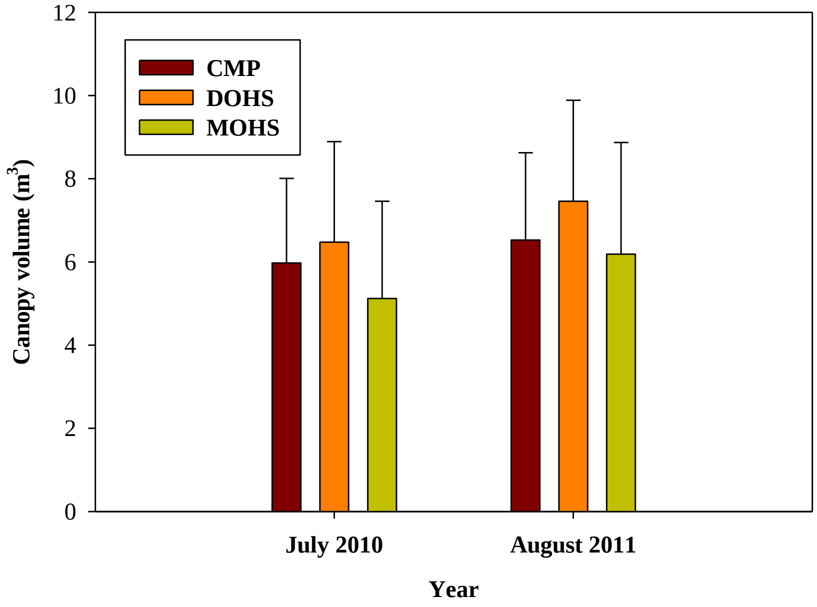
Figure 4-1. Canopy volume as a function of fertilization practice at the Lake Alfred site. Error bars denote one standard deviation of 4 replications



August 2009	CMP vs. DOHS	NS
	CMP vs. MOHS	*
	DOHS vs. MOHS	*
	N	12
July 2010	CMP vs. DOHS	NS
	CMP vs. MOHS	*
	DOHS vs. MOHS	*
	N	60
August 2011	CMP vs. DOHS	NS
	CMP vs. MOHS	NS
	DOHS vs. MOHS	NS
	N	60

*-indicates significance at $p<0.05$; NS-indicates non-significant differences; CMP-Conventional microsprinkler practice, DOHS-Drip open hydroponics system, MOHS-Microsprinkler open hydroponics system

Figure 4-2. Trunk cross-sectional area as a function of fertigation practice at the Immokalee site. Error bars denote one standard deviation



July 2010, August 2011	CMP vs. DOHS	NS
	CMP vs. MOHS	NS
	DOHS vs. MOHS	NS
	N	60

Mean±one standard deviation, NS-Not significant, *-p<0.05, **-p<0.01, CMP-Conventional microsprinkler practice, DOHS-Drip open hydroponics system, MOHS-Microsprinkler open hydroponics system

Figure 4-3. Canopy volume as a function of fertigation method at the Immokalee site

Table 4-7. Trunk cross-sectional area as function of fertigation method at the Lake Alfred site

Fertigation method	TCA-December 2009	TCA-July 2010	TCA-March 2011
		cm^2	
DOHS-Swingle[‡]	4.34±0.73	8.99±0.66	14.44±0.94
CMP[¶]	4.37±1.66	6.51±0.61	10.02±1.55
MOHS	4.23±0.57	8.55±0.81	12.84±2.04
DOHS-C-35	4.71±0.56	9.82±0.39	12.83±1.50
Significance[§]	NS	**	**

[‡]Mean±one standard deviation, [¶]CMP-Conventional microsprinkler practice, DOHS-Swingle-Drip open hydroponic system with Hamlins on Swingle rootstock, DOHS-C-35-Drip open hydroponic system with Hamlins on C35 rootstock, MOHS-Microsprinkler open hydroponic system, [§]NS-Not significant, **-p<0.01, TCA-Trunk cross-sectional area

CHAPTER 5

EFFECTS OF IRRIGATION METHOD AND FREQUENCY ON CITRUS WATER UPTAKE AND SOIL MOISTURE DISTRIBUTION

Accurate estimation of plant water use could improve irrigation management (Gutierrez et al., 1994; Morgan et al., 2006b) leading to a better understanding of plant-water-interactions (Ham et al., 1990; Gutierrez et al., 1994). Plant water use typically called crop evapotranspiration (ET_c) can be determined with the stem heat balance (SHB) method. The SHB technique has been found to be reasonably accurate and dependable in estimating plant water use in pecan (Steinberg et al., 1990a, b), citrus (Steppe et al., 2006), Anacardium excelsum (Meinzer et al., 1993), cotton (Ham et al. 1990), coffee and koa (Gutiérrez and Meinzer, 1994; Gutiérrez et al., 1994) and grapevines (Lascano et al., 1992; Heilman et al., 1994). The SHB approach provides a reliable method for measuring sap flow in the stems of herbaceous plants that is sufficiently accurate for application in many agronomic and biological applications (Baker and van Bavel, 1987; Baker and Nieber, 1989). Using the SHB method, sap flow rates in trees have been found to be within 4 to 10% of transpiration loss (Baker and Nieber, 1989; Steinberg et al., 1989; Lascano et al., 1992; Devitt et al., 1993). Dugas et al. (1994) also showed that cumulative sap flow for 14-day periods was similar to cumulative evapotranspiration or transpiration calculated from a water balance in cotton. SHB technique has several advantages over other methods for measuring water use such as lysimetry and water balance. The technique is non-intrusive, does not require calibration, responds quickly to plant water flow, can be used over long periods of time without damage to the plant (Baker and van Bavel, 1987; Steinberg et al., 1989; Gutierrez et al., 1994) and is simple to use with an appropriate digital datalogger (Baker and van Bavel, 1987).

Using reference evapotranspiration (ET_o), ET_c can be accurately determined once a crop coefficient (K_c) and soil moisture depletion coefficient (K_s) are known (Allen et al., 1998). K_s can be determined through periodic soil moisture measurement at selected depths of the plant root zone (Morgan et al., 2006b; Fares et al., 2008). K_c is defined as the ratio of crop evapotranspiration (ET_c) to potential evapotranspiration (ET_o) when soil water availability is non-limiting and is a function of crop type, climate, soil evaporation and crop growth stage (Allen et al., 1998; Morgan et al., 2006; Fares et al., 2008). Several studies using water balance and drainage lysimeter methods estimated that K_c values of citrus trees range from 0.6 in the fall and winter to 1.2 in the summer (Rogers et al., 1983; Boman, 1994; Martin et al., 1997, Fares and Alva, 1999, Morgan et al., 2006b). Jia et al. (2007) found that K_c values may vary from location to location. For example, they found that annual average K_c values were higher for the citrus grown in the Ridge regions (K_c =0.88) than for the Flatwoods (K_c = 0.72) in Florida, with monthly recommended values ranging from 0.70 to 1.05 for the ridge and from 0.65 to 0.85 for the Flatwoods citrus, respectively. They attributed the differences due to water logging in the root zone of the Flatwoods citrus owing to water table due to the presence of the spodic and/or argillic horizon. In studies on citrus K_c from other regions, different values have been reported depending on climate and method used. Values ranging from 0.80 to 0.90 have been reported using the water balance technique (Allen et al., 1998). For navel-orange tree groves in California, Consoli et al. (2006) found that K_c values ranged from 0.45 to 0.93 using an energy balance method. Rana et al. (2005), using the eddy correlation method, found that K_c values ranged from 0.8 to 1.2, corresponding to citrus phenological growth stage and the effects of high wind speed and high vapor pressure deficit.

Many studies in Florida on citrus tree water use have used other methods such as lysimetry, water balance and the Florida Automated Weather Network (FAWN) to estimate tree water use in citrus trees in the field without partitioning evaporation and transpiration from the ET component (Rogers et al., 1983; Boman, 1994; Obreza and Pitts, 2002; Jia et al., 2007; Morgan et al., 2006b; Fares et al., 2008). We attempted to estimate tree water use using the SHB technique to calculate K_c values basing on plant transpiration and Leaf Area Index (LAI) and correlate the two with root length density (RLD) and canopy volume. Water use through hourly and daily sap flow measurements would help in accurately predicting transpiration and devising ways of minimizing evaporation and percolation losses by synchronizing irrigation applications with peak tree water use. According to Morgan et al. (2006b), estimation of soil water uptake and resulting soil water depletion would allow for a more accurate assessment of soil water depletion, crop water uptake and soil moisture storage capacity.

The hypotheses postulated were:

- 1) citrus water use increases with canopy volume and root length density in-situ irrespective of the irrigation frequency and fertigation method and, that,
- 2) soil water content will be greater using the drip and microsprinkler OHS than grower practice.

The objectives of the study were to:

- 1) determine ET_c and K_c using SHB method on 1.5- and 4-year old citrus using three different irrigation methods and fertigation frequencies on Florida Spodosol and Entisol;
- 2) determine soil water distribution in the citrus irrigated root zone.

Materials and Methods

Experimental design and irrigation methods

A randomized complete block design consisting of three treatments at Immokalee site and two to four treatments at the Lake Alfred site was used, with three to four trees serving as replications. The irrigation treatments were applied to the replicate trees independently within a row. The irrigation treatments were as follows: (1) Conventional practice (CMP) irrigated weekly, with the microsprinkler placed at about 10-15 cm perpendicular to the tree; (2) Drip OHS (DOHS) – irrigated daily in small pulses, with two drip lines spaced at 30 cm from the tree, each delivering four emitters on each side of the tree; (3) Microsprinkler OHS (MOHS) – irrigated daily, with the microsprinkler placed at about 15 cm perpendicular to the tree. All the treatments were replicated four times. The treatments imposed at Lake Alfred were similar to the set-up at Immokalee site except for the modification to DOHS that had one drip line placed within the tree row, with one dripper placed at 15 cm on each side of the tree. The DOHS was imposed on both Swingle and C35 rootstocks. Drip irrigation was provided with integral Uniram (Netafim) pressure-compensating drip emitters (Netafim, Fresno, CA) (2.00 L h^{-1}). At both sites, microsprinkler irrigation was provided with either a single 40 L h^{-1} Max-14 (Maxijet, Dundee, FL) fill-in blue emitter for CMP or a 29 L h^{-1} Max-14 fill-in orange emitter for MOHS at each tree (Schumann et al., 2009; 2010).

Estimation of Soil Moisture

Soil water sensors on Candler sand (VG400, Vegetronix, Sandy, UT) and Immokalee sand (RS-485, Portland, OR), using the capacitance method (Katul et al., 1997; Morgan et al.; 1999; 2002) of estimating volumetric water content were used to measure moisture to determine treatment effects on soil water status. Soil moisture was measured every 30 minutes at 10 cm and 45 cm depths on Candler sand and 10-, 20-, 30-, 40- and 50-cm depths on Immokalee sand using capacitance probes and an automated logging system. Volumetric water content was measured (%) (Hillel, 1998). Rainfall data and other climatic variables were collected from FAWN stations at Southwest Florida Research and Education Center (SWFREC) and Citrus Research and Education Center (CREC) (http://fawn.ifas.ufl.edu/) (Apprendix E).

Estimation of Crop Water Uptake and K_c

Actual transpiration was measured on tree trunks or branches with a heat-balance method using Dynagage Flow32-1K Sap Flow System to evaluate tree water use. The direct transpiration readings were taken from July 2010, March 2011 and August to September 2011 at the Lake Alfred site and February, March and June 2011 at SWFREC. K_c was estimated for each site using the measured citrus transpiration and calculated reference ET_o from FAWN data. Water uptake was measured using sap flow sensors (Dynamax Inc., Houston, TX) on branches of four random trees per treatment (each tree serving as a replicate) at SWFREC. At SWFREC, four healthy trees per treatment were randomly selected to serve as replicates in the measurements.

At Lake Alfred, due to limitation in the size of sensors, sap flow measurements on trunks of six trees were taken on Drip OHS (DOHS-Swingle) and Conventional microsprinkler practice (CMP). Prior to installation of the sensors, measurements were taken of branch and trunk diameter. Also, critical measurements of variables that characterize water use in citrus such as Leaf Area Index (LAI) and canopy volume were determined using a Leaf Area Meter and measuring tape. In the study, we used the Dynamax Flow32-1K sap flow system (Dynamax Inc., Houston, TX) with CR1000 data logger, including PC400 data logger support software (Campbell Scientific Inc., Logan, UT). Trees at Lake Alfred had trunk diameters ranging from 24.92 mm to 31.40 and leaf area index (LAI) was about 1.77±0.71 in July 2010. We used the gauges of SGB25 model at the Lake Alfred site on trunks in July 2010 because the tree trunks were greater than 24 mm in diameter. In the subsequent seasons, the following sizes of sensors were used: SGA13-ws, SGB16-ws, SGB19-ws and SGB25-ws for respective stem diameter ranges of 12-16, 15-19, 18-23 and 24-32 mm. The thermocouple gaps specified were: 4.0 for SGA13, 5.0 for both SGB16 and SGB19, and 7.0 for SGB25.

Tree canopy volumes were estimated by measuring the average canopy diameter using canopy width in the east-west and north-south directions and canopy height using the formula for a sphere= $\frac{4}{3}\pi r^3$, where r is the canopy radius. Trunk diameter was estimated from averaging the diameter in the east-west and north-south directions and then calculating the area using the formula πr^2, where r is the trunk radius.

We adapted the approach for determining sap flow measurements from individual plants recommended by Lascano et al. (1992). Water use for trees was determined from measurement of sap flow in limbs by increasing measured sap flow by the proportion of leaf area of the measured limb over the leaf area of the entire tree. The mean transpiration, was estimated by normalizing the stem flow data on a population per land area basis as:

$$E_{sap} = 1000\left(\frac{M*P}{\rho_{water}}\right) \tag{5-1}$$

Where is E_{sap}=daily value of sap flow per unit land area (mm d^{-1}), M=sap flow per plant (kg d^{-1}), P=plant population m^{-2} and ρ_{water} is water density, 1000 kg m^{-3}.

The index sapflow crop coefficient, $K_{c,}$ was estimated following the equation below:

$$\text{Index sapflow } K_c * K_s = \left(\frac{E_{sap}}{ET_o}\right) \tag{5-2}$$

where ET_c is daily crop evapotranspiration (mm d^{-1}), ET_o is reference evapotranspiraton (mm d^{-1}), E_{sap} is the daily value of sap flow per unit land area (mm d^{-1}), K_s is soil water stress coefficient. Thus, assuming no water stress due to the automated irrigation, K_s, becomes unity.

The variation in soil water storage (ΔS) between two depths at the Lake Alfred site (z_1=0 cm and z_2=45 cm) and Immokalee site (z_1=0 cm, z_2=10 cm, z_3=20 cm, z_4=30 cm, z_5=40 cm, z_6=50 cm) for a given period of time ($\Delta t=t_1-t_2$; i.e., 1 day was used) was calculated based on measured water content readings by the capacitance probes using the following equation already formulated by Fares and Alva (2000b):

$$\Delta S = \int_{z_1}^{z_2} \theta(z, t_1)dz - \int_{z_1}^{z_2} \theta(z, t_2)dz \tag{5-3}$$

Results and Discussion

Tree characteristics at Immokalee and Lake Alfred

To determine leaf area in spring 2011, we categorized leaves at each site by size and measured the leaf area, length and width. Leaf areas for small, medium and large leaves averaged 10.7±4.2, 28.7±8.4, 67.4±16.8 cm^2 at Immokalee. Leaf areas for small, medium and large leaves averaged 15.1±4.7, 36.2±8.0, 68.9±16.0 cm^2 at Lake Alfred (Table 5-1). Tree canopy volumes ranged from 4.40±0.98 to 7.04±0.80 m^3 in February

2011 and from 6.67±1.30 to 9.32±1.10 in June 2011 at Immokalee (Table 5-2). At the Lake Alfred site, tree canopy measurements showed that canopy volumes ranged from 0.90±0.20 to 1.42±0.32 m^3 in July 2010, 2.81±0.73 to 4.89±0.58 in March 2011 and 4.45±0.45 to 6.53±0.88 in August 2011 (Table 5-2). Trunk cross-sectional areas varied from 19.32±4.35 to 27.00±2.14 cm^2 in February 2011 and 25.72±3.92 to 31.51±2.32 cm^2 in June 2011 at Immokalee. Trunk cross-sectional areas varied from 5.59±1.17 to 7.06±0.26, 10.02±1.55 to 14.44±0.94 cm^2 in March 2011 and 18.19±2.01 to 25.59±1.94 cm^2 in August 2011 at Lake Alfred (Table 5-2). To estimate, leaf areas in later sap flow studies, we developed calibration equations as shown in Figures 5-1 and 5-2.

Water Uptake at Immokalee and Lake Alfred

On average most days, we observed no sap flows in the two treatments at 0, 1, 6, 7, 8, 22 and 23 h as exemplified in Figure 5-3 in July 2010. Peak sap flow readings were noted between 10 and 20 h, ranging from 134 to 220 g h^{-1} under DOHS-Swingle. Sap flow readings under CMP peaked between 11 and 19 h, ranging from 110 to 133 g h^{-1}. In March 2011, average hourly sap flows peaked at around 1100 h and 1200 h. On March 17, 2011, for example, peak sap flows recorded were 298, 329, 519 and 336 g h^{-1} for DOHS-Swingle (at 1400 h), CMP and DOHS-C35 (at 1300 h), and MOHS (at 1200 h), respectively. On average hourly sap flow in March ranged from 194±35 to 385±152 g h^{-1}, 117±36 to 297±33 g h^{-1}, 176±32 to 276±46 g h^{-1} and from 154±26 to 248±46 g h^{-1} for DOHS-C35, MOHS, DOHS-Swingle and CMP (Figure 5-3). Similar to observations in July 2010, we noted that sap flows in spring 2011 also showed consistently high readings (>100 g h^{-1}) between 1000 h and 1800 h, probably due to increased solar radiation (averaging 239 and 254 W m^{-2} in July 2010 and March 2011) and temperature (25-30 ^{o}C in July 2010 and 11-22 ^{o}C March 2011) compared with the rest of day.

Similar hourly sap flows among the treatments using Swingle rootstock (DOHS-Swingle, MOHS, CMP) were noted regardless of the fertigation method and irrigation frequency (Figure 5-3). However, DOHS on C35 rootstock, had peak hourly sap flows that were 58% to 61% higher than CMP.

Lowest daily sap flow was approximately 2.05 kg d^{-1} on July 12, 2010 while the highest sap flow was about 4.74 kg d^{-1} on July 18, 2010 under DOHS-Swingle with mean daily sap flow readings averaging 3.96±0.74 g d^{-1} (Figure 5-4). Using CMP, the maximum and minimum values of the average daily sap flows were about 3.83 kg d^{-1} and 1.71 kg d^{-1} on July 10 and July 25, 2010, respectively, with a mean of 2.75±0.59 kg d^{-1} (Figure 5-4). There was very high variability in the daily readings of grower practice as shown in Figure 5-4 while consistently high readings with less variability were observed using DOHS-Swingle. On average, the sap flow was 44% higher under DOHS-Swingle than CMP. It appears the trees under grower practice also had some reasonable variability in trunk cross-sectional area (Table 5-2). Lascano et al. (1992), in their study on grapevines, explained that such variability among trees exists and can be reduced by normalizing the total sap flow by leaf area. Furthermore, in March 2011, all DOHS treatments on Swingle and C35 rootstocks showed sap flows greater than CMP by 7 to 150%. Sap flow for MOHS was higher than CMP on all days except on Julian days 77 and 78 when daily sap flow was 6% less than CMP suggesting that significant gains in water uptake on the ridge soil lie with drip OHS (Figure 5-5). In March 2011, daily transpiration readings were lowest using CMP on March 11, 2011 and peaked on March 23, 2011 using DOHS-C35 (Figure 5-5). Lowest average daily sap flows were observed on 03/11/2011 at the beginning of the study. For example, sapflows for CMP, DOHS-Swingle, DOHS-C35 and MOHS averaged 1.19±0.18, 2.77±1.42, 2.96±1.95 and 2.77±0.90 kg d^{-1}, respectively. Average daily sap flows for the all the treatments but CMP at Lake Alfred peaked on 03/23/2011. CMP showed a peak average sap flow of 4.84±0.94 kg d^{-1} on 03/18/2011. Peak sap flows recorded for DOHS-Swingle, DOHS-C35 and MOHS were 5.73±1.42, 8.98±7.28 and 4.71±2.37 g d^{-1}.

Average hourly and daily sap flows readings for studies conducted at SWFREC in February and March 2011 are given in Figures 5-6 and 5-7. For MOHS and CMP, we noted very low sap flow readings. The statuses of sensors reportedly ranged from 5-7 showing faulty readings that were identified late in the study. DOHS averaged hourly sap flow peaked to 1,361 g h^{-1} at 1100 h on February 27, 2011. MOHS and CMP peaked to about 210 g h^{-1} on February 27 at 1000 h. The data logger used for MOHS and CMP showed no readings most of the time resulting in the extremely low readings. We had to get this fixed at the end of the experiment. Thus, the readings for DOHS might actually represent the SWFREC site. Daily sap flow peaked to 21.6 kg d^{-1} on March 3, 2011 using DOHS. As indicated above, we also observed very low readings for MOHS with maximum daily sap flow of 1.38 kg d^{-1} and for CMP where maximum daily sap flow was 1.09 kg d^{-1}. Minimum daily sap flow readings were 213 and 220 g d^{-1} for MOHS and CMP, respectively.

Average hourly sap flows (Figure 5-8) in June 2011 at SWFREC was high between 1000h and 1600h in all the three fertigation methods peaking to respective values of 3.55, 2.27 and 1.77 kg h^{-1}, for DOHS, MOHS and CMP at 1600 h, 1400 h and 1300 h, respectively. Hourly sap flows peaked between 1000 h and 1900 h for DOHS and CMP, and between 1000 h and 2000 h for MOHS.

The average hourly sap flows at the Lake Alfred site in August- September 2011 (Figure 5-9), peaked between 1000 h and 1700 h. Sap flows followed the pattern DOHS- Swingle>MOHS> CMP>DOHS-C35. DOHS- Swingle, MOHS and CMP peaked to 2.53 kg h^{-1}, 1.62 kg h^{-1}, and 1.19 kg h^{-1} at 1400 h and DOHS-C35 peaked to 0.85 kg h^{-1} at 1300 h. The trees for the Swingle rootstock, including the grower practice (see canopy volumes in Table 5-2), had grown so much in fall 2011 compared with March 2011 at the Lake Alfred site with trunk cross-sectional area increments of 66, 77 and 94% and canopy volume increments of 49, 34 and 90% for the MOHS, DOHS and CMP, respectively. The grower practice, CMP, had the largest increase in canopy volume and significant increase in leaf area, probably due to the use of controlled-release fertilizer in summer 2010 and 2011. The tree size for C35 rootstock did increase by only 16 and 42% in canopy volume and trunk cross-sectional area suggesting a small increase in leaf area.

DOHS hourly sap flow was well above the other two fertigation methods in June 2011 at SWFREC. Daily sap flows (Figure 5-10) peaked in the following order: DOHS > MOHS ≈ CMP with respective maxima and minima of 58.8±28.7 and 33.3±1.7 kg d^{-1}, 33.8±16.6 and 23.5±10.6 kg d^{-1}, and 26.6±14.2 kg d^{-1} and 14.5±11.4 kg d^{-1}. All sap flows for DOHS ranged from 87 to 160% while for MOHS daily sap flow were 10 to 103% greater than CMP.

In August-September 2011, daily sap flow averaged 35, 27, 14 and 13 kg d^{-1} for DOHS-Swingle, MOHS, DOHS-C35, and CMP suggesting increments by 176%, 130% and 16% over CMP at the Lake Alfred site. As explained above we expected much higher sap flows for DOHS-C35 but a small increase in tree size and, probably leaf area compared with the other irrigation methods resulted in lower sap flow values compared with observations in March 2011 (Figure 5-11).

Daily sap flows per unit land area in July 2010 ranged from 0.11 to 0.25 mm d^{-1} using DOHS-Swingle and 0.09 to 0.21 mm d^{-1} using CMP with respective averages of 0.21 and 0.15 mm d^{-1} (Appendix A, Figure A36). Sap flows for the Swingles ranged from 0.20 to 0.31 mm d^{-1} and from 0.28 to 0.39 mm d^{-1} for DOHS-C35 in March 2011 at the Lake Alfred site (Appendix A, Figure A37). The sap flow in February-March 2011at Immokalee averaged 0.81 mm d^{-1} peaking to 1.06 mm d^{-1} on Julian day 61 (Appendix A, Figure A38). In June 2011 at Immokalee daily sap flow averaged 2.3, 1.4 and 1.1 mm d^{-1} for DOHS, MOHS and CMP (Appendix A, Figure A39). In August-September 2011 at the Lake Alfred site, daily sap flow ranged from 1.03±0.67 to 2.80±2.21 mm d^{-1}, 0.23±0.08 to 1.11±0.42 mm d^{-1}, 0.74±0.03 to 1.97±0.28 mm d^{-1}, and 0.62±0.21 to 1.38±0.64 mm d^{-1} for DOHS-Swingle, CMP, MOHS and DOHS-C35 (Appendix A, Figure A40). Large canopies, leaf areas and increased temperatures (averaging 26 ^{o}C at both Immokalee and the Lake Alfred site) accounted for better uptake in the OHS fertigation methods than grower practices at both sites.

Cumulative sap flows at the Lake Alfred site on the studies undertaken between Julian days 190-209 in 2010, 70-82 and 236-251 in 2011 showed that DOHS-Swingle had cumulative sap flow of 4.3 mm on day 209 while cumulative sap flow of CMP was 3.0 mm representing percent increase in sap flow in DOHS-Swingle of 20 to 56% over CMP between Julian days 190 and 209 (Appendix A, Figure A41). Cumulative sap flows were 43%, 35% and 80% higher than CMP for DOHS-Swngle, MOHS and DOHS-C35 representing very high uptake using ACPS fertigation compared with conventional irrigation practice between Julian days 70 and 82 (Appendix A, Figure A42). The cumulative sap flows were 3.34, 2.58, 3.01 and 4.75 mm for DOHS-Swingle, CMP, MOHS and DOHS-C35 between Days 70 and 82. In August-September 2011, the trees had increased in trunk cross-sectional area, canopy volume and leaf area resulting in cumulative sap flows that were 166%, 141% and 65% higher than CMP using DOHS-Swingle, MOHS and DOHS-C35, respectively. The cumulative sap flows on Julian Day 251 peaked to 30, 11, 23 and 17 mm using DOHS-Swingle, CMP, MOHS and DOHS-C35 (Appendix A, Figure A43).

In March 2011 at Immokalee, DOHS-Swingle peaked from 0.77 mm on Julian Day 48 to 11.31 mm on day 61 (Appendix A, Figure A44). The cumulative sap flows of 44 mm and 27 mm using DOHS and MOHS in June 2011 representing, on average, 115% and 37% higher sap flows than CMP, underlining the importance of frequent fertigation as also shown on the ridge site (Appendix A, Figure A45).

Index sap flow K_c averaged 0.029±0.014 and 0.042±0.003 using CMP and DOHS-Swingle, respectively at the Lake Alfred site in July 2010 (Appendix A, Figure A46), increasing to 0.06±0.01 and 0.08±0.02 in March 2011 (Appendix A, Figure A47). In March 2011, K_c values for MOHS and DOHS-C35 were 0.07±0.04 and 0.11±0.09 (Appendix A, Figure A47). The average K_c peaked in August-September ranging from 0.21±0.06 to 0.57±0.43, with high K_c observed in the OHS irrigation methods compared with grower practice probably because of frequent irrigation, vigorous tree growth and large canopies (Appendix A, Figure A48). At SWFREC, sap flow K_c ranged from 0.25±0.10 to 0.34±0.15 in February-March 2011 (Appendix A, Figure A49). The K_c in June 2011, ranged from 0.30±0.11 to 0.54±0.26, 0.21±0.09 to 0.34±0.14 and 0.13±0.10

to 0.25±0.15 using DOHS, MOHS, and CMP, respectively, suggesting that water uptake followed the order DOHS>MOHS>CMP (Figure A50). The sap flow K_c for the <2.5 yr-old trees at the Lake Alfred site suggests that transpiration accounted for about 3 to 10% of the actual evapotranspiration because the trees were young with small canopy volumes (ranging from 0.71 to 1.72 m^3) and leaf area (LAI ranged from 1.23±0.42 to 2.30±0.49) and thus had little ground cover. Soil evaporation tends to account for the greatest part of actual transpiration for a uniformly wetted surface not covered by the canopy (Testi et al., 2004). With trees getting older ~3 years or older, the transpiration component, as expected, increased and accounted for about 25 to 70% of the actual evapotranspiration. This is because citrus K_c for Florida conditions ranges from 0.6 in the fall and winter to 1.2 in the summer (Rogers et al., 1983; Boman, 1994; Fares and Alva, 1999; Morgan et al., 2006b; Jia et al., 2007) and water use tends to increase with age and increase in canopy volume (Morgan et al., 2006b). It is important to assess actual tree water use for proper irrigation scheduling and planning because, depending on tree age, water may need to be applied in the actual root zone for tree uptake as was the case with the OHS treatments. The sap flow K_c values in June/July and August/September (for trees>3 yr-old) are close to or slightly lower than many crop coefficients from other regions that included the evaporation component (Hoffman et al., 1982; Castel et al., 1987; Sepaskhah and Kashefipour, 1995; Martin et al., 1997; Consoli et al., 2006; Petillo and Castel, 2007; Snyder and O'Connell, 2007) or split the evaporation and transpiration components (Villalobos et al., 2009). Our study focused on trees <5 yr-old young trees while the studies from the other regions above focused on trees $\geq$7-yr-old mature trees. Rogers et al. (1983) explained that frequent rains in

Florida produce wet soil and leaf conditions that result in the actual ET being a great percentage of the potential ET than is true for semi-arid or arid conditions of California, USA (Consoli et al., 2006; Snyder and O'Connell, 2007), Texas, USA (Hoffman et al., 1982), Arizona, USA (Martin et al., 1997), Iran (Sepaskhah and Kashefipour, 1995), Japan (Yang et al., 2003; 2010) and Spain (Castel et al., 1987; Testi et al., 2004; Villalobos et al., 2009). This suggests that, ceteris paribus, Florida does have high water evaporative demand due to the hot humid climate and the deep drainage ascribed to the sandy soil characteristic.

Soil moisture distribution at Lake Alfred and Immokalee

The soil moisture distribution pattern showed that there was ample soil moisture in the root zone in all the treatments in July 2010 at the Lake Alfred site. For example, average soil moisture measurements as shown by time of day using grower practice (CMP) show that maximum soil moisture content was 8.42% (at 17.0 h) and minimum of 6.31% (at 15.8 h) at 10 cm soil depth layer and a maximum of 9.02% (at 18.0 h) and a minimum of 6.88% (at 15.8 h) at the 45 cm soil depth layer. MOHS yielded maximum soil moisture of 13.65% (at 9.8 h) and a minimum of 8.98% (at 8.0 h) at10 cm soil depth and 12.02% (at 17.5 h) and 11.26% (at 9.3 h) at 45 cm soil layer. The maxima and minima soil moisture using DOHS-C35 were 19.50% (at 8.5 h) and 9.99% (at 13.0 h) at 10 cm soil depth and 12.43% (at 17.5 h) and 11.65% (around 8.3-8.8 h) at 45 cm soil depth (Figure 5-12). Daily soil moisture at 10 and 45 cm soil depths averaged 7.6±1.6 and 8.2±0.9%, 10.2±3.2 and 11.5±0.8%, and 11.8±4.5 and 12.0±0.4% (Figures 5-13 and 5-14) using CMP, MOHS and DOHS-C35. Lower average soil moisture content at 10 cm than 45 cm suggests water removals either through tree uptake, soil evaporation or downward drainage.

In March 2011 at the Lake Alfred site, the soil moisture peaked to around 8.22, 12.08 and 14.79% between 7.30am and 8.30am at 10 cm depth, decreased to 6.44, 10.86 and 7.18% in the afternoon and at night in the respective treatments CMP, MOHS, DOHS-C35 (Figure 5-15). At 45 cm soil depth, soil moisture was higher than the upper top 10 cm soil layer (Figure 5-15) probably due to downward drainage. Daily soil moisture averaged 7.3, 11.3 and 10.5% at 10 cm depth (Figure 5-16) and 10.5, 12.3 and 7.6% at 45 cm depth (Figure 5-17) using CMP, MOHS and DOHS-C35 irrigation treatments in March 2011. Our own results in Chapter 4 and those of Zhang et al. (1996) confirm that tree uptake should be greater in the 0-15 cm soil layer than lower horizons owing to high root density in the range of 55-67% on length basis (this study) and 70-75% on weight basis (Zhang et al., 1996) in the top 15 cm. Our observations are also supported by earlier studies (Goldberg et al., 1971; Alva and Syvertsen, 1991; Khan et al. 1996; Alva et al., 1999; Fares and Alva, 2000a, b; Badr, 2007; Davenport et al., 2008; Badr and Abuarab, 2011). Khan et al. (1996) showed that soil water content increased up to 25 cm depth and 30 cm radial distance at application rates ranging from 1.5-2.5 L h^{-1} and input concentration falling between 100 and 500 mg L^{-1} on coarse loamy soil. They also showed that solute concentration increased with high input concentration, applied volume and application rate up to about the same depth (~25 cm) and radial distance (~30 cm) as for soil water content. Davenport et al. (2008) further observed that soil moisture distribution for drip-irrigated vineyards was adequate in the 0-45 cm depth and within 20-40 cm radius, either diagonal or perpendicular to the drip line. Our observations are also supported by Goldberg et al. (1971) who concluded in their study that soil moisture resulting from drip irrigation was two dimensional, with moisture contents high along and beneath the row and decreasing laterally. Thus, according to Goldberg et al. (1971) the effect of shorter irrigation intervals, as was the case with drip and microsprinkler ACPS/OHS, with proportionally smaller amounts of water applied in a single irrigation, is to decrease the variations in moisture content in the root zone and establish a continuously higher moisture regime. Eventually, drip that was developed to conserve water in arid environments (Goldberg and Shmueli, 1970) has been adapted to semi-arid and humid regions to manage water in sandy soils with high conductivity and supplement water where rainfall is inadequate or is not uniformly distributed throughout the year.

In August and September 2011, a contrary soil moisture distribution trend was noted. The moisture content averaged 12.63 and 10.94% (CMP), 10.88 and 8.06% (MOHS) and 11.55 and 9.32% (DOHS-C35) at 10 cm and 45 cm depth layers, respectively, suggesting that soil moisture decreased with depth probably because of the frequent rainfall that kept the top 10 cm layer wet throughout the study period (Figures 5-18, 5-19 and 5-20).

On Immokalee sand, the DOHS soil moisture varied between 7.5 and 10.0% in the top 10-30 cm and remained between 5 and 6.5% at 40- and 50 cm depths in February and March 2011 (Figure 5-21). In June 2011, the moisture contents ranged from 7.5 to 12.0% in the top 30% and between 6.5 and 7.7 at 40- and 50-cm soil depths (Figure 5-22). The soil water at Immokalee using MOHS ranged from 8.5 to 14% and around 6 to 8% in the 40 to 50 cm soil depths in February-March 2011 (Figure 5-23) and June 2011 (Figure 5-24). The grower practice had soil moisture contents varying between 8 and 13% in the top 20 cm, and between 6 and 7% in the 30-50 cm soil depth layers in

February-March 2011 (Figure 5-25). In June 2011, the soil moisture varied from 10-20% in the top 20 cm and ranged from 6 to 13% in the lower 30-50 cm soil depth (Figure 5-26). The lower soil moisture contents in the lower 30-50 cm depth suggests that probably root water extraction in the top 30 cm resulted in less water percolating to lower soil depth layers. This might hold because the Immokalee sand has a shallow water table (Obreza and Pitts, 2002) that limits root development in the top 30 cm (Bauer et al., 2004).

Factors affecting water uptake on the two soils

Linear and nonlinear analysis revealed the major factors controlling cumulative water uptake for young citrus trees at Lake Alfred and Immokalee sites. In July 2010, when the trees at the Lake Alfred site were fairly small (<2 yr-old) with small canopies (<1.74 m^3), cumulative water uptake was largely a function of trunk cross-sectional area (R^2=0.98, $p<0.001$) and canopy volume (R^2=0.67, $p=0.046$) and less influence from soil water, leaf area and root length density ($R^2<0.56$, $p>0.05$) (Table 5-3). At about 2.5 years, the trees at Lake Alfred showed that soil water at Lake Alfred ($p<0.001$) influenced water uptake to a larger extent while canopy volume, soil water at 45 cm, trunk cross-sectional area and leaf area were less influential ($p>0.05$) (Table 5-4). This observation was also supported by results for 6 yr-old trees at Immokalee in June 2011 and 3 yr-old trees at Lake Alfred later in September 2011. For example, cumulative water uptake at Immokalee was largely influenced by soil water at 10, 20, 30, 40 and 50 cm soil depth ($p<0.001$) and not necessarily canopy volume ($p=0.400$), leaf area ($p=0.96$) and trunk cross-sectional area ($p=0.576$). Also, the soil water at 10 cm ($p=0.001$) and 45 cm ($p=0.002$) depths at Lake Alfred in September 2011 exerted significant influence on water uptake compared with canopy volume ($p=0.826$), trunk cross-sectional area (p=0.053) and leaf area (R^2=0.27) (Tables 5-3 and 5-4). However, longterm analysis of water uptake versus tree characteristics suggests that canopy volume (Figure 5-27) will be the major determinant of overall tree water uses matched with good irrigation practice. An exponential model adequately described the relationship between cumulative water uptake and canopy volume. Thus, it appears for young trees (<6 yr-old) irrigation scheduling is a critical management practice especially for the sandy soil as shown by the good correlation with water uptake. Despite weak correlation with root length density, the results on root density showed increased root intensity in the top 0-30 cm soil depth layer indicating that water extraction would be enhanced with an increase in available water.

Summary

The chapter described the citrus water uptake and soil moisture distribution patterns in the irrigated zone on the citrus producing regions of central and southwest Florida. The results showed that hourly, daily and cumulative sap flow were higher using the ACPS/OHS irrigation methods compared with the conventional grower practices (fertigated or receiving granular fertilization), albeit, not significantly different. The citrus water use, in agreement with the postulated hypothesis, did increase with canopy volume and root length density in-situ irrespective of the irrigation frequency and fertigation method and correlated strongly with soil moisture content, trunk crossectional area and canopy volume. The high uptake in the ACPS/OHS irrigation methods is ascribed to the frequent irrigation and vigorous growth resulting in trees with large canopy volumes, leaf areas and trunk cross-sectional areas compared with weekly irrigation associated with the grower practice. The results support the thinking behind the novel ACPS/OHS practices that nutrient leaching would be minimized while accelerating tree growth as a result of enhanced water and corresponding nutrient uptake. Thus, the irrigated root zones of DOHS or MOHS which have about 4% and 20% of the area irrigated by CMP, respectively, showed that the trees would not be stressed by the ACPS practices.

The K_c followed a similar pattern to that of sap flow and was generally higher using drip OHS compared with microsprinkler irrigation. For young trees 1.5 to 2.3 yr-old at the Lake Alfred site, index sap flow K_c averaged 0.029±0.014 and 0.042±0.003 using CMP and DOHS-Swingle, respectively at the Lake Alfred site in July 2010, increasing to 0.06±0.01 and 0.08±0.02 in March 2011. For older trees greater than 3 yr-old, K_c varied from 0.25±0.10 in March, to 0.54±0.26 in June and 0.57±0.43 in September. Thus, these studies revealed that tree water uptake accounted for about 3 to 10% of the actual ET when the trees are small and over 60% of the ET after three years when the trees increased in size with regard to leaf area and canopy volume.

The soil moisture distribution patterns in all the irrigation methods were similar and maintained soil moisture close to or slightly above field capacity largely in the range of 7 and 15% suggesting that soil moisture was non-limiting at both sites. Thus, the hypothesis that ‘drip and microsprinkler OHS would result in greater soil water content in the irrigated zone than grower practices’ was not true. The increased availability of water in the top 30 cm suggests that the leaching threat is minimal under such frequent irrigation practices due to increased root water and probably nutrient extraction from this layer. These results support intensive irrigation management practices in young trees to insure ample water is available in the root zone.

Table 5-1. Average leaf area

Site	Small	Medium	Large
		cm^2	
Immokalee	[§]10.71±4.19	28.68±8.39	67.27±16.77
Lake Alfred	15.13±4.70	36.22±8.04	68.93±16.01

[§]All values are mean areas of 20 leaves ± one standard deviation

Table 5-2. Tree canopy volume (CV), stem cross-sectional area (SCA), and trunk cross-sectional area (TCA)

Immokalee site						
Irrigation method	February 2011			June 2011		
	CV (m^3)	SCA (cm^2)	TCA (cm^2)	CV (m^3)	SCA (cm^2)	TCA (cm^2)
DOHS	[‡]7.04±0.80	2.48±0.96	27.00±2.14	9.32±1.10	3.30±1.24	31.51±2.32
MOHS	4.40±0.98	2.34±0.80	19.32±4.35	6.67±1.30	3.47±1.43	26.19±4.44
CMP	6.47±1.20	2.05±0.81	20.21±2.60	7.61±1.26	3.09±1.23	25.72±3.92

Lake Alfred site						
Irrigation method	July 2010		March 2011		August 2011	
	CV (m^3)	TCA (cm^2)	CV (m^3)	TCA (cm^2)	CV (m^3)	TCA (cm^2)
[¶]DOHS-Swingle	1.42±0.32	7.06±0.26	4.89±0.58	14.44±0.94	6.53±0.88	25.59±1.94
CMP	0.90±0.20	5.59±1.17	2.81±0.73	10.02±1.55	5.33±0.48	19.46±1.60
MOHS	NA	NA	3.91±0.67	12.84±2.04	5.84±0.85	21.33±3.41
DOHS-C-35	NA	NA	3.83±0.79	12.83±1.50	4.45±0.45	18.19±2.01

[‡]Mean±one standard deviation, n=3 per treatment for trees sampled in July 2010, n=4 for trees sampled in February, March and August 2011, mean ± 1 standard deviation, [¶]CMP-Conventional microsprinkler practice, DOHS-Swingle-Drip open hydroponic system with Hamlins on Swingle rootstock, DOHS-C-35- Drip open hydroponic system with Hamlins on C-35 rootstock, MOHS-Microsprinkler open hydroponic system

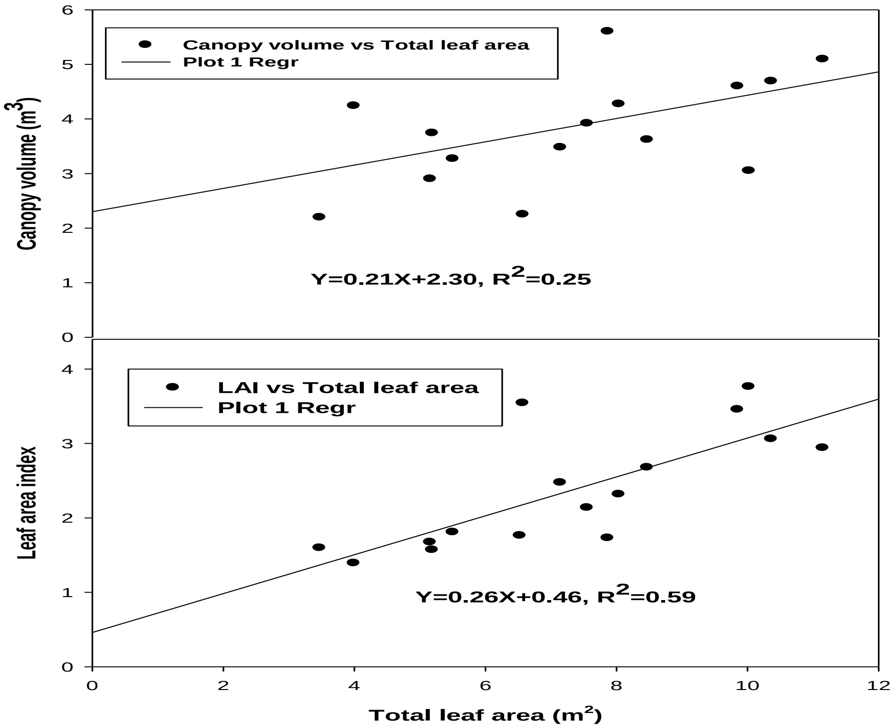


Figure 5-1. Linear correlations of leaf area index and canopy volume as a function of leaf area in March 2011 at the Lake Alfred site

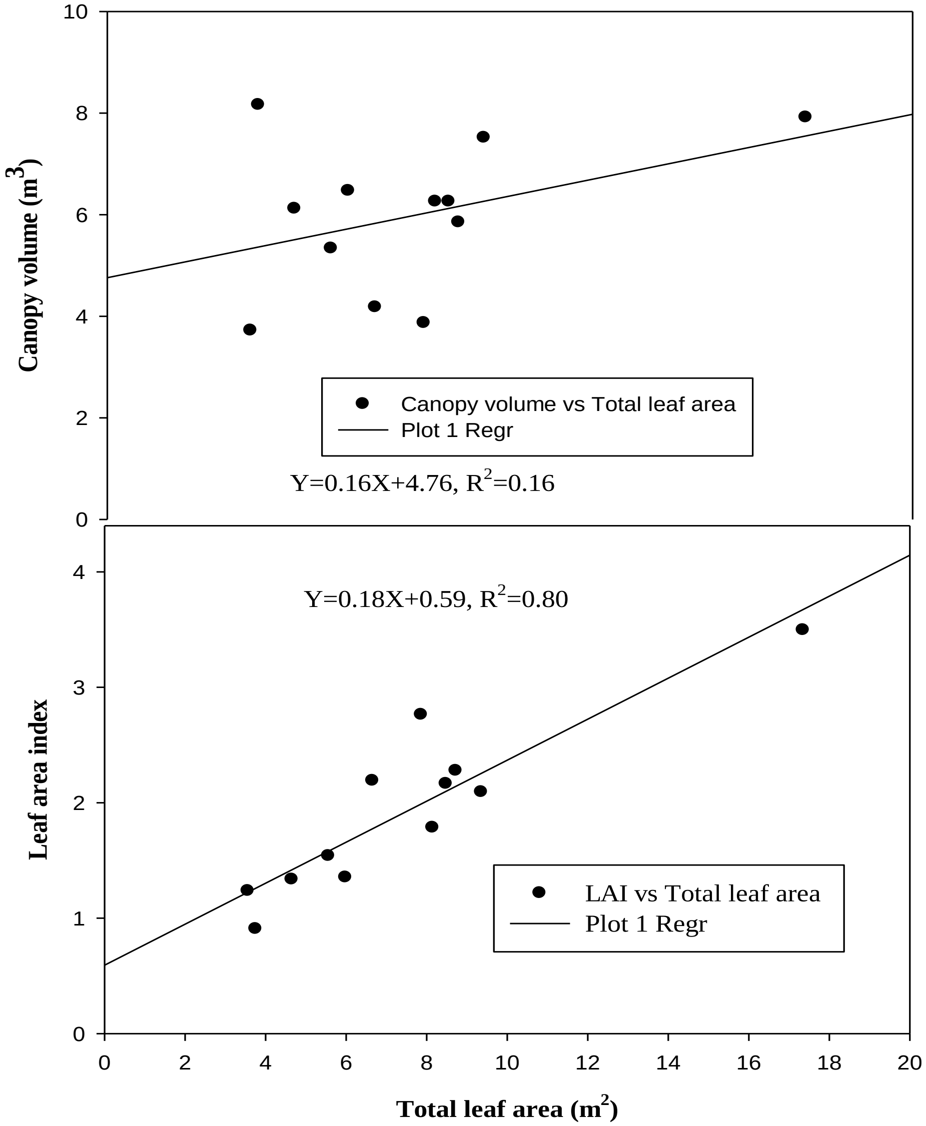


Figure 5-2. Correlations of leaf area index (LAI) and canopy volume as a function of total leaf area at Immokalee site in March 2011

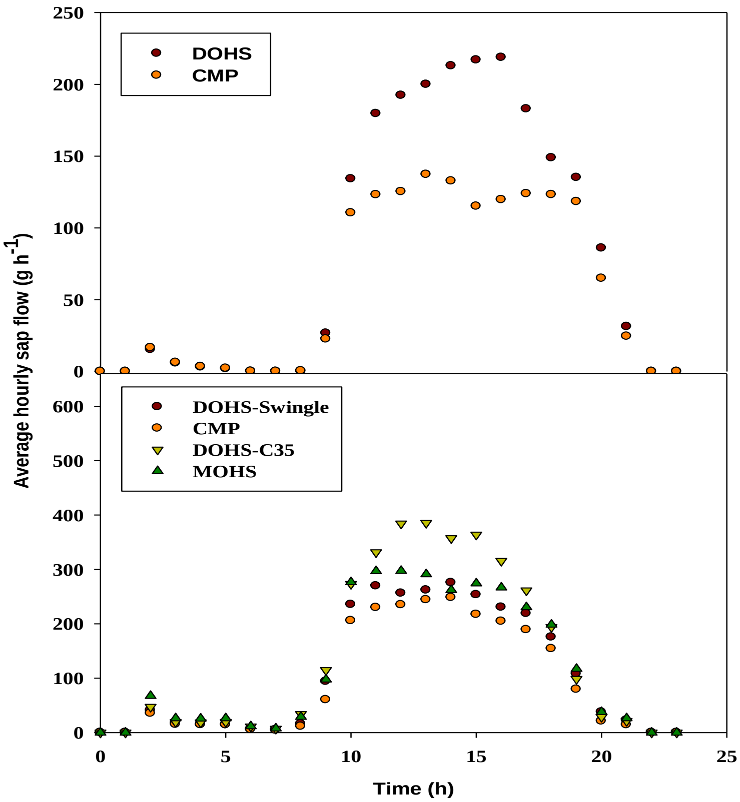


Figure 5-3. Average hourly sap flow in July, 2010 (top) and March, 2011 (bottom) at Lake Alfred site

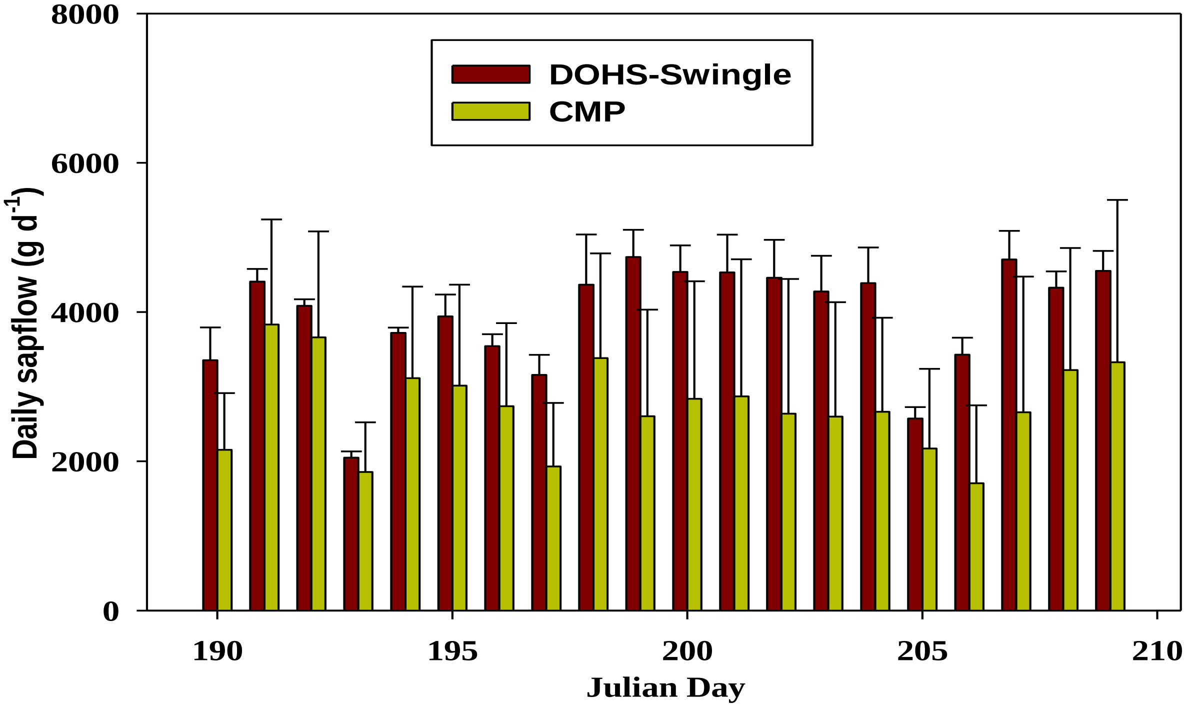


Figure 5-4. Average daily sap flow in July, 2010 at the Lake Alfred site. Error bars represent one standard deviation

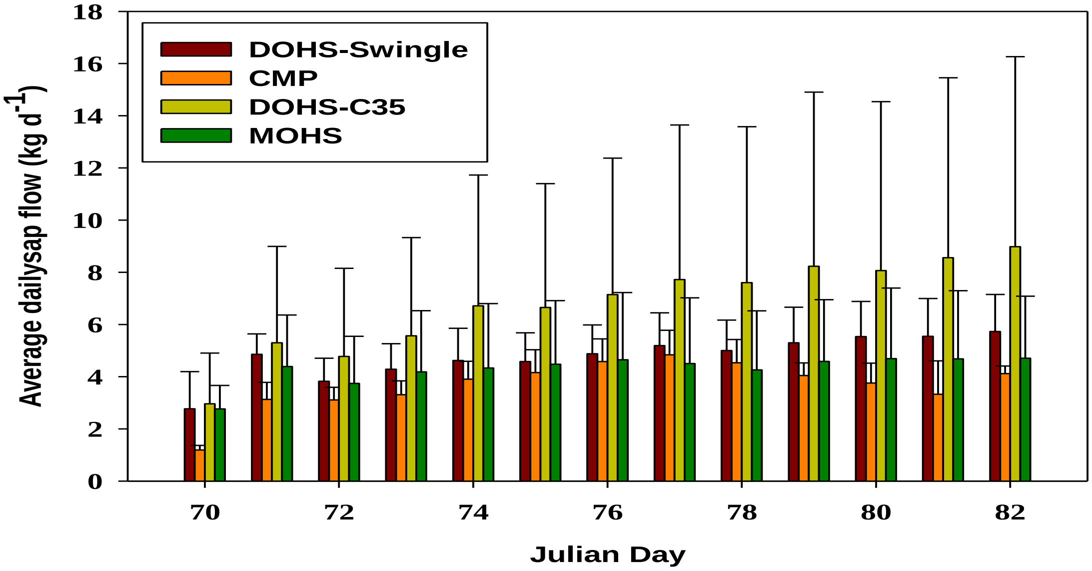


Figure 5-5. Average daily sap flow in March, 2011 at the Lake Alfred site. Error bars represent one standard deviation

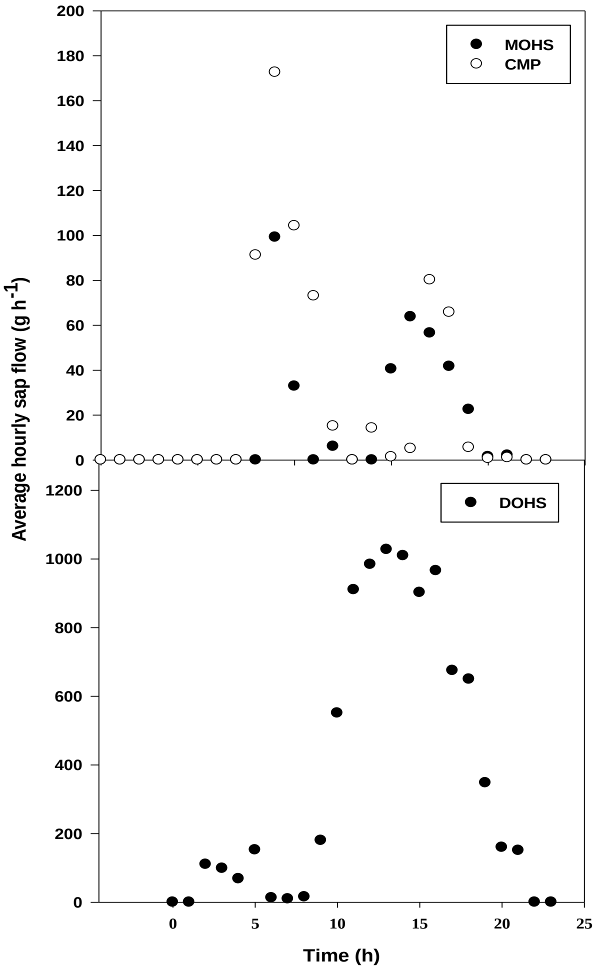


Figure 5-6. Average hourly sap flow in February-March 2011 at SWFREC. Data logger used for CMP and MOHS had a fault and showed very low sap flow readings

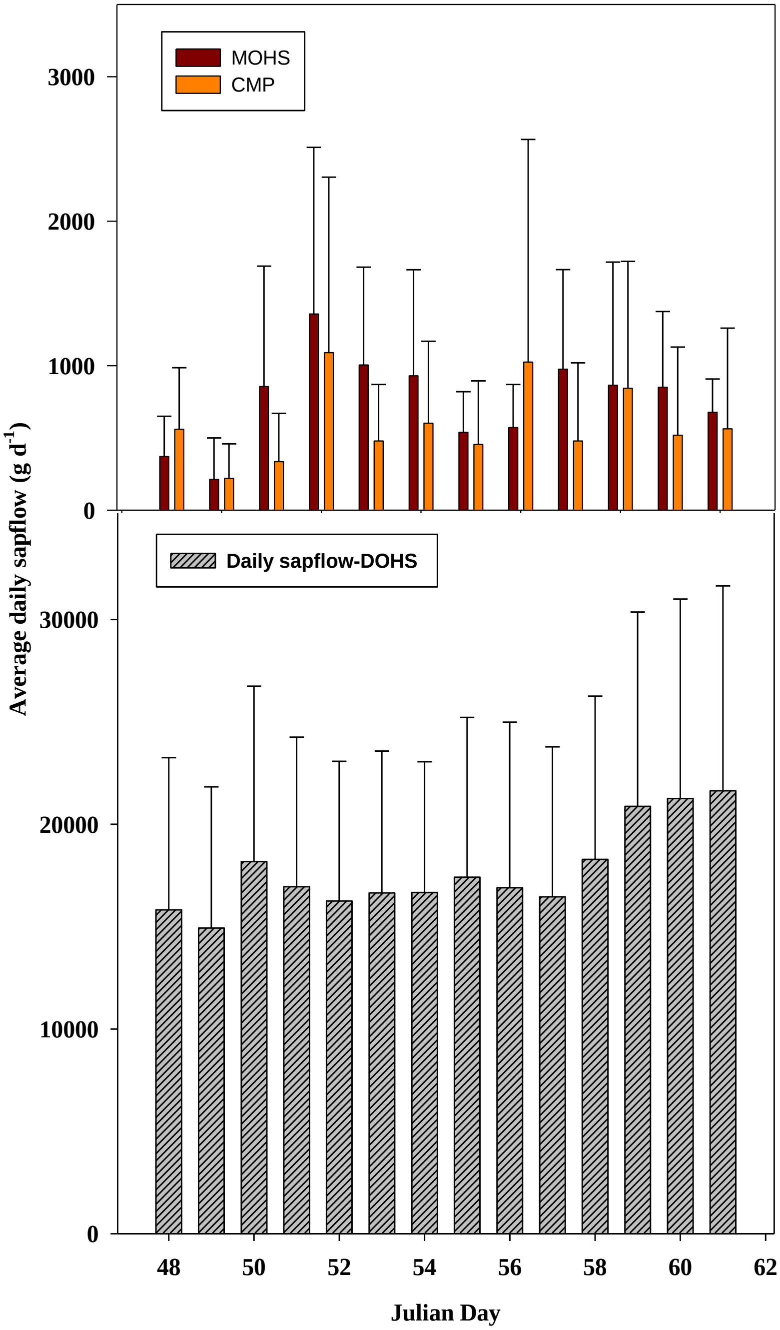


Figure 5-7. Average daily sap flow in February-March 2011 at SWFREC. Error bars represent one standard deviation. Data logger used for CMP and MOHS had a fault and showed very low sap flow readings

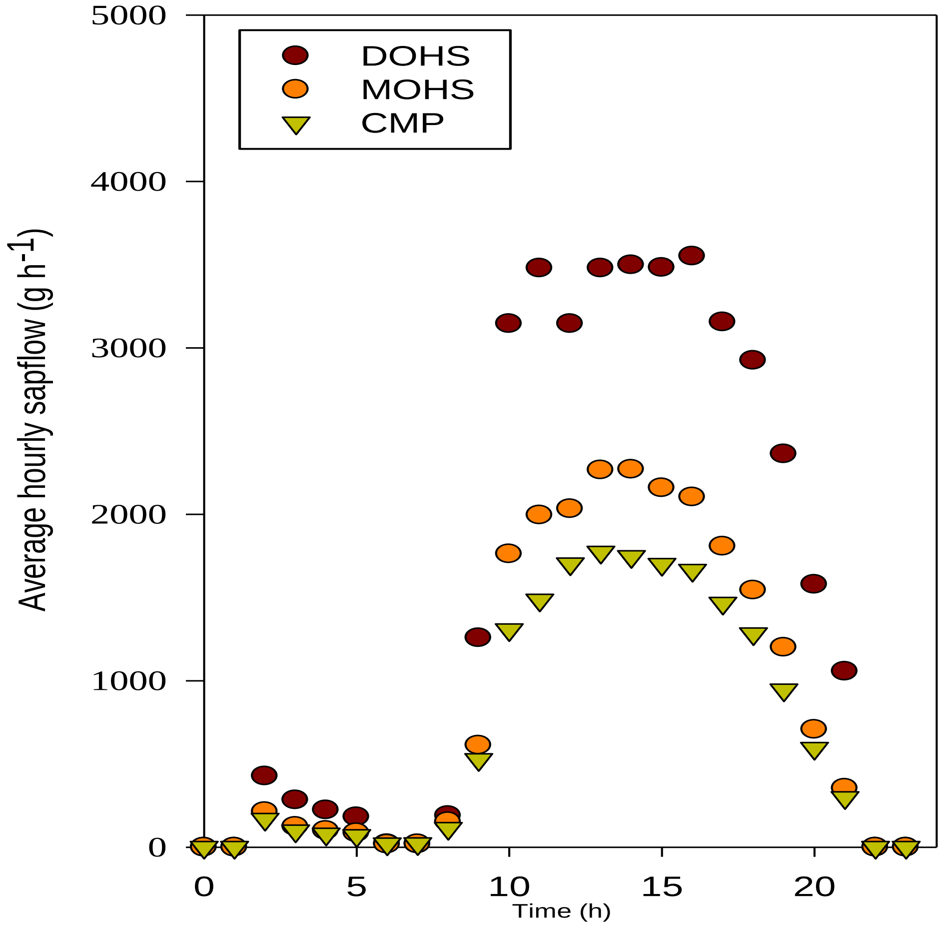


Figure 5-8. Average hourly flow in June 2011 at the Immokalee site

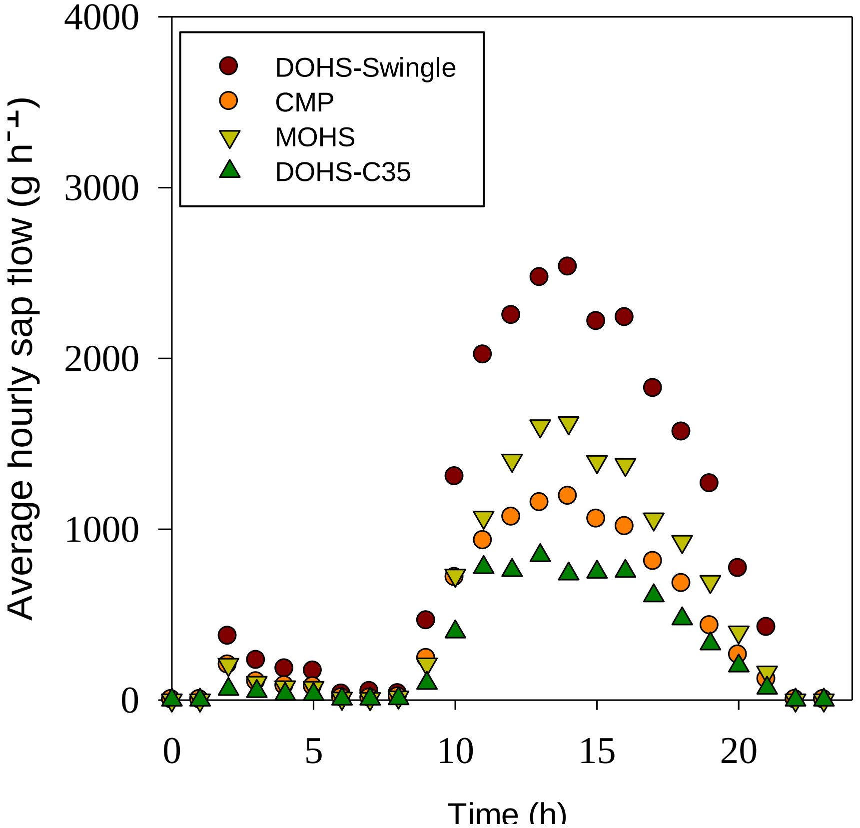


Figure 5-9. Average hourly sap flow in August-September, 2011 at the Lake Alfred site

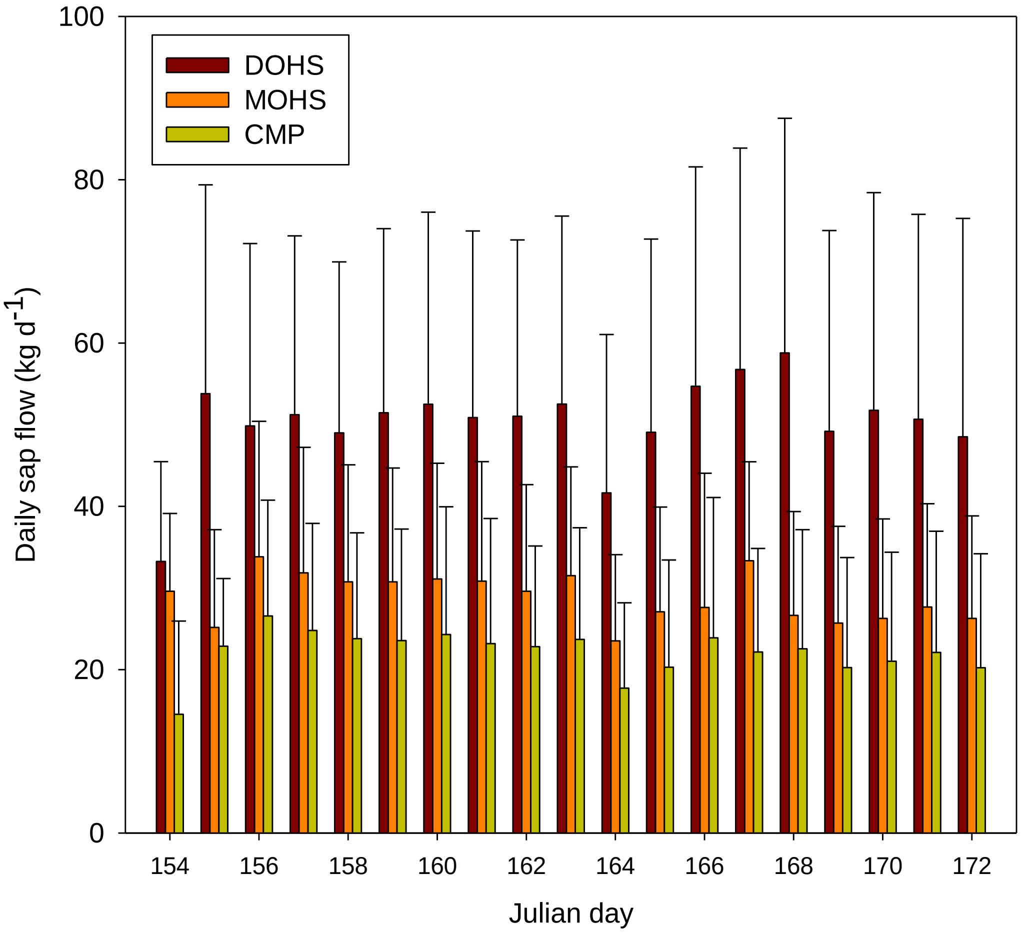


Figure 5-10. Average daily sap flow in June 2011 at the Immokalee site. Error bars represent one standard deviation

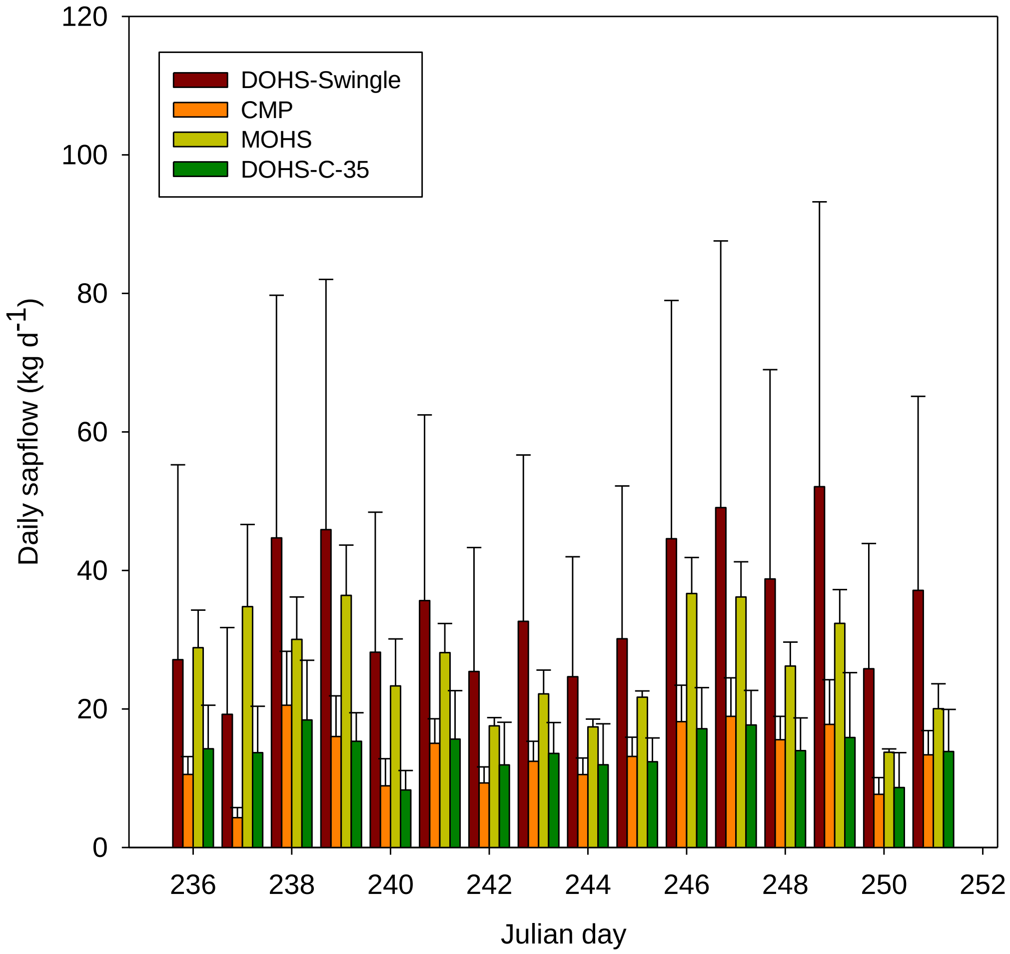


Figure 5-11. Average daily sap flow in August-September, 2011 at the Lake Alfred site. Error bars represent one standard deviation

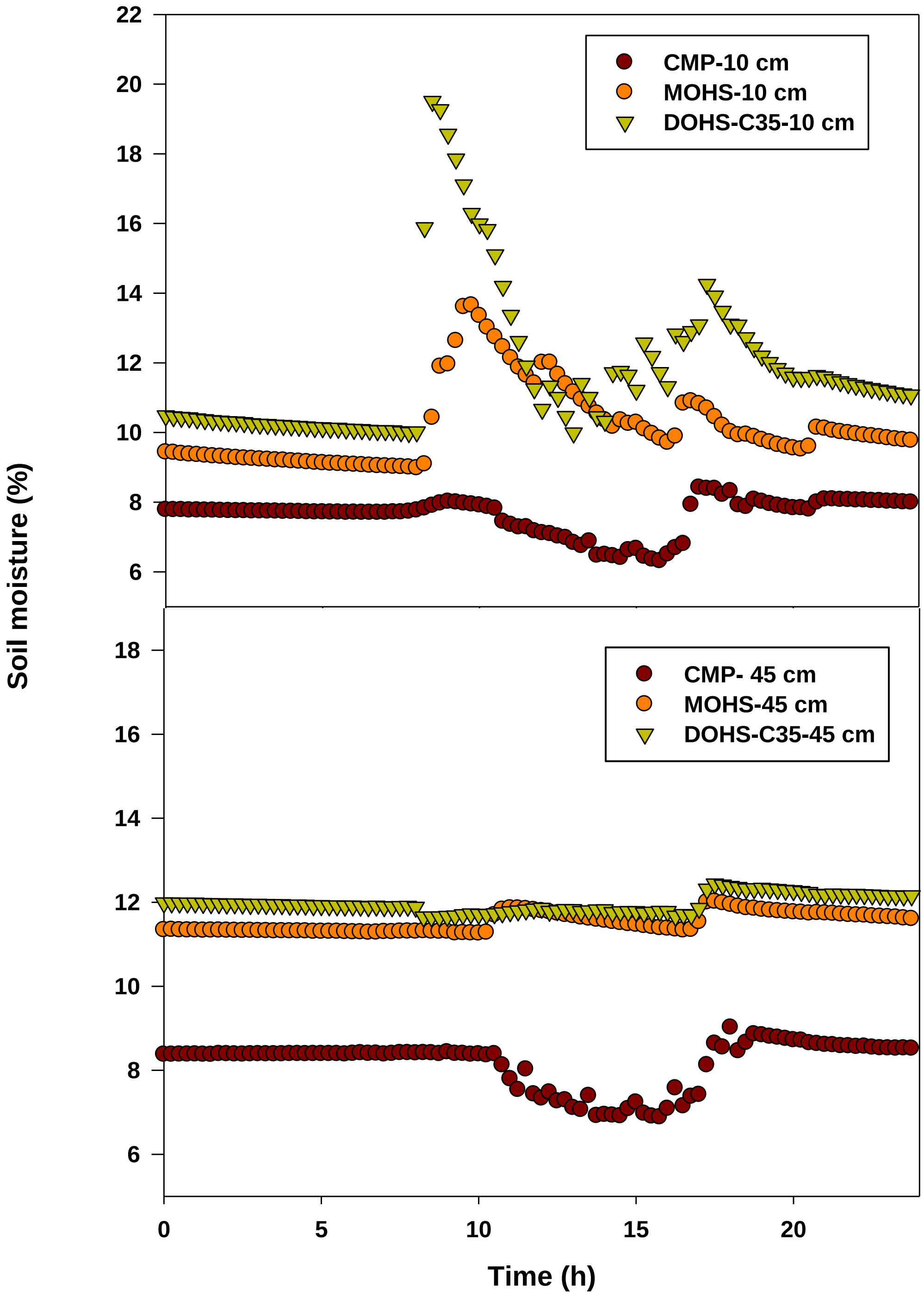


Figure 5-12. Average hourly soil moisture distribution in July 2010 at the Lake Alfred site measured at 10- and 45 cm soil depth layers

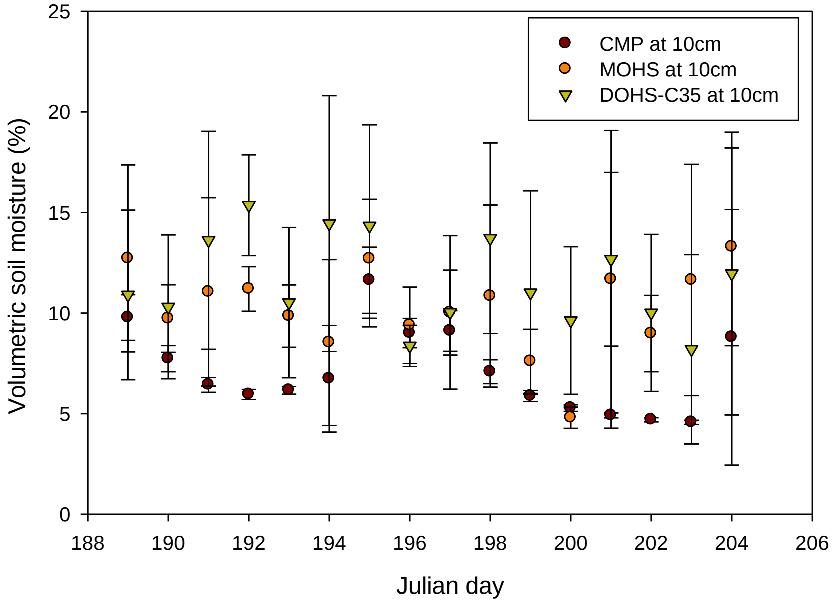


Figure 5-13. Average daily soil moisture distribution in July 2010 at the Lake Alfred site measured at 10 cm soil depth layer. Error bars denote one standard deviation

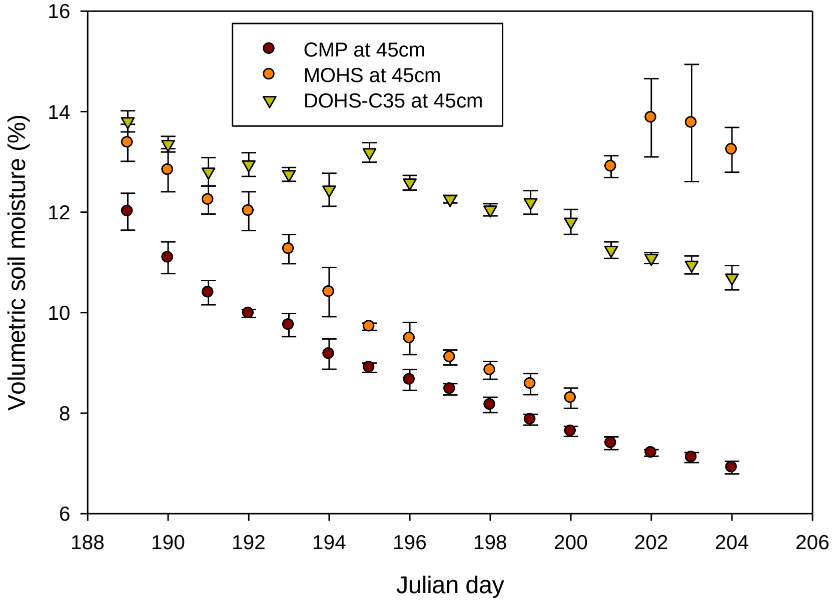


Figure 5-14. Soil moisture distribution in July 2010 at the Lake Alfred site measured at 45 cm soil depth layer. Error bars denote one standard deviation

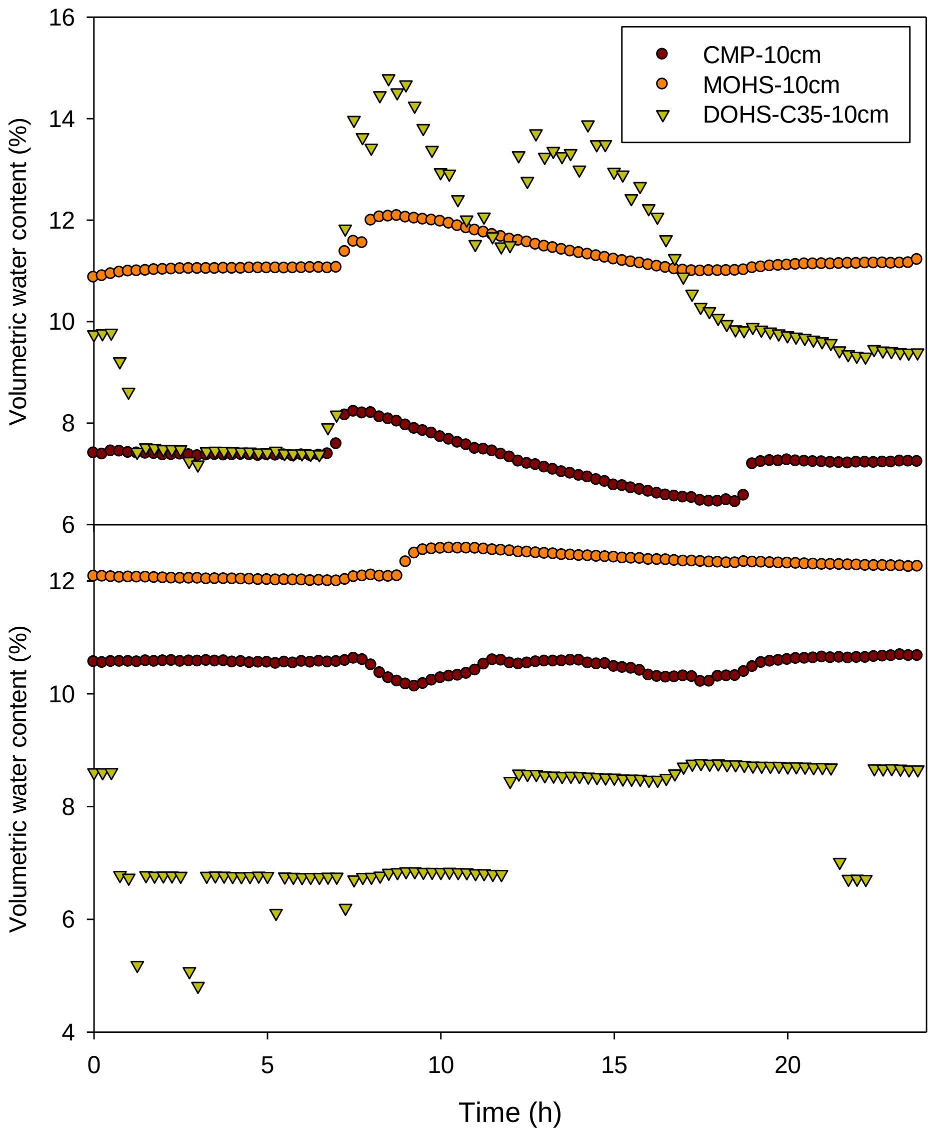


Figure 5-15. Average hourly soil moisture distribution at the Lake Alfred site measured at 10 cm (top) and 45 cm (bottom) soil depth layers in March 2011.

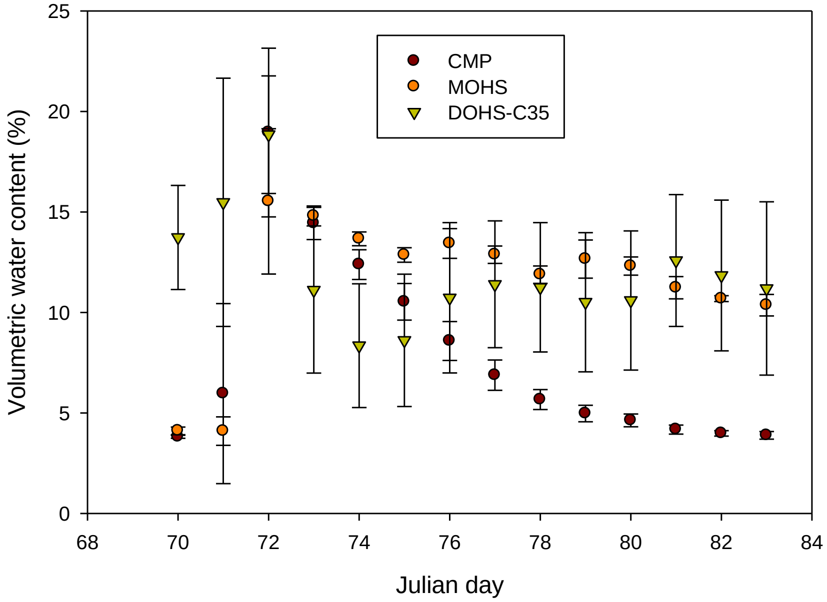


Figure 5-16. Daily soil moisture distribution at the Lake Alfred site measured at 10 cm soil depth layer in March 2011. Error bars denote one standard deviation

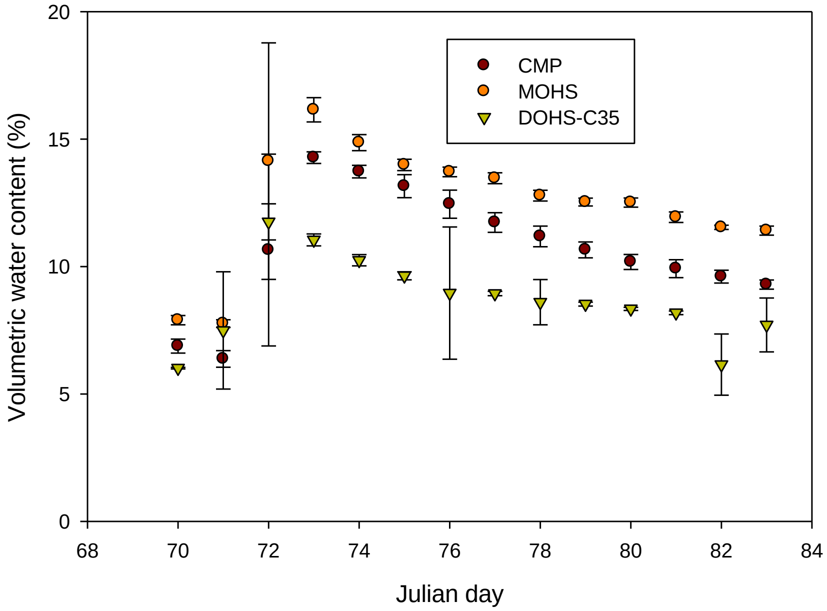


Figure 5-17. Daily soil moisture distribution at the Lake Alfred site measured at 45 cm soil depth layer in March 2011. Error bars denote one standard deviation

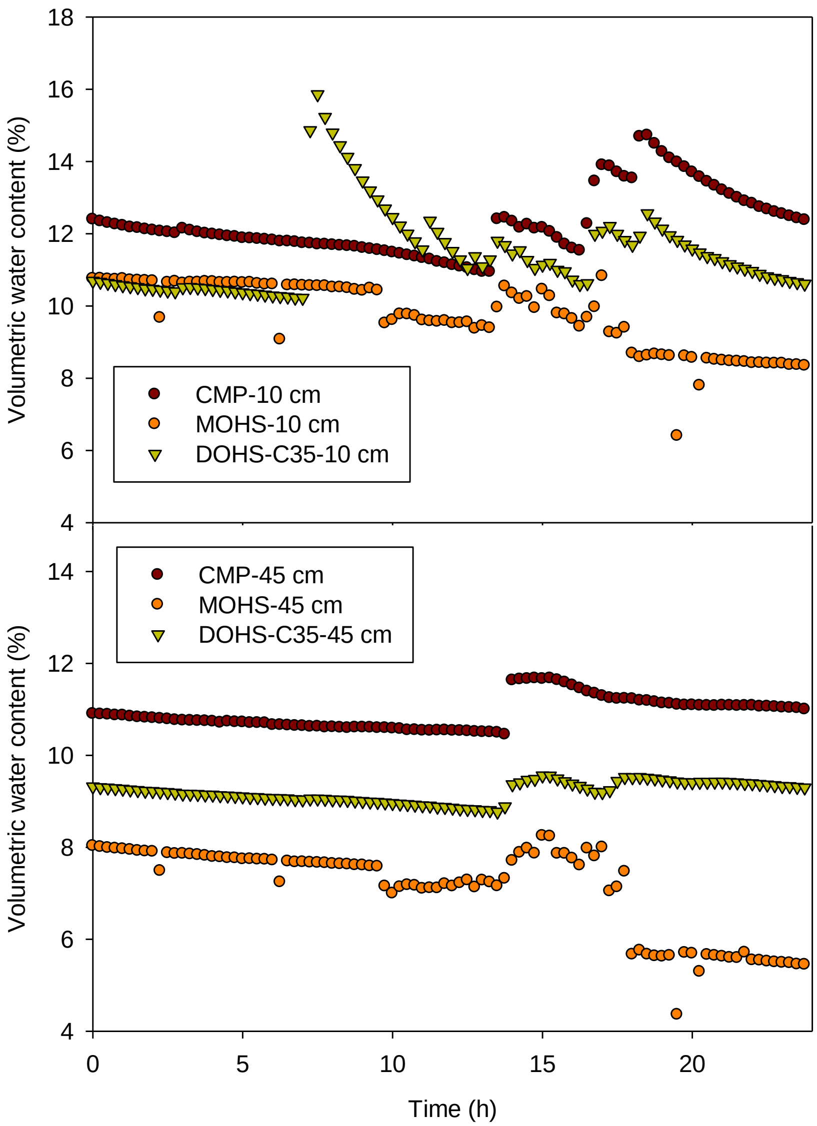


Figure 5-18. Average hourly soil moisture distribution at the Lake Alfred site measured at 10- and 45 cm soil depth layers in August-September 2011

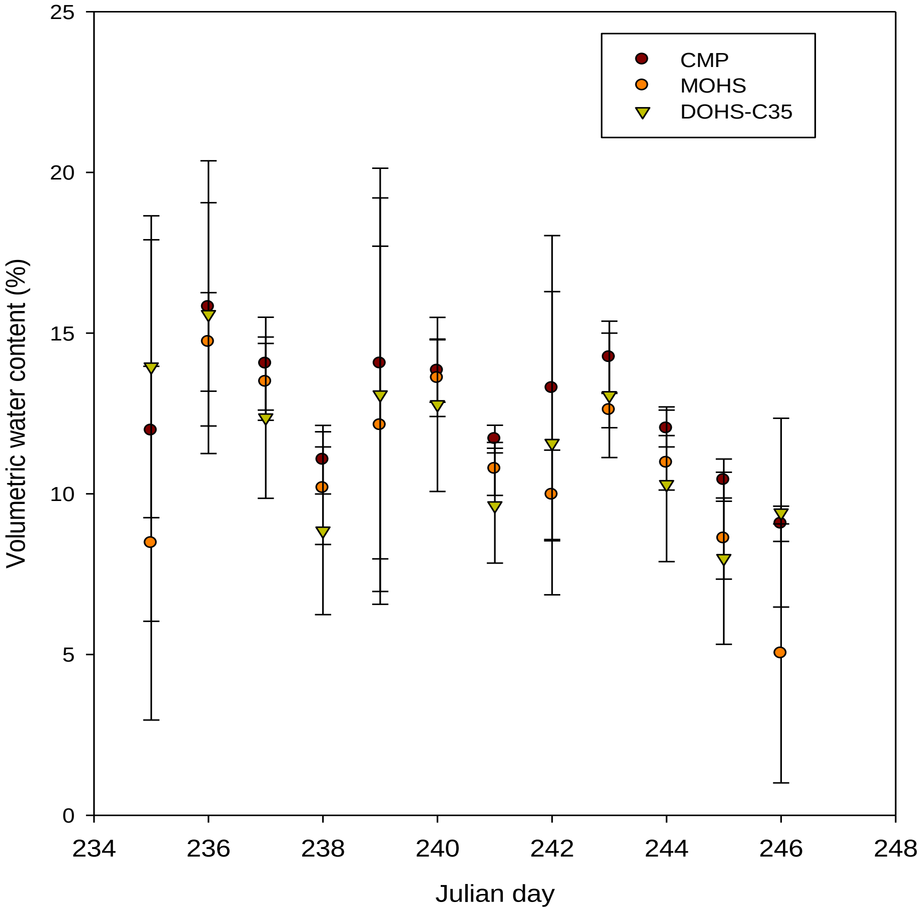


Figure 5-19. Average daily soil moisture distribution at the Lake Alfred site measured at 10 cm soil depth layer in August-September 2011. Error bars denote one standard deviation

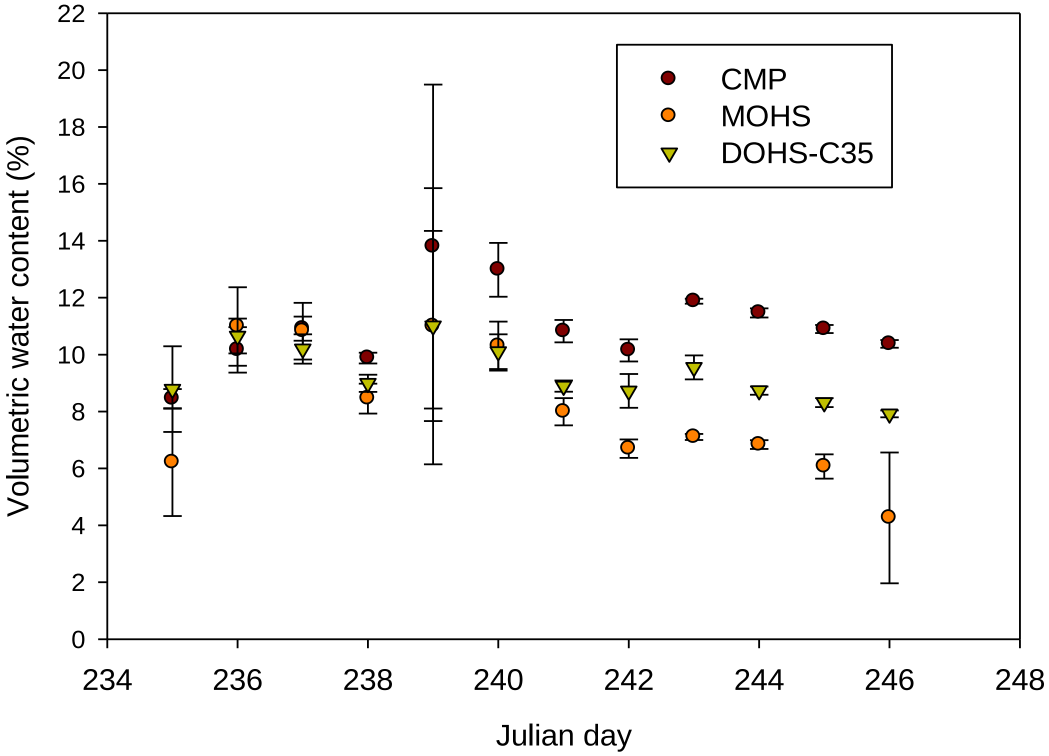


Figure 5-20. Average daily soil moisture distribution at the Lake Alfred site measured at 45 cm soil depth layer in August-September 2011. Error bars denote one standard deviation

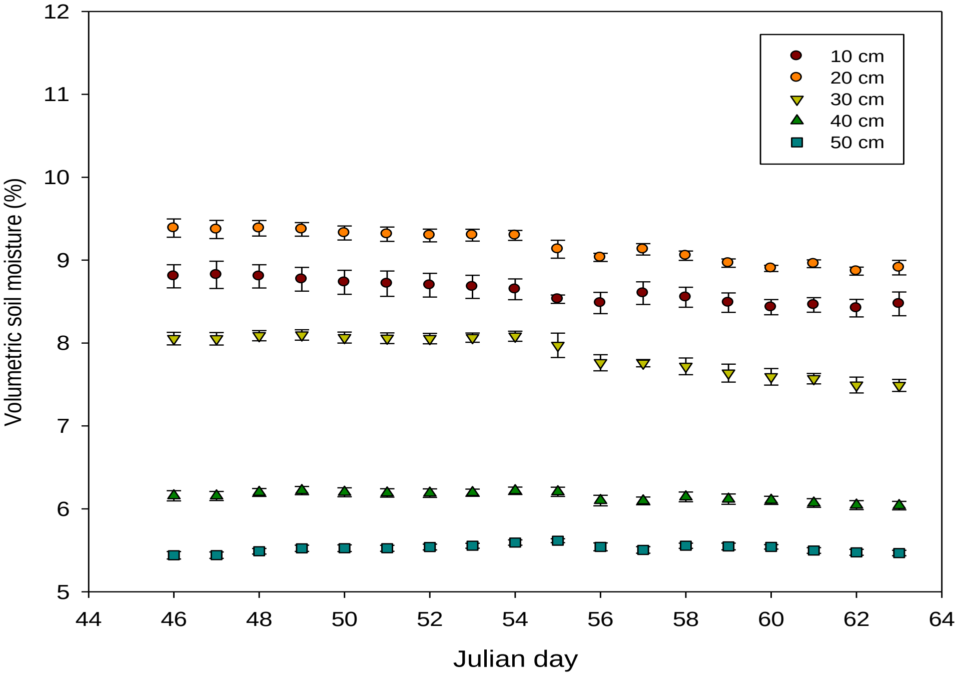


Figure 5-21. Soil moisture distribution for DOHS in February-March 2011 at Immokalee site measured at 10-, 20-, 30-, 40- and 50 cm soil depth layers. Error bars denote one standard deviation

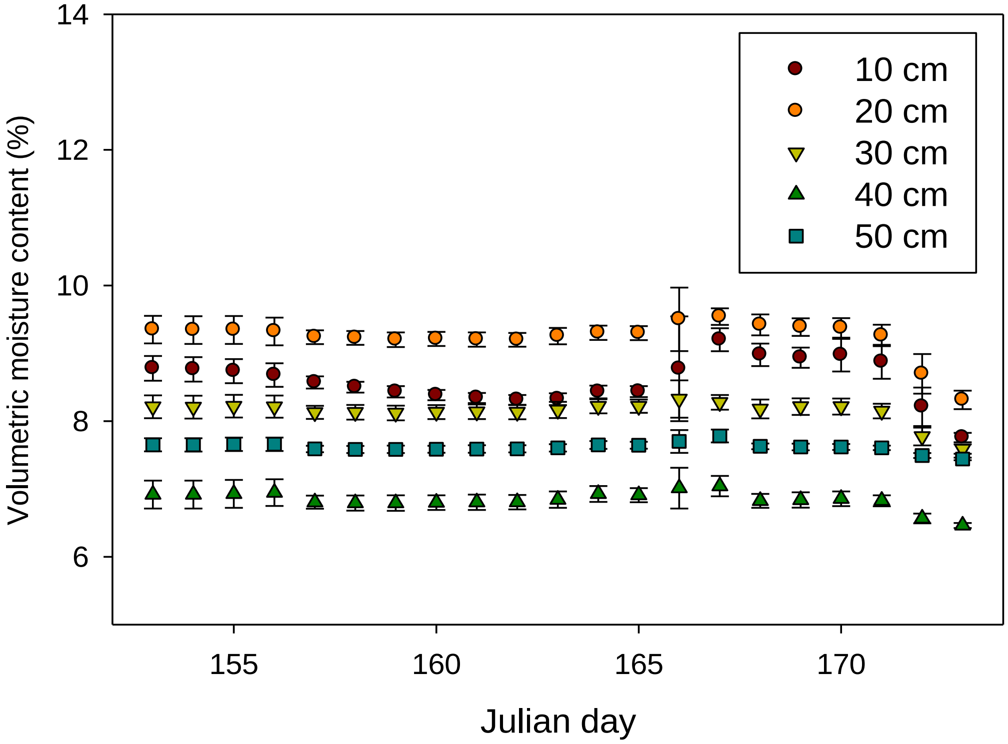


Figure 5-22. Soil moisture distribution for DOHS in June 2011 at Immokalee site measured at 10-, 20-, 30-, 40- and 50 cm soil depth layers. Error bars denote one standard deviation

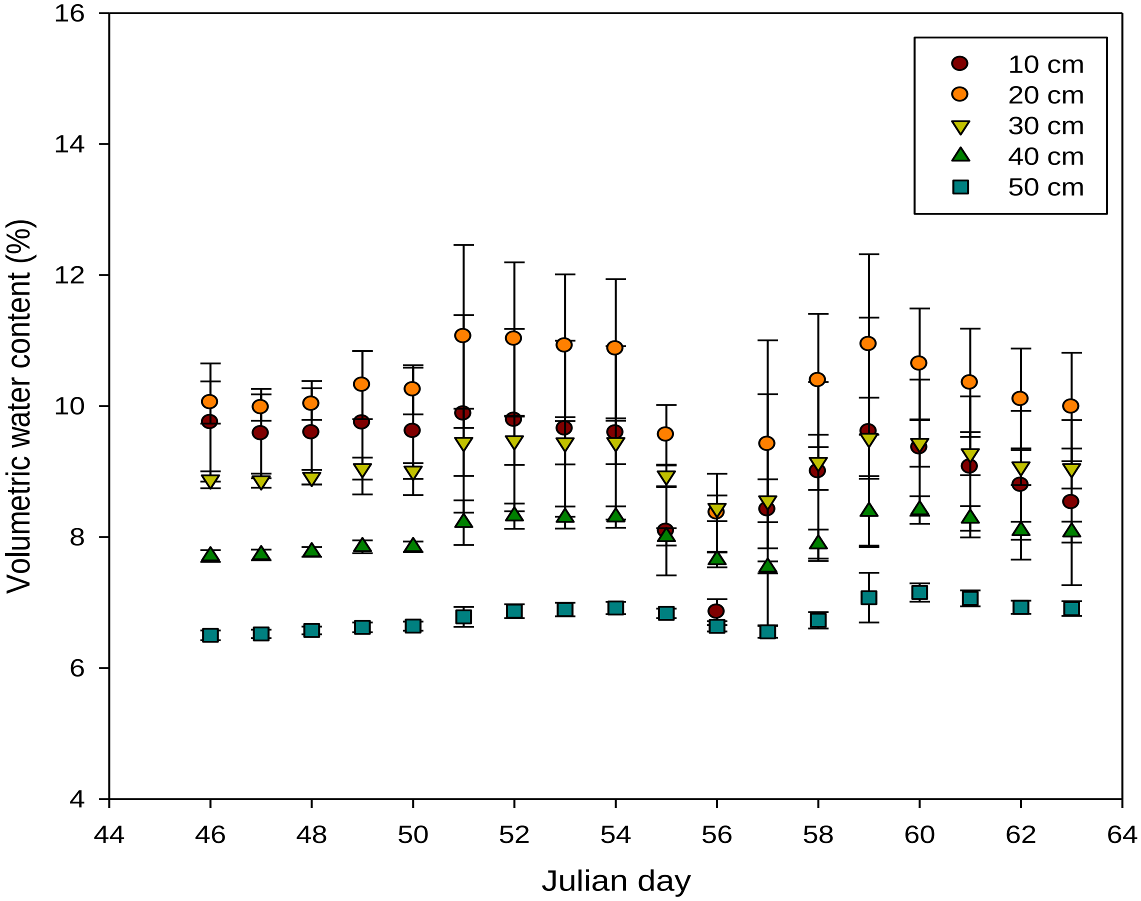


Figure 5-23. Soil moisture distribution for MOHS in February-March 2011 at Immokalee site measured at 10-, 20-, 30-, 40- and 50 cm soil depth layers. Error bars denote one standard deviation

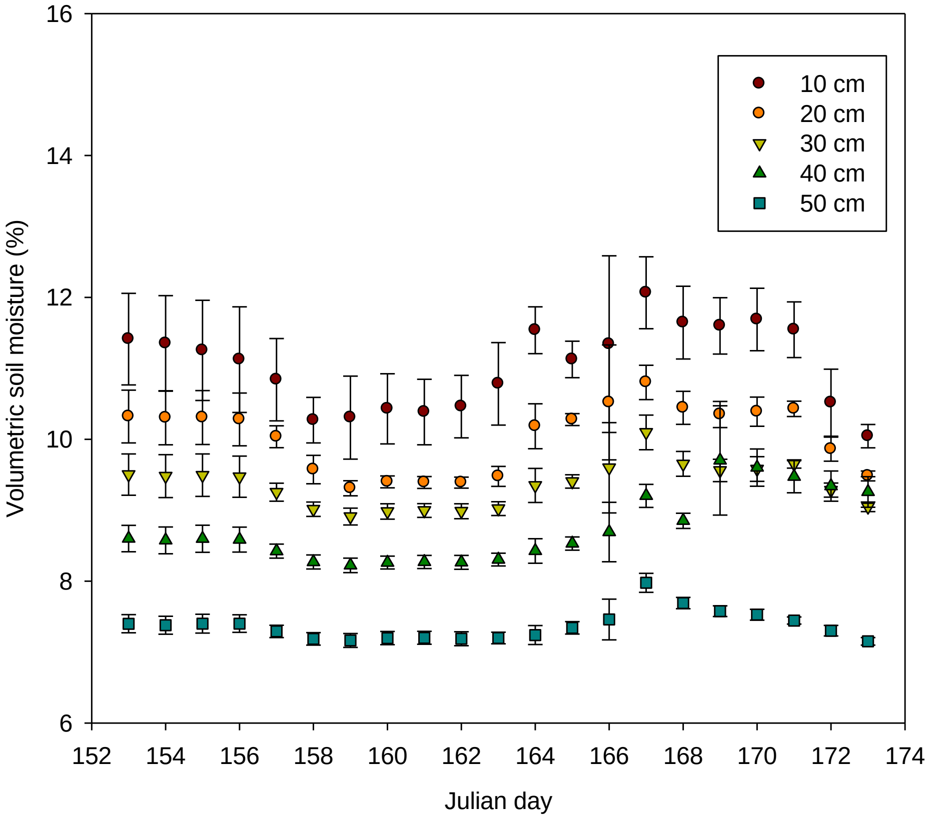


Figure 5-24. Soil moisture distribution for MOHS in June 2011 at Immokalee site measured at 10-, 20-, 30-, 40- and 50 cm soil depth layers. Error bars denote one standard deviation

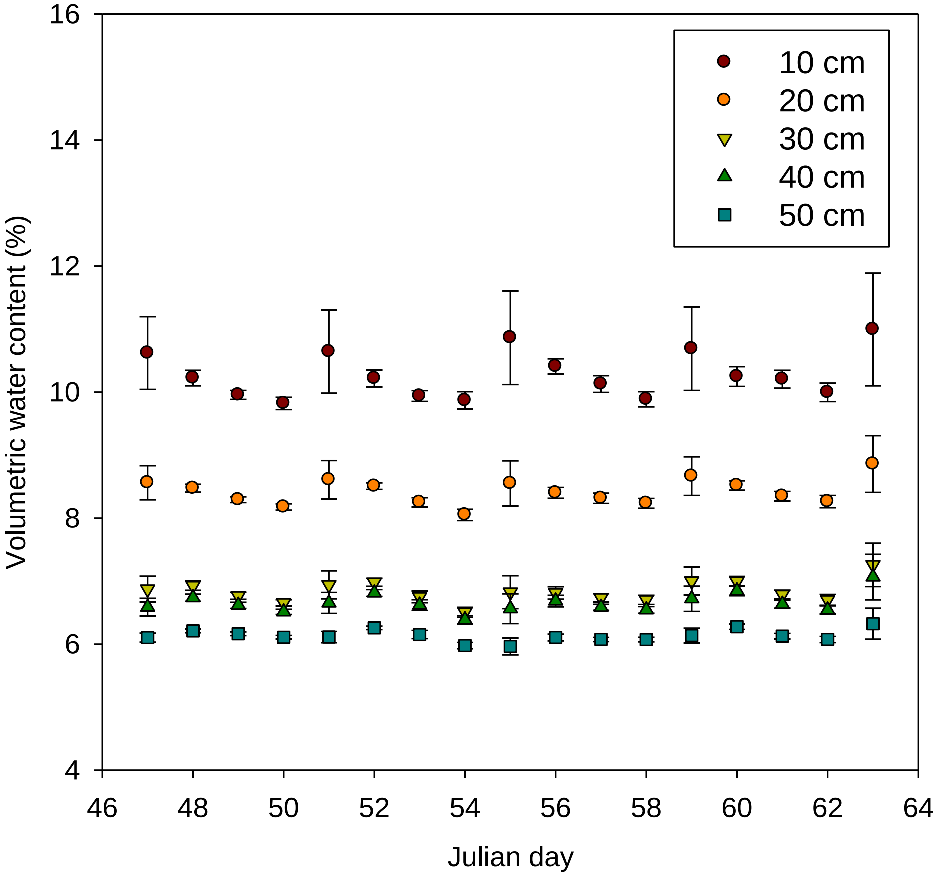


Figure 5-25. Soil moisture distribution for CMP in February-March 2011 at Immokalee site measured at 10-, 20-, 30-, 40- and 50 cm soil depth layers. Error bars denote one standard deviation

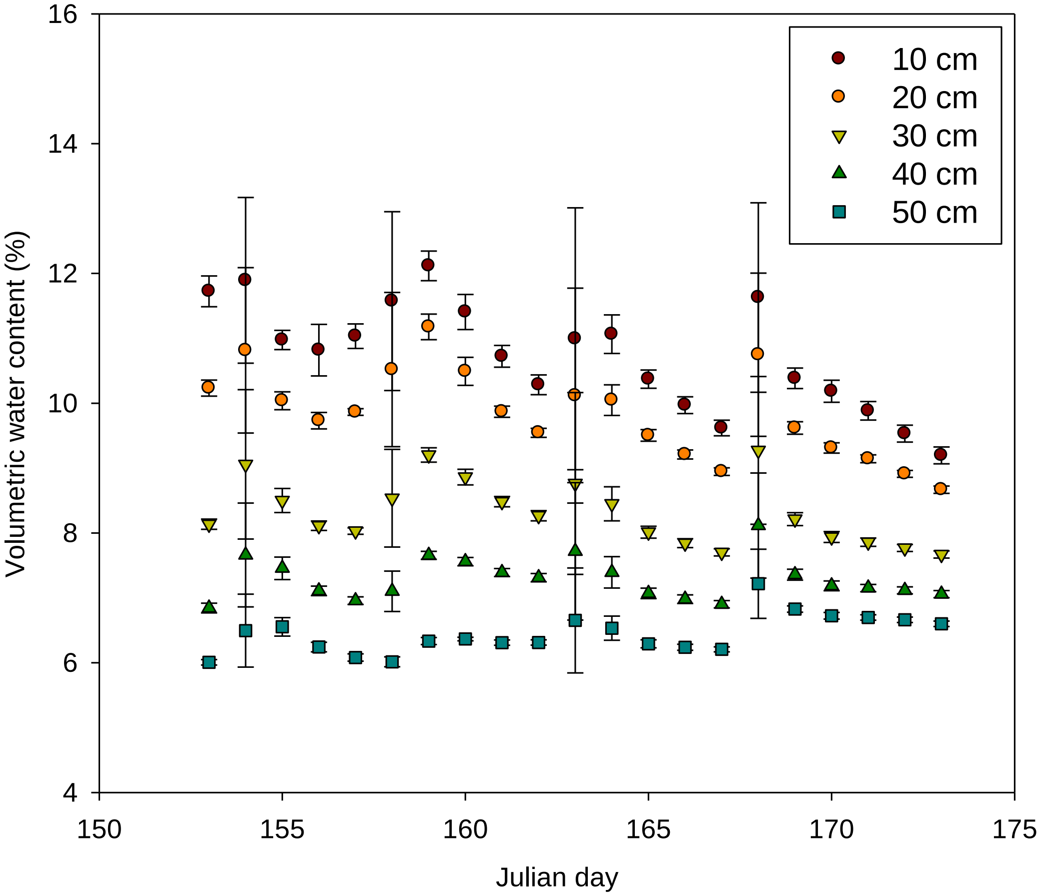


Figure 5-26. Soil moisture distribution for CMP in June 2011 at Immokalee site measured at 10-, 20-, 30-, 40- and 50 cm soil depth layers. Error bars denote one standard deviation

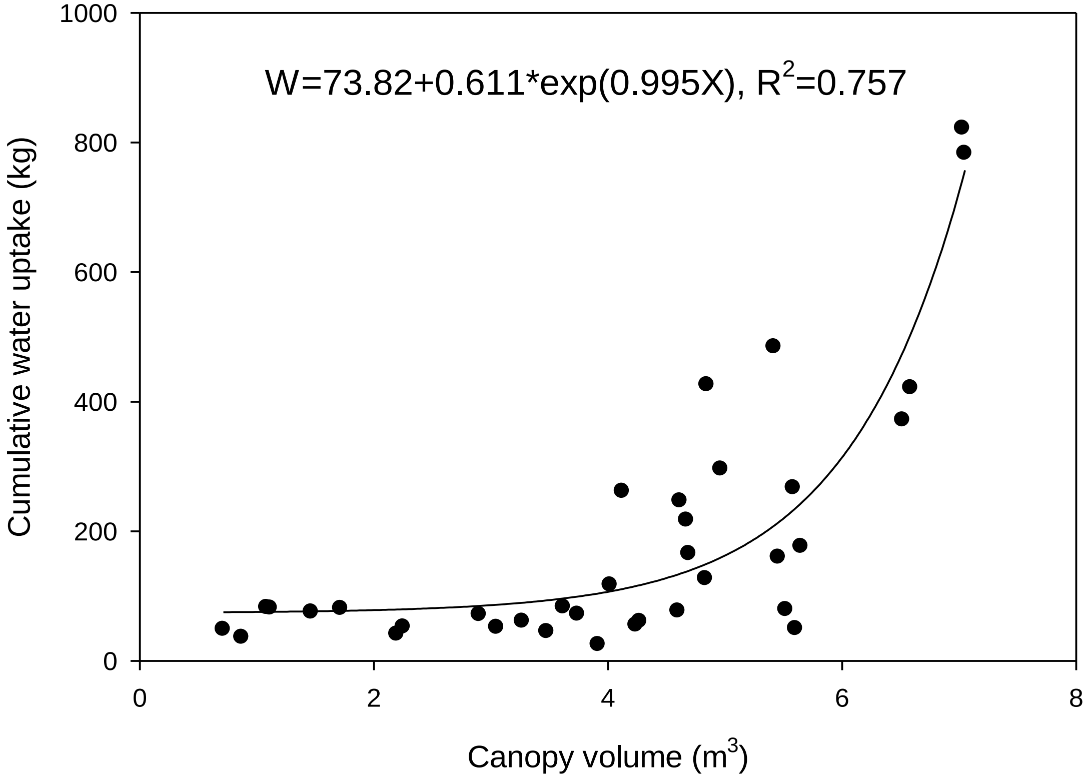


Figure 5-27. Correlation of water uptake and canopy volume at the Immokalee and Lake Alfred sites

Table 5-3. Linear regression models relating cumulative water uptake to tree and soil characteristics at the Lake Alfred site in July 2010 and September 2011[†]

Tree/soil characteristic	[¶]β_0	β_1	R^2	P-value
Canopy volume	0.55	2.63	0.67	0.046
Soil water at 10 cm	-0.20	0.11	0.55	0.091
Soil water at 45 cm	-0.79	0.13	0.56	0.086
Root length density	2.46	0.28	0.35	0.217
Trunk cross-sectional area	-1.33	0.80	0.98	<0.001
Leaf area-2010	1.78	0.36	0.49	0.120
Leaf area-2011	6.39	0.95	0.27	0.038

[†]Only leaf area measured in September 2011 at Lake Alfred was included in this table, the rest are variables measured in July 2010, [¶]β_0-Constant, β_1=Coefficient, SW-Soil water, R^2=coefficient of determination

Table 5-4. Multiple linear regression model coefficients for cumulative water uptake

Site	Date	†Y_o	Canopy volume	SW at 10 cm	SW at 20 cm	SW at 30 cm	SW at 40 cm	SW at 45 cm	SW at 50 cm	TCA	Leaf area	RMSE	R^2
Lake Alfred site	March, 2011	4.4	-0.56	0.16	NA	NA	NA	-0.132	NA	0.204	-0.220	1.37	0.60
Immokalee	June, 2011	-184.82	-0.0012	-2.937	16.38	-27.11	12.84	NA	9.79	0.00013	-0.000004	0.001	1.00
Lake Alfred site	September, 2011	-0.60	0.43	1.11	NA	NA	NA	-0.45	NA	1.14	NA	4.42	0.80

†Y_o-Constant, SW-Soil water, TCA-Trunk cross-sectional area, RMSE=Root mean square error, R^2=coefficient of determination

CHAPTER 6

CALIBRATION AND VALIDATION OF WATER, N, P, BR AND K MOVEMENT ON A FLORIDA SPODOSOL AND ENTISOL USING HYDRUS-2D

Šimůnek et al. (1999; 2007) developed HYDRUS-2D model to simulate the two-dimensional movement of water, heat, and multiple solutes in variably saturated media. The HYDRUS program numerically solves the Richards' equation for variably-saturated water flow and convection-dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by roots (Šimůnek et al., 1999; 2007). Soil hydraulic parameters of this model can be represented analytically using different hydraulic models such as the Brooks and Corey (1964) and van Genuchten (1980) equations. Several researchers have used HYDRUS in irrigated systems in the last decade (Fares et al., 2001; Gärdenäs et al., 2005; Bovin et al., 2006; Fernández-Gálvez and Simmonds, 2006; Hanson et al., 2006; Šimůnek and Hopmans, 2009). Despite problems associated with identification of the actual physical processes when conducting simulation, Pang et al. (2000) found that HYDRUS model was able to accurately describe soil water contents with minor discrepancies. Studies by Gärdenäs et al. (2005) and Hanson et al. (2006) assessed fertigation strategies using HYDRUS-2D for nitrogen fertilizers. They found that HYDRUS-2D model described the movement of urea, ammonium, and nitrate during irrigation and accounted for the reactions of hydrolysis, nitrification and ammonium adsorption.

Model simulations help to describe and predict complex processes and scenarios that are difficult to understand in nature. Simulation modeling can offer a viable alternative to predicting expected outcomes in various situations (such as changes in climate, crop type, age of crop, soil type, season etc) within a given set of parameters. The models are generally incomplete and not conclusive but with some degree of accuracy can help decision-makers come up with rational and informed decisions such as sustaining environmental quality and ensuring high yields among commercial growers.

The model simulations were performed to:

- calibrate HYDRUS-2D for water and solute movement as a possible decision support system for the Candler and Immokalee fine sand using data from conventional microsprinkler and drip irrigation methods,
- validate the performance of HYDRUS-2D using field results of microsprinkler and drip OHS irrigation methods,
- determine the effect of supporting electrolyte on K_D for predicting phosphorus movement at 30 cm soil depth using HYDRUS-1D,
- investigate bromide, nitrate and water movement using weather data from Immokalee and Lake Alfred.

The hypotheses tested were that:

- Measured soil water content, Br, ammonium N, nitrate N, phosphorus and potassium correlate well with simulated outputs thus helping in decision support in citrus production systems,
- K_D values for P sorption have an effect on P transport in the top 0-30 cm soil depth and would vary depending on the supporting electrolyte,
- Bromide, nitrate and water movement for Candler and Immokalee sand could provide the basis for determining fertilizer residence time in the 0-60 cm soil depth.

Materials and Methods

Governing Equations and Parameters for Water Flow, Nutrient Transport and Uptake

The governing flow equations for water flow and nutrient transport are given by the Richards (1931) and convection-dispersion equations (CDE) (Šimůnek et al., 1999; Šimůnek and Hopmans, 2009):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - s(h) \qquad (6\text{-}1)$$

Where θ is the volumetric water content [L^3L^{-3}], h is the pressure head [L], , x_i (i=1, 2) are the spatial coordinates [L] for two-dimensional flow, t is time [T], K_{ij}^{A} are components of a dimensionless anisotropy tensor K^A (which reduces to the unit matrix when the medium is isotropic), K is the unsaturated hydraulic conductivity function (LT^{-1}), and s is a sink/source term [$L^3L^{-3}T^{-1}$], accounting for root water uptake (transpiration). The sink/source represents the volume of water removed per unit time from a unit volume of soil due to compensated citrus water uptake.

The equation (CDE) governing transport of independent solutes i.e. single-ion transport is given as:

$$\frac{\partial \rho b c_1}{\partial t} + \frac{\partial \theta c_2}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c_{12}}{\partial x_j}\right) - \frac{\partial q_i c_2}{\partial x_i} - \Phi - r_a(c,h) \quad (6\text{-}2)$$

Where c_1 and c_2 are solute concentrations in the solid (MM^{-1}) and liquid (ML^{-3}) phases, respectively; q_i is the i^th component of volumetric flux density (LT^{-1}), Φ is the rate of change of mass per unit volume by chemical or biological reactions or other sources (negative) or sinks (positive) ($ML^{-3}T^{-1}$), respectively, providing connections between individual chain species, ρ_b is the soil bulk density ($M\ L^{-3}$), D_{ij} is the dispersion coefficient tensor for the liquid phase [L^2T^{-1}]. The term r_a represents the root nutrient uptake ($ML^{-3}T^{-1}$) which is the sum of actual active and passive nutrient uptake. The solid phase concentration, c_1, accounts for nutrient either sorbed in the solid phase or precipitated in various minerals. This is usually quantified by the adsorption isotherm relating c_1 and c_2 described by the linear equation of the form:

$$c_1 = K_d c_2 \quad (6\text{-}3)$$

Where K_D ($L^3\ M^{-1}$) is the distribution coefficient of species 1. Nitrate or a tracer (e.g. Bromide) are assumed to have a K_D=0 $cm^3\ g^{-1}$ while ammonium has a K_D in the range of 1.5 to 4.0 (Hanson et al., 2006; Paramasivam et al., 2002; Lotse et al., 1992). The first order decay constant ranges from 0.36-0.56 d^{-1} (Ling and El-Kadi, 1998). Rate coefficient for the nitrification of ammonium nitrate ranges from 0.02-0.72 d^{-1} (Jansson and Karlberg, 2001; Lotse et al., 1992; Selim and Iskandar, 1981; Ling and El-Kadi, 1998; Misra et al., 1974). For phosphorus, K_D is reportedly in the range of 19 to 185 $cm^3 g^{-1}$ (Kadlec and Knight, 1996; Grosse et al., 1999). The K_D for potassium is reported to be 28.7 $cm^3 g^{-1}$ (Silberbush and Barber, 1983). Bulk density for the soil is in the range 1.59-1.72 g cm^{-3} (Immokalee) and 1.55-1.93 g cm^{-3} (Lake Alfred) (T.A. Obreza, unpublished).

The sink term, s, for the Richards equation represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake. Thus, s is defined as:

$$s(h) = \alpha b L_t \frac{Tp}{w} \tag{6-4}$$

Where the water stress response function $\alpha(h)$ is a prescribed dimensionless function of the soil water pressure head, b is the normalized water uptake distribution, L_t is the width of the soil surface associated with the transpiration process and T_p is the potential transpiration rate (LT^{-1}) and w is the water stress index.

The predictive equation for the unsaturated hydraulic function in terms of soil water retention parameters is given by van Genuchten (1980) as:

$$\theta(h) = \begin{matrix} \theta_r + & \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \theta_s & & h \geq 0 \end{matrix} \tag{6-5}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{6-6}$$

Where

$$m = 1 - \frac{1}{n}, \ n > 1 \tag{6-7}$$

$$S_e = \frac{(\theta - \theta r)}{(\theta_s - \theta_r)} \tag{6-8}$$

Where θ_r, θ_s, K_s and *l* are residual water content (L^3L^{-3}), saturated water content (L^3L^{-3}), saturated hydraulic conductivity (LT^{-1}), and pore connectivity parameter (estimated to be an average of 0.5 for many soils). α (L^{-1}) and *n* are empirical coefficients affecting the shape of the hydraulic functions. We estimated the hydraulic functions α and n after fitting the water content and matric potential data using the van Genuchten model in Community Analyses System (CAS) 2007 (Bloom, 2009) developed for determination of soil hydraulic functions.

Model Calibration Processes

Sorption isotherms determination

HYDRUS-2D was calibrated using experimentally measured site-specific values reported in Appendices B and C. The methods for calculating and estimating the parameters are also documented in Appendices B and C. Sorption isotherms on the disturbed soil samples (0-15 cm, 15-30 cm) were determined using the batch equilibration procedure. The initial solution concentrations for P in 0.005M $CaCl_2$ and 0.01M KCl were 10, 25, 50 ppm P. In the fertilizer mixture, the initial concentrations were 6, 32 and 64 ppm NH_4-N, 5, 25 and 50 ppm P and 6, 32 and 63 ppm K. The initial concentrations for N, P, and K were chosen based on University of Florida IFAS recommendations for young, non-bearing orange trees (Obreza and Morgan, 2008).

In this set of observations, soil samples were obtained from 5 positions per site at two depths giving a total of 10 samples. Each sample was weighed in triplicates plus a blank check. A 10 g air-dried, <2mm subsample of soil was placed in a centrifuge tube and equilibrated with 20 ml (soil solution ratio 1:2) of 3 initial concentrations of NH_4^+-N, P and K solutions. The centrifuge tubes were shaken for 24 h, and centrifuged for 20 min and filtered. The supernatant was passed through a Whatman filter paper (Q2). All these procedures were done at room temperature ~25±1 ^oC as recommended by Graetz and Nair (2009) but the filtrate was later stored at <4 ^oC until analysis for NH_4^+-N, P and K. The samples from 0.005 M $CaCl_2$ and 0.01 M KCl were analyzed for P while the fertilizer mixture was analyzed for NH_4^+-N, P and K. The amount of chemical sorbed to the soil was calculated from the difference between the initial and equilibrium solution concentration:

$$S_e = \frac{V_o}{m}(C_o - C_e) \qquad (6\text{-}9)$$

Where S is the adsorbed concentration (mg kg^{-1}); V_o is the volume of initial solution (L); m is the soil mass (kg); C_o is the initial concentration of the standard solution (mg L^{-1}), and, C is the soil solution concentration at equilibrium (mg L^{-1}). KH_2PO_4 was used as a source for both P and K, while NH_4NO_3 was used as a source of NH_4^+-N.

The linear sorption isotherm was determined from the following model:

$$S_e=K_DC_e \qquad (6\text{-}10)$$

Where K_D=sorption distribution coefficient (L kg^{-1})

Sorption isotherms for P were calculated using the Freundlich equation:

$$S_e = K_f C_e^N \qquad (6\text{-}11)$$

Where K_f = the Freundlich sorption coefficient (mg^{1-N} kg^{-1} L^N) and N are empirical constants related to adsorption phenomena (Bowman, 1982)

The linearized form of the Freundlich equation was used to calculate K_f and N:

$$\ln S_e = \ln K_f + N \ln C_e \tag{6-12}$$

Where S is the adsorbed equilibrium concentration (mg kg^{-1}); C is the equilibrium concentration (mg L^{-1}) and K_f and N are calculated from the intercept and slope of Eq. B-4. To find average K_D for the Freundlich isotherm, the integrated form of the equation was used:

$$K_D = \frac{\int_0^{C_{max}} NK_f C^{N-1} dC}{\int_0^{C_{max}} dC} = K_f C^{N-1} \tag{6-13}$$

The range of sorption coefficients used for potassium and ammonium are presented in Appendix B, Table B2. Ammonium adsorption for Immokalee and Candler fine sand followed a linear isotherm with distribution coefficients (K_D) of 1.12±0.42 and 1.64±0.25 kg L^{-1} and 1.66±0.39 and 1.76±0.39 kg L^{-1} for the 0-15- and 15-30 cm depths, respectively. The range of linearized K_D values for P for calibration are documented in Table B-3, with the three supporting electrolytes. P adsorption was well described by a Freundlich model with linearized K_D ranging from 0.50±0.19 to 0.75±0.13 kg L^{-1} for Immokalee fine sand and from 1.73±0.15 to 4.43±0.50 kg L^{-1} for Candler fine sand. P sorption isotherm for Immokalee fine sand determined using fertilizer mixture was linear with K_D averaging about 0.44±10 kg L^{-1}.

Determination of soil water retention and hydraulic functions

Twenty undisturbed soil core samples were taken at 0 to 15 cm, 15 to 30 cm, 30 to 45 cm, and 45 to 60 cm at random locations at both Flatwoods and Ridge sites to determine soil water release curves (Klute, 1986; van Genuchten, 1980; Paramasivam et al., 2002) and saturated hydraulic conductivity at each depth for each site (Klute and Dirksen, 1986). Soil physical parameters determined include bulk density, field capacity (at 5 kPa at the Ridge and at 8 kPa Flatwoods), available water capacity, saturated hydraulic conductivity, and saturated water content. Textural classes were determined from literature. The water flux (q) was calculated using Darcy's law by taking the Reference Level at the 60 cm depth using average volumetric water content at different soil depths for different treatments:

$$q = -K(h)\frac{(H_1 - H_2)}{(X_1 - X_2)} \qquad (6\text{-}14)$$

where K(h) = conductivity of the soil layer at suction (h, cm); (H_1-H_2) = differences in total water potential between two points in the soil profile; (X_1-X_2) = the thickness of the soil profile (cm);

Soil water retention curves were determined in the laboratory according to the process described by Klute (1986) using Tempe Cells and were adapted from (Sanchez, 2004). Each sample was covered with a plastic bag and wrapped with a rubber band to avoid any soil loss. The samples were stored in the refrigerator to maintain the original soil water content until processing in the laboratory. To determine the water retention curves between 0 and 100 kPa, the soil cores were placed in the base cap of a Tempe cell containing a 0.5 bar porous ceramic plate. The soil sample was covered with the top cap of the Tempe cell. The Tempe cell was placed in a container with appropriate water level to saturate the soil sample. After the samples reached saturation, the Tempe cells were removed from the water container and excess water was allowed to drain from the saturated samples under gravity. The Tempe cells were weighed and the initial weights were recorded. After the first point of equilibrium, the pressure line was connected to the top inlet of the Tempe cell. The weights were recorded, each time the Tempe cell reached equilibrium with the corresponding pressure applied. The Tempe cells were subjected to 13 levels of pressure: 0.3, 2.0, 2.9, 4.4, 5.9, 7.8, 9.8, 14.7, 19.6, 33.8, 50.0, 70.0 and 100 kPa. The moisture content at 1500 kPa was determined from literature on earlier studies done on same soil series (Carlisle et al., 1989; Obreza et al., 1997, Obreza, unpublished). After applying the last level of pressure and reaching equilibrium, the Tempe cell was opened and the soil core was carefully removed. Then, the weight of the core was recorded. Saturated hydraulic conductivity was determined by constant head method. To determine saturated hydraulic conductivity, another brass ring was attached and sealed with a duct tape on top of the soil core. The surface of the soil sample in the cylinder was covered with a filter paper to avoid any disturbance during water application. The soil sample in the core-assembly was rewetted in a water container. The core-assembly was then transferred to the hydraulic conductivity apparatus where water was applied to the top cylinder and the water level was kept constant. Once a steady flow was established, the drainage water under the soil sample was collected for a known period of time for each sample. The volume of drained water and time was recorded and the saturated hydraulic conductivity determined. The soil water desorption curves for both Immokalee and Candler fine sand were simulated using the VanGenuchten model described in Equations 6-5 and 6-6.

Data collected related to residual and saturated moisture contents, moisture contents at field capacity, available water content, K_{sat} and bulk density. The soil physical parameters were calculated to show the variation in soil physical characteristics as a function of depth and the soil water release curves developed using the nonlinear regression analysis using the CAS software developed by Bloom (2009).

The range of soil water retention parameters α, and n, used for calibration are presented in Appendic C, Table C1. The respective α and n value ranges were 0.03-0.04 cm^{-1} and 1.29-2.06 for Immokalee fine sand,and 0.02-0.04 cm^{-1} and 1.70-2.22 for Candler fine sand. The *l* value used was 0.5, as recommended by Simunek et al. (1999). The soil physical parameters like residual and saturated moisture content, saturated hydraulic conductivity, and bulk density are documented in Table C2. The residual moisture contents from literature are 0.013 and 0.009 cm^3 cm^{-3} for Immokalee and Candler fine sand (Carlisle et al., 1989). The saturated moisture contents ranged from 0.318 to 0.390 cm^3 cm^{-3} on Immokalee fine sand and from 0.313 to 0.421 cm^3 cm^{-3} on Candler fine sand. The saturated hydraulic conductivity ranged from 13.22 to 15.82 cm h^{-1} on Immokalee and 14.76 to 15.94 cm h^{-1} on Candler fine sand. The bulk densities, similar for the two soils, ranged from 1.59 to 1.62 g cm^{-3} and from 1.57 to 1.68 g cm^{-3} for Immokalee and Candler fine sand, respectively. For model calibration, we based on spring 2011 soil water movement to avoid the effects of rainfall in summer 2011.

All the parameters for use in the model for validation, assuming a homogenous soil profile, are presented in Table 6-4. The bulk density, K_{sat}, θ_{sat}, θ_r, α, n, and *l* values were 1.61 and 1.64 g cm^{-3}, 14.40 and 15.49 cm h^{-1}, 0.35 and 0.36 cm^3 cm^{-3}, 0.01 cm^3 cm^{-3}, 0.033 and 0.028 cm^{-1}, 1.34 and 1.8, and 0.5 for Immokalee and Candler fine sand, rerespectively. Sorption coefficients for P, NH_4^+ and K^+ for Immokalee and Candler fine sand were 0.44 and 0.98 L kg^{-1}, 1.37 and 1.89 L kg^{-1}, and, 1.17 L kg^{-1}.

Sensitivity Analysis of Selected Parameters for HYDRUS-2D

The aim of sensitivity analysis (SA) is to determine how sensitive the output of a model is, with respect to the elements of the model which are subject to uncertainty or variability (Monod et al., 2003). SA helps explore efficiently the model responses when the input or parameter varies within given ranges (Sacks et al., 1989; Welch et al., 1992; Monod et al., 2003). The uncertainty in model structure, model parameters and input variables calls for SA to 1) check that the model output behaves as expected when the input varies; 2) identify which parameters need to be estimated more accurately and which input variables need to be measured with maximum accuracy; 3) identify which parameters have a small or large influence on the output; 4) detect and quantify interaction effects between parameters, between input variates or between parameters and input variates (Saltelli et al., 2000; Monod et al., 2003)

Two methods of conducting SA are well known: local and global sensitivity analysis. Local sensitivity analysis (LCA), on the one hand, is based on the local derivatives of output with respect to input variable or parameter which indicate how fast the output increases or decreases locally around given values of the input variable or parameter. In global sensitivity analysis (GSA), on the other hand, the output variability is evaluated when the input factors vary their whole uncertainty domains (Saltelli et al., 2000; Garnier, 2003; Monod et al., 2003; Saltelli et al., 2004). Of the two methods GSA if preferred because it helps the modelers identify inputs or parameters that deserve an accurate measure or estimation. One method to conduct a GSA is to vary one factor at a time, while other factors are fixed at their nominal values. The relationship between z_i of factor Z_i and the responses $f(z_{0,1} \ldots z_{0,\, i-1}, z_i, z_{0,i+1}, \ldots z_{0,s})$ determines a one-at-a-time response profile. Each input factor or parameter z_i takes k equispaced values from zmin, i to z_{max}, i with increments:

$$\delta = \frac{(z_{max,i} - z_{max,i})}{k-1} \qquad (6\text{-}15)$$

The model responses $f(z_{0,1}\ldots z_{0, i-1}, z_{i,z0,i+1},\ldots z_{0,s})$ are then calculated for the k discretized values zi. Graphical representations and the Bauer and Hamby Index are used to determine the influence of the model parameters on the model output. The Bauer and Hamby Index, I_i^{BH} (Bauer and Hamby, 1991) is approximated by the difference between maximum and minimum simulated values given as:

$$I_i^{BH} = \frac{\max z_i\, f(z_{0,1}\ldots z_{0,i-1,} z_i, z_{0,i+1,}\ldots z_{0,s}) - \min z_i f(z_{0,1}\ldots z_{0,i-1,} z_i, z_{0,i+1,}\ldots z_{0,s})}{\max z_i\, f(z_{0,1}\ldots z_{0,i-1,} z_i, z_{0,i+1,}\ldots z_{0,s})} \qquad (6\text{-}16)$$

In this study, an attempt was made to conduct a GSA of HYDRUS-2D focusing on the following state variables: NO_3-N and water content (θ), on the Immokalee Candler sand. The simulations were done for 14 days to mimic the dynamics of a time of the field experiment at 1-d time step for drip and microsprinkler fertigation systems in a 50 cm wide and 60 cm deep transect subdivided into four layers each site and drippers located at 15 cm from the tree and microsprinklers irrigating the top 45 cm. The hypothesis governing the GSA is that variance of water content (θ), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), phosphorus (P) and potassium (K) are reasonable within the given set of parameters. Once the parameters having a major influence on the outputs are known, a choice of which parameters to use for the various fertigation scenarios will be made based on the values that result in the least influence on the two study sites. GSA for the Immokalee sand was done separately from the Candler series near Lake Alfred due to the heterogeneity in drainage characteristics. Outputs of interest included: soil water content, soil NO_3-N, NH_4-N, Br, P and K with depth.

Data were analyzed using General Linear Model (GLM) and ProcReg procedures in SAS statistical package (SAS Institute, 2011). Coefficients of determination (R^2) and root mean square errors (RMSE) between the simulated and measured values were determined to allow for statistical comparison of the correspondence between the measured and simulated data or between the results of different models.

Simulation Domain-Microsprinkler irrigation

The microsprinkler irrigation system for the two sites was simulated as a line source, planar two-dimensional geometry perpendicular to the simulated domain assuming that the lateral flow on boundaries was zero (zero flux boundary condition) and the free drainage condition was imposed at the bottom boundary at each site with time-variable flux surface boundary condition. The simulation domain was 50 cm wide and 60 cm deep. The presence of a water table ~70 cm below the ground at Immokalee was assumed not to affect the drainage within the 60 cm simulation domain. The transport domain was discretized into 3834 triangular elements and 1918 nodes. The smallest finite element was 0.1 cm at the top of the simulation domain and the largest at the bottom of the domain was 2 cm. The non-symmetry coefficients were assumed to be 1 and flow was assumed to be isotropic in both lateral and vertical directions. The maximum rooting depth was assumed to be 45 cm with maximum root intensity observed at 15 cm. Maximum citrus root lateral extension (<5 yr-old) was assumed to be 45 cm while maximum lateral root intensity was found at 30 cm from the tree. Detailed information related to the flow related parameters and experimental scenarios are presented in Tables 6-1 through 6-5.

Simulation Domain-Drip irrigation

Drip irrigation was simulated as a point source, with an axi-symmetrical two-dimensional plane assuming that the lateral flow on boundaries was zero (zero flux boundary condition). Like above, a free drainage condition was imposed along the bottom boundary at each site with a time-variable flux boundary condition on the top surface. The simulation domain was also 50 cm radius and 60 cm deep. The presence of a water table ~70 cm below the ground at Immokalee was assumed not to affect the drainage within the 60 cm simulation domain. The transport domain was discretized into 2462 triangular element and 1232 nodes. The smallest finite element was 0.1 cm and the largest at the bottom of the domain was 2 cm. The non-symmetry coefficients were assumed to be 1 and flow was assumed to be isotropic in both radial and vertical directions. The maximum rooting depth was assumed to be 45 cm with maximum root intensity observed at 15 cm. Maximum citrus root lateral extension (<5 yr-old) was assumed to be 45 cm while maximum lateral root intensity was found at 30 cm from the tree. Details related to the initial conditions and parameters are also presented in Tables 6-1 through 6-4.

Results and Discussion

Sensitivity analysis and calibration of selected model parameters

The conceptual model for the uptake and movement of water, tracer Br and nutrients on Florida's Immokalee and Candler fine sand is presented in Figure 6-1. Measured soil characteristic values (presented in Appendix C) and soil nutrient sorption constants (presented in Appendix B) were used to calibrate HYDRUS-2D for the Entisol and Spodosol at the Lake Alfred and Immokalee sites. The model was calibrated for both Candler and Immokalee sand for simulating water and solute transport as shown in Figures 6-2, 6-3 and 6-4. The statistics reveal that the model outputs are close to the measured values with R^2>0.80.

Sensitivity indices calculated suggest that saturated hydraulic conductivity and empirical parameter n were the most sensitive (sensitivity index=0.29) in predicting water movement (Table 6-5). Also, the simulation experiments on Candler fine sand suggest that any n>3.085 would yield no output with respect to water content and uptake. Similarly, on Immokalee fine sand, no water content and water uptake values were obtained when n>4.63 (the nominal value) was used as a parameter. We also noted that no outputs on water content and uptake were obtained on Candler fine sand when $\theta_{sat}<0.34$ m^3 cm^{-3} was used. It is presumed that the parameter values for HYDRUS recommended for sandy soils and optimized using ROSETTA software (Carsel and Parrish, 1988; Schaap et al., 2001) are for less 'sandier' soils than typical sands for Florida's citrus growing regions (>95% sands) suggesting the need for using site specific parameters for Florida's soils. Thus, we collected four replicated samples at four 0.15 m depth increments in the field to determine hydraulic functions. The values reported by several Florida researchers were close to our measured values because they were determined on similar soil series used in the study and were the basis for the global and local sensitivity analysis on both soils (Obreza, unpublished; Carlisle et al., 1989; Fares et al., 2008; Obreza and Collins, 2008). Most of literature values used for the sensitivity analysis of sorption coefficients with regard to P, K and NH_4 transport, were several times higher than what we estimated with soil samples collected from the research sites (Appendix B). Thus, the sorption confidents for P, K and NH_4 presented in Appendix B were used for the simulation experiments.

Water, Br, K, P, NO_3 and NH_4 movement with drip and microsprinkler irrigation

To validate the calibrated model, measured water and solute movement were compared with model predicted values. Model predictions showed that with similar initial water contents and similar schedules, microsprinkler (in a line source, planar domain) and drip irrigation (with water from a point source, in an axi-symmetric domain), water movement were similar for both irrigation systems albeit, higher amounts of water were retained in the upper 0.15 m than when using the microsprinkler system. Very close agreement was obtained (Table 6-6) between simulated and measure values for the two systems where the predictions accounted for 90% of the measured water contents. Several researchers have reported good predictions on water in one- and two-dimensional domains using numerical models (Angelakis et al., 1993; Andreu et a., 1997; Fares et al., 2001; Skaggs et al., 2004; Gardenas et al., 2005; Testi et al., 2006; Kandelous and Simunek, 2010a, b; Kandelous et al., 2011). Bromide distribution showed good agreements (R^2~0.63-0.90) with measured outputs with root mean square errors (RMSE) in the range of 0.04-7.57 (Figures 6-5 and 6-6 and Table 6-7). However, despite the good agreements, Br was under predicted by about 5 to 20% and there was very poor agreement at Immokalee, especially after 6 days of simulation . Phosphorus was well predicted at Lake Alfred but poor correlations were noted at Immokalee. The phosphorus initial conditions were based on Mehlich 1 extractable P which might be several times greater than water soluble P (Nair and Harris, 2004; Nair et al., 2004) and thus our prediction might have overestimated the actual leaching P potential. Nitrate and ammonium were well predicted by the model (Table 6-7, Figures 6-8 and 6-9). Potassium, despite the under-predictions, showed very good correlation at Immokalee, but poor correlation at Lake Alfred using microsprinkler (Table 6-7, Figure 6-10 and 6-11).

Phosphorus movement with microsprinkler irrigation as function of K_D value

Phosphorus movement was predicted using three different K_Ds estimated with fertilizer mixture, 0.01M KCl and 0.005M $CaCl_2$ for a duration of 21 days, assuming no rainfall events (Figure 6-12). The assumption is that a K_D value obtained using fertilizer mixture typifies that of field conditions with regard to chemical processes. The results on

Candler fine sand at Lake Alfred showed that that P contents for the K_D estimated with 0.01M KCl and 0.005M $CaCl_2$ were 10-15% higher than those predicted with a K_D value measured with fertilizer mixture. The predictions on Immokalee fine sand showed that that P contents for the K_D estimated with fertilizer mixture and 0.005M $CaCl_2$ were 12-20% higher than those predicted with a K_D value measured with 0.01M KCl. The outputs with K_D measured with 0.005M $CaCl_2$ appear to be close to those predicted with a K_D measured with fertilizer mixture. However, the analysis of the K_D values across all electrolytes on the two soils studied revealed that 0.01M KCl is the electrolyte that yields K_D values fairly close to fertilizer mixture while 0.005M $CaCl_2$ tends to give K_D values two to threefold in magnitude to those determined with fertilizer mixture suggesting that the latter would overestimate P sorption and retardation during unsaturated or saturated flow than the former (0.01M KCl). Thus, it would be appropriate to use 0.01M KCl as supporting electrolyte for Florida's Candler and Immokalee fine sand.

Investigating bromide, nitrate and water movement using weather data from Immokalee and Lake Alfred.

The nitrate, bromide and water movement as influenced by weather at Lake Alfred (August 22 to November 22, 2011) and Immokalee (June 4 to September 4, 2011) were predicted using climatic data obtained from the Florida Automated Weather Network for a 90 day period. The nitrate and bromide at Lake Alfred (Figure 6-13A and B) was largely leached out beyond 60 cm depth within <20 days, a period corresponding with 158 mm of rain. The nitrate and bromide at Immokalee showed that most of the nitrate was leached in 20 days and bromide leached after 25 days, dates corresponding with 57 and 108 mm of rain. Mostly during the 90 days simulation, water contents remained between 15 and 25% and only went above 30% when it rained. The leaching of NO_3 in this case would be minimized if we accounted for uptake and transformation of nitrate into other forms. However, the incorporation of weather data into the simulation would serve as a guide in making decisions to apply mobile nutrients such as nitrate containing fertilizers when the weather forecast is good i.e. no chances of rainy events. The plausible approach with the irrigation practices used in this study is that they try to maintain soil moisture in the top 10 cm depth at near field capacity and applying nutrients in the morning hours when transpiration and photosynthesis are high to avoid leaching losses (Schumann et al., 2010). Such irrigation and nutrient management decisions should be incorporated in the simulations ahead of a rainy season using say historical data to insure environmental quality is sustained.

Summary

The model showed reasonably good agreement between measured and simulated values for soil water content, Br, ammonium N, nitrate N, phosphorus and potassium movement, agreeing with the hypothesis that ‘measured soil water content, Br, ammonium N, nitrate N, phosphorus and potassium correlate well with simulated outputs thus helping in decision support in citrus production systems thus helping in decision support in citrus production systems.’ The sorption K_D value has a bearing on P transport in the root zone, the greater the value, the more retarded and adsorbed P is in the soil. Thus, the use of 0.01M KCl, which yielded K_D values close to those of fertilizer mixture, appears to be the appropriate supporting electrolyte for Candler and Immokalee fine sand while 0.005M $CaCl_2$ tends to overestimate the P sorption process. The model could further be used as an important guideline for predicting Br or nutrient residence time. For example, the Br at Immokalee leached between 15 to 25 d and in less than 10 d at 60 cm depth near the Lake Alfred site. The NO_3-N leached between 15 to 20 d at Immokalee and between 10-12 d at the Lake Alfred site. Importantly, HYDRUS-2D could also be used for irrigation decision support if one could account for water use, drainage and evaporation losses.

The parameters used for HYDRUS should be carefully determined for meaningful predictions. When in doubt, own parameter estimation through laboratory or field measurements where time and resources permit should be done. Cases of under- or over-prediction were noted particularly for P, K, NO_3 and NH_4, probably due to transformations and adsorption.

The model could be successfully used for scheduling irrigation and predicting nutrient leaching for both microsprinkler and drip irrigation systems on Florida's Spodosols and Entisols. A correction factor may need to be used for the NH_4, NO_3, P and K outputs to account for soil processes such as chemical transformations (largely considered negligible in HYDRUS) and sorption to successfully predict nutrient leaching, on case by case basis, according to soil type and management practice. Additionally, initial conditions for adsorbed solutes should probably be determined using water extraction to mimick natural conditions.

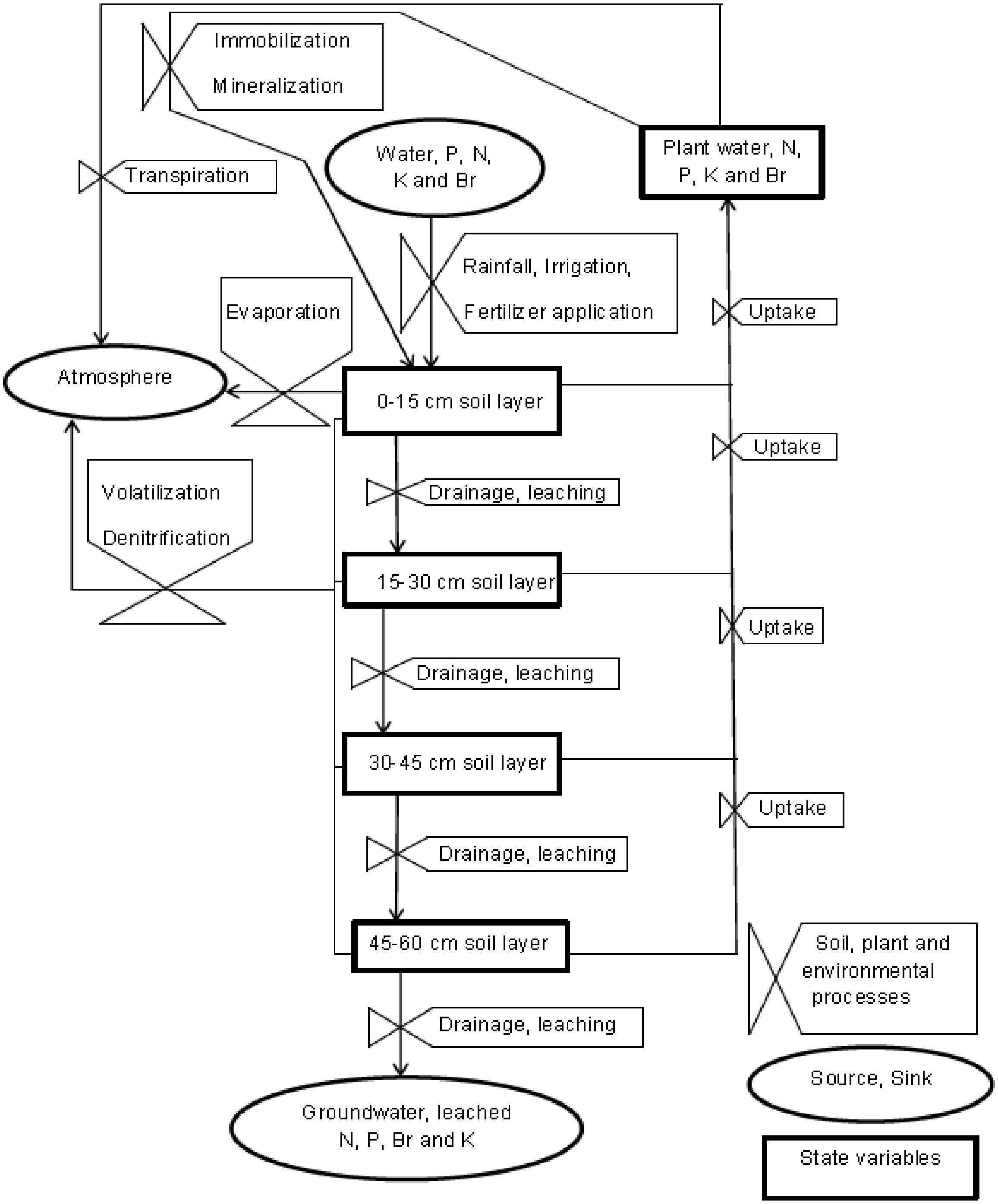


Figure 6-1. A forrester diagram describing the conceptual model for water and nutrient uptake and movement processes

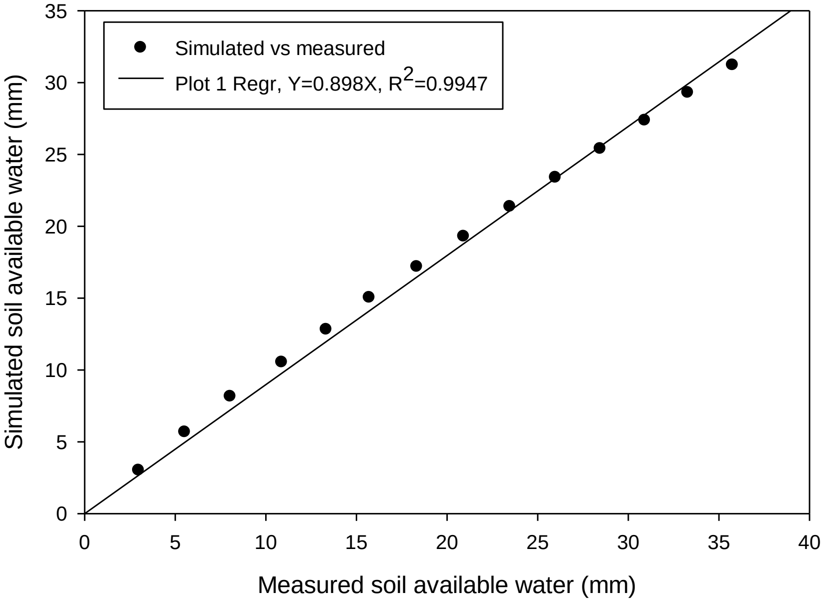


Figure 6-2. Calibration of HYDRUS-2D for simulating soil water content at 10 cm soil depth at Lake Alfred site using drip irrigation

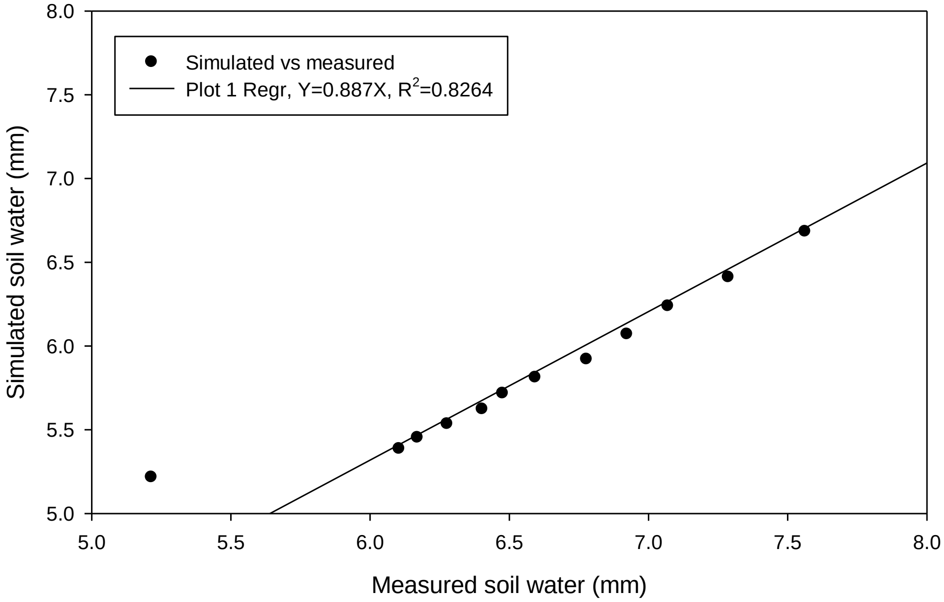


Figure 6-3. Calibration of HYDRUS-2D for simulation soil water content at 40 cm soil depth at Lake Alfred site using microsprinkler irrigation

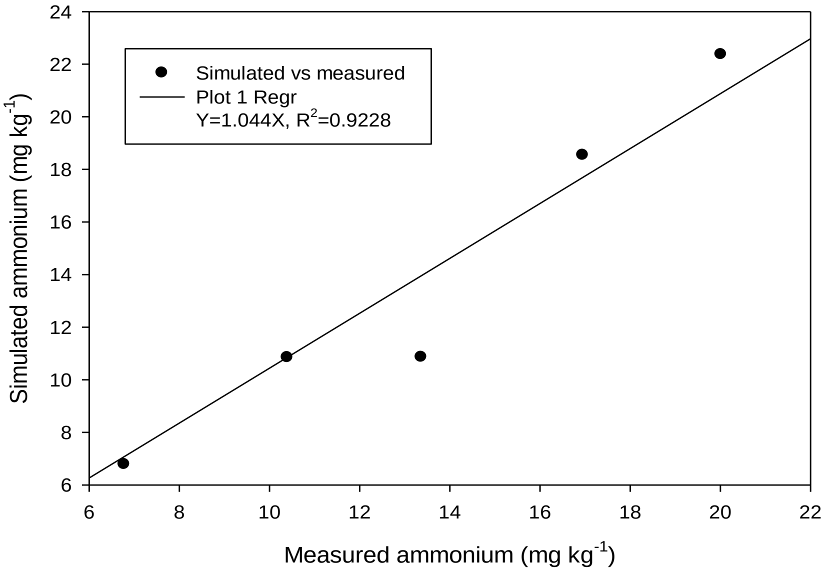


Figure 6-4. Calibration of HYDRUS model for simulating ammonium N movement on Candler fine sand

Table 6-1. Selected parameters for sensitivity analysis for simulating water flow and nutrient movement in citrus using HYDRUS-2D

Parameter	Units	Nominal value	Range	Source
$\theta^{\P}_{rIM}$	$cm^3\ cm^{-3}$	0.010	-	T.A. Obreza (unpublished data)
θ_{sIM}	$cm^3\ cm^{-3}$	0.340	0.33-0.35	T.A. Obreza (unpublished data)
α_{IM}	cm^{-1}	0.023	0.022-0.023	T.A. Obreza (unpublished data)
n_{IM}	-	4.631	3.19-6.07	T.A. Obreza (unpublished data)
K_{sIM}	$cm\ d^{-1}$	586.800	242.40-931.20	Carlisle et al., 1989
$\theta^{\P\P}_{rLA}$	$cm^3\ cm^{-3}$	0.009	-	T.A. Obreza (unpublished data)
θ_{sLA}	$cm^3\ cm^{-3}$	0.385	0.36-0.41	T.A. Obreza (unpublished data)
α_{LA}	cm^{-1}	0.061	0.04-0.079	T.A. Obreza (unpublished data)
n_{LA}	-	2.571	2.28-2.87	T.A. Obreza (unpublished data)
K_{sLA}	$cm\ d^{-1}$	600.500	455.00-746.00	Fares et al., 2008
K_{DNH4}	$cm^3\ g^{-1}$	2.75	1.50-4.00	Selim and Iskandar, 1981; Lotse et al., 1992; Ling and El-Kadi, 1998
K_{DP}	$cm^3\ g^{-1}$	102.0	19.00-185.00	Silberbush and Barber, 1983; Kadlec and Knight, 1996; Gross et al., 1999
K_{DK+}	$cm^3\ g^{-1}$	28.7	11.48-45.92	Silberbush and Barber, 1983
w_c	-	0.5	0.20-0.80	Šimůnek and Hopmans, 2009
π_c	-	0.5	0.20-0.80	Šimůnek and Hopmans 2009

[¶]IM denotes soil hydraulic functions for Southwest Florida Research and Educational Center (SWFREC), Immokalee, [¶¶]LA denotes soil hydraulic functions for Citrus Research and education Center (CREC), Lake Alfred

Table 6-2. Irrigation system parameters for HYDRUS-2D for Immokalee and Candler fine sand

Irrigation system parameter	Drip	Microsprinkler
Irrigation		
Discharge rate (L/h)	2	40
Irrigation time (day)	0.13	0.08
Irrigation interval (day)	1	1
Within- x cross-row tree spacing (cm)-Immokalee	305 x 671	306 x 671
Within- x cross-row tree spacing (cm)-Lake Alfred	305 x 610	306 x 610
Water use		
Transpiration February/March (mm/day)	1	1
Transpiration June/July (mm/day)	3	3
Evaporation February/March (mm/day)	2	2
Evaporation June/July (mm/day)	2.5	2.5
¶Crop coefficient February/March (mm/day)	0.71	0.71
¶Crop coefficient June/July (mm/day)	0.83	0.83
Simulated domain		
Source	Point	Line
Two-dimensional geometry	Axisymmetrical	Planar
Width (cm)	NA	50
Radius (cm)	50	NA
Depth (cm)	60	60
Number of triangular finite elements	2462	3834
Number of nodes	1232	1918
§Root water uptake Feddes pressure heads		
P0 (cm)	-10	-10
Popt (cm)	-25	-25
P2H (cm)	-200	-200
P2L (cm)	-1000	-1000
P3 (cm)	-8000	-8000
r2H (cm/day)	0.5	0.5
r2L (cm/day)	0.1	0.1
Root zone parameters		
Root distribution model	Vrugt	Vrugt
Maximum rooting depth (cm)	45	45
Depth with maximum root density (cm)	15	15
Maximum root lateral extension (cm)	45	45
Distance with maximum root density (cm)	30	30
Non-symmetry coefficients, p_z and p_r	1	1

¶Obtained from Morgan et al. (2006b); §Obtained from Feddes et al. (1978)

Table 6-3. Simulation experiment scenarios for the Ridge and Flatwoods soils

Irrigation system	Fertigation frequency	Irrigation frequency	Outputs of interest[¶]
[¶]Drip	Daily	Daily	NO_3-N, Br, soil water content, NH_4-N, P, K
[¶]Microsprinkler	Weekly	Daily	NO_3-N, Br, soil water content, NH_4-N, P, K
Microsprinkler	Weekly	Daily	NO_3-N, Br, soil water content

[¶]Outputs in the soil will be predicted on observation nodes at 15 cm and 60 cm for NO_3-N, Br, soil water content depths while P and K will be predicted at 15 cm depth at 15 cm from the tree while

Table 6-4. Soil physical characteristics and initial conditions of the Immokalee and Candler fine sands

Soil	[#]ρ_b	[¶¶]K_{sat}	[§]θ_{sat}	[§§]θ_r	α	n	*l*	[##]K_{dP}	K_{dNH4}	K_{dK}	[§§§]Br	NO_3	NH_4	M1P	M1K
Immokalee	1.61	14.40	0.35	0.01	0.033	1.34	0.5	0.44	1.37	1.17	0.2	3.0	3.0	50.0	40.0
Candler	1.64	15.49	0.36	0.01	0.028	1.80	0.5	0.98	1.89	1.17	0.1	12.0	6.0	100.0	60.0

[#]ρ_b - Bulk density, g cm^{-3}

[¶¶]K_{sat} – saturated hydraulic cponductivity, cm h^{-1}

[§]θ_{sat} – Saturated moisture content, cm^3 cm^{-3}

[§§]θ_r – Residual moisture content obtained from Obreza, unpublished data, cm^3 cm^{-3}

[##]K_d – Sorption coefficient (L kg^{-1}) for P, K and NH_4

[§§§]Br, NO_3, NH_4, M1P, M1K – initial concentrations of Br, NO_3, NH_4, M1P, M1K, mg kg^{-1}

Table 6-5. Sensitivity indices for selected parameters for soil available water, P, ammonium and K movement using HYDRUS-2D

Parameter	Units	Nominal value	Bauer and Hamby sensitivity index
$\theta^{¶}_{rIM}$	$cm^3\ cm^{-3}$	0.01	0.04
θ_{sIM}	$cm^3\ cm^{-3}$	0.34	0.24
α_{IM}	cm^{-1}	0.02	0.07
n_{IM}	-	4.63	0.29
K_{sIM}	$cm\ d^{-1}$	586.80	0.24
$\theta^{¶}_{rLA}$	$cm^3\ cm^{-3}$	0.01	0.04
θ_{sLA}	$cm^3\ cm^{-3}$	0.385	0.08
α_{LA}	cm^{-1}	0.061	0.17
n_{LA}	-	2.571	0.21
K_{sLA}	$cm\ d^{-1}$	600.50	0.29
K_{dNH4IM}	$cm^3\ g^{-1}$	2.75	0.31
K_{dPIM}	$cm^3\ g^{-1}$	102.0	0.21
K_{dKIM}	$cm^3\ g^{-1}$	28.7	0.33
K_{dNH4LA}	$cm^3\ g^{-1}$	2.75	0.19
K_{dPLA}	$cm^3\ g^{-1}$	102.0	0.06
K_{dKLA}	$cm^3\ g^{-1}$	28.7	0.03

[¶] IM denotes soil hydraulic functions for Southwest Florida Research and Educational Center (SWFREC), Immokalee

[¶¶] LA denotes soil hydraulic functions for the site near Citrus Research and education Center (CREC), Lake Alfred

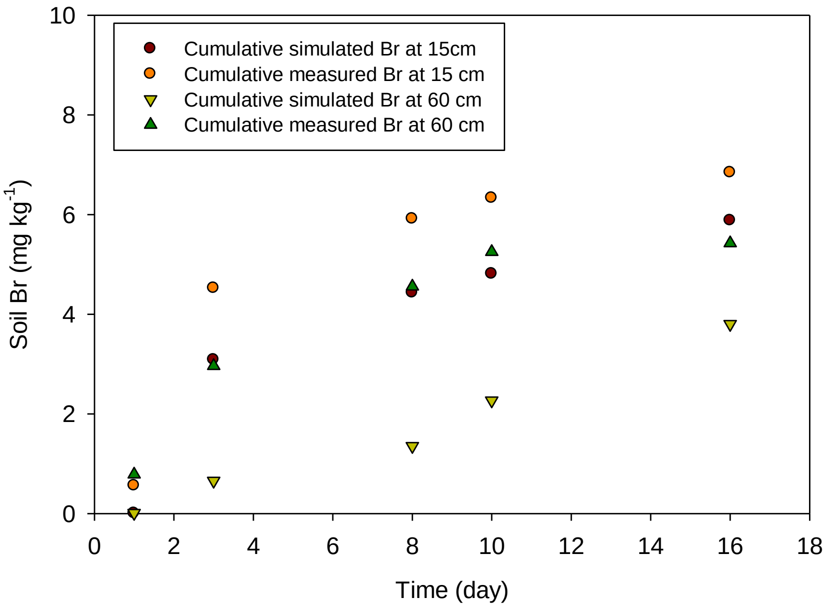


Figure 6-5. Soil Br monitored at 15- and 60 cm depth using drip irrigation at the Lake Alfred site

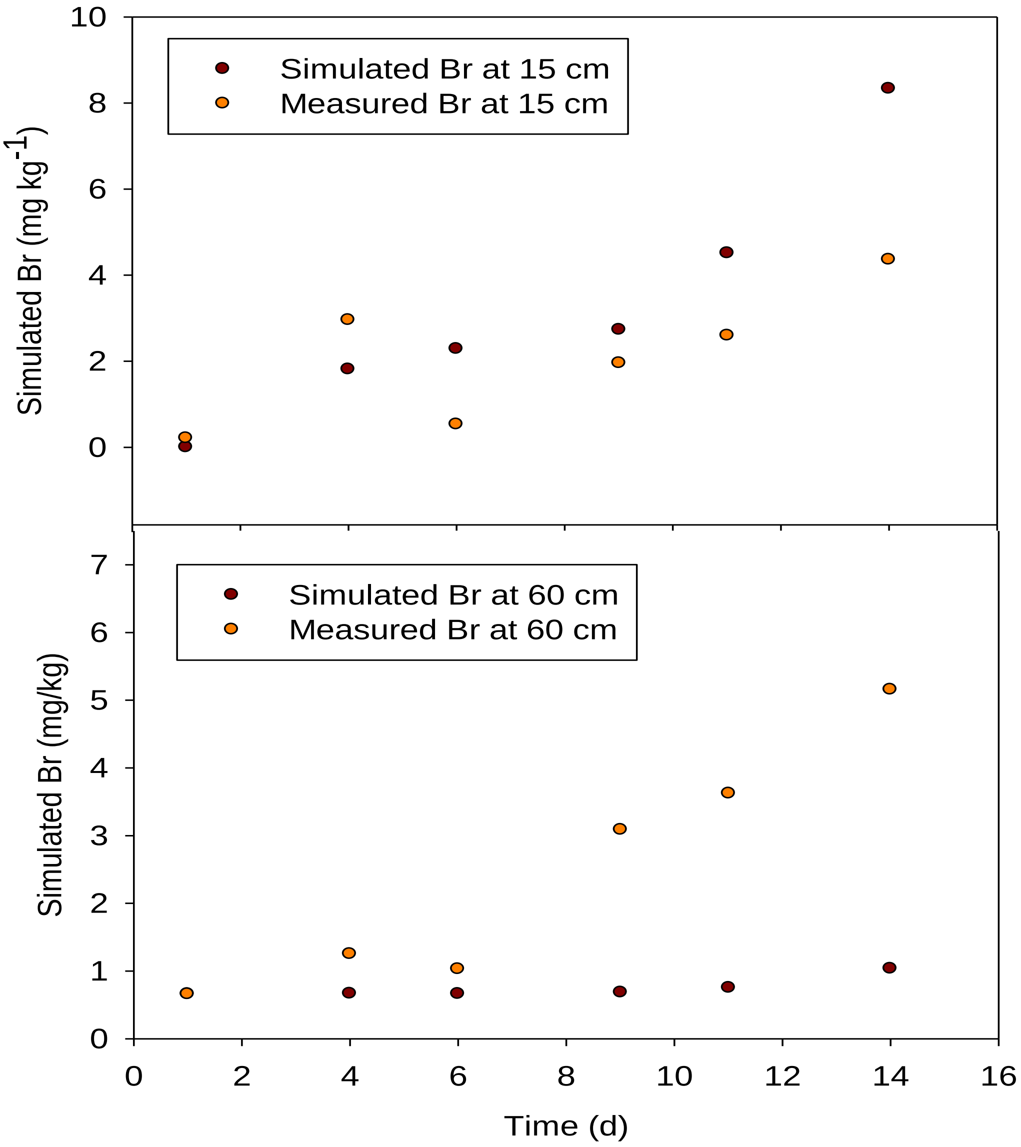


Figure 6-6. Measured and simulated Br concentration at 15 and 60 cm at Immokalee site using microsprinkler irrigation

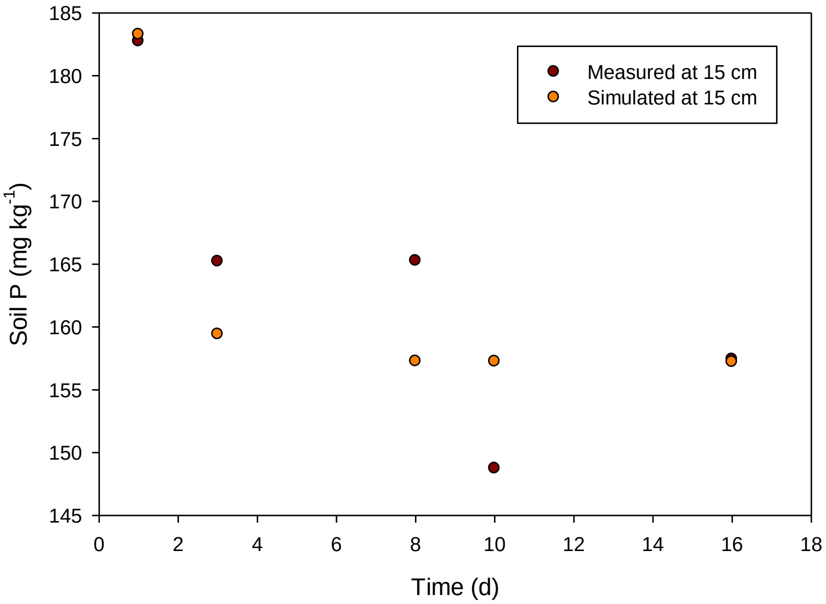


Figure 6-7. Soil P monitored at 15 cm depth using drip irrigation at the Lake Alfred site

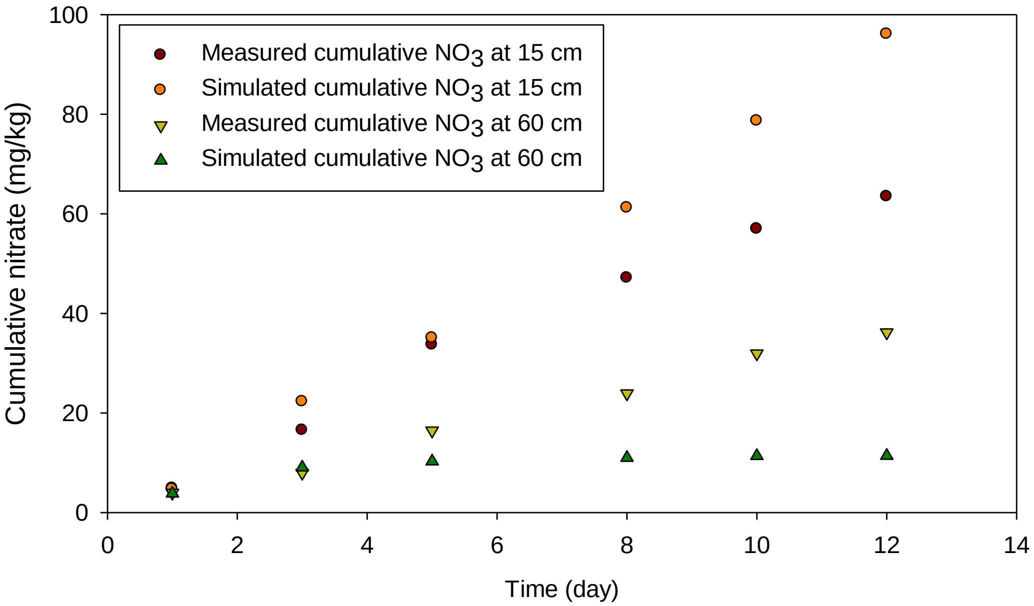


Figure 6-8. Simulated and measured cumulative nitrate concentration using microsprinkler irrigation at the Immokalee site

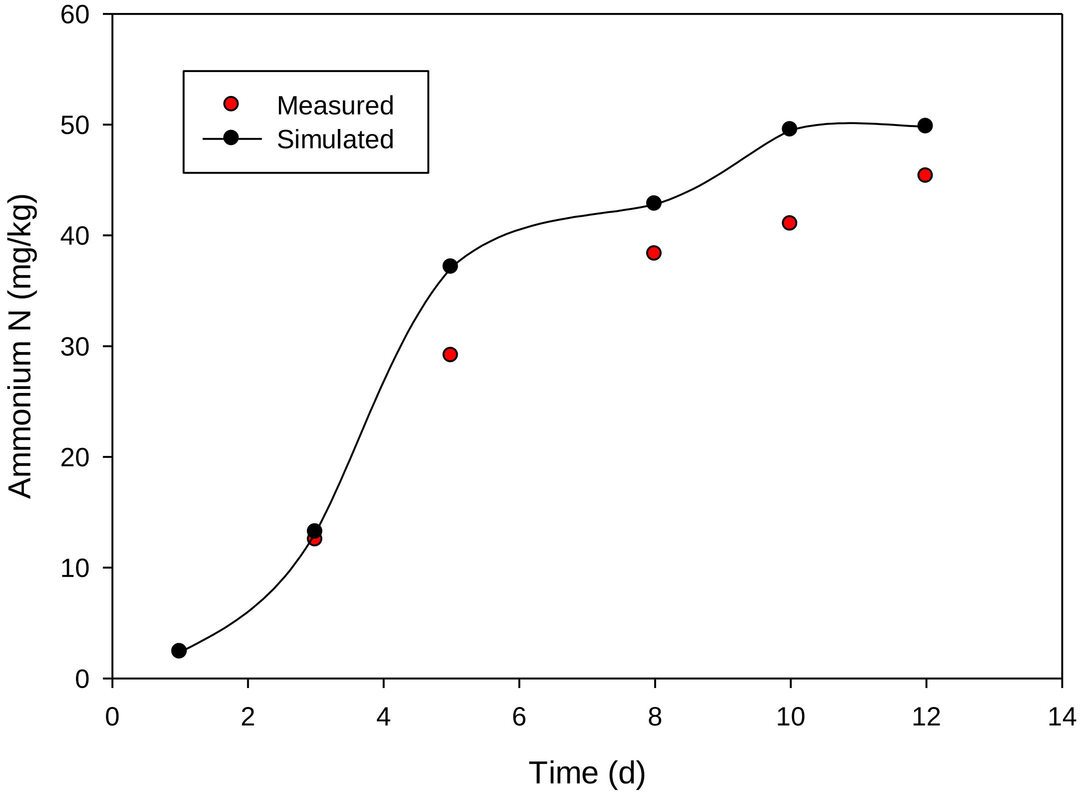


Figure 6-9. Simulated and measured cumulative ammonium concentration using drip irrigation at the Immokalee site

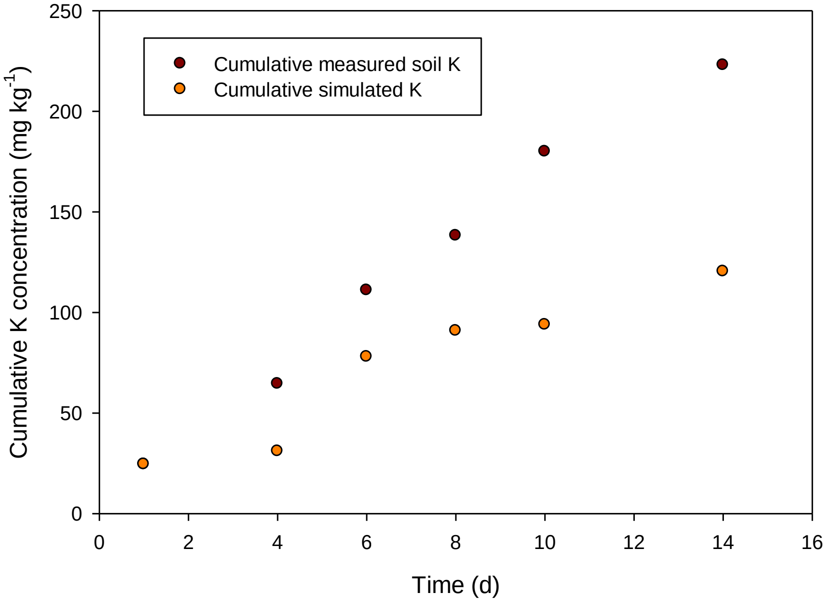


Figure 6-10. Cumulative K distribution at 15 cm soil depth at Immokalee site using microsprinkler irrigation

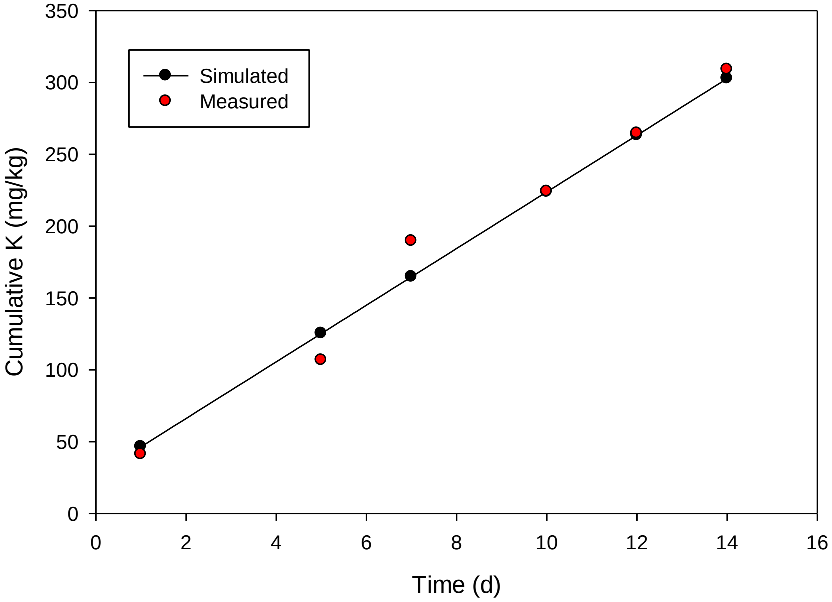


Figure 6-11. Cumulative K distribution at 15 cm soil depth at Immokalee site using drip irrigation

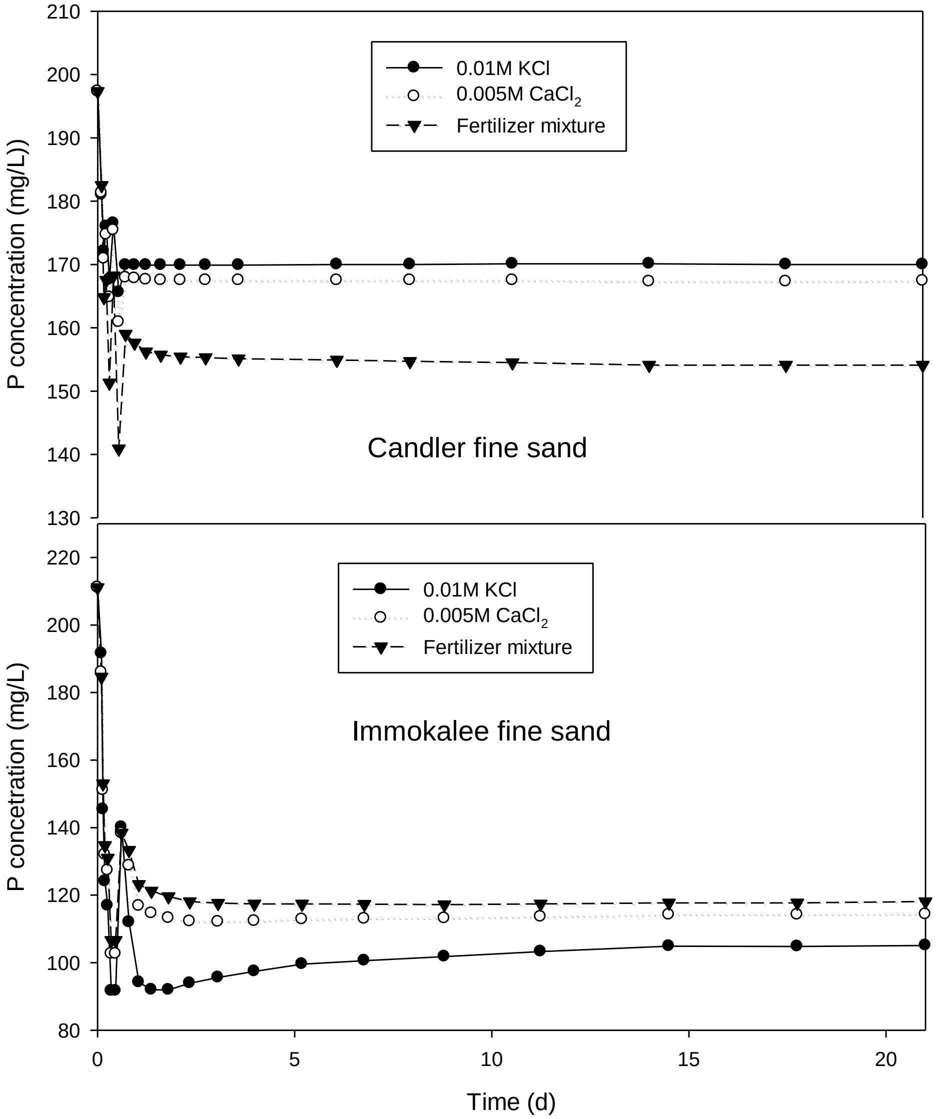


Figure 6-12. Phosphorus movement on Candler and Immokalee fine sand depending on K_D value estimated using HYDRUS-1D

Table 6-6. Statistical comparison between the observed and simulated water contents and uptake in spring and summer on Candler and Immokalee sand

Soil	Comparison[¶]	Soil available water (mm) R^2[§]
Candler	OBS vs. MS –spring at 10 cm	0.99
Candler	OBS vs. MS –spring at 40 cm	0.87
Candler	OBS vs. DRIP-spring at 10 cm	0.99
Candler	OBS vs. DRIP-spring at 40 cm	0.93
Candler	DRIP vs. MS at 10 cm	1.00
Candler	DRIP vs. MS at 40 cm	1.00
Immokalee	OBS vs. MS-spring at 10 cm	0.99
Immokalee	OBS vs. DRIP-spring at 10 cm	1.00
Immokalee	OBS vs. MS-spring at 40cm	1.00
Immokalee	OBS vs. DRIP-spring at 40 cm	0.95
Immokalee	DRIP vs. MS-spring at 10 cm	1.00
Immokalee	Drip vs. MS-spring at 40 cm	0.99
Immokalee	OBS vs. MS-summer at 10 cm	0.99
Immokalee	OBS vs. DRIP-summer at 10 cm	0.96
Immokalee	OBS vs. MS-summer at 40cm	0.99
Immokalee	OBS vs. DRIP-summer at 40 cm	1.00

[¶]OBS-Observed or measured in the field, MS-Microsprinkler irrigation, DRIP-Drip irrigation, [§]R^2-Coefficient of determination,

Table 6-7. Statistical comparison between the observed and simulated Br, NO_3, NH_4, M1P and M1K on Candler and Immokalee sand

Soil	Comparison[¶]	Br		NO_3		NH_4		M1P		M1K	
		RMSE (mg kg^{-1})	$R^{2§}$	RMSE[§§] (mg kg^{-1})	R^2	RMSE (mg kg^{-1})	R^2	RMSE (mg kg^{-1})	R^2	RMSE (mg kg^{-1})	R^2
Candler	OBS vs MS –Fall at 15 cm	2.08	0.89	1.65	0.88	1.06	0.98	57.9	0.78	21.74	0.44
Candler	OBS vs MS –Fall at 60 cm	1.25	0.76	1.52	0.84	[§§§]NA	NA	NA	NA	NA	NA
Candler	OBS vs DRIP- Fall at 15 cm	0.35	0.96	5.48	0.98	1.98	0.91	6.74	0.74	14.64	0.99
Candler	OBS vs DRIP-Fall at 60 cm	0.86	0.75	1.90	0.66	NA	NA	NA	NA	NA	NA
Immokalee	OBS vs MS-summer at 15 cm	7.57	0.79	5.25	0.75	1.33	0.95	55.62	0.25	11.22	0.93
Immokalee	OBS vs DRIP-summer at 15 cm	0.44	0.90	1.66	0.91	1.15	0.93	15.74	0.69	10.64	0.94
Immokalee	OBS vs MS-summer at 60cm	0.06	0.74	4.88	0.82	NA	NA	NA	NA	NA	NA
Immokalee	OBS vs DRIP-summer at 60 cm	0.04	0.63	1.95	0.85	NA	NA	NA	NA	NA	NA

[¶] OBS-Observed or measured in the field, MS-Microsprinkler irrigation, DRIP-Drip irrigation

[§] R^2-Coefficient of determination, [§§] RMSE-Root mean square error, mm, [§§§] NA-Not applicable

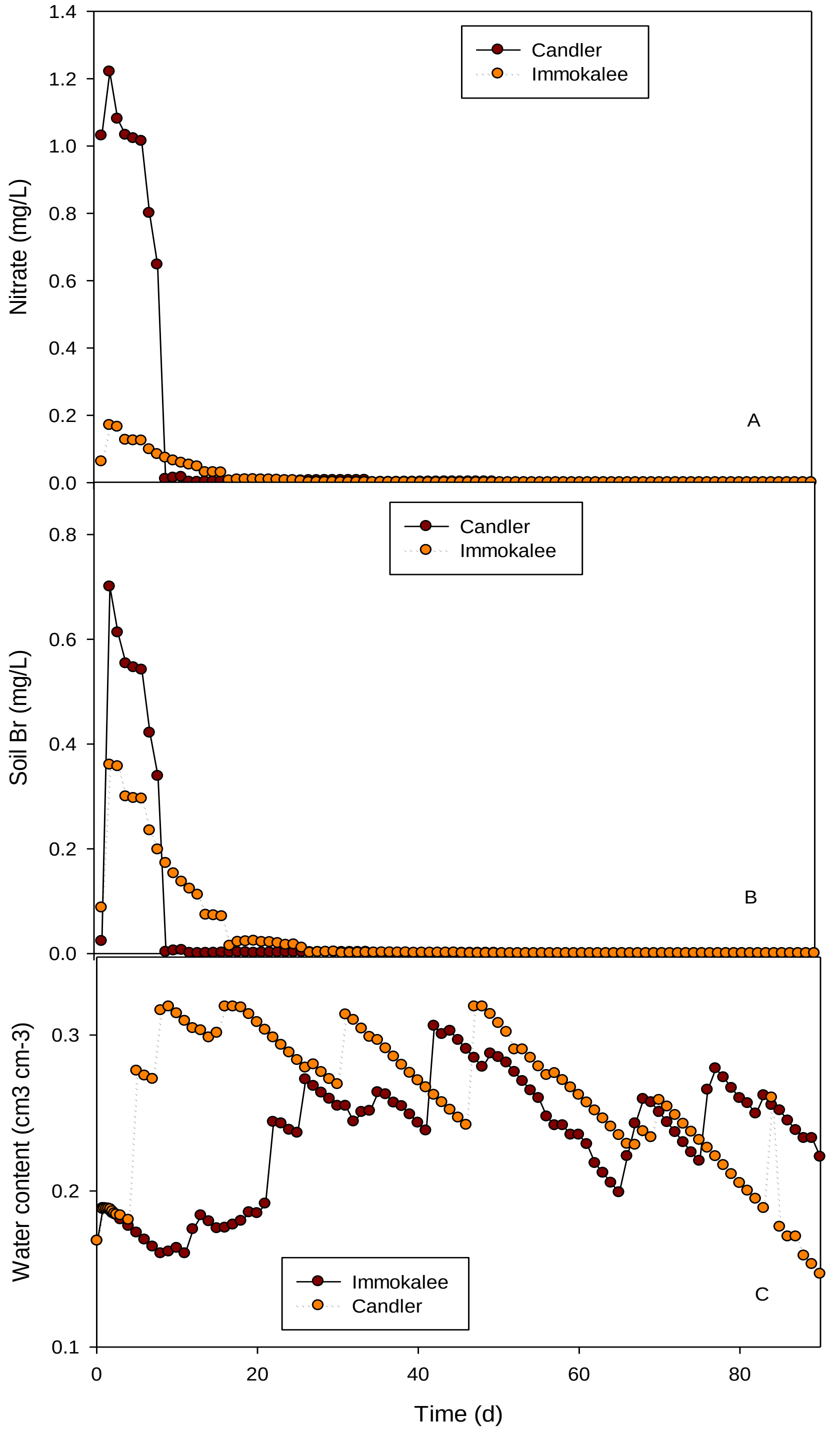


Figure 6-13. Simulated nitrate (A), bromide (B) and water (C) movement over a 90 day period at 60 cm using grower practice

CHAPTER 7
CONCLUSIONS

The study had sought to address the general research objectives and goals as conceptualized: 1) develop optimum irrigation rate, method, and timing for young citrus trees, 2) determine growth and yield effects of fertigation on young citrus trees at selected frequencies, 3) measure effect of irrigation method and frequency on rooting patterns, nutrient retention, and water and nutrient uptake, 4) characterize the soil physical parameters and sorption of K, P and NH_4 of Immokalee and Candler sand, 5) calibrate HYDRUS for water and nutrient movement using site specific soil hydraulic characteristics and nutrient sorption behavior, and 6) characterize HYDRUS as a possible decision support system for predicting soil moisture distribution and solute transport in the vadose zone. The appropriate general hypotheses formulated to answer the above research goals were as follows: 1) Microsprinkler and drip OHS will increase citrus growth rate, above ground biomass, and nutrient uptake resulting in higher plant N, P and K content than the conventional practice. 2) Spatial nutrient and root length density distribution will be greater in irrigated zones of microsprinkler and drip OHS than conventional grower practices. 3) Citrus water use and K_c increase with canopy volume and root length density in-situ irrespective of the irrigation frequency and fertigation method. 4) Measured soil water content, ET and Br correlate positively with simulated outputs thus helping in decision support in citrus production systems.

Overall, NH_4^+-N, NO_3^--N, M1P and M1K concentration and root length density decreased with distance from the irrigated zone and with depth, and were greater in irrigated than nonirrigated zones. This confirmed the hypotheses that ‘spatial nutrient and root length density distribution would be greater in irrigated zones of microsprinkler and drip OHS than conventional grower practices'. This suggests the potential for increased nutrient retention and root uptake because the irrigated zone was associated with increased root density. Overall, the study found 60-90% increased nutrient retention with ACPS than grower practice. The use of Br suggested consistent trends in the movement of NH_4^+-N, NO_3^--N, M1P and M1K in the irrigated and nonirrigated zones, and could be used as an important guideline for making nutrient management decisions with regard to nutrient residence time.

The results at both sites showed increased tree size with ACPS than grower practices. For example the results at Immokalee, showed that annual increments in trunk cross-sectional area respectively for CMP, DOHS, and MOHS were 97, 123 and 122% in year 2, and 44%, 56% and 66% in year 3 at Immokalee suggesting vigorous tree growth with ACPS/OHS. This also underscored the hypothesis that 'Microsprinkler and drip OHS will increase citrus growth rate and above- and below-ground biomass than the conventional practice.' The gains on canopy volumes and trunk cross-sectional area with ACPS and OHS compared with grower practices appear to be more pronounced during the first 3 years of establishing a grove as shown by the results at Lake Alfred.

Proportional nutrient accumulation patterns revealed that OHS fertigation increased N accumulation by 45% over grower practice at Immokalee, but P and K accumulation were fairly similar between the three practices, though CMP showed slightly higher P and K accumulation than OHS. Thus, N accumulation confirmed the hypothesis that 'accumulation would be greater for OHS than grower practices' but the this hypothesis did not hold for P and K accumulation. The N, P and K concentration using granular fertilization at the Lake Alfred site suggests that grower practices are just as effective in promoting tissue nutrient concentration. The biomass and nutrient (N, P and K) accumulation using granular fertilization or fertigation revealed that grower practices are just as effective in promoting nutrient and biomass accumulation. However, the grower practices do require more fertilizer and water applied per ha to achieve rapid tree development within 1 to 5 years of establishing a grove compared with ACPS practices.

Root length density measured using the line intersection method showed a positive correlation with those predicted by the calibration equation relating RLD and scanned root area. The results show that use of the scanning method could be used to increase the accuracy and reduce the time for determination of RLD. Generally, RLD was highest in the 0-15 cm depth and decreased with depth and distance away from the tree. Positions below the dripper of DOHS and in the irrigated zones of MOHS showed higher root length density than non-irrigated zones. Despite having irrigated zones around the tree using CMP, the infrequent irrigation probably resulted in lower RLD compared with the irrigated zones of DOHS and MOHS treatments at both study sites.

The experiments on water uptake estimation showed that water uptake was higher using the ACPS/OHS fertigation methods compared with the conventional grower practices (fertigated or receiving granular fertilization). The high uptake in the ACPS/OHS fertigation methods are ascribed to vigorous growth resulting in trees with large canopy volumes, leaf areas and trunk cross-sectional areas. The results further support the thinking behind ACPS/OHS that nutrient leaching would be minimized while accelerating tree growth and fruit yield. Regression analysis further revealed that for young trees (<5 yr-old) irrigation scheduling is a critical management practice especially for the sandy soil as shown by the good correlation of water uptake with soil moisture at 10, 20, 30, 40, 45 and 50cm soil depths. Tree size characteristics such as trunk cross-sectional area and canopy volume also correlated well with water uptake. Despite weak correlation of cumulative sap flow with root length density, the results on root density showed increased root intensity in the top 0-30 cm soil depth layer indicating that water extraction would be enhanced with an increase in available water.

The results from laboratory sorption work show that P adsorption in the top 0-30 cm was greater for Candler than Immokalee sand using tap water in fertilizer mixture, 0.005M $CaCl_2$ and 0.01M KCl. The adsorption for P followed the Freundlich model and was best explained with 0.005M $CaCl_2$ as the supporting electrolyte. The simulations with HYDRUS1D suggest that 0.005M $CaCl_2$ would be an appropriate electrolyte for Immokalee fine sand with low organic matter content (<0.65%) because the outputs were failry close to those of fertilizer mixture. For Candler fine sand, both 0.005M $CaCl_2$ and 0.01M KCl tend to over-estimate P leaching making use of fertilizer mixture a viable option for estimating the sorption coefficients. It appears the addition of a supporting electrolyte with a divalent or monovalent cation, unlike using fertilizer mixture, increases the surface charge for adsorption of orthophosphate anions. The adsorption mechanism of both ammonium and potassium was linear and similar for both soils though ammonium adsorption coefficients were greater than those of potassium.

The determination of the hydraulic conductivity and water retention characteristics yielded important site-specific parameters like saturated and residual moisture contents, and hydraulic conductivity for use in the HYDRUS-2D model to describe water and solute transport to aid decision-making in predicting environmental fate of fertilizers.

The model simulations revealed that HYDRU-2D is a good model for predicting water and solute movement on Candler and Immokalee sand as long as it is carefully calibrated with site-specific parameters. However, the model appears to under predict most of the solutes of interest such as P, K and NH_4 suggesting that a correction factor might need to be estimated with measured values. This under-prediction or over-estimation is ascribed to the use of Mehlich 1 extractable P and K in the initial conditions for the simulations. Probably, the use of water extractable values of P and cations of interest that give a better indication of leaching potential would be appropriate. Also, caution with the model relates to its inability to account for uptake in perennial crops like citrus and other transformation process of soil nutrients such as ammonium and nitrate. However, the HYDRUS-2D model could successfully be used to determine fertilizer residence timeand for irrigation decisions if the modeler or grower has all the necessary parameters and climatic data for the site of interest.

Based on the results from the field and laboratory experiments, the key points for citrus growers eager to try the novel practices of ACPS/OHS are documented here. First, water uptake with drip or microsprinkler OHS is similar to conventional microsprinkler practice, but nutrient uptake, particularly N, is increased with the former two than the fertigated grower practice. Also, the amount of water applied with drip or microsprinkler OHS would be substantially less due to a limited root and irrigated zone, without stressing the tree with water deficit. However, it appears one could use one drip line with two to four drippers per tree within the first two to three years of installing the

ACPS/OHS. As the tree root and canopy volume expands with increase in tree age, there would be a need to increase irrigation frequency and the number of drip lines from one to two per tree row, and the number of drippers per tree from two or four to eight or greater to effectively manage the greater tree sizes. This requires training of personnel in managing automated irrigation and fertigation, repairs and other maintenance procedures. Second, ACPS/OHS has the potential to accelerate tree growth and bring trees into production within the first five years after grove establishment. Third, ACPS/OHS installed on a coated sand like Candler fine sand presents greater potential for vigorous tree growth and production due to better nutrient retention and higher soil organic matter (1.50-1.96%) than Immokalee fine sand with low nutrient retention and organic matter (0.40-0.61%). Last but not least, HYDRUS-2D could successfully be used for providing irrigation and nutrient management guidelines for Florida’s sandy soils once the soil parameters are known.

APPENDIX A
SUPPLEMENTARY FIGURES TO CHAPTERS 3, 4 AND 5

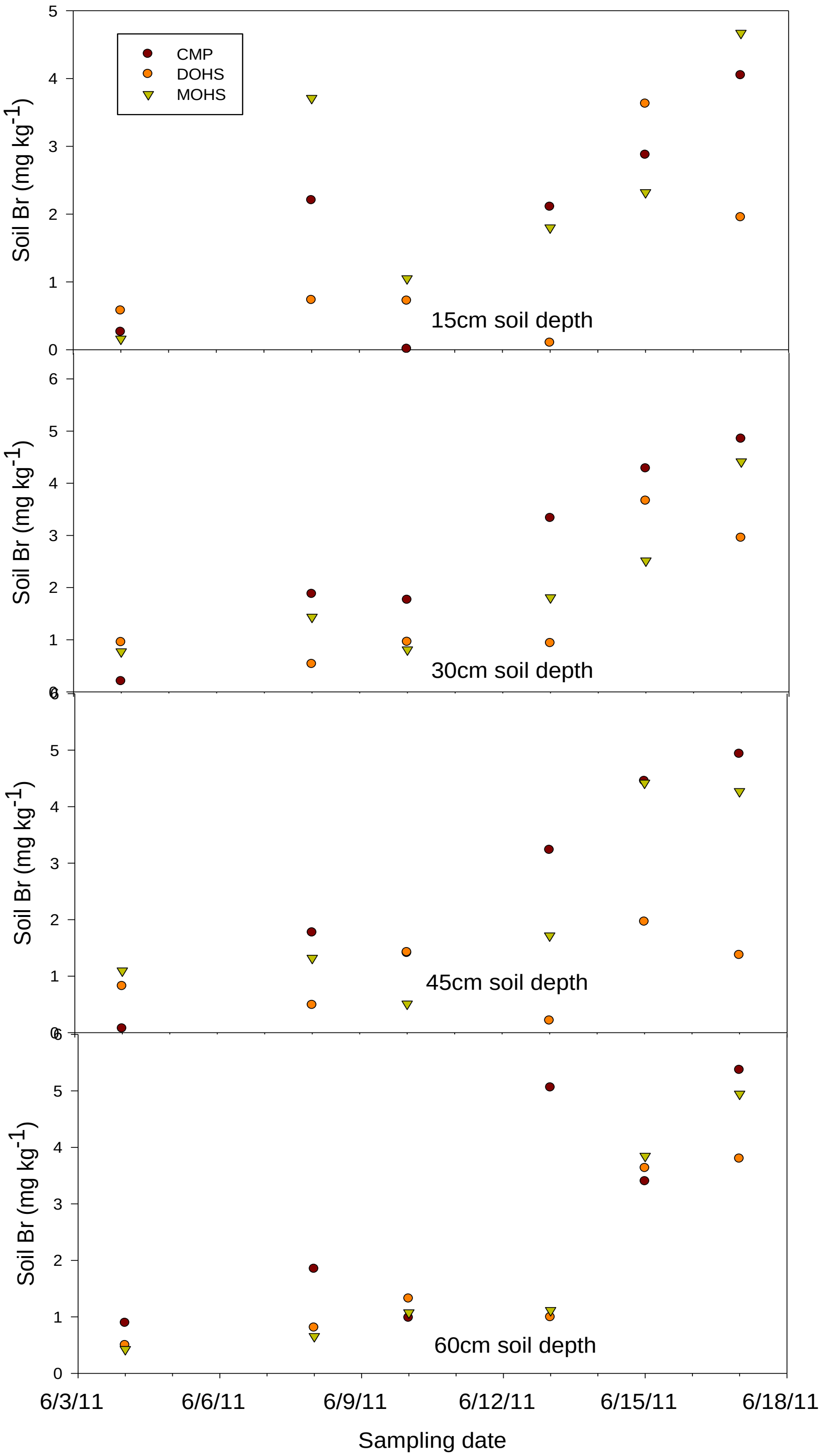


Figure A1. Soil Br distribution on Immokalee sand in the irrigated zone

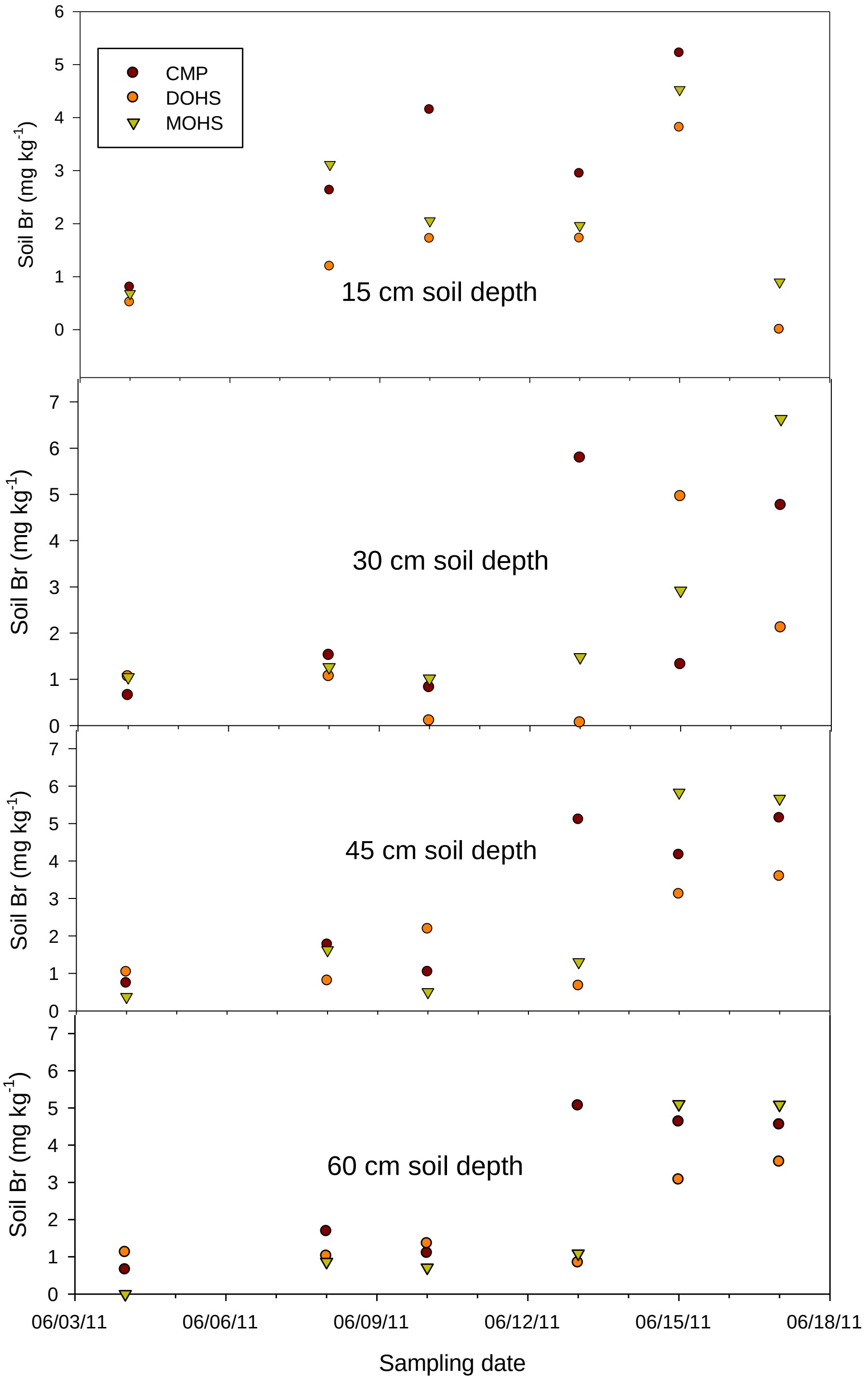


Figure A2. Soil Br distribution on Immokalee sand in the non-irrigated zone

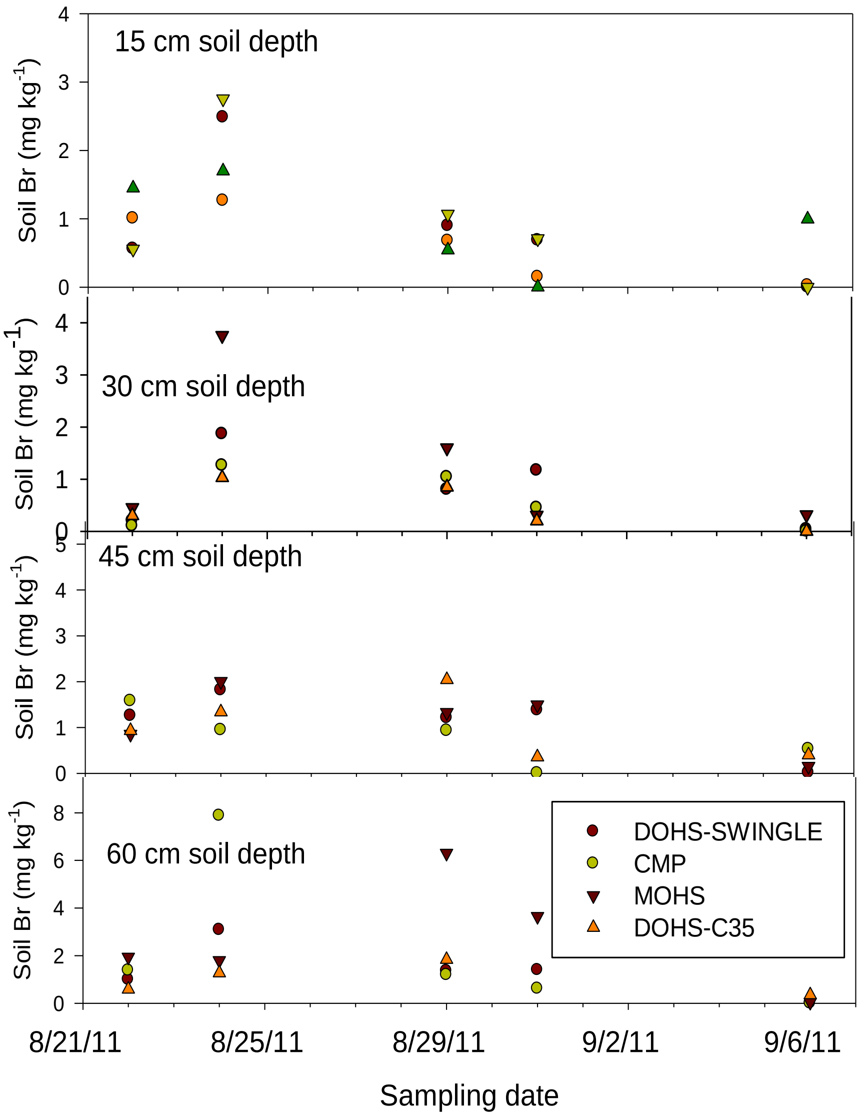


Figure A3. Soil Br distribution on Candler sand in the irrigated zone

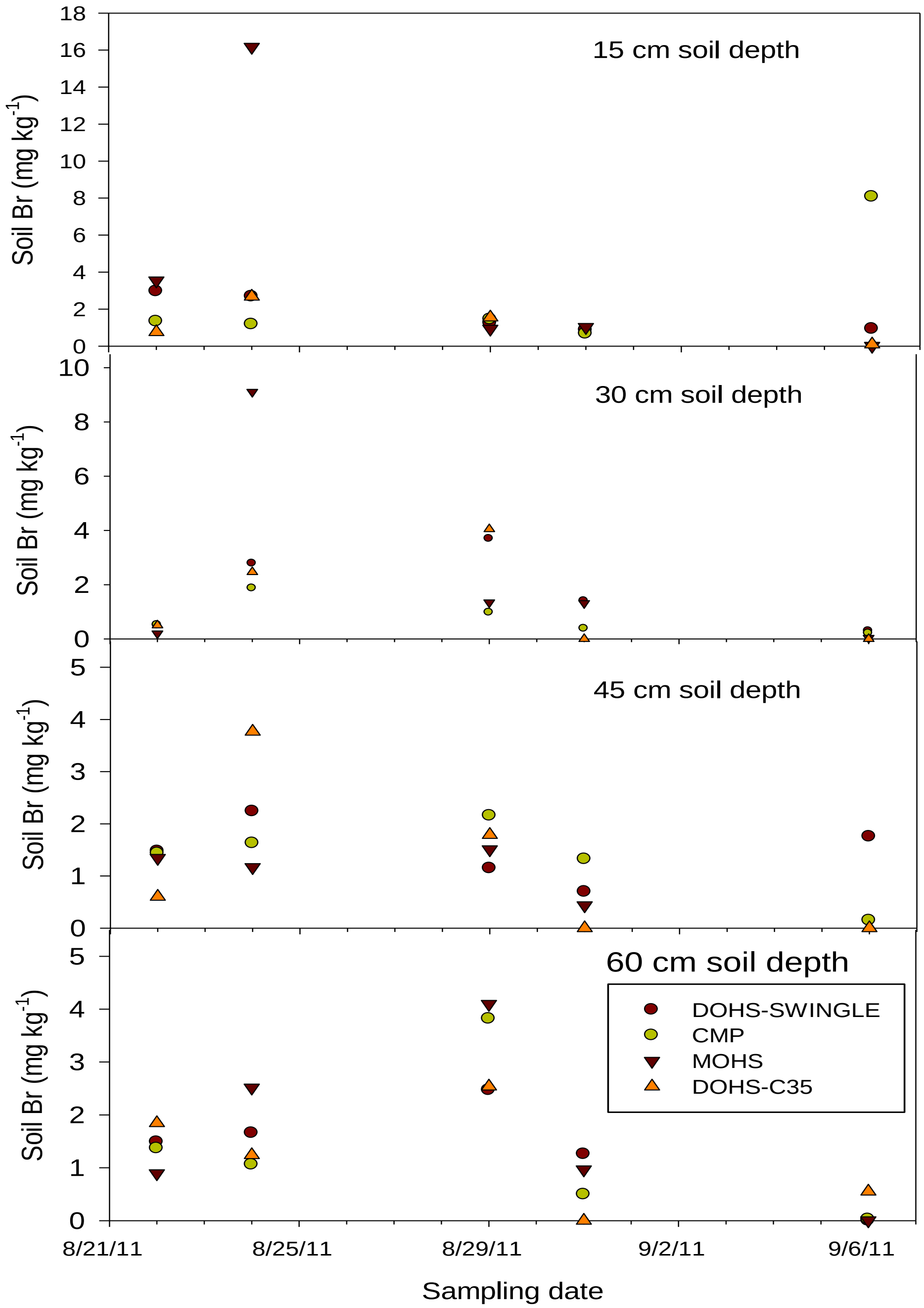


Figure A4. Soil Br distribution on Candler sand in the nonirrigated zone

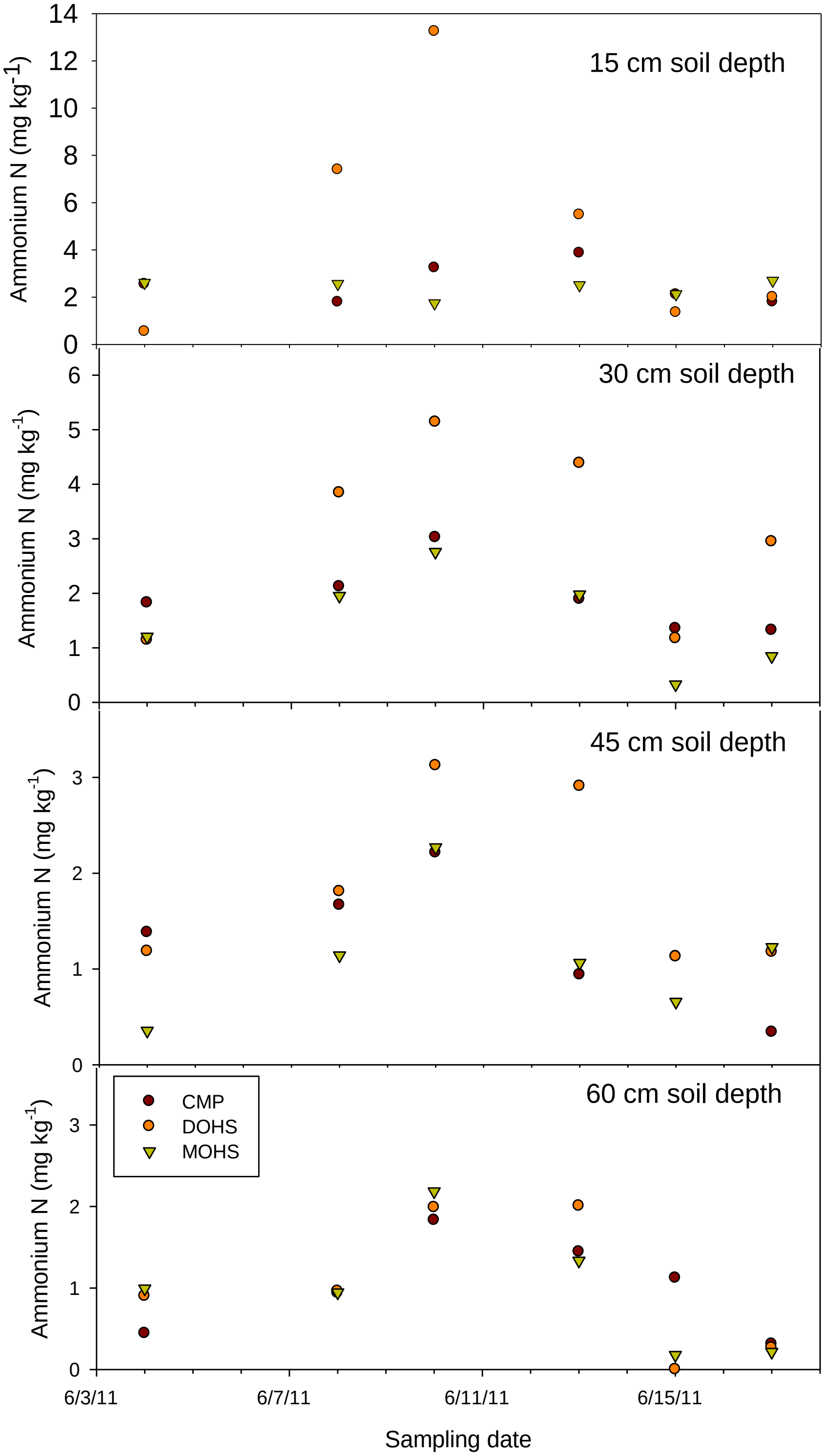


Figure A5. Soil ammonium N leaching on Immokalee sand in the irrigated zone

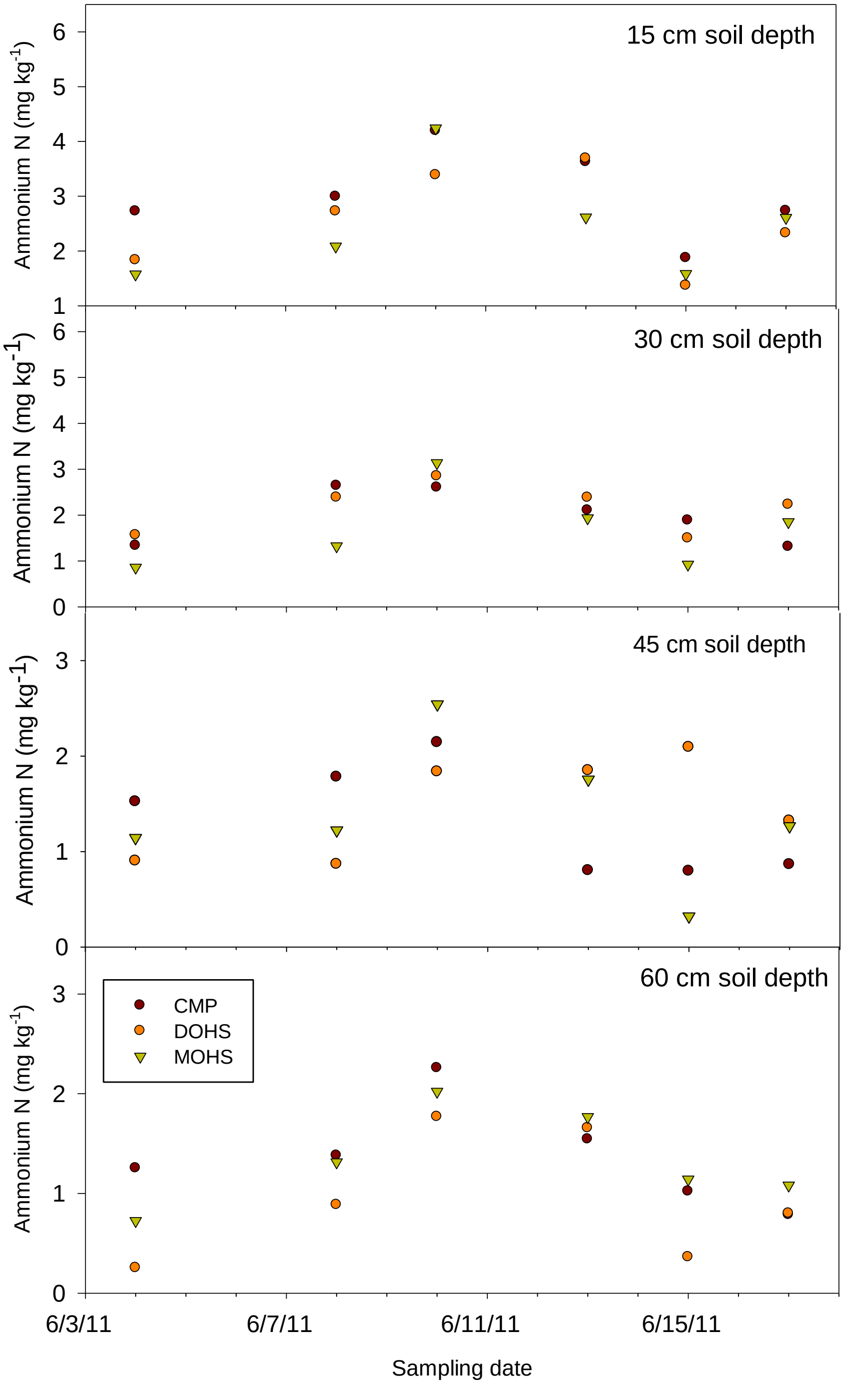


Figure A6. Soil ammonium N leaching on Immokalee sand in the nonirrigated zone

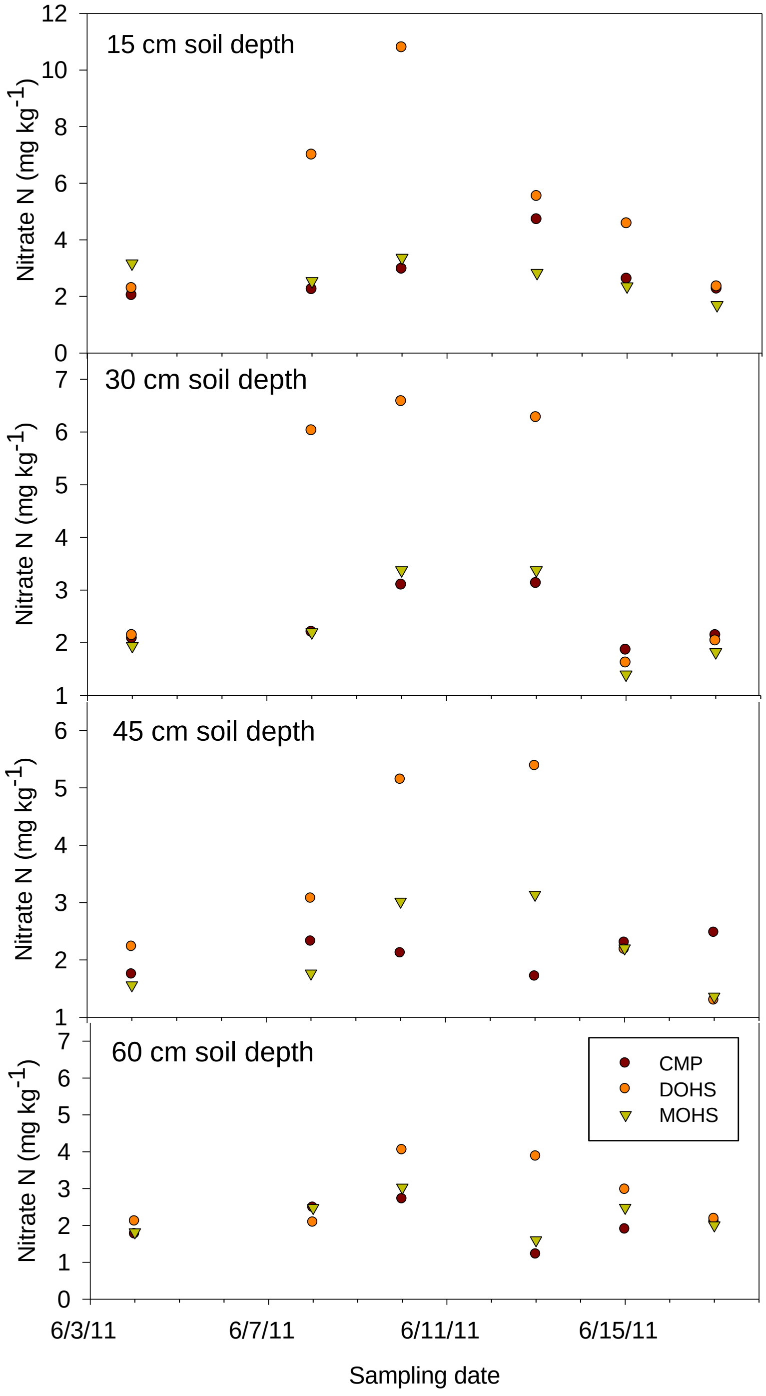


Figure A7. Soil nitrate N leaching on Immokalee sand in the irrigated zone

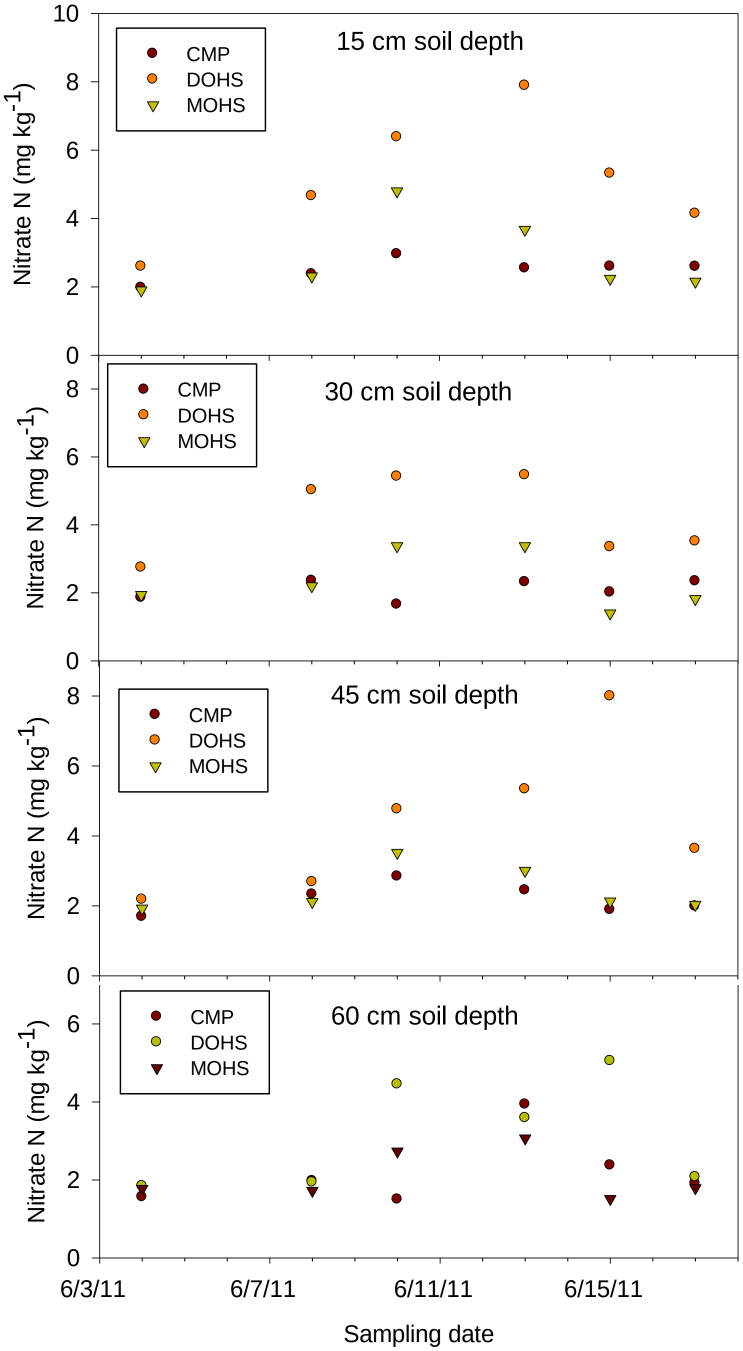


Figure A8. Soil nitrate N leaching on Immokalee sand in the nonirrigated zone

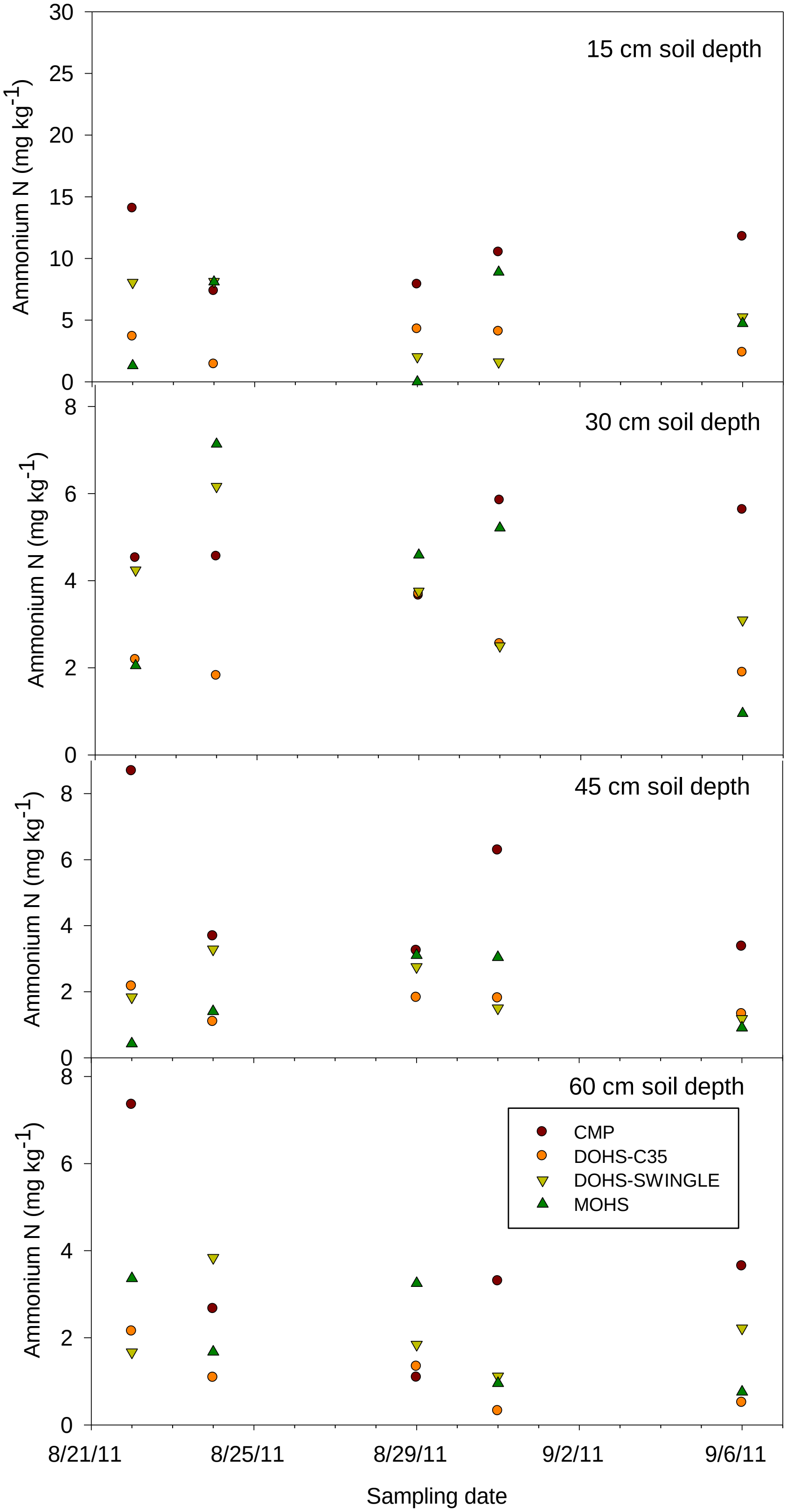


Figure A9. Soil ammonium N leaching on Candler sand in the irrigated zone

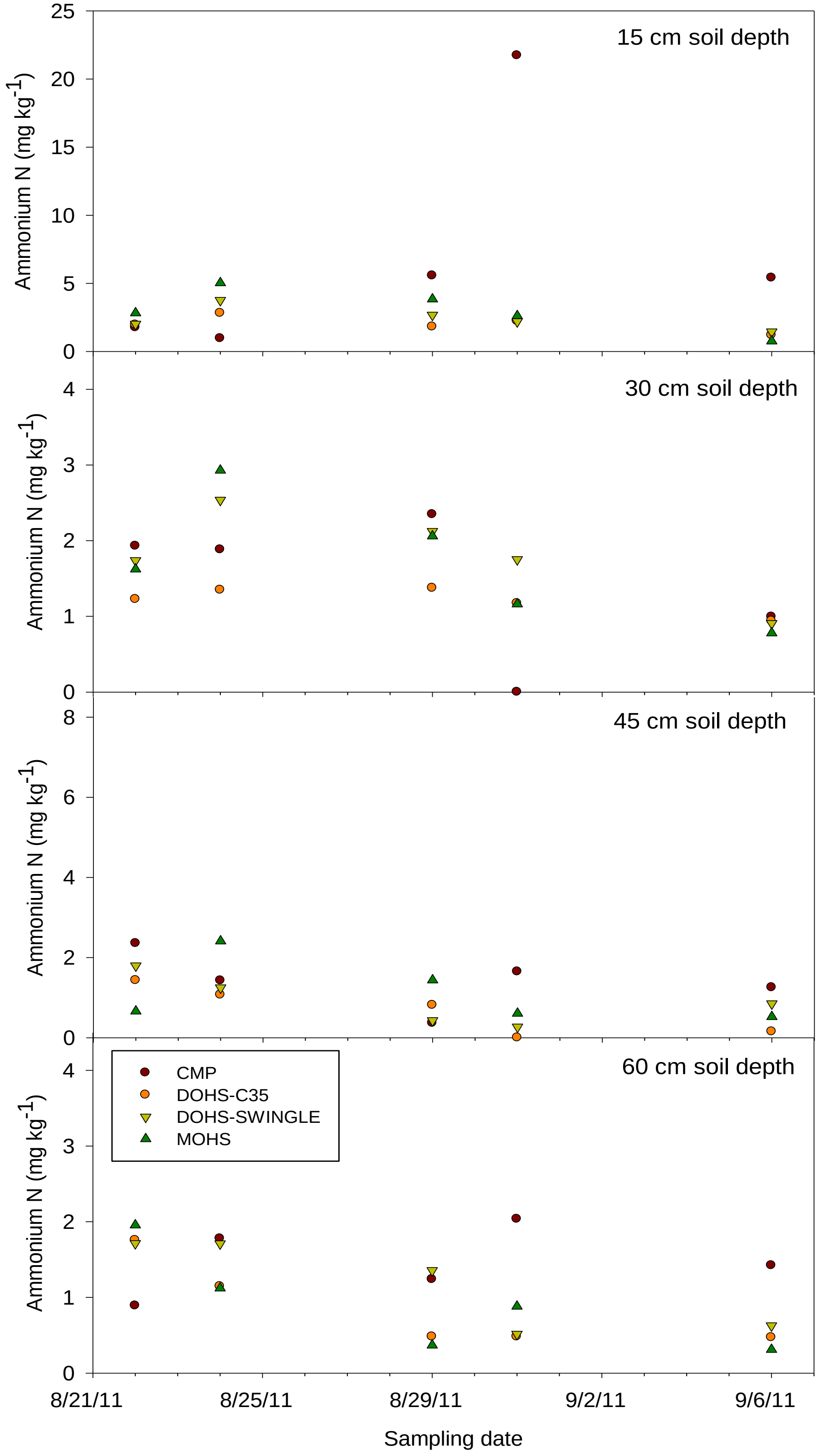


Figure A10. Soil ammonium N leaching on Candler sand in the nonirrigated zone

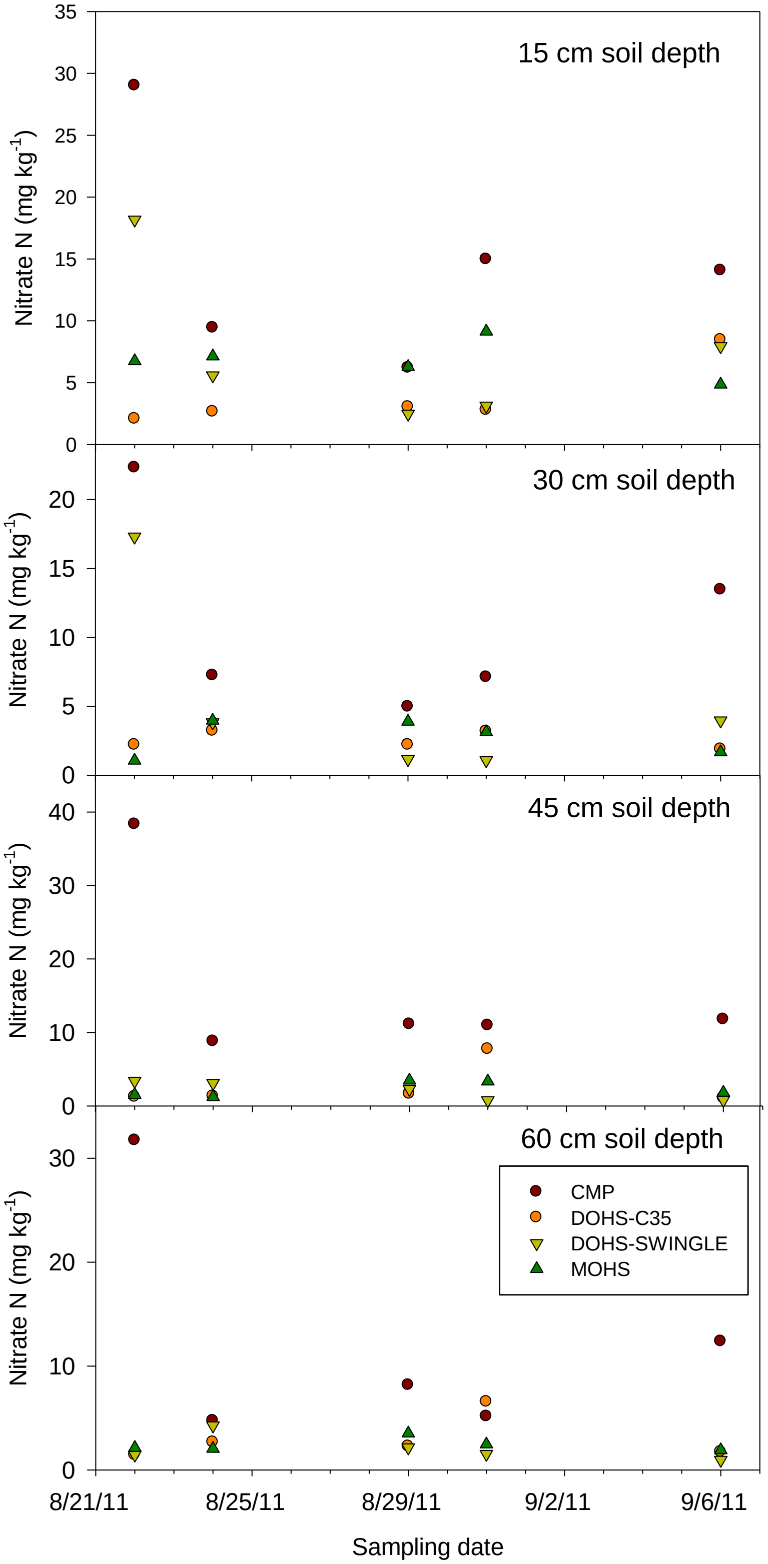


Figure A11. Soil nitrate N leaching on Candler sand in the irrigated zone

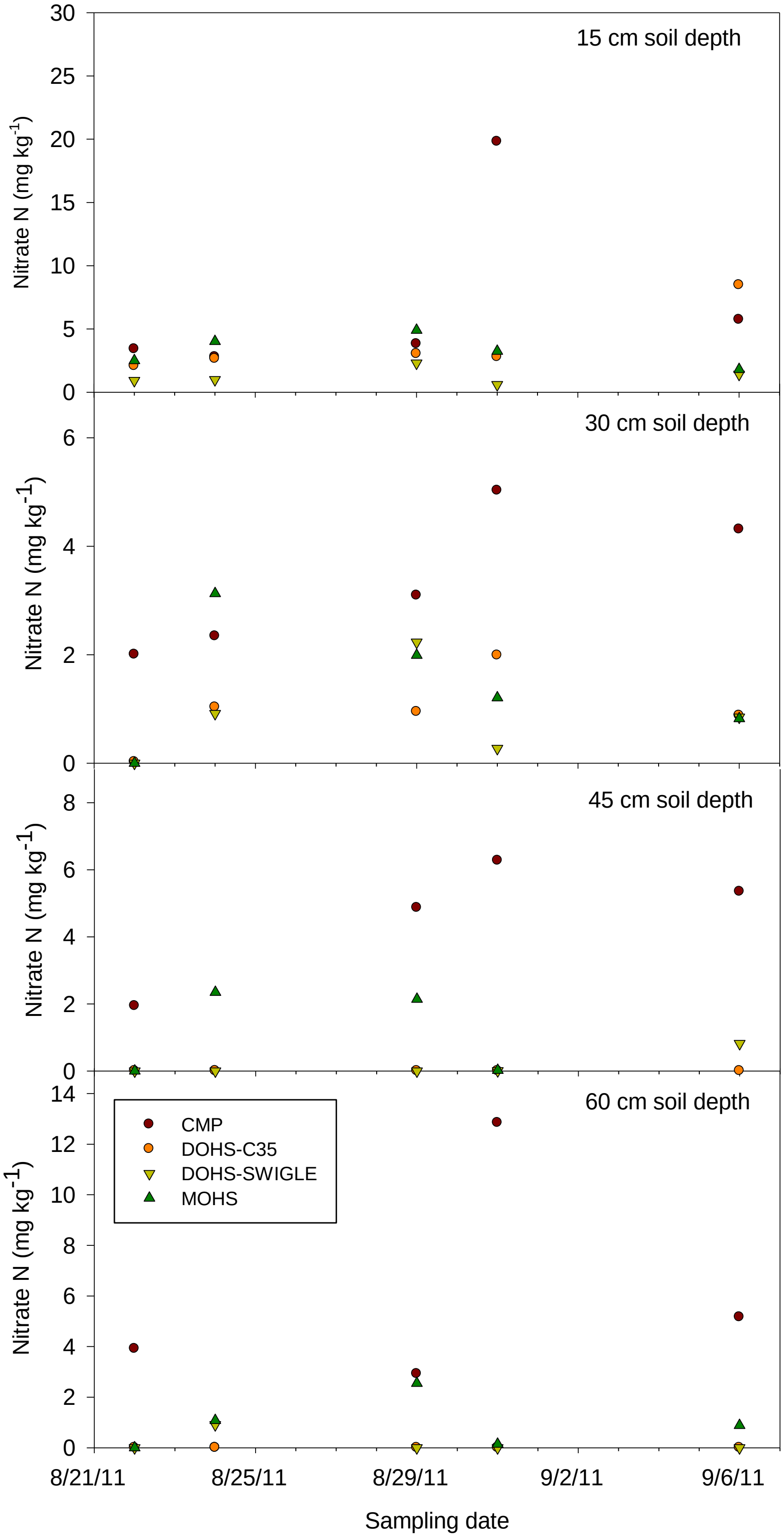


Figure A12. Soil nitrate N leaching on Candler sand in the nonirrigated zone

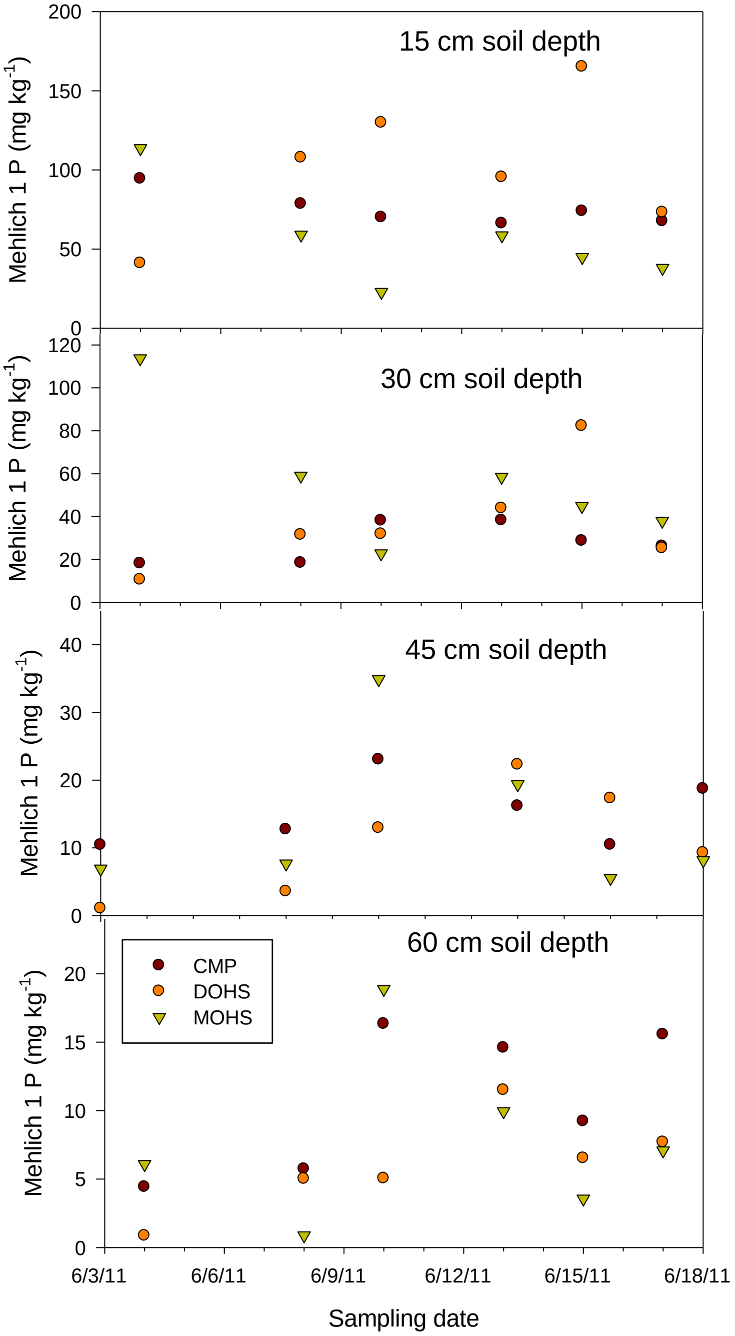


Figure A13. Soil P leaching on Immokalee sand in the irrigated zone

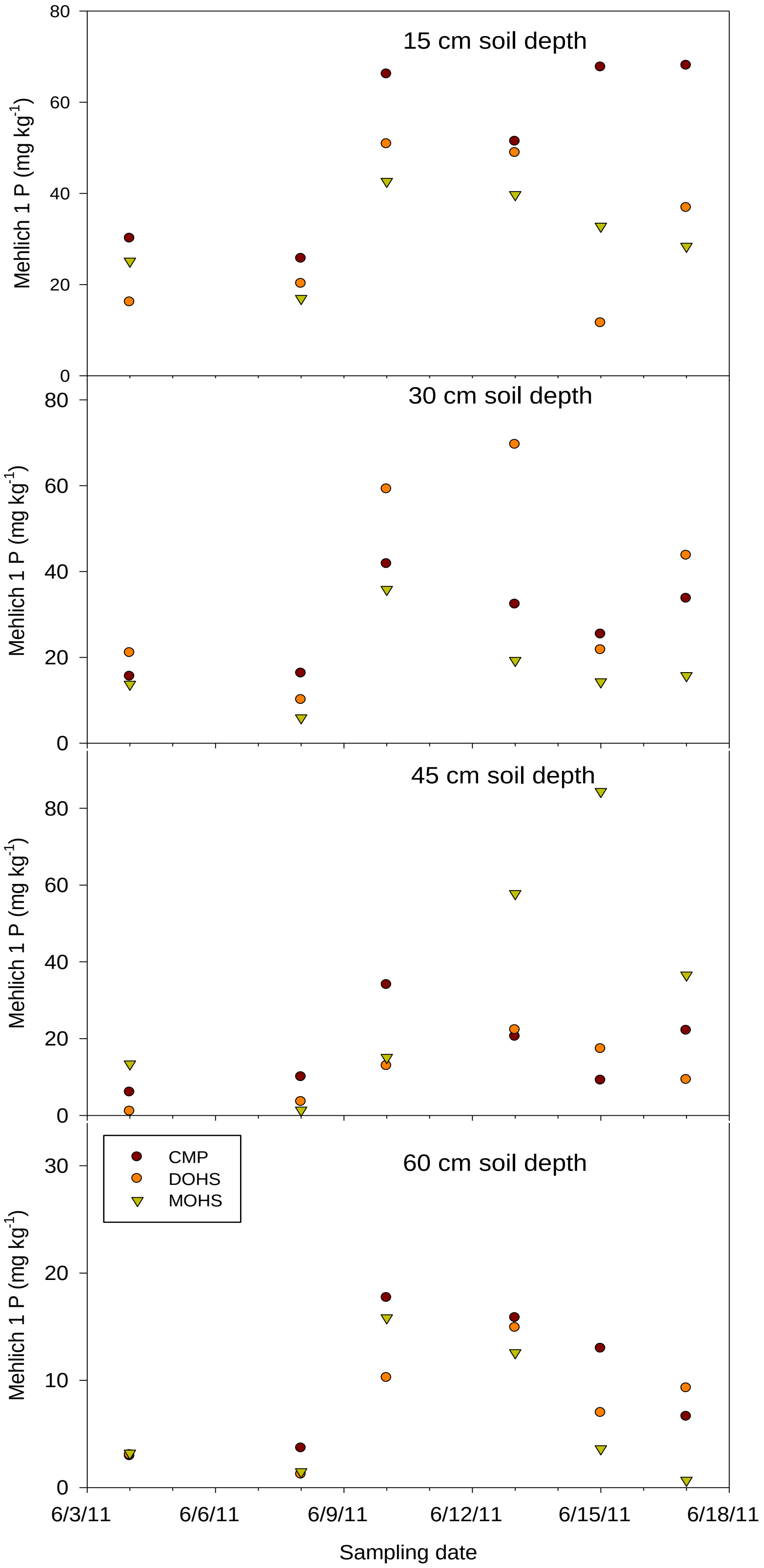


Figure A14. Soil P leaching on Immokalee sand in the nonirrigated zone

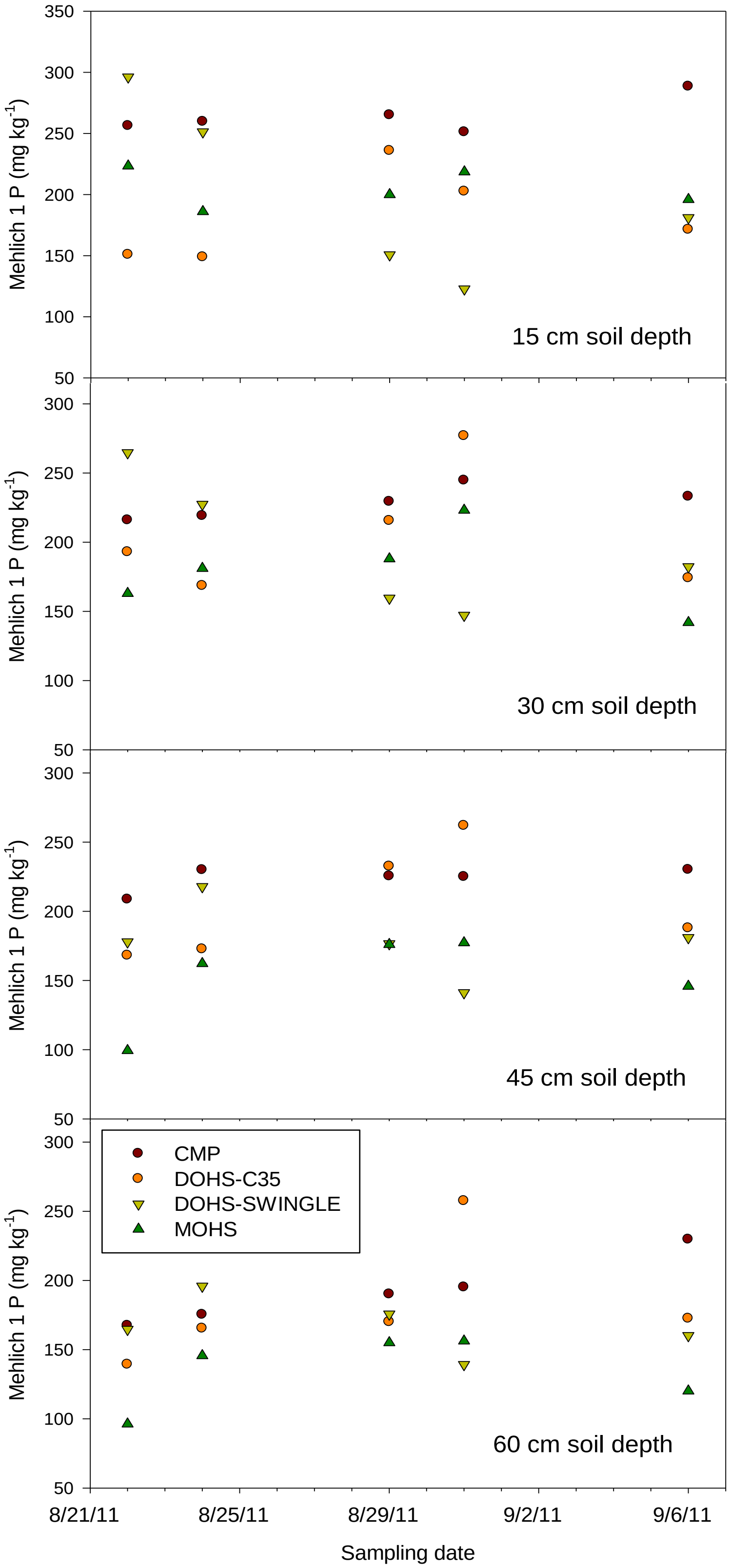


Figure A15. Soil P leaching on Candler sand in the irrigated zone

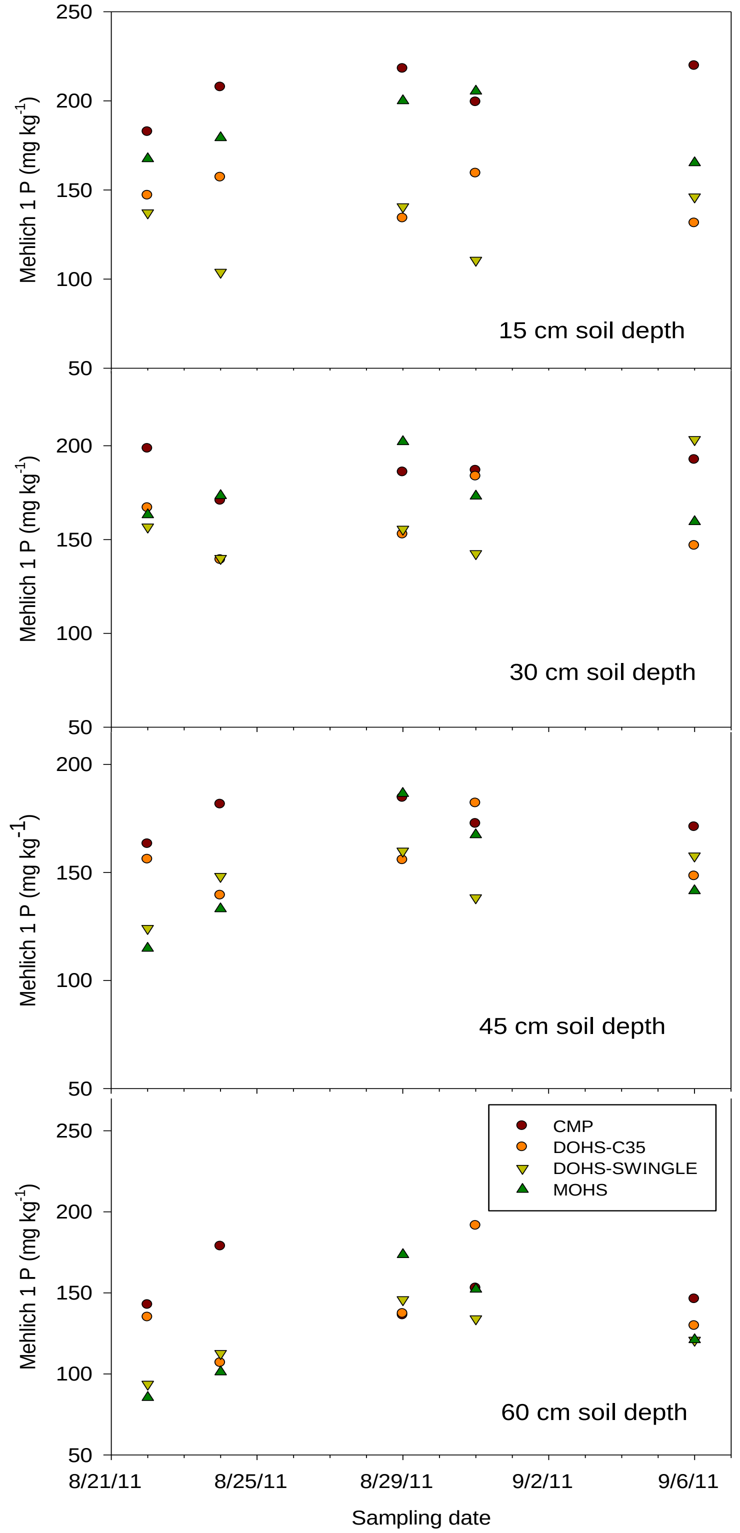


Figure A16. Soil P leaching on Candler sand in the nonirrigated zone

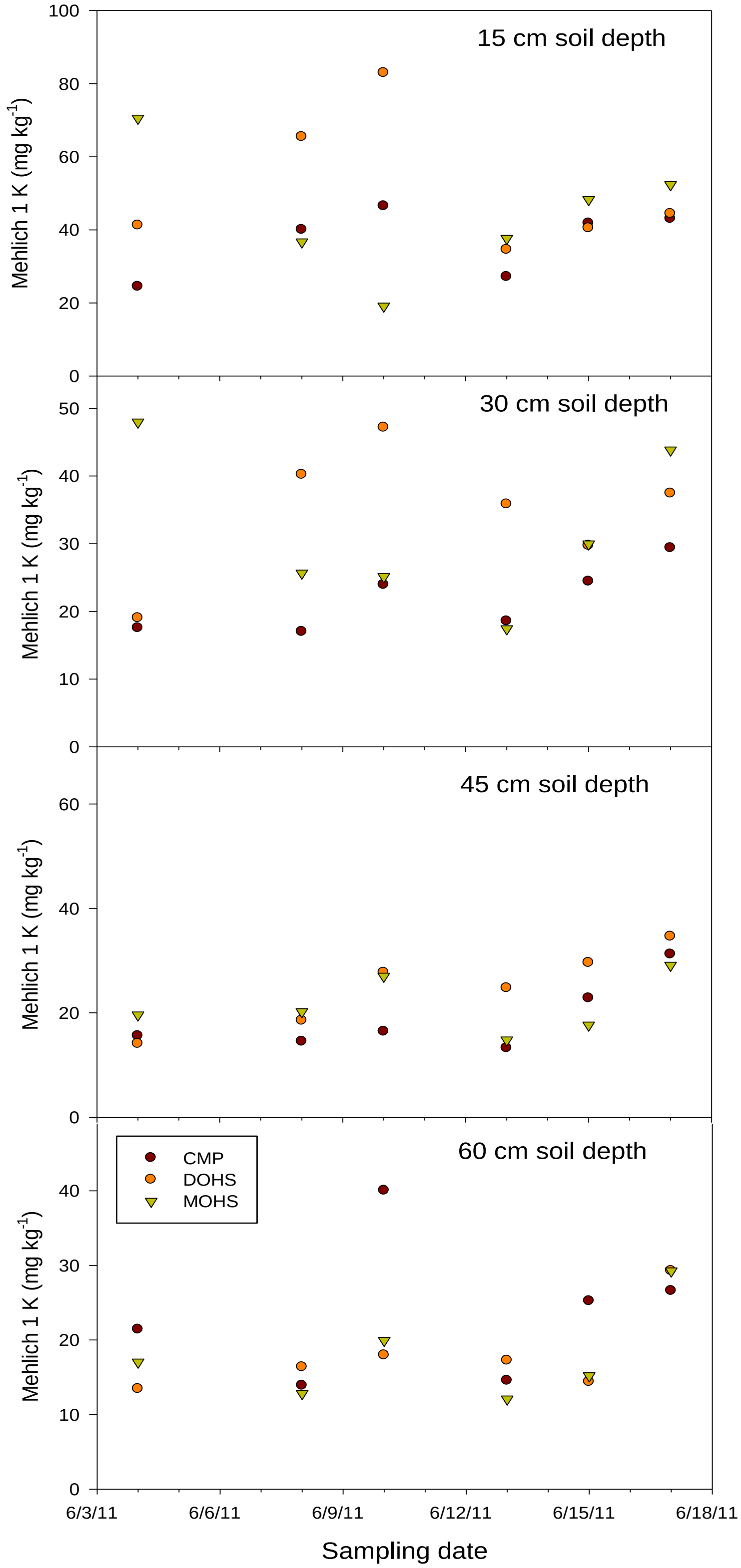


Figure A17. Soil K leaching on Immokalee sand in the irrigated zone

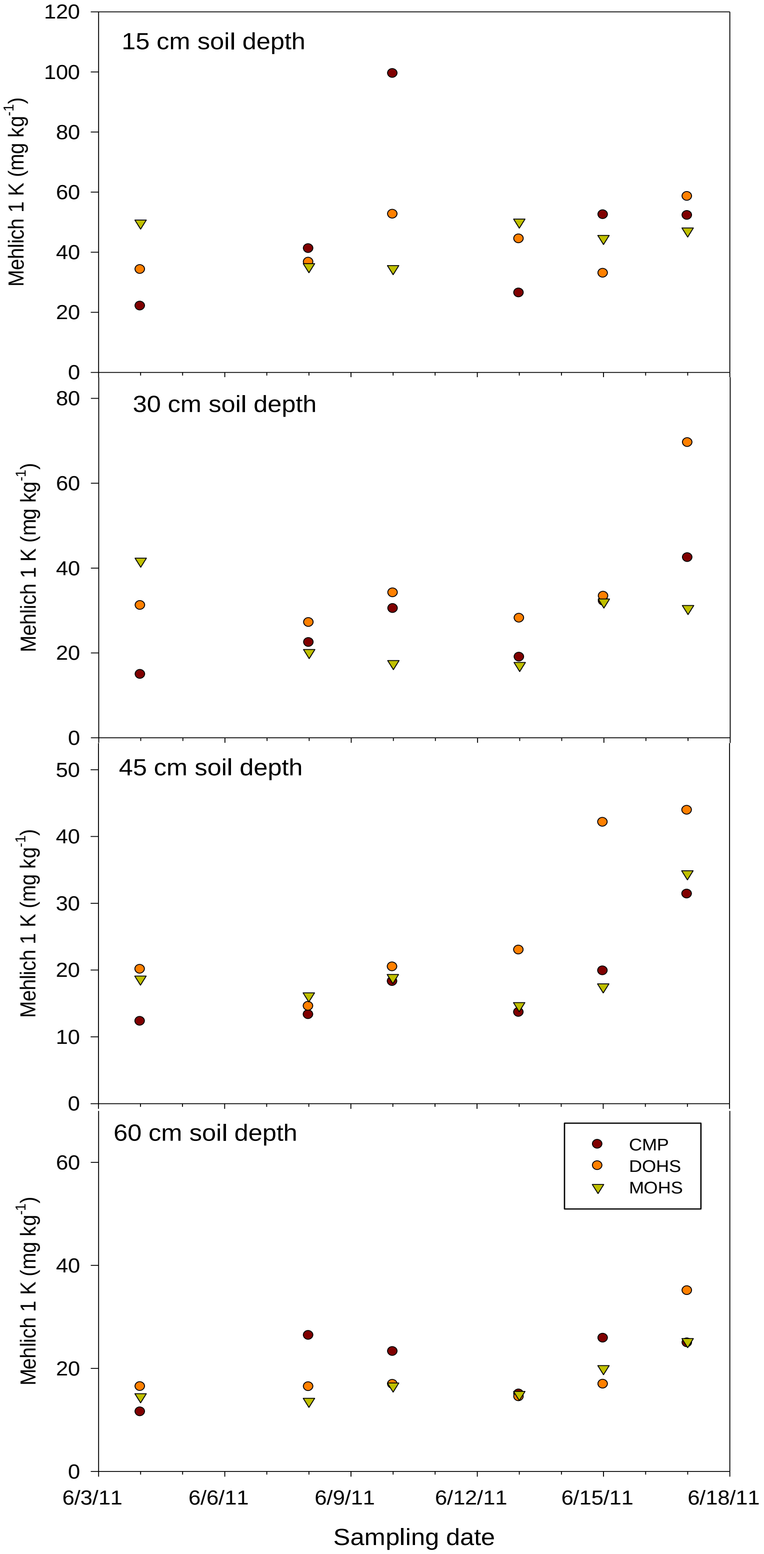


Figure A18. Soil K leaching on Immokalee sand in the nonirrigated zone

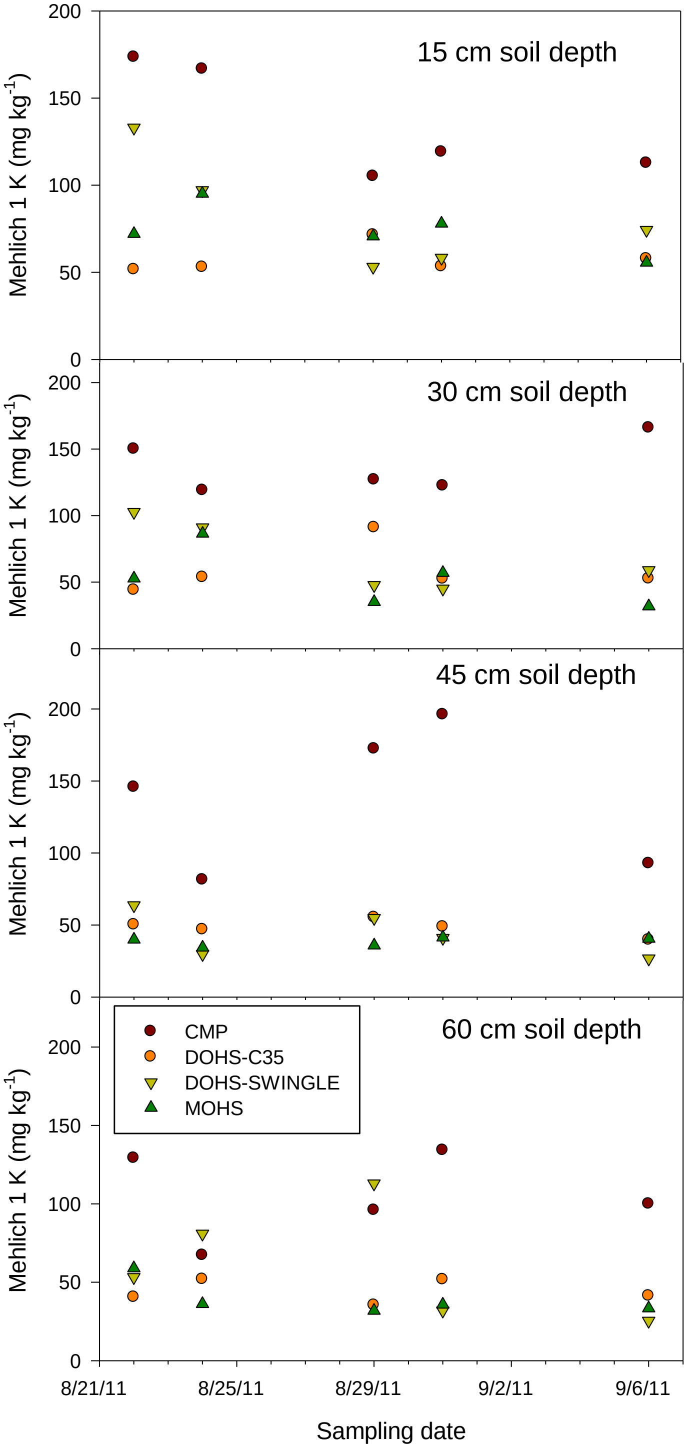


Figure A19. Soil K leaching on Candler sand in the irrigated zone

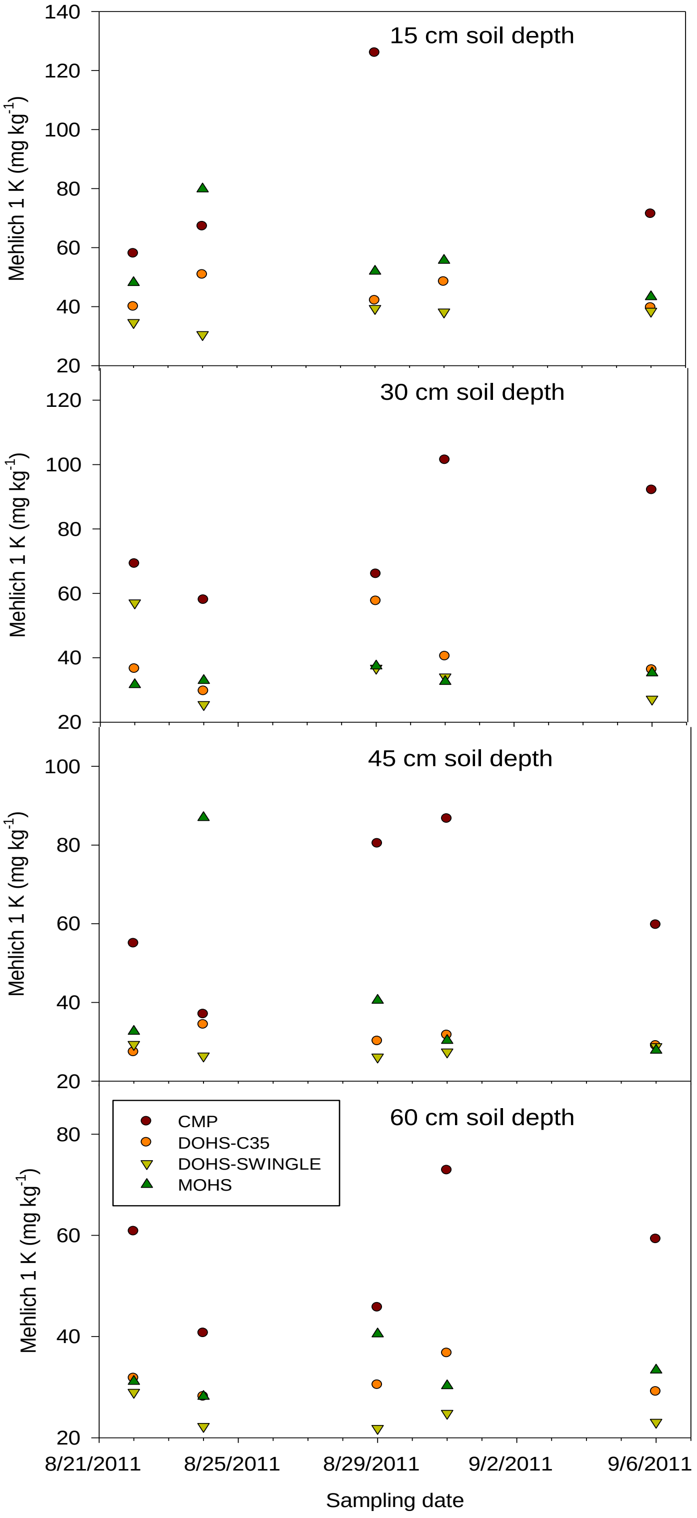


Figure A20. Soil K leaching on Candler sand in the nonirrigated zone

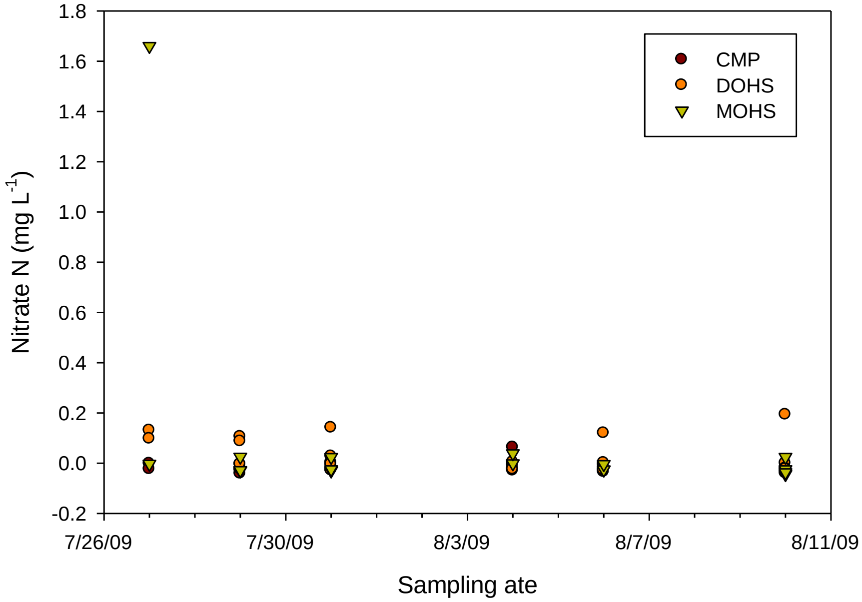


Figure A21. Nitrate N leaching using water samples on Immokalee site in the irrigated zone

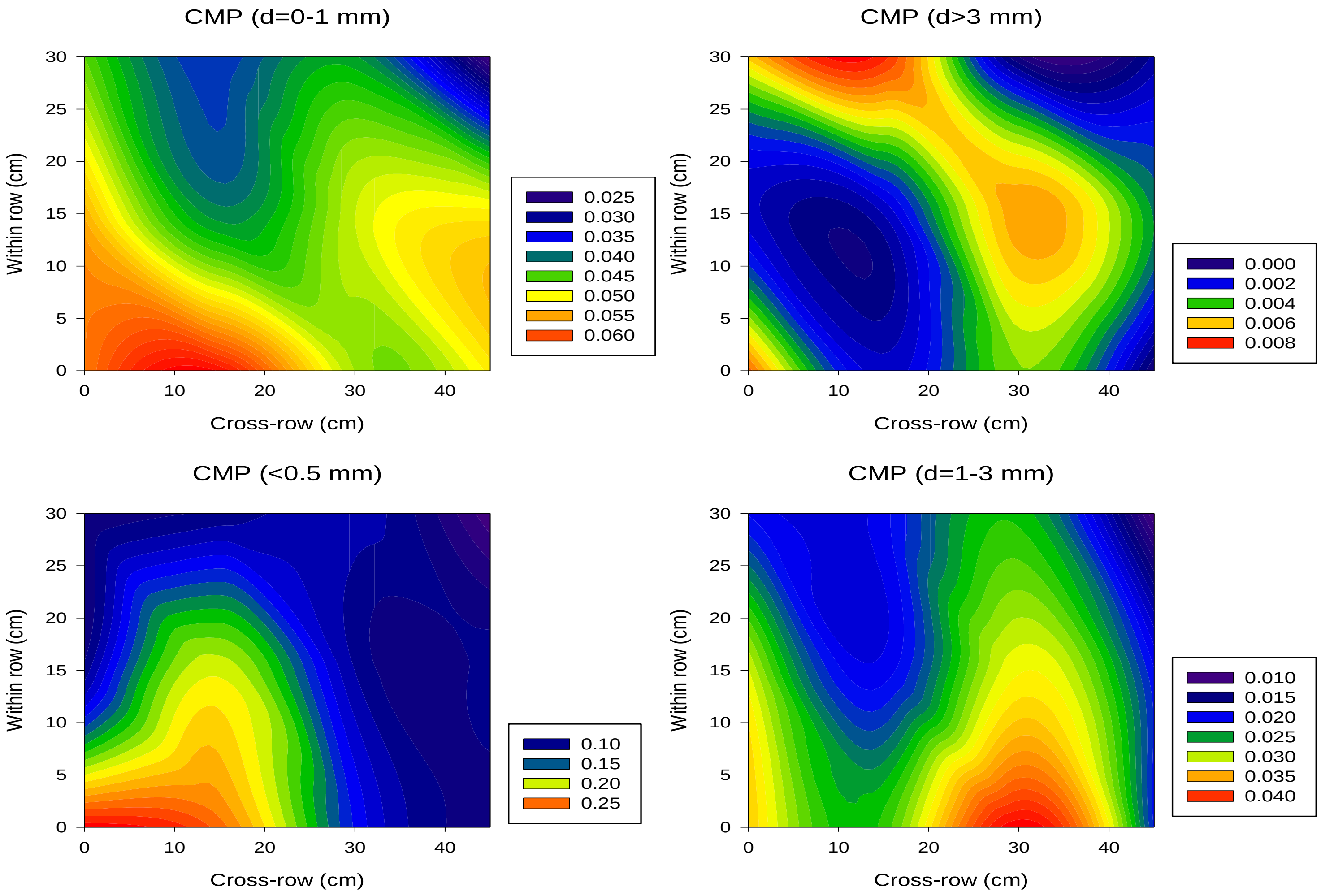


Figure A22. Lateral RLD distribution at the Immokalee site in June 2009 using CMP in the 0-30 cm soil depth layer. All color scales are in cm cm^{-3}

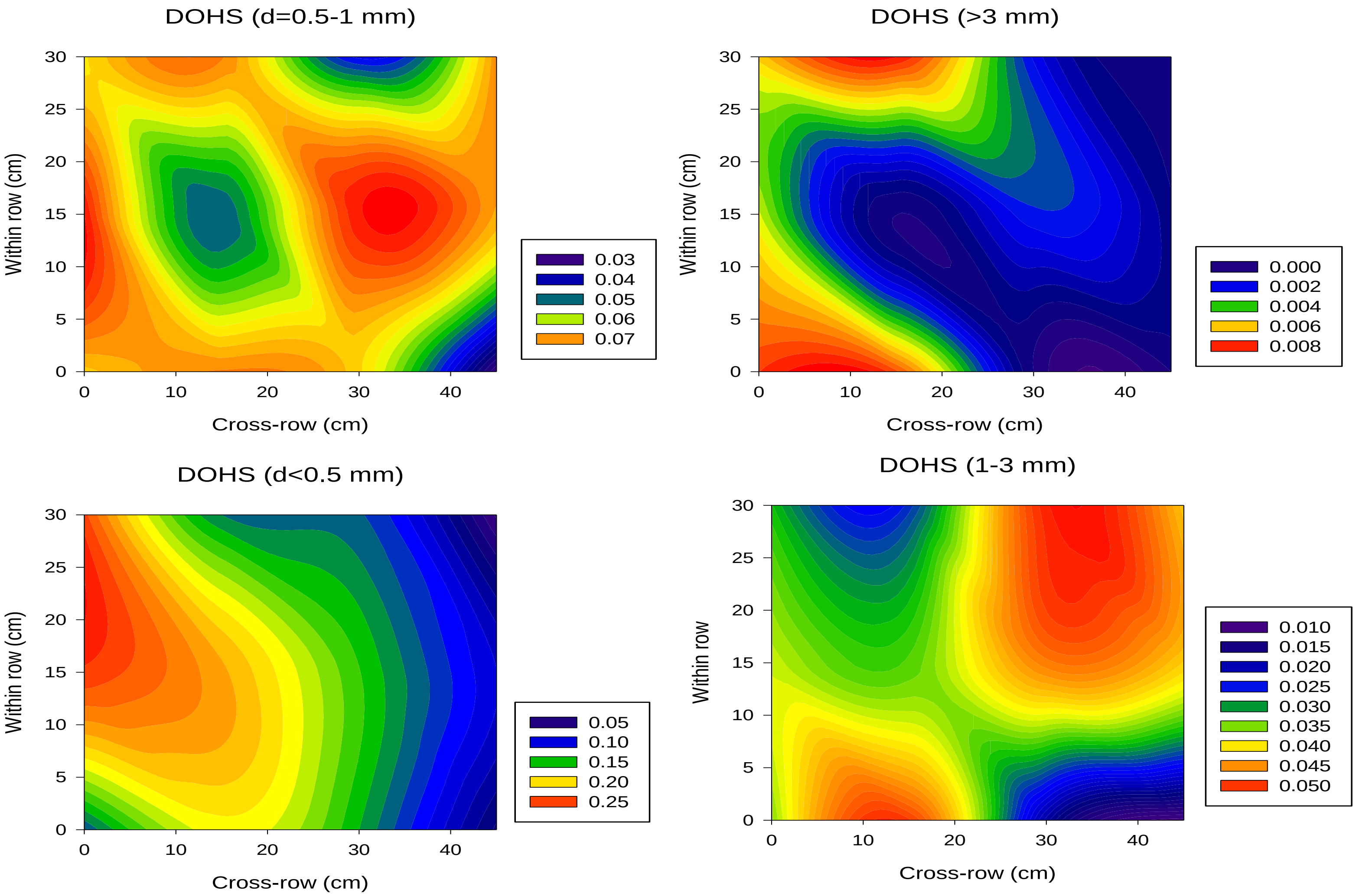


Figure A23. Lateral RLD distribution at the Immokalee site in June 2009 using DOHS in the 0-30 cm soil depth layer. All color scales are in cm cm^{-3}

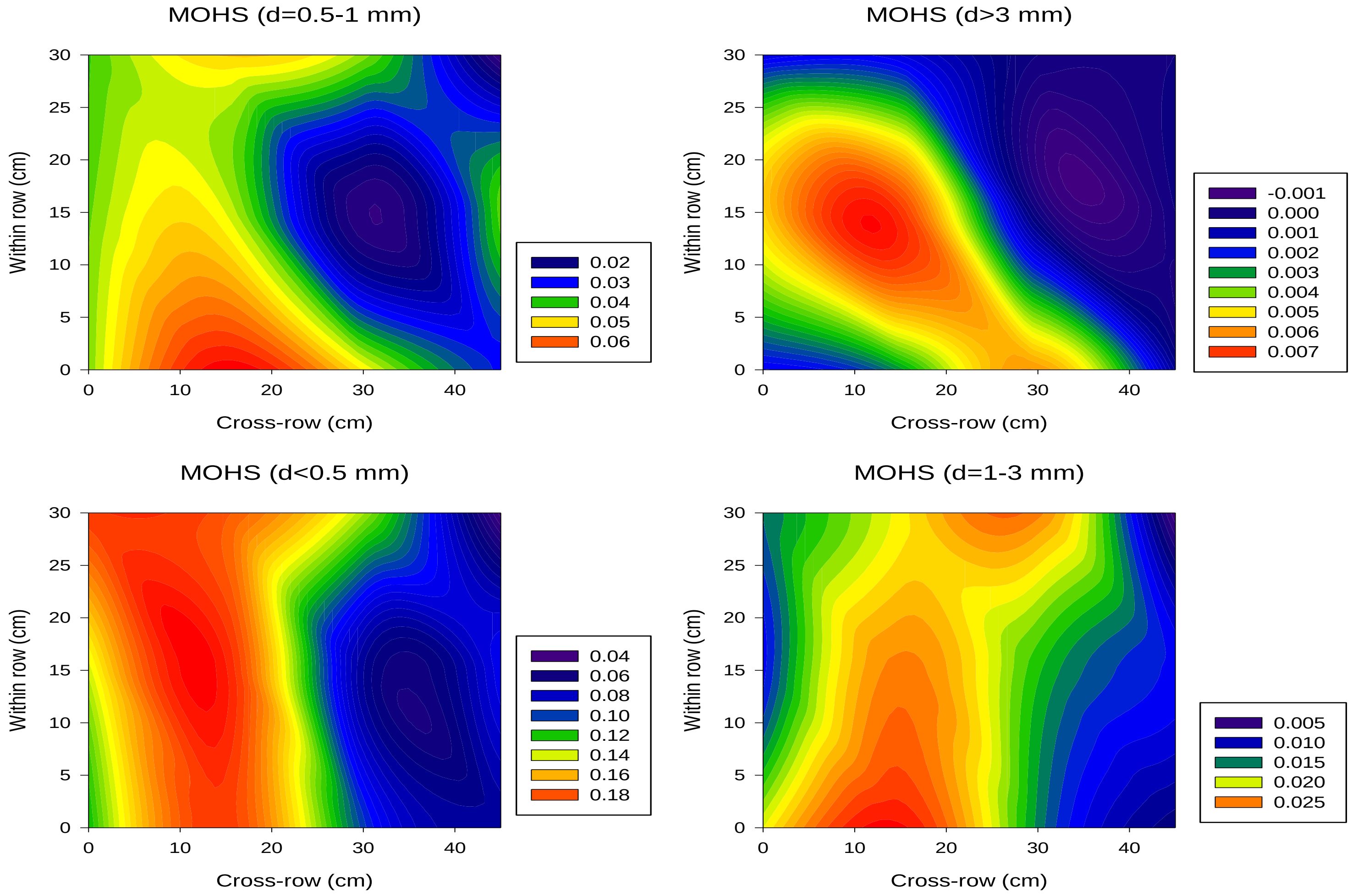


Figure A24. Lateral RLD distribution at the Immokalee site in June 2009 using MOHS in the 0-30 cm soil depth layer. All color scales are in cm cm^{-3}

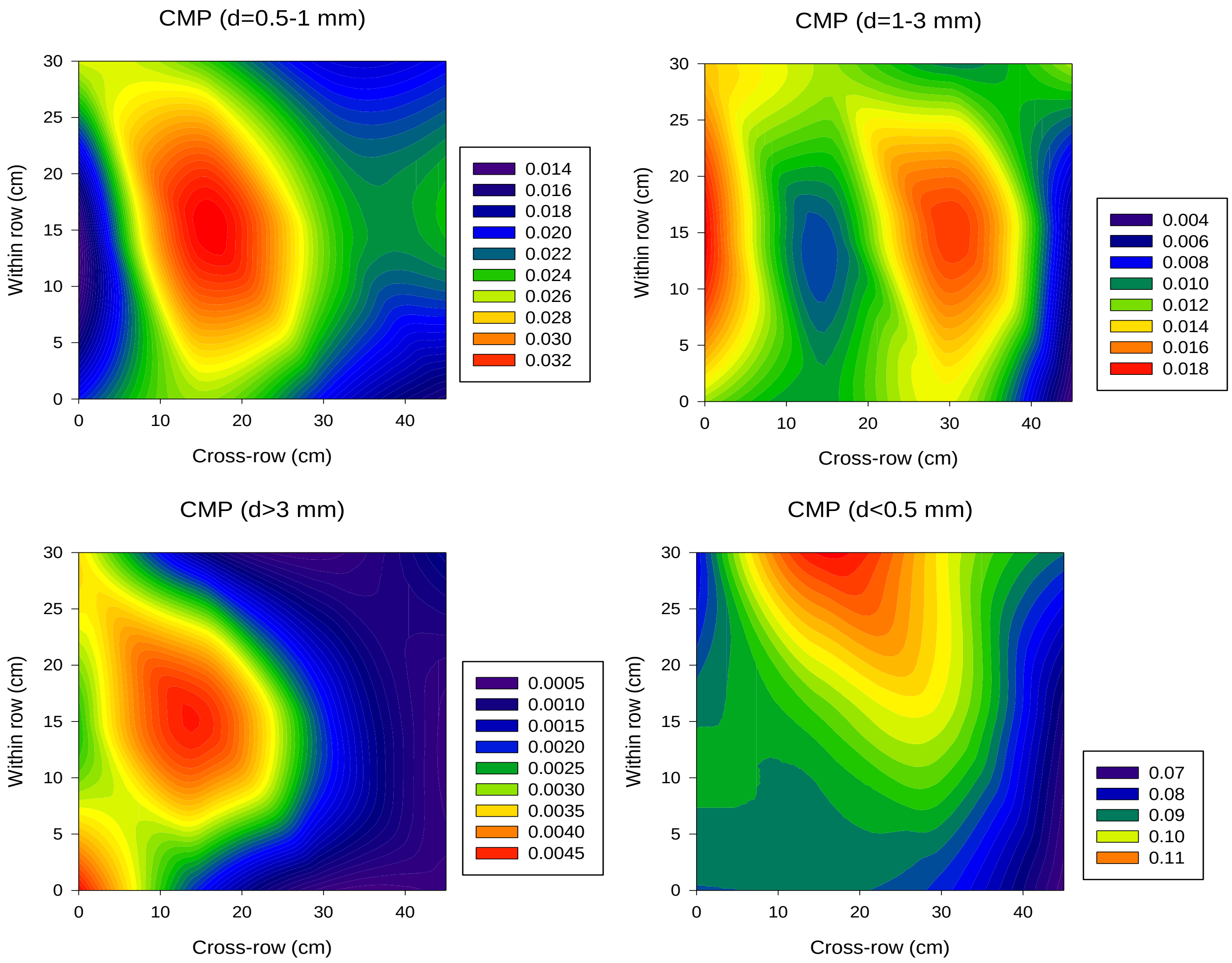


Figure A25. Lateral RLD distribution at the Immokalee site in June 2010 using CMP in the 0-45 cm soil depth layer. All color scales are in cm cm^{-3}

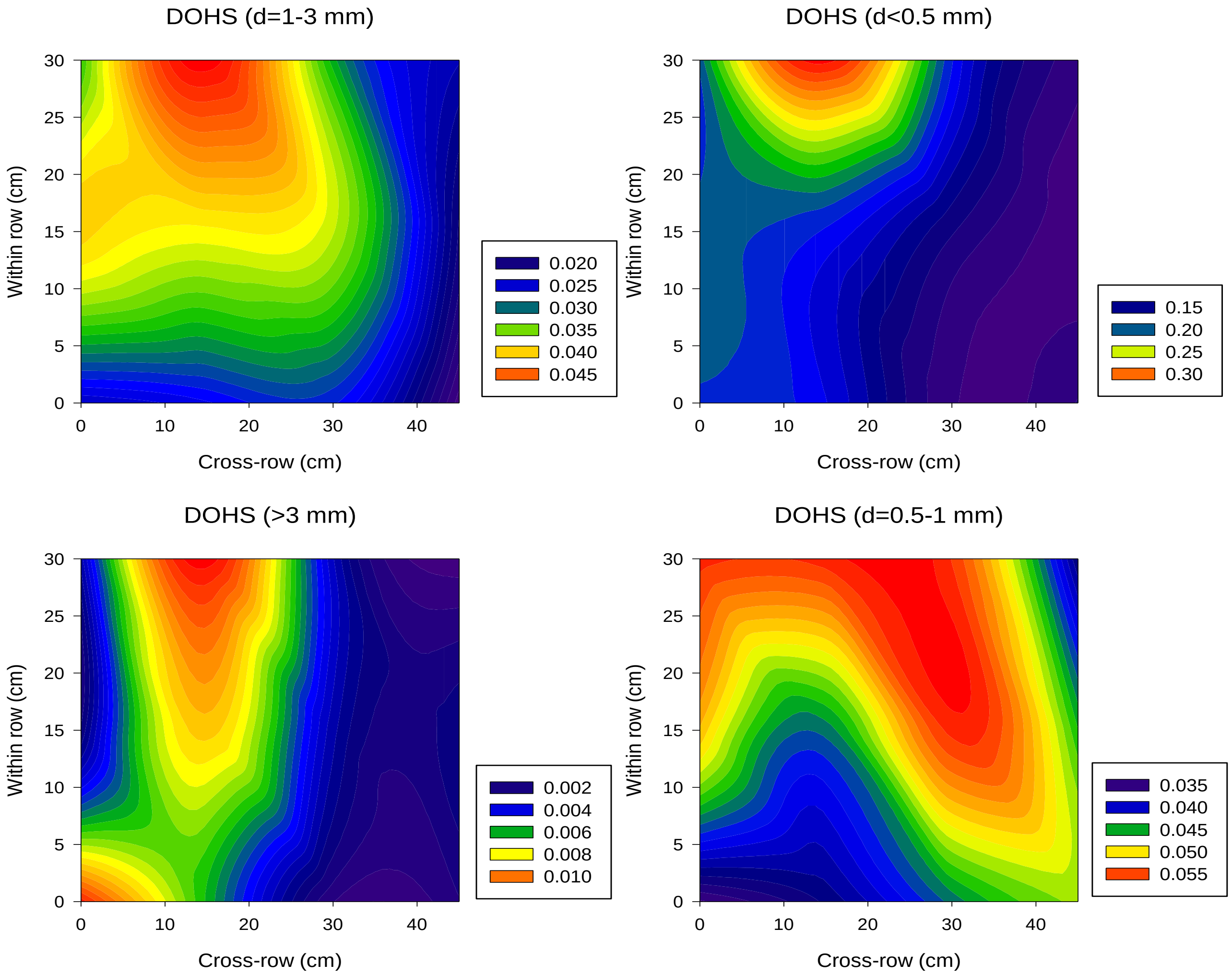


Figure A26. Lateral RLD distribution at the Immokalee site in June 2010 using DOHS in the 0-45 cm soil depth layer. All color scales are in cm cm^{-3}

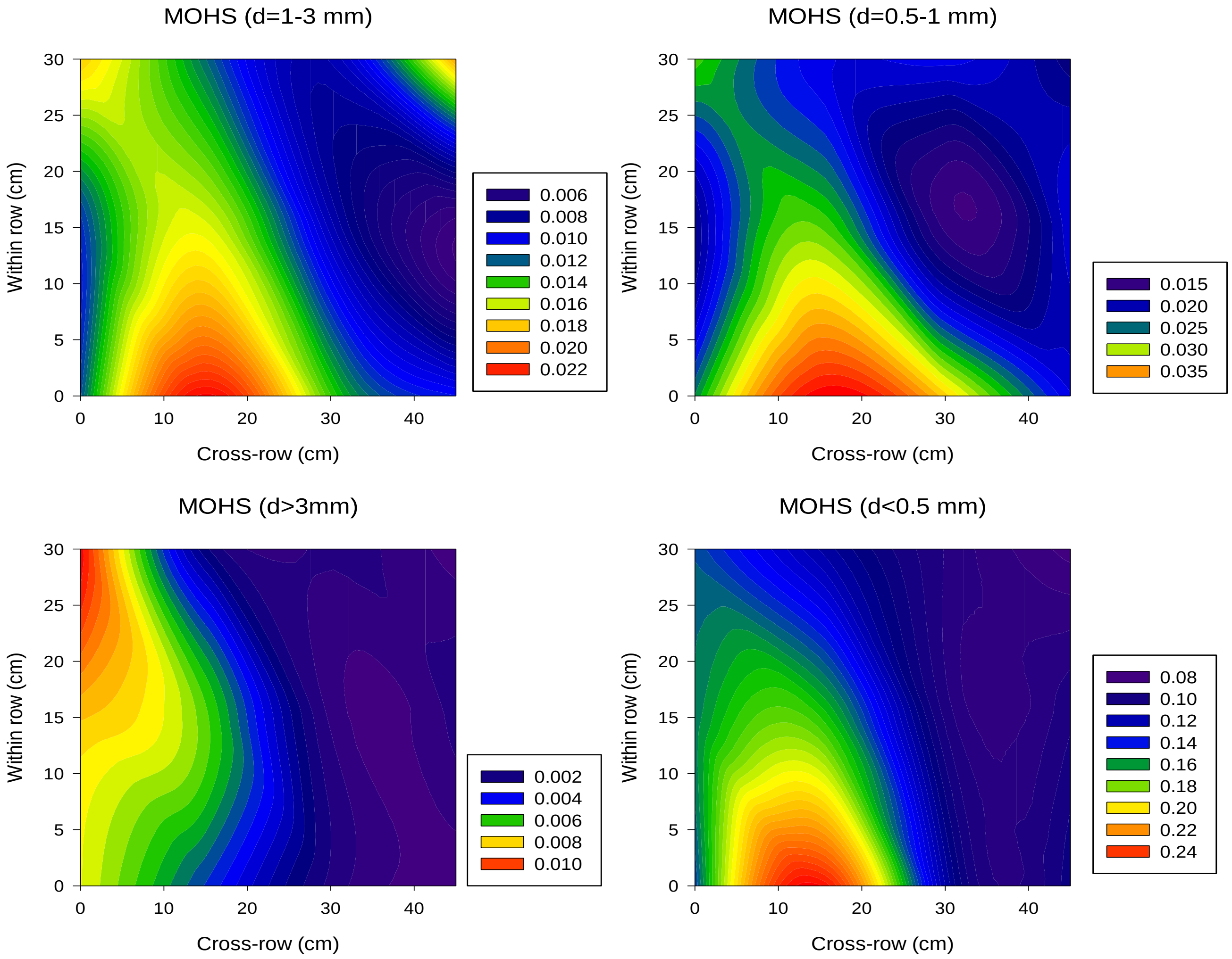


Figure A27. Lateral RLD distribution at the Immokalee site in June 2010 using MOHS in the 0-45 cm soil depth layer. All color scales are in cm cm^{-3}

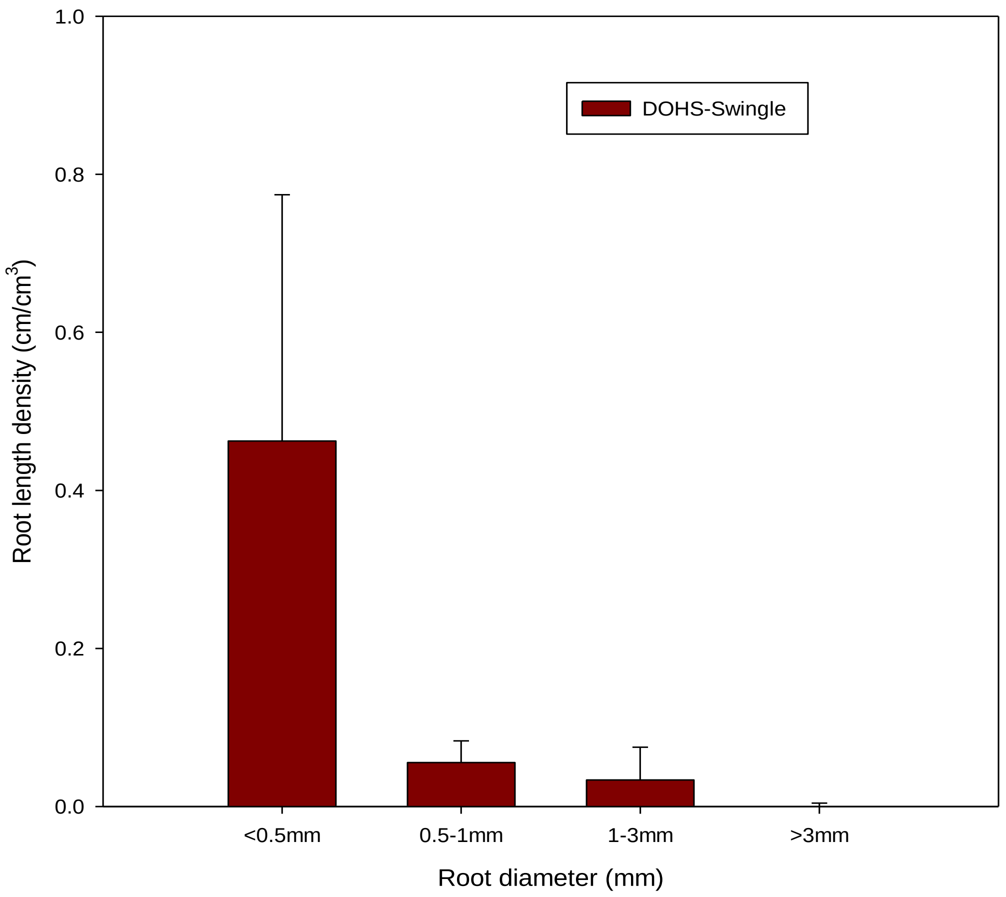


Figure A28. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in December 2009 using DOHS-Swingle. Error bars denote one standard deviation

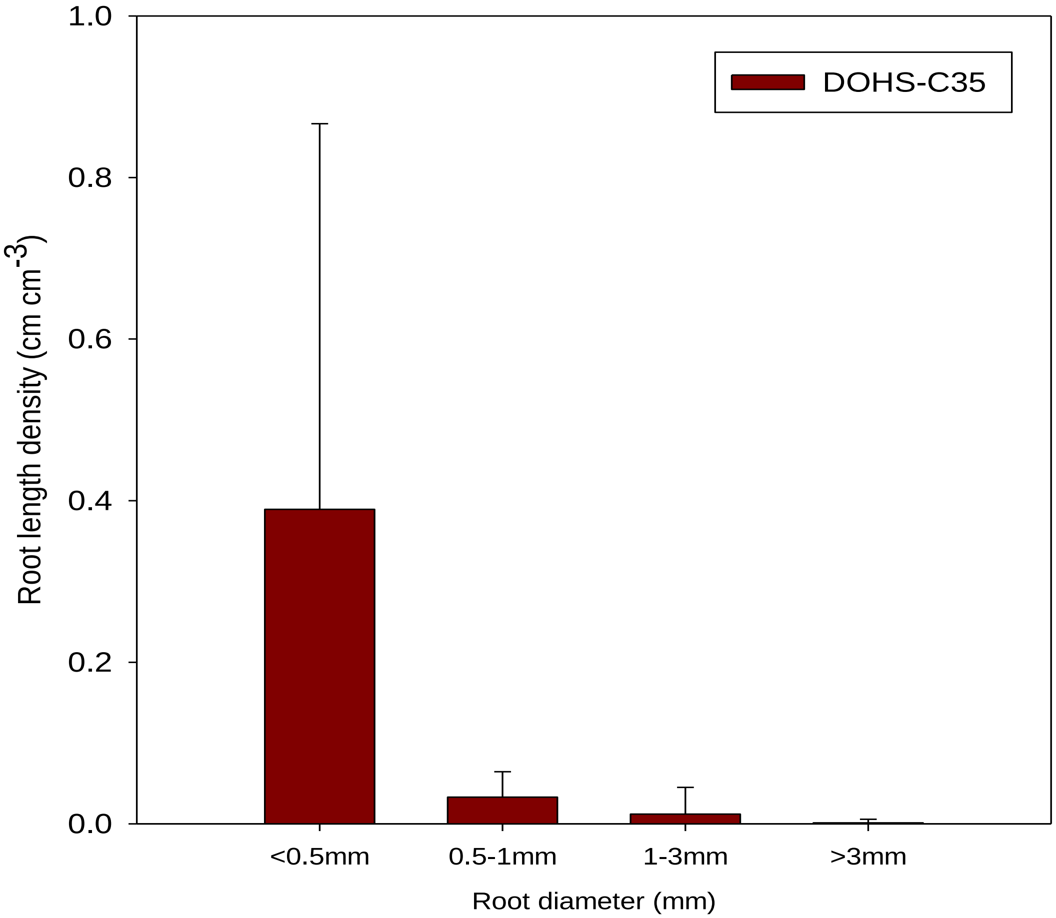


Figure A29. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in December 2009 using DOHS-C35. Error bars denote one standard deviation

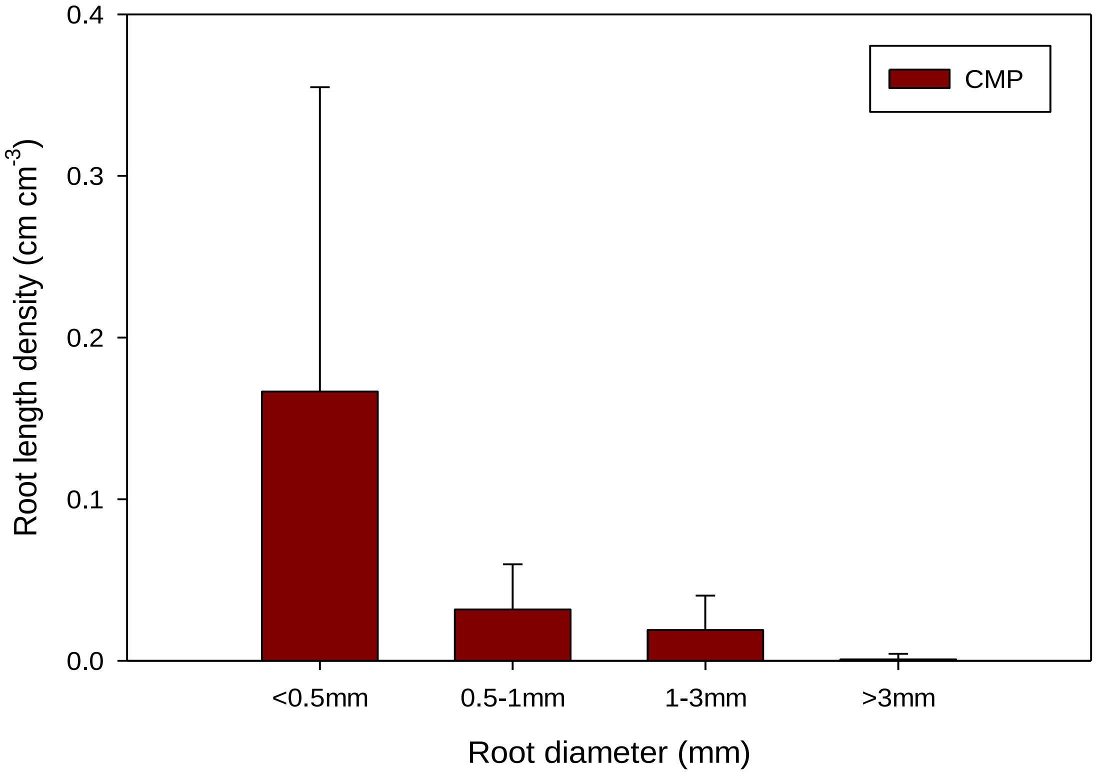


Figure A30. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in December 2009 using CMP. Error bars denote one standard deviation

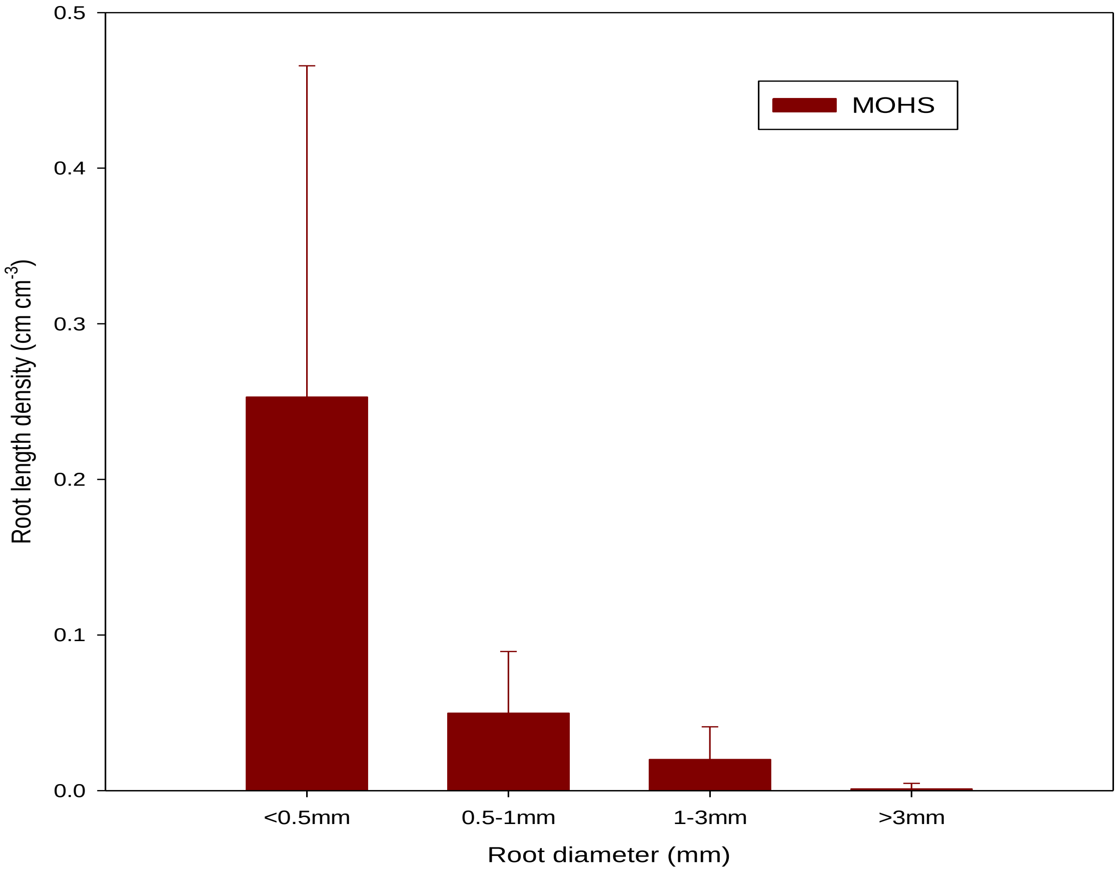


Figure A31. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in December 2009 using MOHS. Error bars denote one standard deviation

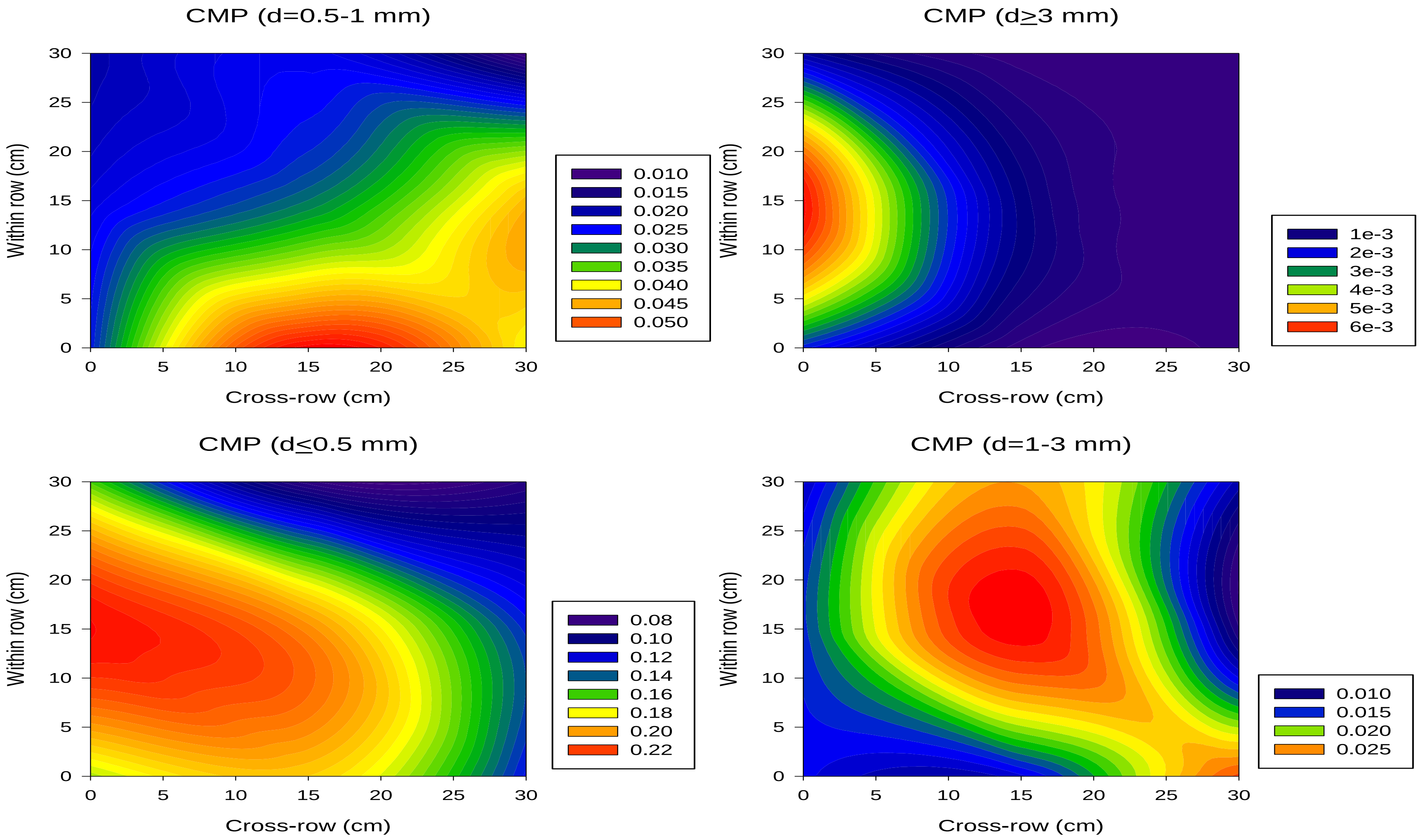


Figure A32. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in July 2010 using CMP. The color scale is in cm cm^{-3}

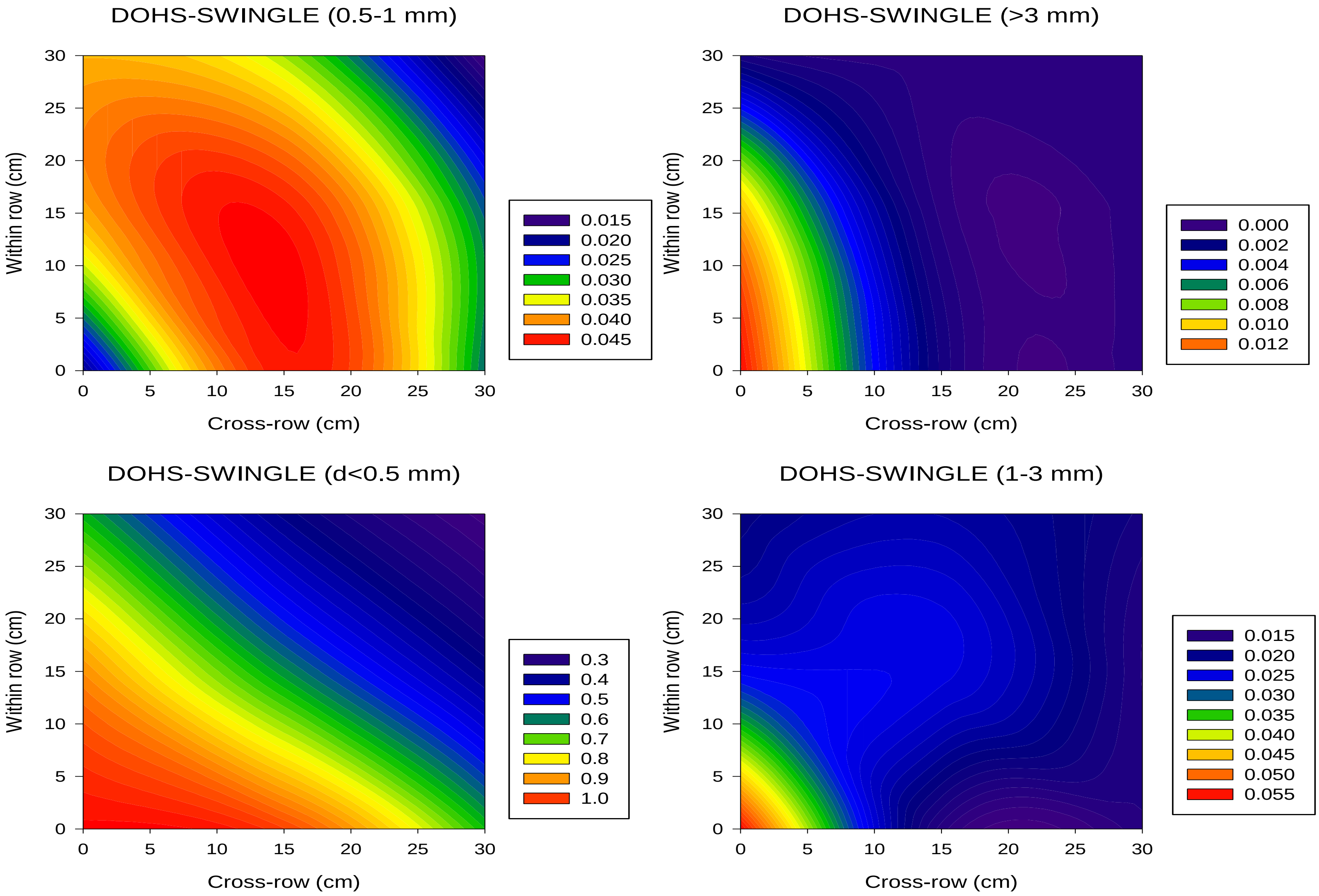


Figure A33. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in July 2010 using DOHS-Swingle. The color scale is in cm cm^{-3}

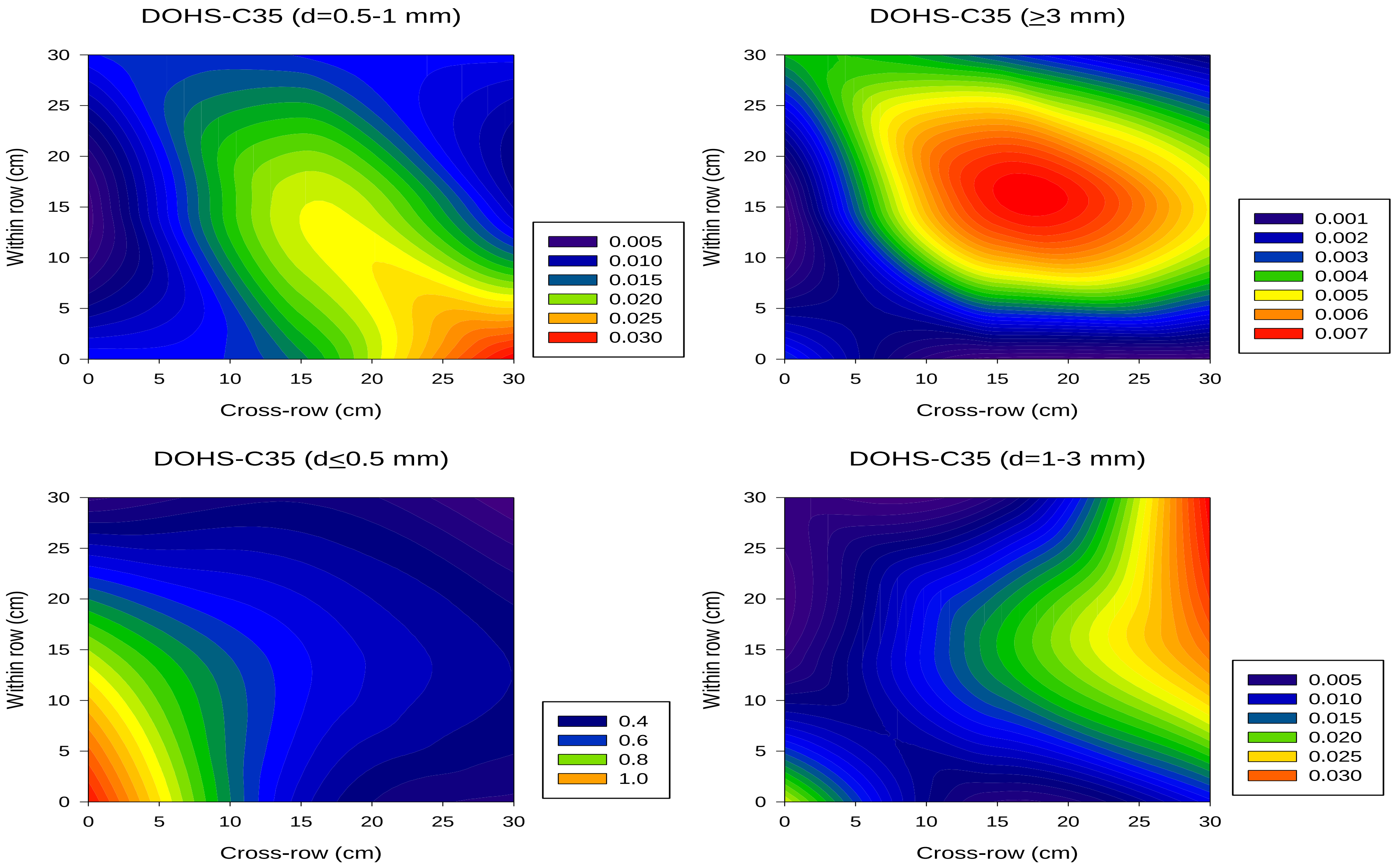


Figure A34. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in July 2010 using DOHS-C35. The color scale is in cm cm^{-3}

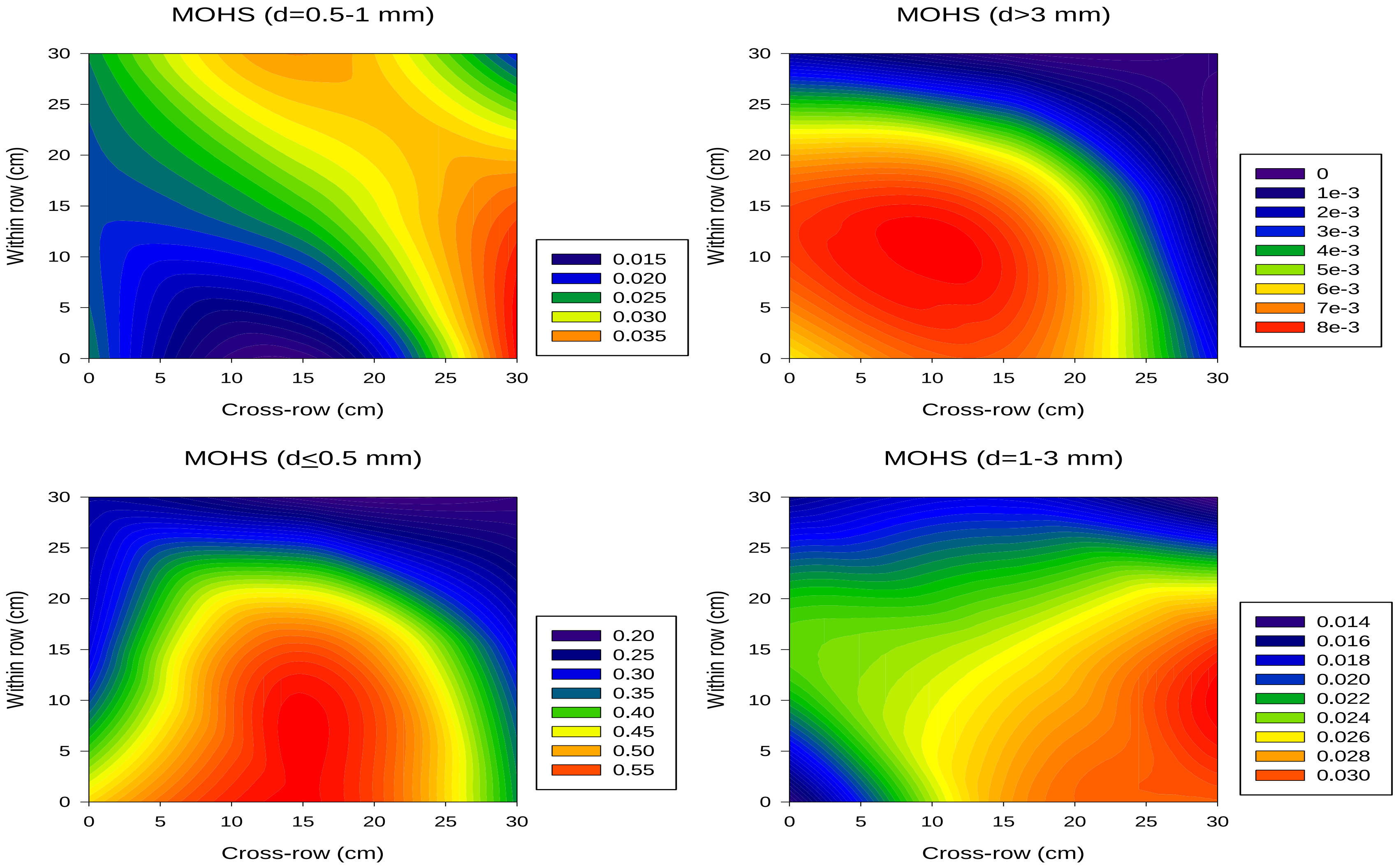


Figure A35. Lateral RLD distribution as a function of irrigation method at the Lake Alfred site in July 2010 using MOHS. The color scale is in cm cm^{-3}

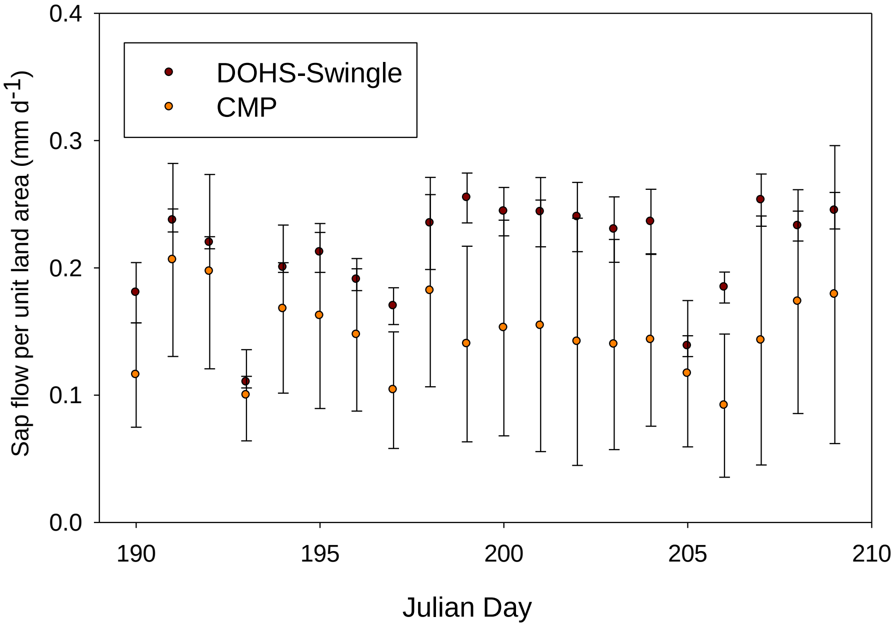


Figure A36. Average sap flow per unit land area at Lake Alfred site in July 2010. Error bars denote one standard deviation

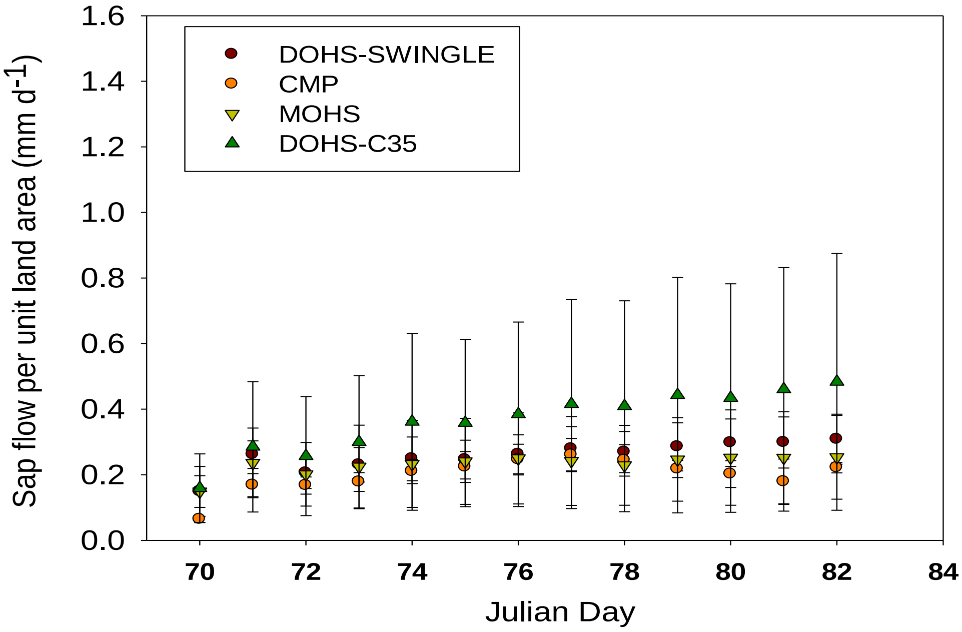


Figure A37. Average sap flow per unit land area at Lake Alfred site in March 2011. Error bars denote one standard deviation

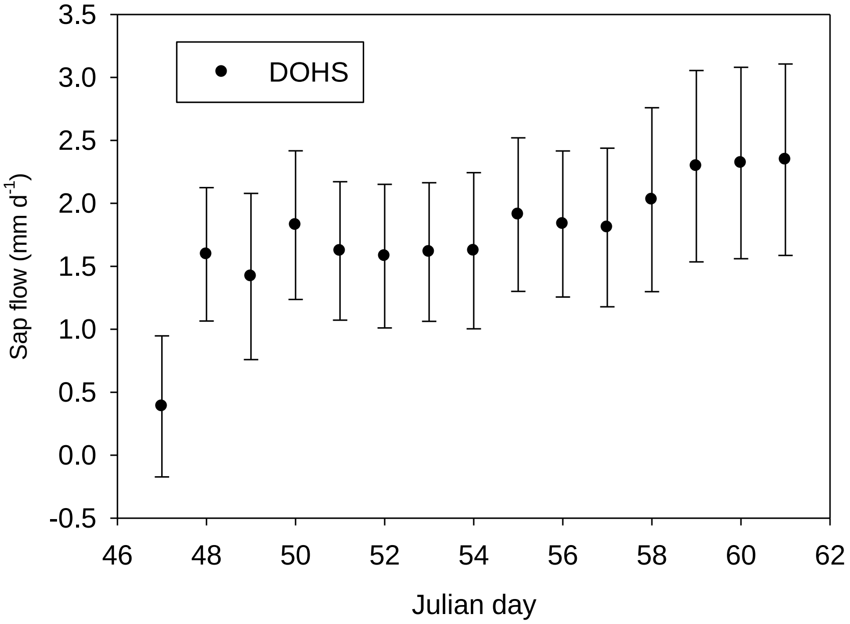


Figure A38. Average sap flow per unit land area at Immokalee in March 2011. Error bars denote one standard deviation

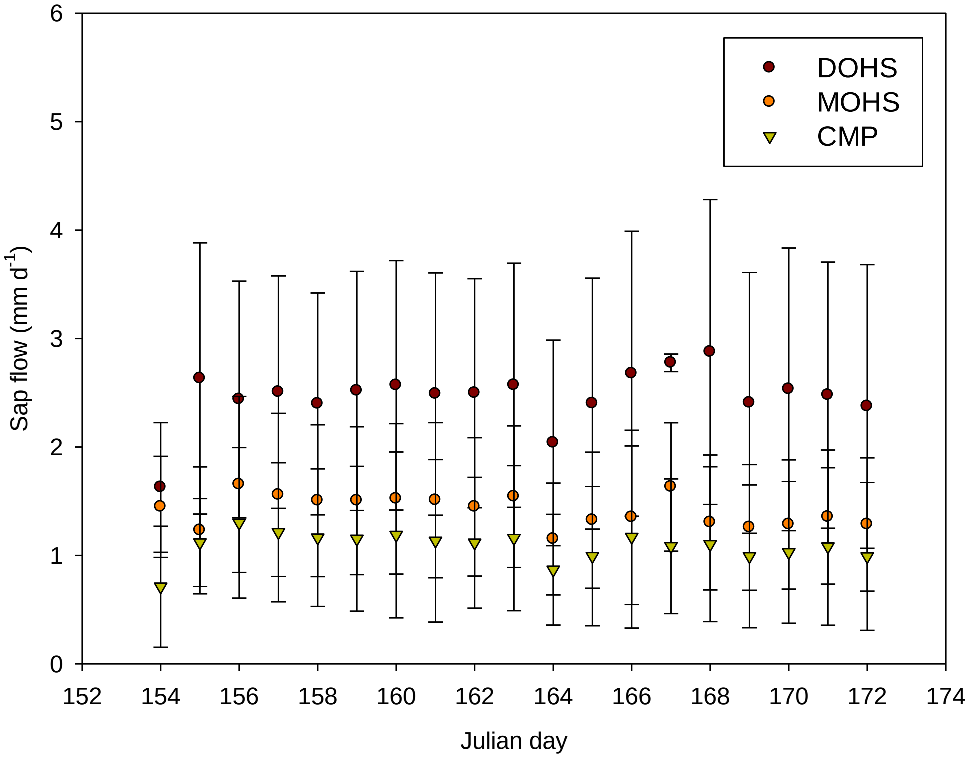


Figure A39. Average sap flow per unit land area at Immokalee in June 2011. Error bars denote one standard deviation

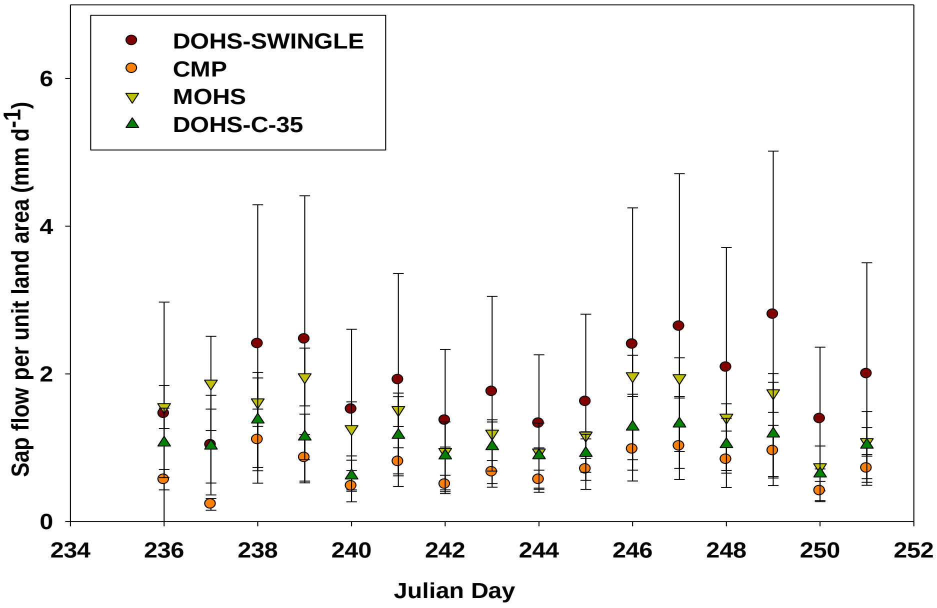


Figure A40. Average sap flow per unit land area at Lake Alfred site in August-September 2011. Error bars denote one standard deviation

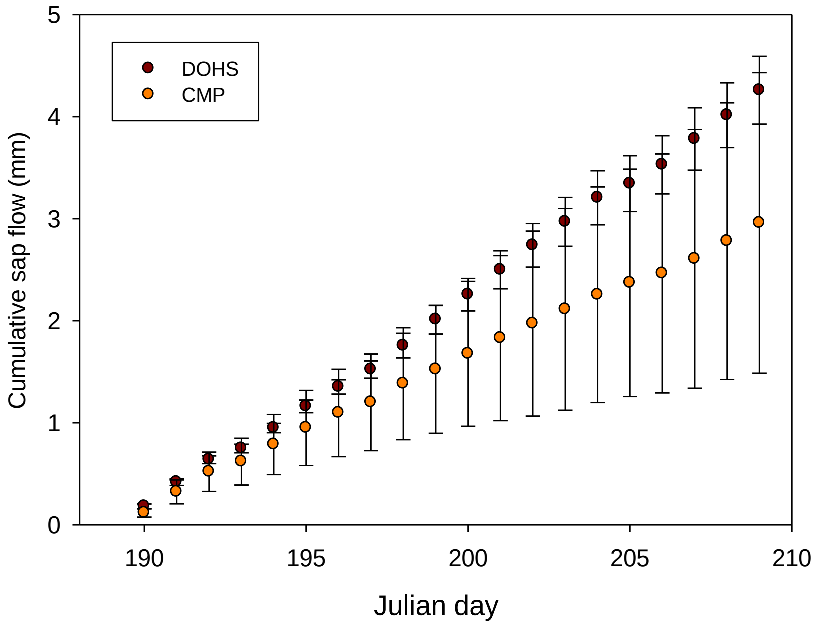


Figure A41. Cumulative sap flow at Lake Alfred site in July 2010. Error bars denote one standard deviation

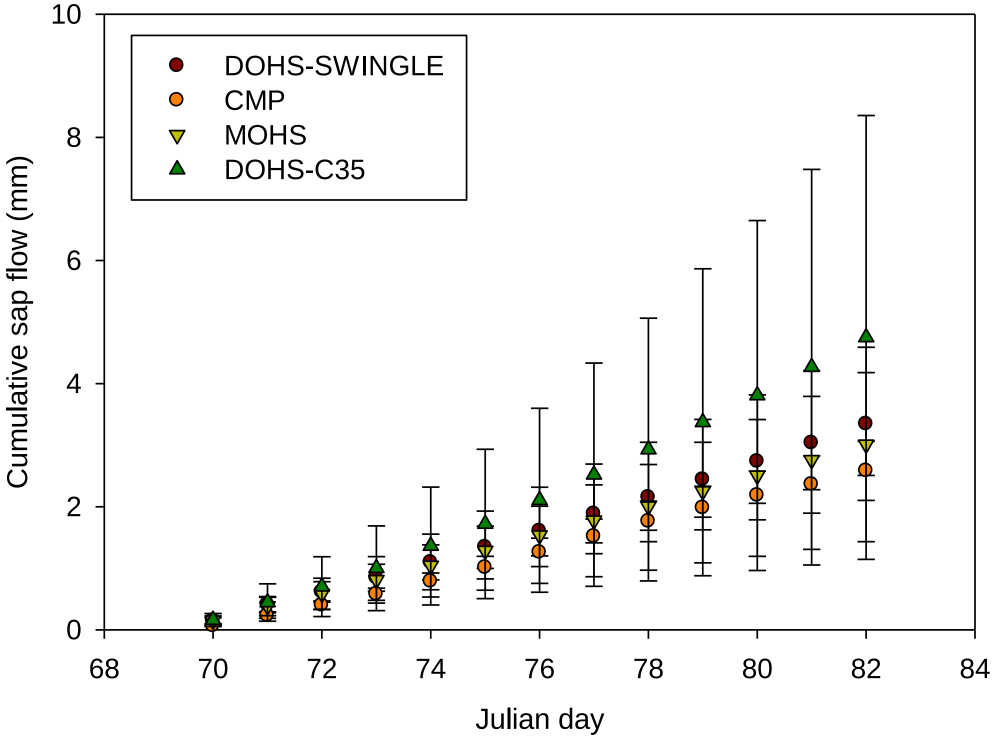


Figure A42. Cumulative sap flow at Lake Alfred site in March 2011. Error bars denote one standard deviation

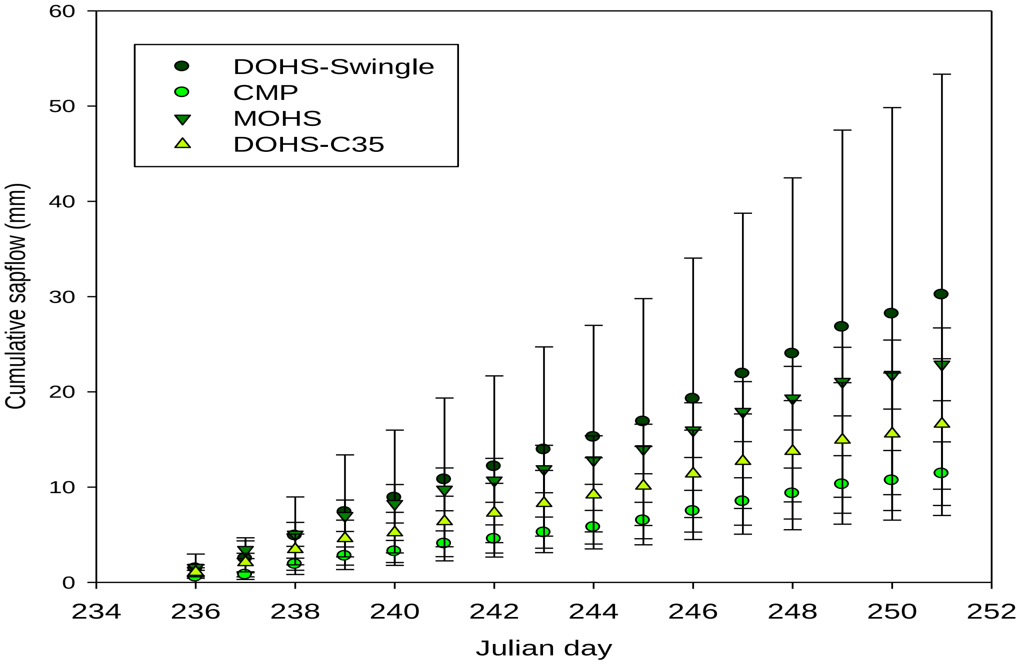


Figure A43. Cumulative sap flow at Lake Alfred site in August-September 2011. Error bars denote one standard deviation

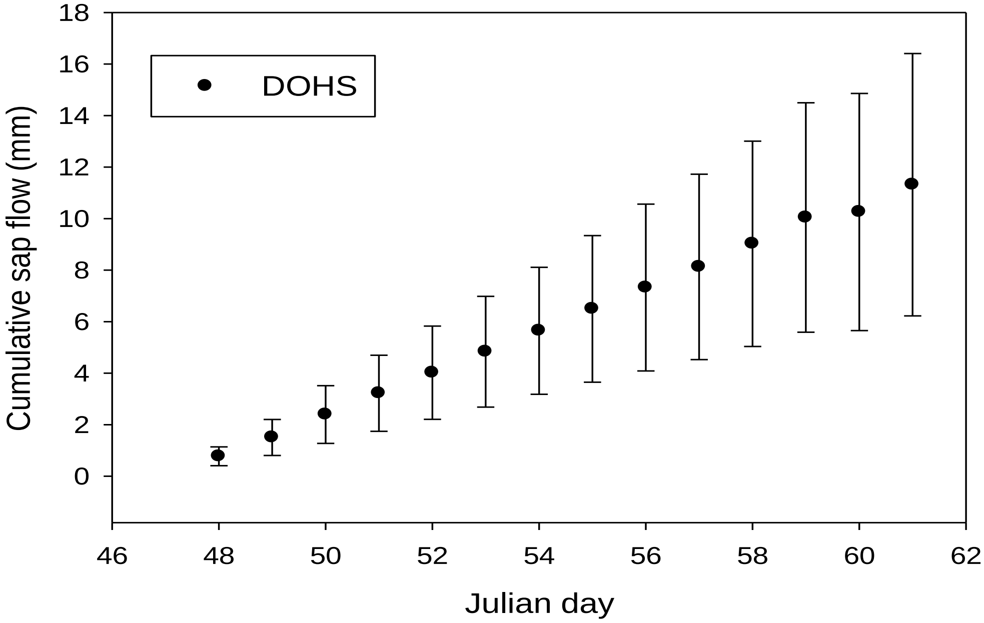


Figure A44. Cumulative sap flow at Immokalee site in February-March 2011. Error bars denote one standard deviation

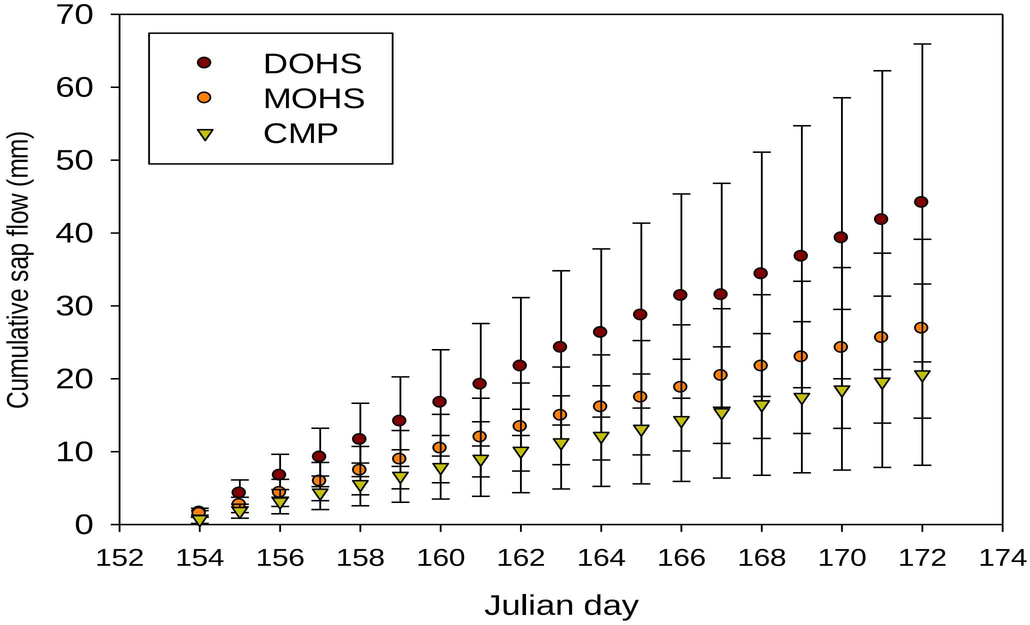


Figure A45. Cumulative sap flow at Immokalee site in June 2011. Error bars denote one standard deviation

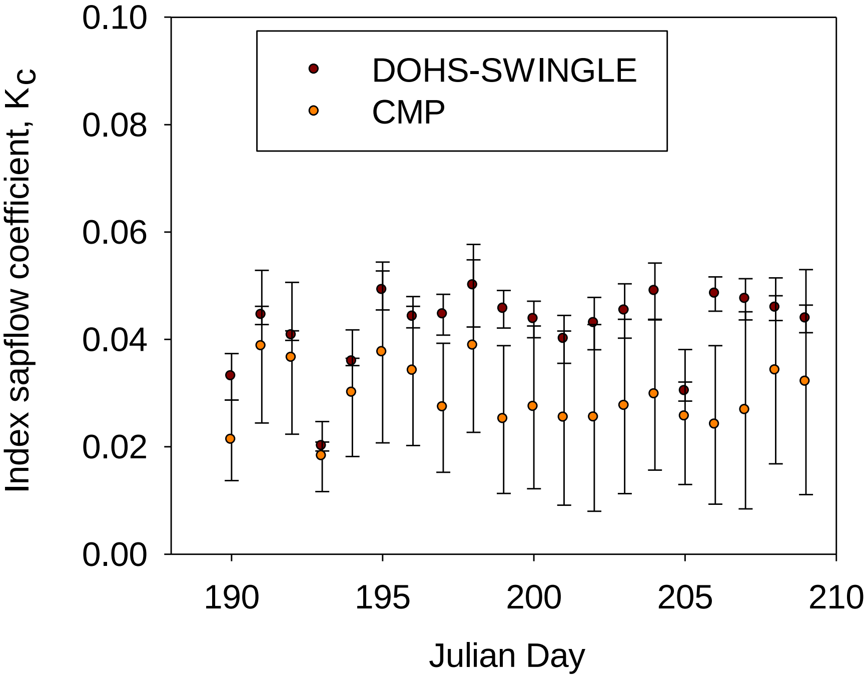


Figure A46. Average index sap flow K_c at the Lake Alfred site in July 2010. Error bars denote one standard deviation

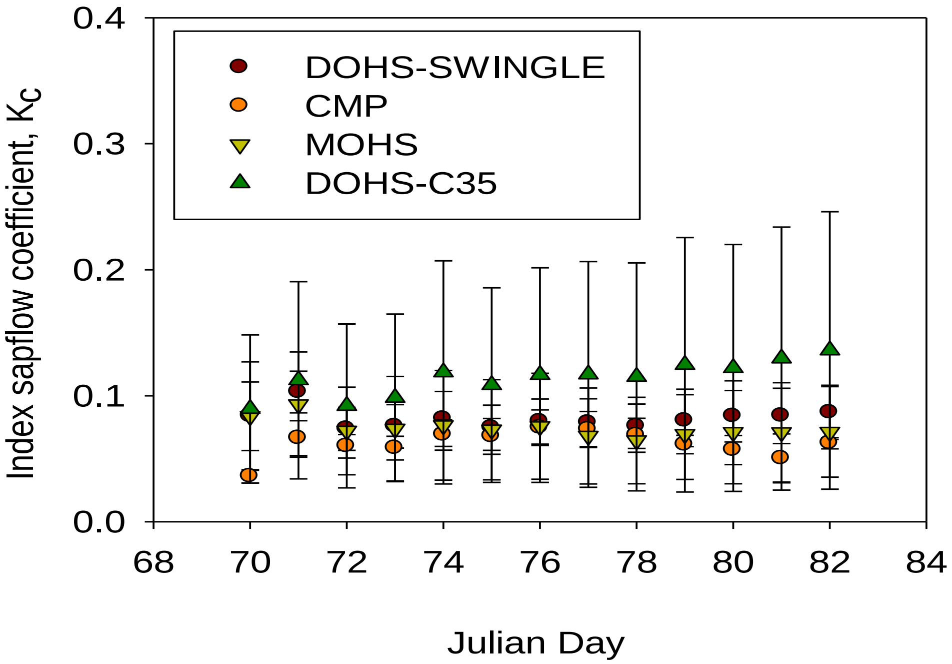


Figure A47. Average index sap flow K_c at the Lake Alfred site in March 2011. Error bars denote one standard deviation

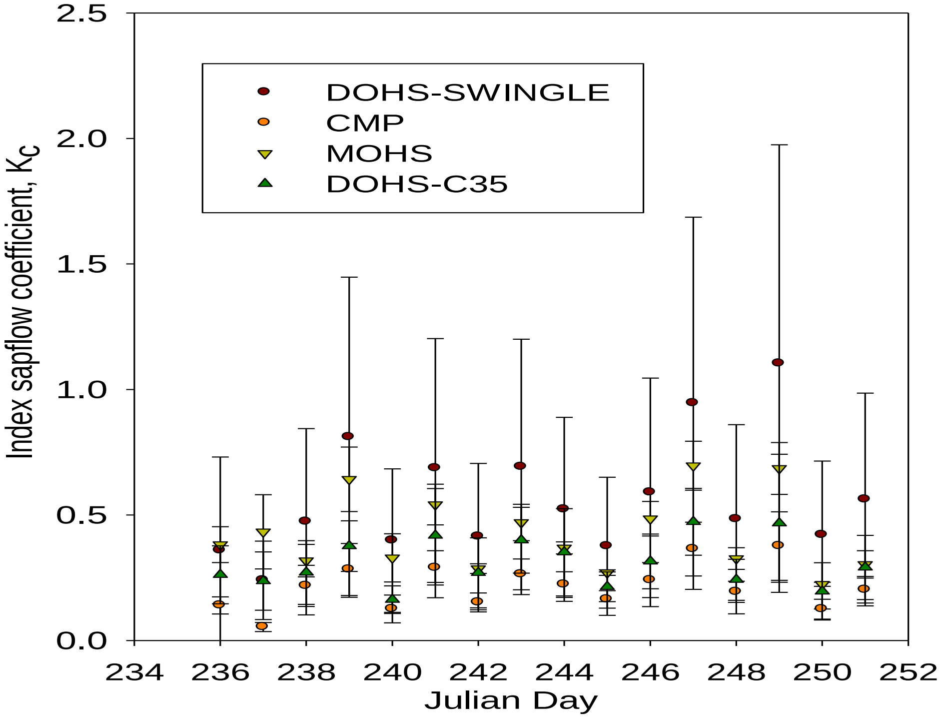


Figure A48. Average index sap flow K_c at the Lake Alfred site in August-September 2011. Error bars denote one standard deviation

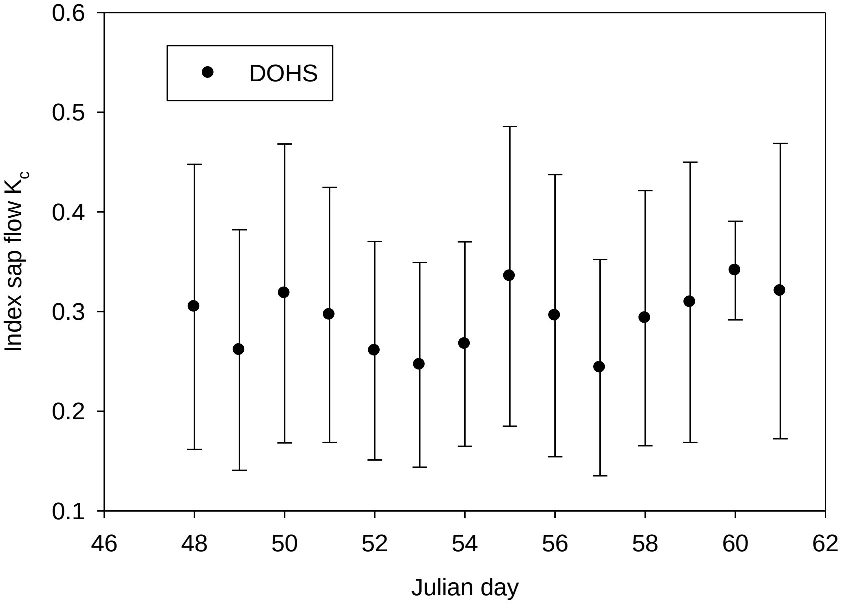


Figure A49. Average index sap flow K_c at the Immokalee site in February-March 2011. Error bars denote one standard deviation

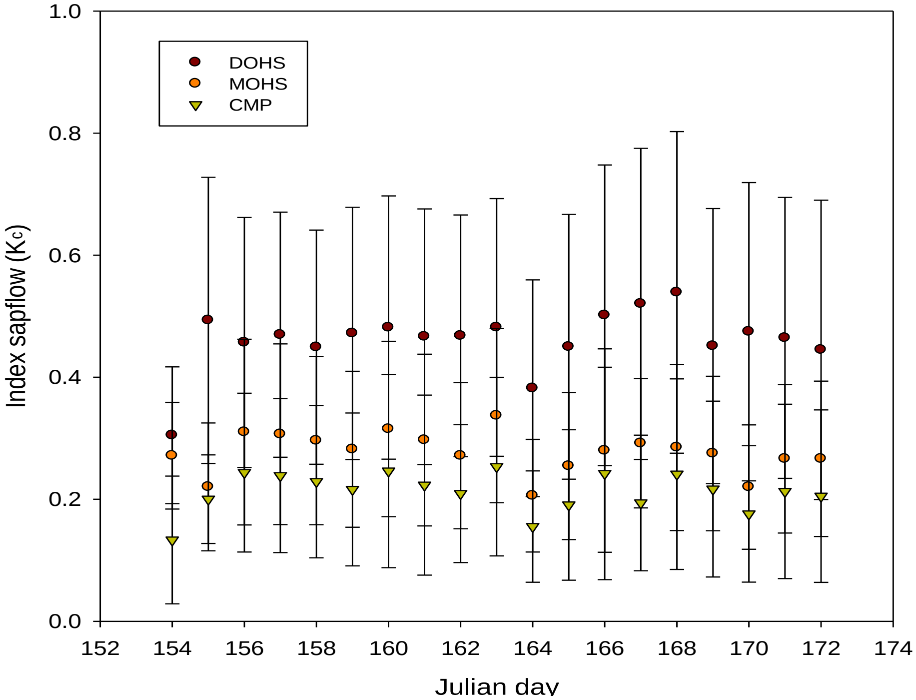


Figure A50. Average index sap flow K_c at the Immokalee site in June 2011. Error bars denote one standard deviation

APPENDIX B
CHARACTERIZATION OF SORPTION ISOTHERMS FOR AMMONIUM-N, K AND P ON THE FLATWOODS AND RIDGE SOILS

The chemical characteristics of soils dominating the Flatwoods and Ridge regions of Florida are well described in Obreza and Collins (2008) and some were also determined in this study. The Immokalee and Candler fine sand are moderately acidic (pH ranging from 4.9 to 5.6), have low organic matter content (ranging from 0.41 to 0.61% on Immokalee fine sand and from 1.56 to 1.96% on Candler fine sand) and low cation exchange capacity (CEC) (ranging from 2 to 6 cmol (+) kg^{-1}), have inorganic N in the range of 8.20 and 11.24 mg kg^{-1}, moderate to very high P (in the range of 28.73-46.45 mg kg^{-1} for Immokalee sand and 112.79-115.82 mg kg^{-1} for Candler fine sand) and K in the range of 11.83-15.23 mg kg^{-1} for Immokalee fine sand and 23.03-29.70 mg kg^{-1} for Candler fine sand (Table B1). The study speculates that the properties such as organic matter content and CEC are behind the adsorption processes of the nutrients in this study.

Adsorption is the mechanism most commonly responsible for the retention of solutes by soils, particularly cations and phosphorus. The sorption process tends to restrict compound's mobility and bioavailability (Essington, 2004). Thus, the procedure for determining the NH_4-N, P and K sorption isotherms could then provide information on their mobility in the soil. The supporting electrolyte concentration is chosen to mimic that of soil solution. Most commonly 0.01 M $CaCl_2$ (Singh and Jones, 1975; Belmont et al., 2009), 0.01 N $CaCl_2$ (Bowman et al., 1981), 0.005 M $CaCl_2$ (Essington, 2004), 5-100 mg K L^{-1} KCl (Sparks et al., 1980), 0.05 M KCl (Harris et al., 1996; Zhou and Li, 2001), and 0.01 M KCl (Nair et al., 1998; Villapando and Graetz, 2001) have been used as electrolytes in studies on P and K sorption. Nair et al. (1984) reported that P sorption varies with ionic strength and cation species of the supporting electrolyte. For example, Nair et al. (1984) showed that P adsorption was generally lower with K^+ as the supporting electrolyte cation compared with Ca^{2+}. These studies and others have not explained the rationale behind use of a particular electrolyte other than equilibrating the solutions in deionized or tap water. This study attempted to 1) determine sorption isotherms for NH_4^+, K and P on the Flatwoods and Ridge soils with the aim of predicting the mobility, availability and uptake of NH_4^+, P and K in citrus production, and 2) determine the effect of supporting electrolyte on P sorption. We hypothesized that P adsorption and NH_4^+ and K^+ exchange on the Flatwoods and Ridge soils do not adversely affect availability and uptake as a result of adsorption to soil colloids.

Results and Discussion

The results of adsorption of K^+, NH_4^+-N, and P are presented and described in Fig. B1 through B3, Tables B2 and B3, and Appendices G through I for Candler and Immokalee fine sand. Ammonium adsorption for Immokalee and Candler fine sand followed a linear isotherm with distribution coefficients (K_D) of 1.12±0.42 and 1.64±0.25 kg L^{-1} and 1.66±0.39 and 1.76±0.39 kg L^{-1} for the 0-15- and 15-30 cm depths, respectively. P adsorption was described by a Freundlich model with linearized K_D ranging from 0.50±0.19 to 0.75±0.13 kg L^{-1} for Immokalee fine sand and from 1.73±0.15 to 4.43±0.50 kg L^{-1} for Candler fine sand using a C_{max} of 15 mg L^{-1}. P sorption isotherm for Immokalee fine sand determined using fertilizer mixture was linear with K_D averaging about 0.44±10 kg L^{-1}.

The adsorption of K^+ and NH_4^+ was similar for both 0-15- and 15-30 cm soil depth layers while P adsorption was linear for the P concentration range studied on the Immokalee sand using fertilizer mixture. Ammonium K_D was higher than that of potassium probably due to a larger hydrated radius in the former (ammonium ionic radius =0.56 nm and potassium ionic radius =0.53 nm). In other words more NH_4^+ would be retained in the limited exchange sites of the colloidal fractions (due low organic matter content ~1-2%, and a small clay fraction ~0.5% (Obreza and Collins, 2008) while letting K^+ desorb into the soil solution for plant uptake. Lumbanraja and Evangelou (1990; 1994) also reported similar phenomena regarding K^+ and NH_4^+-N on clay loam and silt loams soils of Kentucky, USA. They showed that the addition of K^+ stimulated the adsorption of NH_4^+-N on high affinity sites while K^+ adsorption was suppressed by labile NH_4^+. In a later study done in Florida's Spodosol and Entisol, Wang and Alva (2000) showed that NH_4^+ adsorption was greater for surface soils than that of the subsurface soils. They found that the potential NH_4^+ buffering capacity was greater for Wabasso (at 0-30 and 60-90 cm) than the Candler soil (0-60cm) owing to the presence of smectite in the former. Studies regarding ammonia sorption done over the years have yielded mixed observations. For example, Wagenet et al. (1977) assumed reversible, linear equilibrium sorption with distribution coefficients between 1 and 10 L kg^{-1} on a Tyndall silty loam. Yet, Rodríguez et al. (2005) found that representing ammonium adsorption-desorption as a kinetic process better described their results. They noted that ammonium adsorption on the sandy clay loam soil was higher than adsorption on the loamy sand. The ammonium K_D values found in this study agree with those proposed by several researchers (Wagenet et al., 1977; Selim and Iskandar, 1981; Lotse et al., 1992; Ling and El-Kadi, 1998).

Khakural and Alva (1996) studied transformation of urea and ammonium nitrate in an Entisol and a Spodosol under citrus production. The percentage of transformation of

NH_4^+-N into NO_3^--N was 33 to 41 and 37 to 41% in the Candler fine sand and Wabasso sand, respectively, at application rates of 1 g N kg^{-1}. The rate of transformation of NH_4 in these sandy soils dictates the availability of NH_4^+-N and NO_3^--N forms of N for plant uptake and losses due to volatilization, leaching, and denitrification. We had speculated that some NH_4^+ would volatilize and transform into NO_3^- but 24 h equilibration time, under laboratory conditions at 25±1 ^oC renders this volatilization negligible while retaining the possible transformation due to nitrification.

Freundlich sorption coefficients (K_f) (Appendix I) were lower for Immokalee fine sand than for Candler. High coefficients observed on Candler fine sand with K_f eightfold greater than that of Immokalee fine sand. The K_f value obtained with 0.005 M $CaCl_2$ was approximately twice that obtained with 0.01 M KCl and threefold that obtained in the fertilizer mixture suggesting the influence of the cation effect on P adsorption than with water. According to Zhou and Li (2001), the lower Freundlich sorption coefficients (K_f), indicate low P retention capacity at low P concentrations suggesting that the potential risk of subsurface P movement and leaching would be high when the concentration of P in surface soils is high. The K_f and K_D values reported in Appendix I are generally lower than those reported for carbonatic soils in south Florida (Zhou and Li, 2001) where K_D ranged from 14.8 – 76.3 L kg^{-1} and K_f from 12-58 mg^{1-N} kg^{-1} L^N. However, the results in this study agree with those of other researchers (Barrow et al., 1980; Nair et al., 1984; Havlin et al., 2005). According to Havlin et al. (2005), divalent cations on the CEC enhance P adsorption relative to monovalent cations because they increase the accessibility of (+)–charged edges of clay minerals to P. This occurs at pH<6.5, because at greater soil pH Ca-P minerals would precipitate. Barrow et al.

(1980) also showed that at equal ionic strength below pH=6, there was more phosphate adsorption from $CaCl_2$ than from NaCl on goethite. This phenomenon, according to Barrow and colleagues, is caused because high concentration of positive charges near the negatively charged soil surface may be induced by replacing a monovalent cation with a divalent one and also if the added divalent cation has a specific affinity for the adsorption surface. Addition of cations from the supporting electrolyte, unlike using the fertilizer, induced a greater negative charge for phosphate adsorption. The higher sorption coefficients for Candler might be due to high organic matter and some Fe/Al coatings that might bind P. This might explain, in part, why Mehlich 1 P was several times higher for Candler than for Immokalee fine sand as summarized in Table B1 and discussed thoroughly in Chapter 3. The high K_f value in the top 0-15 cm than the 15-30 cm layer is ascribed to higher organic carbon and organic matter in the former layer resulting in increased P adsorption.

Summary

The results show that P adsorption in the top 0-15 cm was greater for Candler than Immokalee sand using the fertilizer mixture, 0.005 M $CaCl_2$ and 0.01 M KCl. The distribution coefficients (K_D) for P estimated using 0.01 M KCl were similar to K_D values determined using fertilizer mixture for Immokalee and Candler fine sand, respectively. The K_D values determined using 0.005 M $CaCl_2$ as the supporting electrolyte were two- to threefold greater than the K_D of the fertilizer mixture on Immokalee and Candler fine sand suggesting that divalent Ca^{+2} might result in overestimation of P sorption on Candler and Immokalee sandy soils. It appears the addition of a supporting electrolyte with a divalent or monovalent cation, unlike fertilizer mixture, increases the surface charge for adsorption of orthophosphate anions. The adsorption isotherms of both ammonium and potassium were linear and greater for Candler than Immokalee sand probably due to Al and Fe coatings and higher organic matter in the former. For the two soils soils, ammonium adsorption coefficients were greater than those of potassium.

Table B1. Selected soil chemical characteristics for Immokalee and Candler sand

Soil	Soil depth (cm)	pH[¶]	OM[§]	CEC[‡]	NH_4^+	NO_3^-	M1P[†]	M1K[‡‡]	IN[¶¶]
Immokalee	0-15	5.6	0.61	2-6	3.45	4.93	46.45	15.23	8.37
Immokalee	15-30	5.2	0.41	2-6	2.32	4.07	28.73	11.83	6.40
Candler	0-15	5.3	1.96	2-4	2.55	8.69	115.82	29.70	11.24
Candler	15-30	4.9	1.56	2-4	2.88	5.31	112.79	23.03	8.20

[¶] Soil to water ratio=1:2 (mass/volume), [§] OM-organic matter expressed as a percentage, [‡] CEC-cation exchange capacity expressed in cmol(+) kg^{-1} (CEC reported by Obreza and Collins, 2008), [†] Mehlich 1 P (mg kg^{-1}), [‡‡] Mehlich 1 K (mg kg^{-1}), [¶¶] IN=Inorganic N (mg kg^{-1})

Table B2. Sorption coefficients for NH_4^+ and K^+ on Immokalee and Candler fine sand using fertilizer mixture in tap water

Soil	Depth (cm)	NH_4^+	K^+
		¶K_D (L kg^{-1})	K_D (L kg^{-1})
Immokalee	0-15	1.12±0.42	0.91±0.38
Immokalee	15-30	1.64±0.25	0.87±0.74
Candler	0-15	1.66±0.39	1.65±0.56
Candler	15-30	1.76±0.39	0.93±0.28

¶K_D =Mean±one standard deviation of 3 replications

Table B3. Sorption coefficients for P on Immokalee and Candler fine sand

Soil	Depth (cm)	Supporting electrolyte	‡K_D (L kg^{-1})
Immokalee	0-15	0.01 M KCl	0.53 ± 0.11
Immokalee	15-30	0.01 M KCl	0.50 ± 0.19
Candler	0-15	0.01 M KCl	2.87 ± 0.43
Candler	15-30	0.01 M KCl	3.79 ± 0.87
Immokalee	0-15	0.005 M $CaCl_2$	0.75 ± 0.13
Immokalee	15-30	0.005 M $CaCl_2$	0.74 ± 0.32
Candler	0-15	0.005 M $CaCl_2$	3.46 ± 0.65
Candler	15-30	0.005 M $CaCl_2$	4.43 ± 0.50
Immokalee	0-15	Fertilizer mixture	0.45 ± 0.10
Immokalee	15-30	Fertilizer mixture	0.43 ± 0.20
Candler	0-15	Fertilizer mixture	1.73 ± 0.15
Candler	15-30	Fertilizer mixture	2.05 ± 0.89

‡K_D=Linearized K_D using Equation 6-6 presented as mean±one standard deviation of 3 replications and a C_{max} of 15 mg L^{-1}

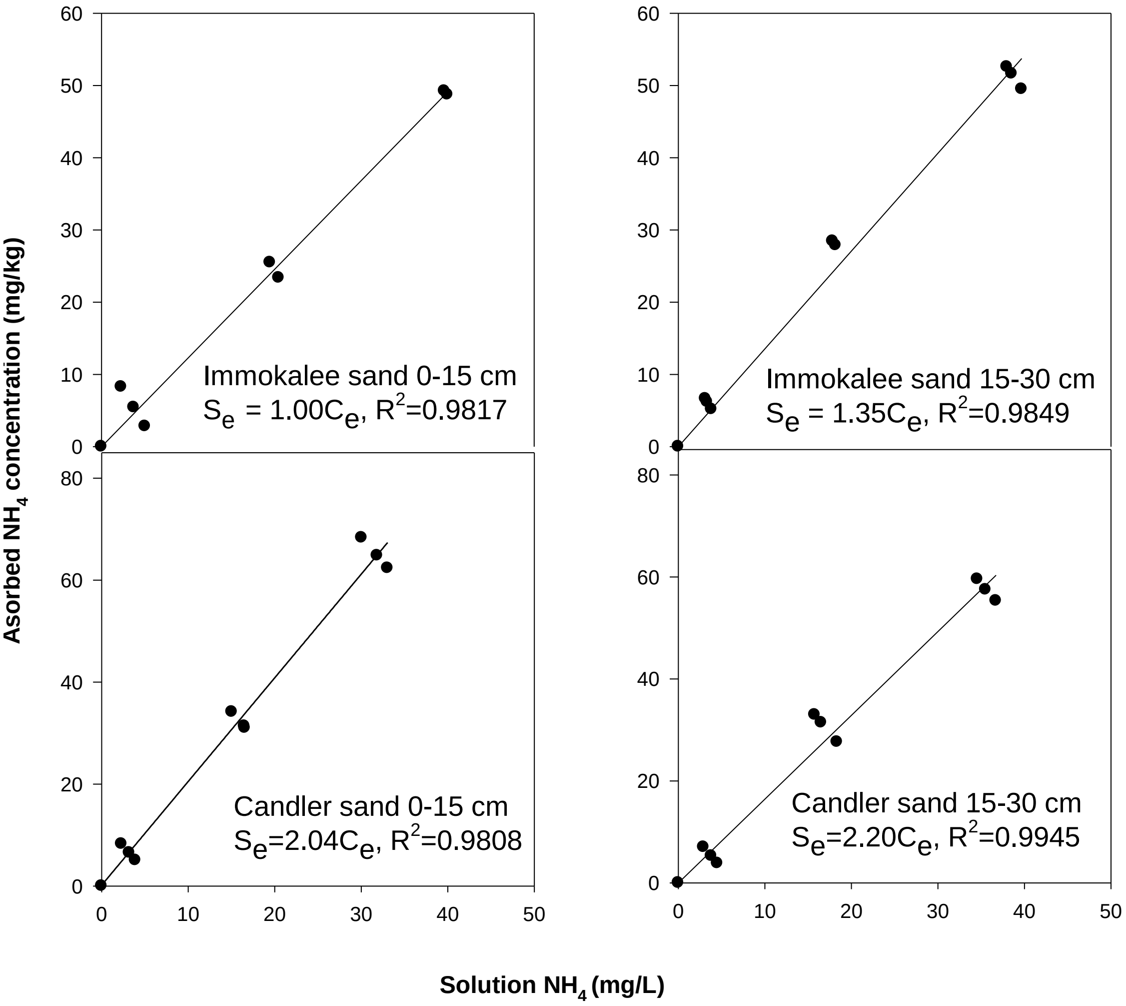


Figure B1. Selected linear isotherms for NH_4^+ for Immokalee and Candler sand

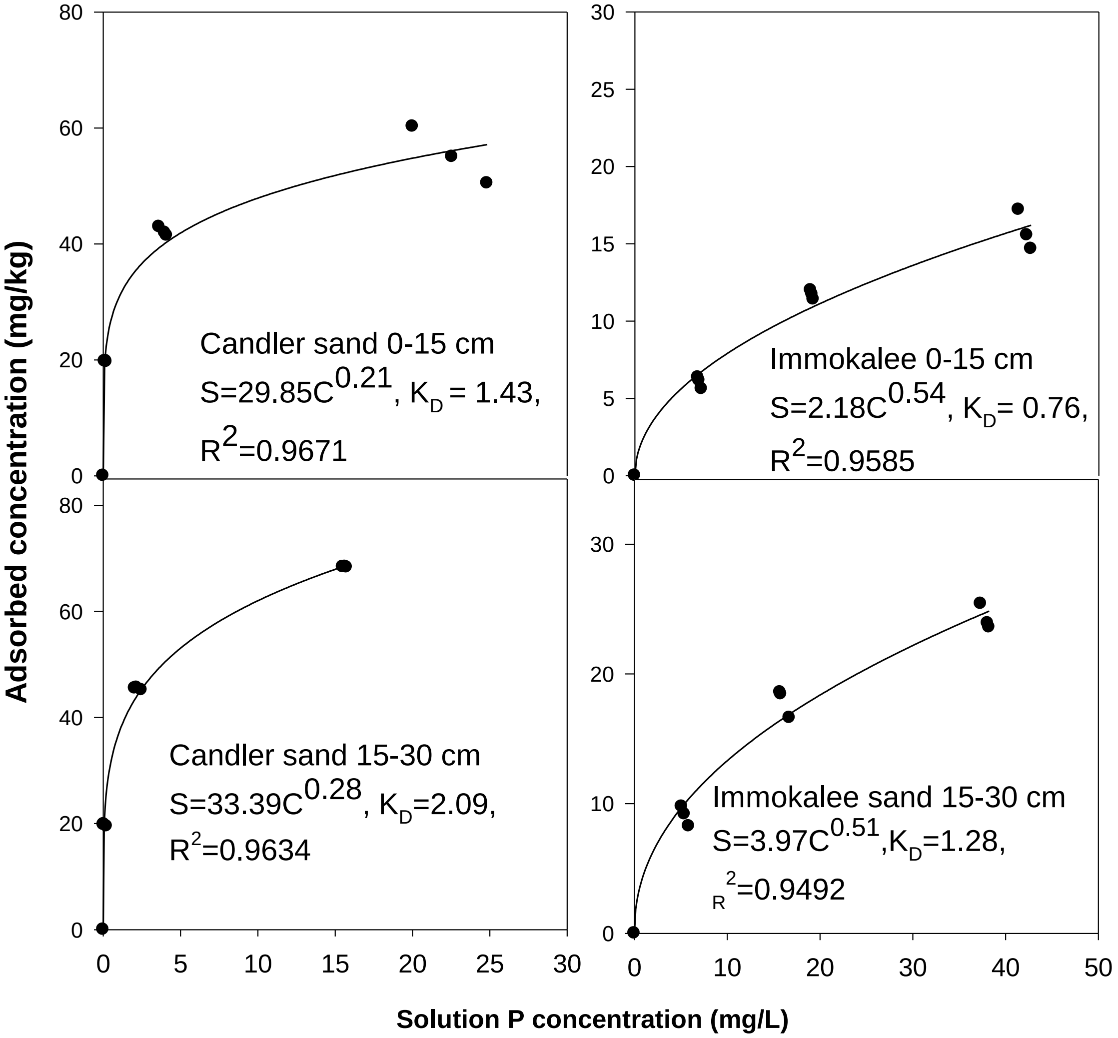


Figure B2. Selected Freundlich isotherms for P for Immokalee and Candler sand using 0.005M $CaCl_2$

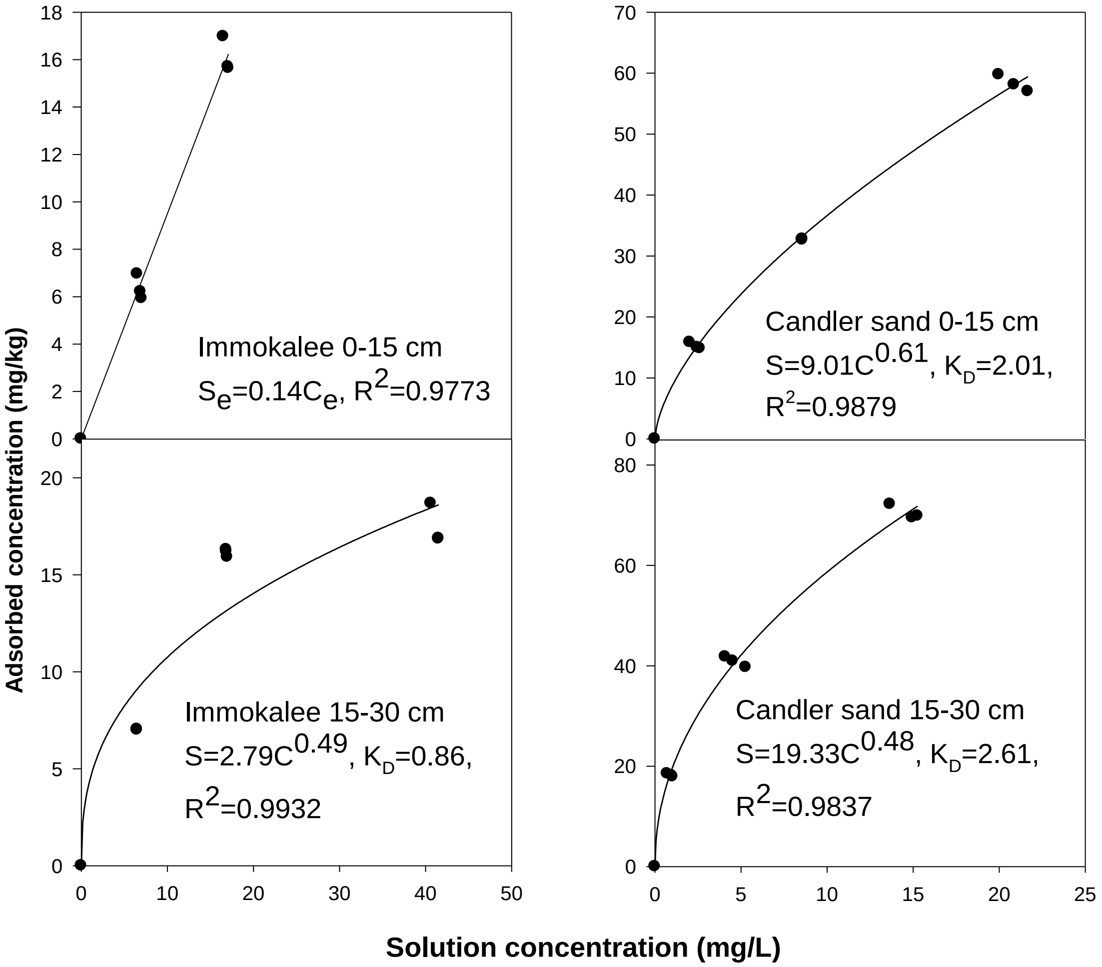


Figure B3. Selected linear and Freundlich isotherms for P for Immokalee and Candler sand using 0.01M KCl

APPENDIX C
SOIL WATER CHARACTERISTIC CURVE AND HYDRAULIC FUNCTIONS FOR THE IMMOKALEE AND CANDLER SAND

The soil properties that determine the behavior of soil water flow systems are the hydraulic conductivity and water retention characteristics. The relation between soil water content and the soil water suction is a fundamental part of the characterization of the hydraulic properties of soil (Klute, 1986). The conductivity of a soil depends on pore geometry and the properties of the fluid flowing through or retained in the pores. Viscosity and density are the two properties that directly affect hydraulic conductivity while soil porosity and water retention function are determined by soil texture and structure (Klute and Dirksen, 1986). The hydraulic conductivity is defined by Darcy's Law (Klute and Dirksen, 1986; Hillel, 1998) which for one-dimensional vertical flow may be written as:

$$q = -K(\theta)\frac{\partial H}{\partial z} \qquad \text{(C-1)}$$

where q is the volume flux density, $\frac{\partial H}{\partial z}$ is the gradient of the hydraulic head H, and K(θ) is the hydraulic conductivity. The driving force is expressed as the negative gradient of the hydraulic head composed of the gravitational head, z, and the pressure head, h, mathematically given as:

$$H=h+z \qquad \text{(C-2)}$$

Mualem (1986) also explained that there are some independent variables of interest that describe soil water retention characteristics such as the degree of saturation (S), effective water content (θ_e), effective saturation could also be used to describe water retention characteristics.

The amount of water retained in the soil at any given moment is dependent upon factors such as the type of plant cover, plant density, stage of plant growth, rooting depth, evaporation and transpiration rates, amount of water infiltrated, rate of wetting, nature of horizonation and the length of time since the last irrigation or rainfall event (Cassel and Nielsen, 1986). Amount of water available for plant use is determined through estimation of available water capacity, field capacity and permanent wilting point. The traditional field capacity for well-drained sandy soil under laboratory conditions is estimated at 10 kPa of soil water tension for a sandy soil and 33 kPa for medium or fine-textured soil (Obreza et al., 1997). However, in their study on soil water-holding characteristic on Florida Flatwoods and Ridge soils, Obreza and co-workers showed that soil water tension of 5 kPa would be appropriate for the Ridge and 8 kPa for the Flatwoods soil due to their inherent differences in porosity, conductivity and horizonation.

Thus, the objectives of the laboratory experiments were to 1) determine water retention characteristics for the Immokalee and Candler sand and 2) calculate hydraulic parameters for use in HYDRUS model. We hypothesized basing on literature and field observations that the soil water retention characteristics for the two sites would vary as a function of soil depth. Thus, it would be important to sample by depths of interest at each study site for use of selected site-specific parameters in the simulation model.

Results and Discussion

The volumetric moisture contents at soil tensions ranging from 0-100 kPa (0-1020 cm) are presented in Fig. C1and C2. The Van Genuchten model water retention parameters (α, n and *l*) are documented in Table C1. The saturated and residual moisture contents, moisture contents at field capacity (10 kPa), available soil water content, saturated hydraulic conductivity and bulk density are presented in Table C2. The residual moisture contents from literature are 0.013 and 0.009 cm^3 cm^{-3} for Immokalee and Candler fine sand (Carlisle et al., 1989). The saturated hydraulic conductivity ranged from 13.22 to 15.82 cm h^{-1} on Immokalee and 14.76 to 15.94 cm h^{-1} on Candler fine sand. Field capacities averaged 0.096 and 0.093 cm^3 cm^{-3} for the two soils. Available water capacities ranged from 0.077 to 0.087 and 0.065 to 0.095 cm^3 cm^{-3} for Immokalee and Candler fine sand. The available water capacities were estimated using soil tensions of 10 kPa as field capacity and 1500 kPa as wilting point. The results suggested very high hydraulic conductivities, good drainage and permeability for both soils due to the strong sandy soil characteristic in the top 0.60 m soil depth. The soil desorption curves also indicate large soil pore sizes and a narrow pore-size distribution in both soils (Klute, 1986; Klute and Dirksen, 1986; Obreza et al., 1997; Obreza and Pitts, 2002). The high hydraulic conductivity values suggest the importance of careful water and nutrient management due to the potential threat of nutrient leaching and downward drainage of water beyond the plant root zone.

Summary

The soil the hydraulic conductivity and water retention characteristics are important for better nutrient and water management particularly in fertigated and irrigated systems. The experiment yielded important site-specific parameters like alpha, n, m, field capacity, available water capacity and hydraulic conductivity for use in the HYDRUS-2D model to describe water and solute transport to aid decision-making in predicting environmental fate of fertilizers.

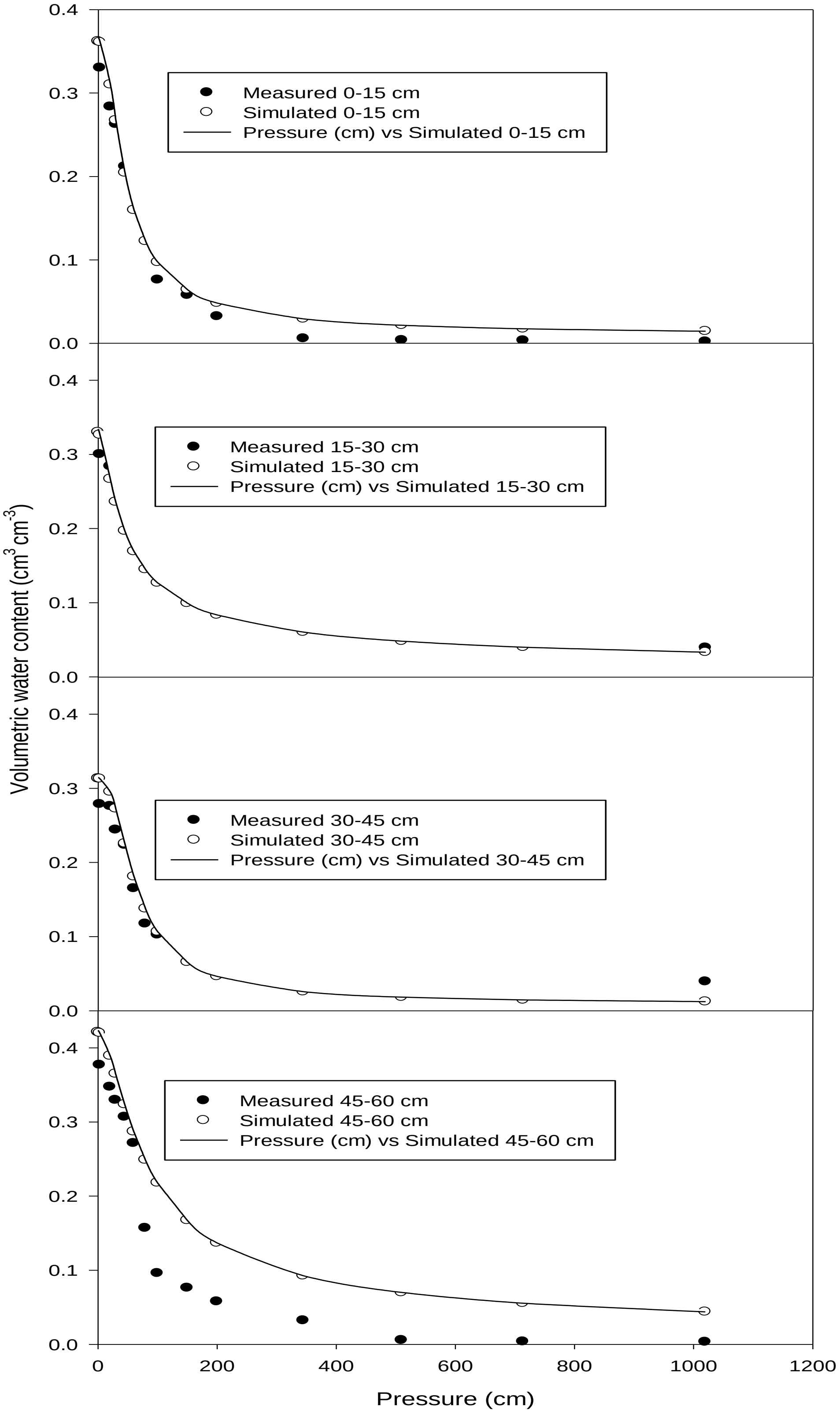


Figure C1. Measured and simulated soil water release curves for Candler fine sand

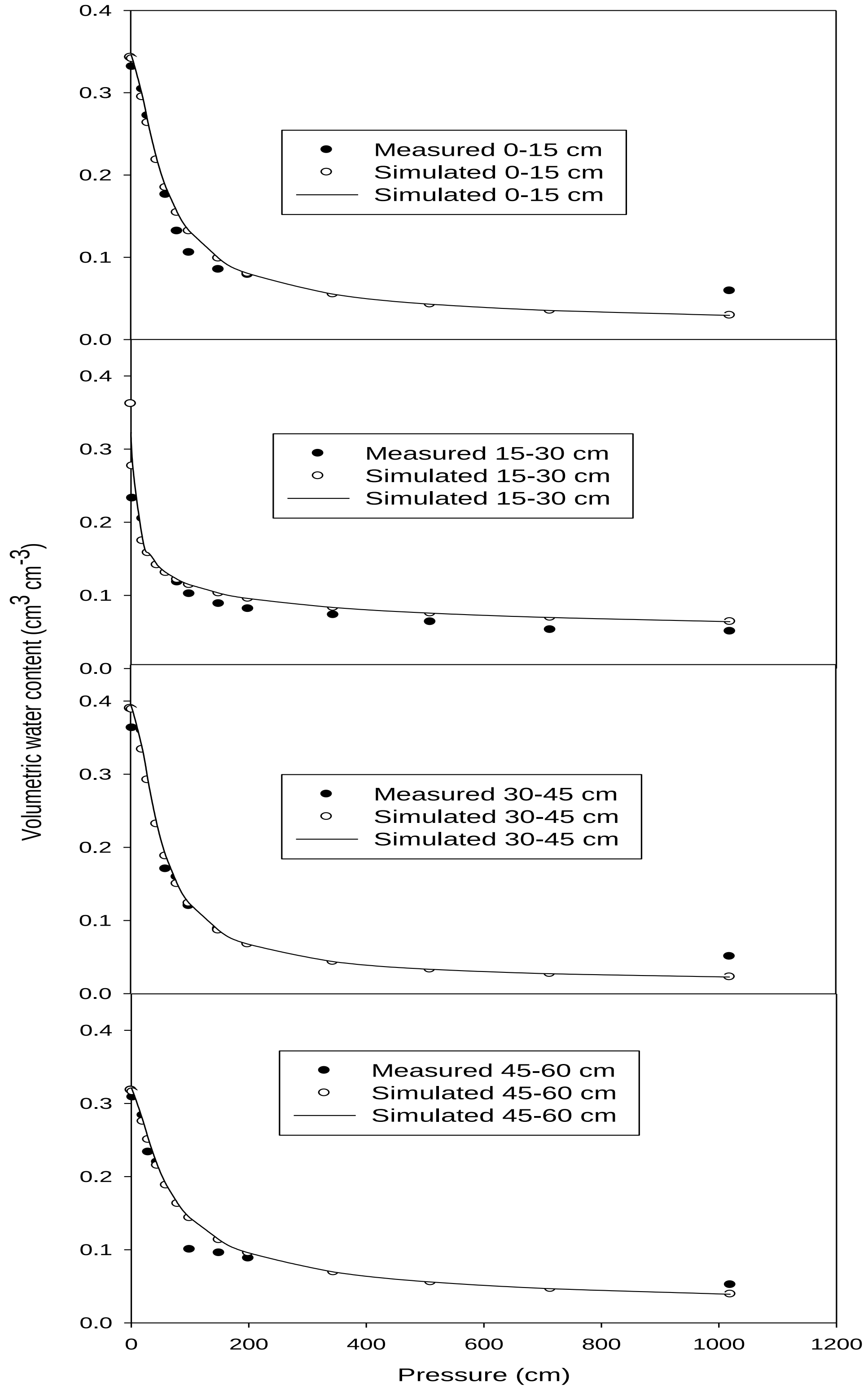


Figure C2. Measured and simulated soil water release curves for Immokalee fine sand

Table C1. Soil water retention parameters of Immokalee and Candler fine sand estimated using CAS software developed by Bloom (2009)

Soil	Depth (cm)	α (cm^{-1})	n	m	¶l
Immokalee	0-15	0.03	1.87	0.47	0.5
Immokalee	15-30	0.04	1.29	0.23	0.5
Immokalee	30-45	0.03	2.06	0.52	0.5
Immokalee	45-60	0.03	1.71	0.42	0.5
Candler	0-15	0.03	2.22	0.55	0.5
Candler	15-30	0.04	1.70	0.41	0.5
Candler	30-45	0.02	2.50	0.60	0.5
Candler	45-60	0.02	1.82	0.45	0.5

¶Pore connectivity parameter (estimated to be an average of 0.5 for many soils)

(Simunek et al., 2007)

Table C2. Soil physical characteristics of the Immokalee and Candler fine sand

Soil	Depth (cm)	Bulk density (g cm^{-3})	‡‡K_{sat} (cm h^{-1})	§θ_{sat} (cm^3 cm^{-3})	§§θ_r (cm^3 cm^{-3})	‡FC (cm^3 cm^{-3})	†AWC (cm^3 cm^{-3})
Immokalee	0-15	1.62	15.82	0.343	0.013	0.090	0.077
Immokalee	15-30	1.62	13.97	0.362	0.013	0.100	0.087
Immokalee	30-45	1.59	13.22	0.390	0.013	0.100	0.087
Immokalee	45-60	1.61	14.57	0.318	0.013	0.095	0.082
Candler	0-15	1.65	15.53	0.362	0.009	0.074	0.065
Candler	15-30	1.64	15.94	0.330	0.009	0.104	0.095
Candler	30-45	1.57	14.76	0.313	0.009	0.100	0.091
Candler	45-60	1.68	15.73	0.421	0.009	0.094	0.085

‡‡K_{sat} – Saturated hydraulic conductivity

§θ_{sat} – Saturated moisture content

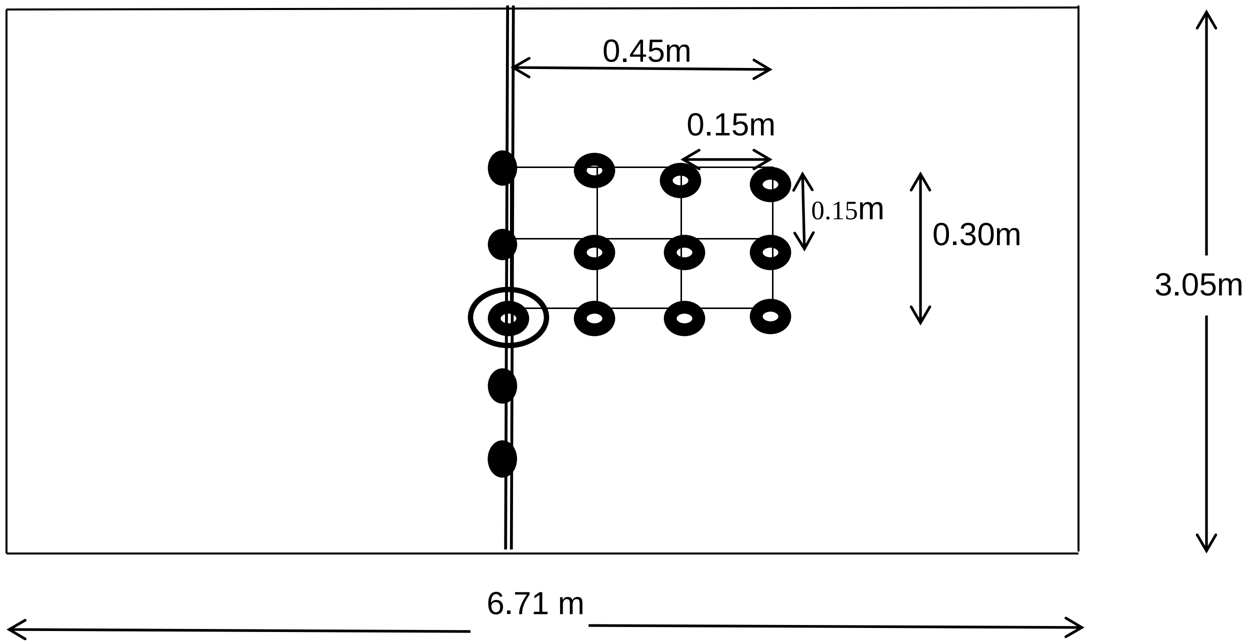
§§θ_r – Residual moisture content obtained from Obreza, unpublished data

‡FC – Field capacity at 10 kPa

†AWC – Available water content

APPENDIX D

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF DRIP OPEN HYDROPONIC SYSTEM AT IMMOKALEE IN 2009



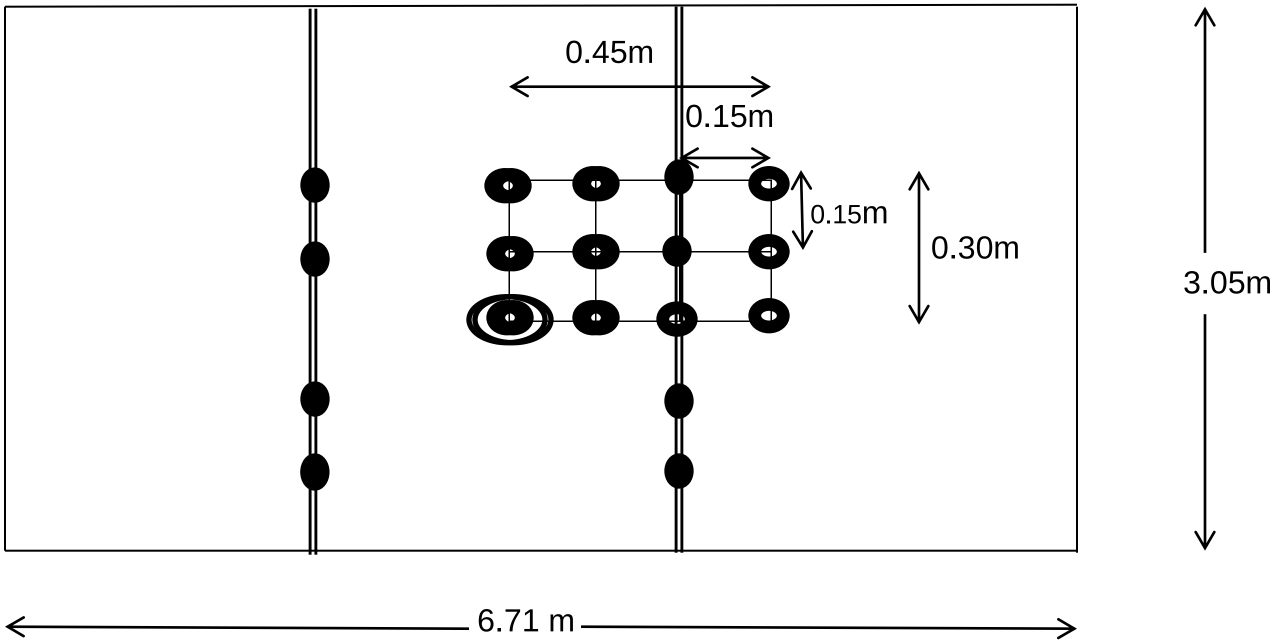
○ – tree,

◉ - sampling position,

● - dripper,

═ - drip line, spacing between trees=3.05m, row spacing=6.71m, positions below the dripper within the sampling grid were also sampled

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF DRIP OPEN HYDROPONIC SYSTEM AT IMMOKALEE IN 2010 AND THEREAFTER



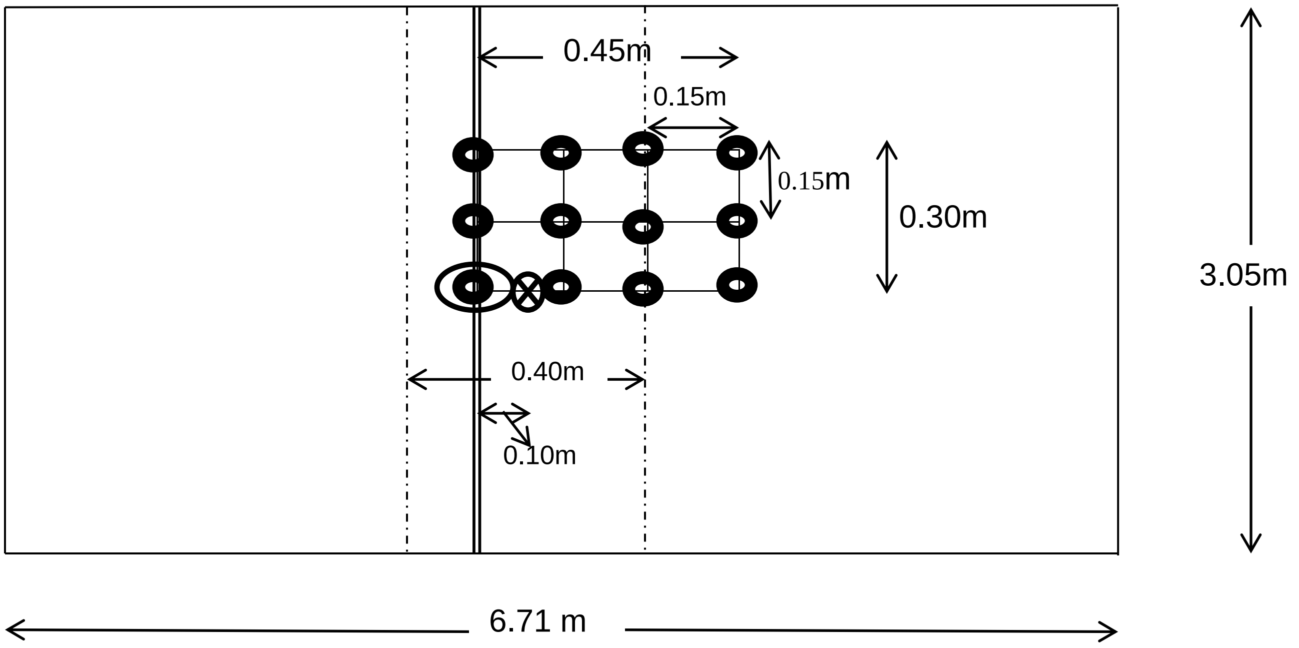
○ – tree,

◉ - sampling position,

● - dripper,

═ - drip line, spacing between trees=3.05m, row spacing=6.71m, positions below the dripper within the sampling grid were also sampled

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF MICROSPRINKLER OPEN HYDROPONIC SYSTEM ON IMMOKALEE SAND



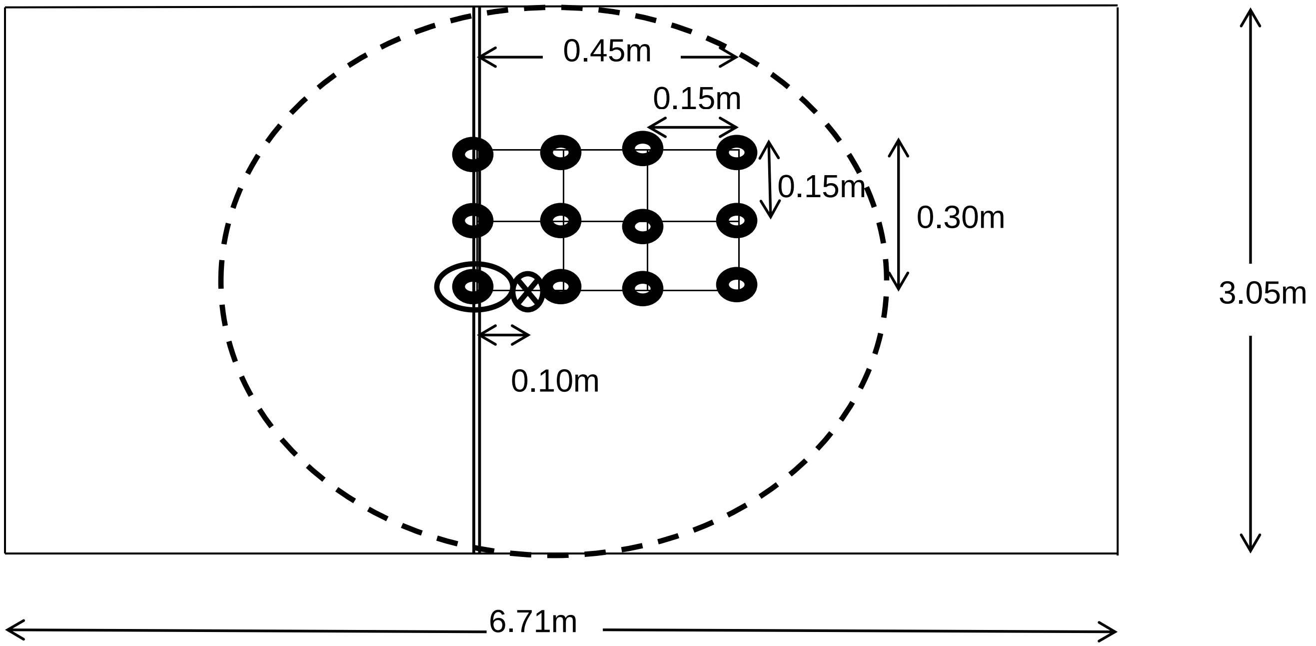
○ – tree,

● - sampling position

═ - irrigation main line,

⊗ - microsprinkler emitter, spacing between trees=3.05m, row spacing=6.71m, area between the dashed lines was the irrigated zone

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF CONVENTIONAL MICROSPRINKLER SYSTEM ON IMMOKALEE SAND



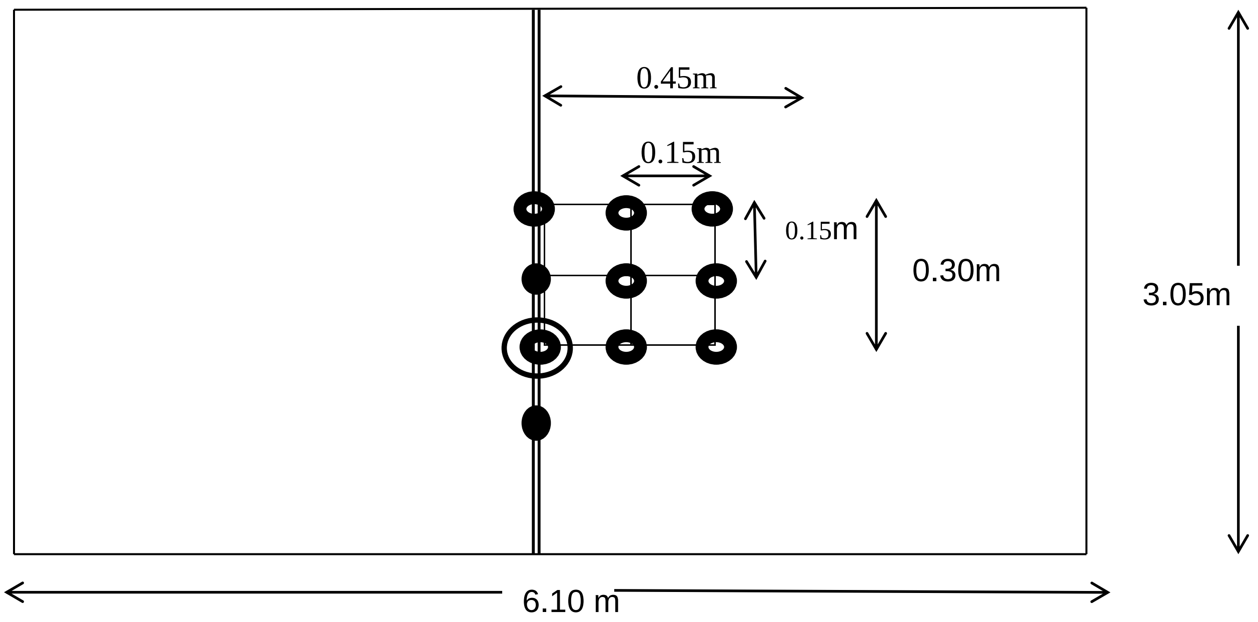
○ – tree,

● - sampling position

═ - irrigation main line,

⊗ - microsprinkler emitter, spacing between trees=3.05m, row spacing=6.71m, area within the dashed circle was the irrigated zone

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF DRIP OPEN HYDROPONIC SYSTEM (DOHS-SWINGLE) ON CANDLER SAND



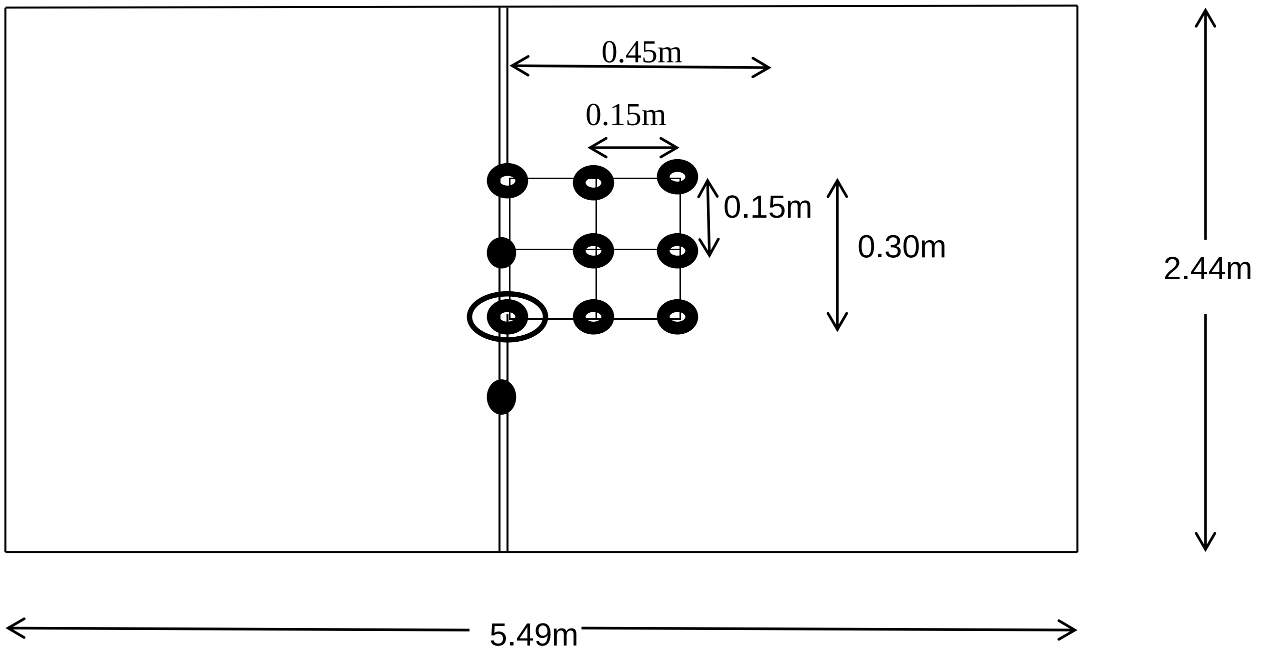
○ – tree,

◉ - sampling position,

● - dripper,

═ - drip line, spacing between trees=3.05m, row spacing=6.10m, positions below the dripper within the sampling grid were also sampled

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF DRIP OPEN HYDROPONIC SYSTEM (DOHS-C35) ON CANDLER SAND



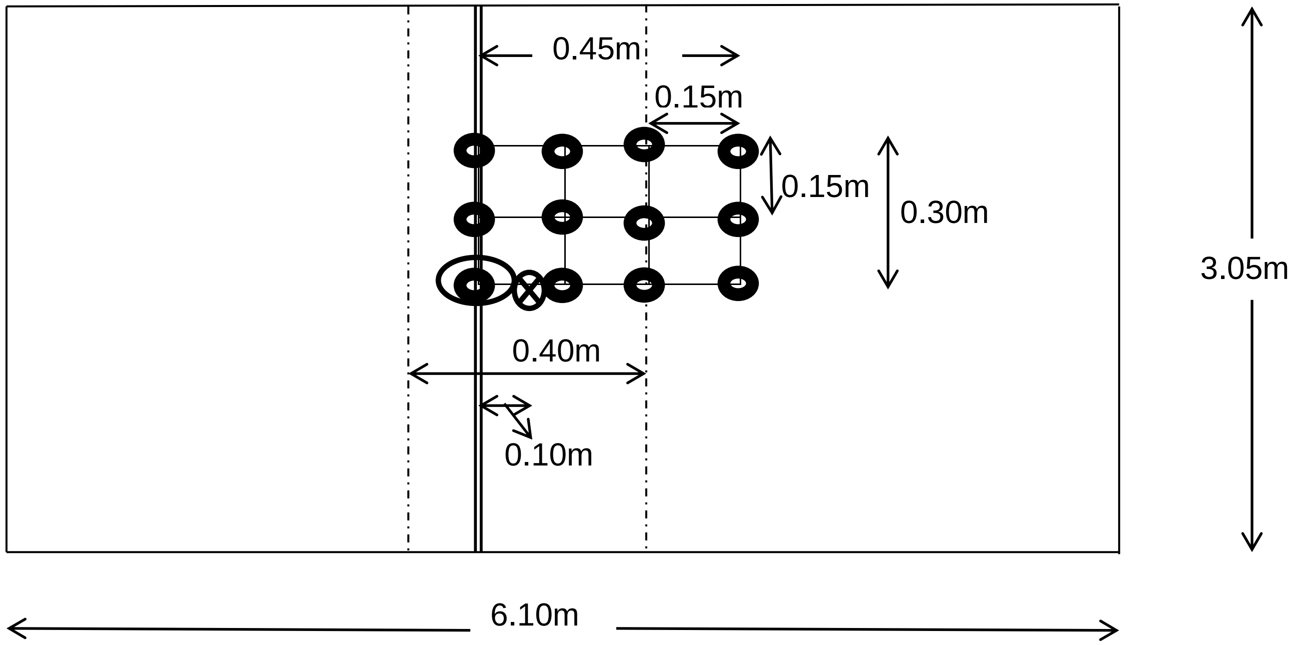
○ – tree,

◉ - sampling position,

● - dripper,

═ - drip line, spacing between trees=2.44m, row spacing=5.49m, positions below the dripper within the sampling grid were also sampled

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF MICROSPRINKLER OPEN HYDROPONIC SYSTEM ON CANDLER SAND



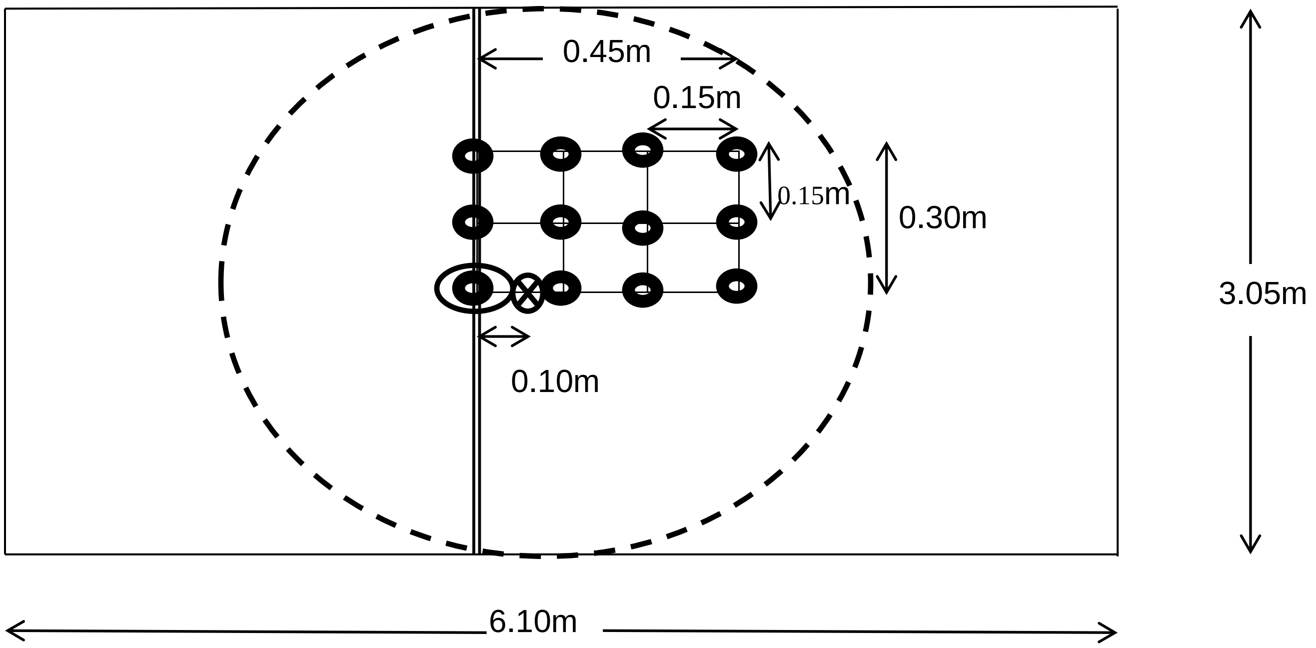
○ – tree,

◉ - sampling position

═ - irrigation main line,

⊗ - Microsprinkler emitter, spacing between trees=3.05m, row spacing=6.10m, area between the dashed lines was the irrigated zone

A SCHEMATIC FIELD DIAGRAM SHOWING THE SET-UP OF CONVENTIONAL MICROSPRINKLER SYSTEM ON CANDLER SAND



○ – tree,

◉ - sampling position

═ - irrigation main line,

⊗ - Microsprinkler emitter, spacing between trees=3.05m, row spacing=6.10m, area within the dashed circle was the irrigated zone

APPENDIX E

AVERAGE MONTHLY TEMPERATURE, RELATIVE HUMIDITY, RAINFALL, SOLAR RADIATION AND EVAPOTRANSPIRATION AT IMMOKALEE SOURCED FROM THE FLORIDA AUTOMATED WEATHER NETWORK (HTTP://FAWN.IFAS.UFL.EDU/) FROM 2009 TO 2011

Month	Average temperature (^{o}C)	Minimum temperature (^{o}C)	Maximum temperature (^{o}C)	Relative Humidity (%)	Rainfall (mm)	Solar radiation (W m^{-2})	Evapotranspiration (mm d^{-1})
January	[¶]15.5±1.4	-1.8±1.7	28.9±0.3	77.7±2.1	35.8±29.5	154.3±5.7	1.5±0.0
February	16.9±2.5	1.1±3.3	28.9±1.2	74.7±4.5	27.9±35.3	193.8±16.8	2.4±0.3
March	19.0±2.0	1.9±2.4	31.6±2.0	74.0±2.0	94.0±111.7	230.4±12.3	3.0±0.3
April	22.9±1.3	9.6±3.1	32.7±2.1	73.0±3.0	94.0±90.3	267.3±14.8	4.1±0.4
May	25.5±1.1	15.8±4.0	35.1±0.6	76.0±1.7	116.4±64.9	277.4±21.0	4.8±0.5
June	27.0±1.3	19.7±2.8	36.0±0.5	80.0±2.0	202.2±122.5	259.8±12.7	4.8±0.3
July	27.5±0.7	21.6±1.0	35.7±0.4	83.0±1.0	137.8±51.3	239.8±3.8	4.6±0.0
August	27.5±0.5	22.4±1.1	36.1±0.6	85.0±1.0	133.9±8.9	223.8±13.6	4.3±0.3
September	26.9±0.4	20.5±0.8	34.7±0.9	84.7±1.5	138.9±53.4	213.9±2.8	3.9±0.1
October	24.2±1.1	9.9±1.3	33.5±1.3	79.3±3.5	74.6±120.4	195.2±20.5	3.0±0.4
November	20.8±0.1	6.8±2.5	32.0±0.7	79.7±2.1	21.3±20.6	166.9±8.9	2.0±0.0
December	17.0±3.6	0.2±2.4	28.9±2.5	79.7±4.9	45.0±40.8	143.4±16.3	1.4±0.1

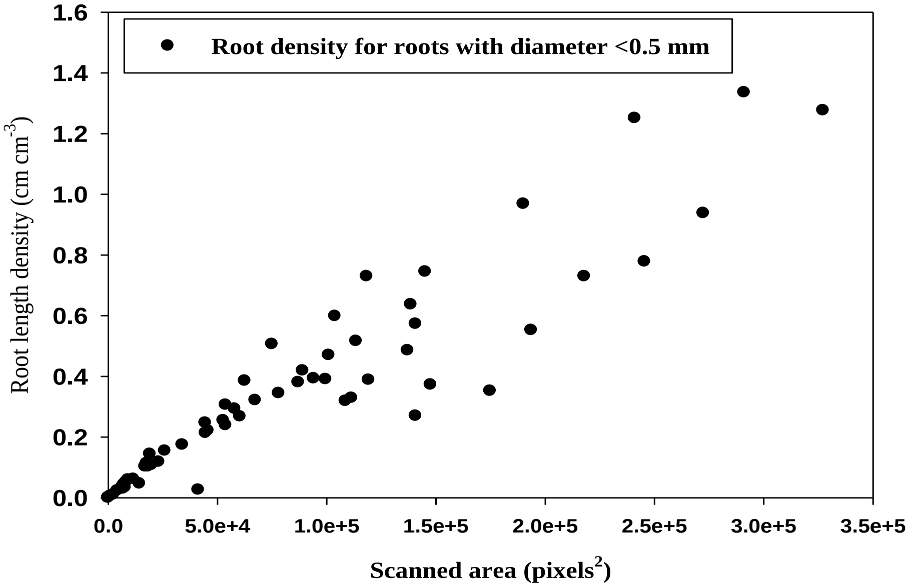
[¶] Mean ± 1 standard deviation

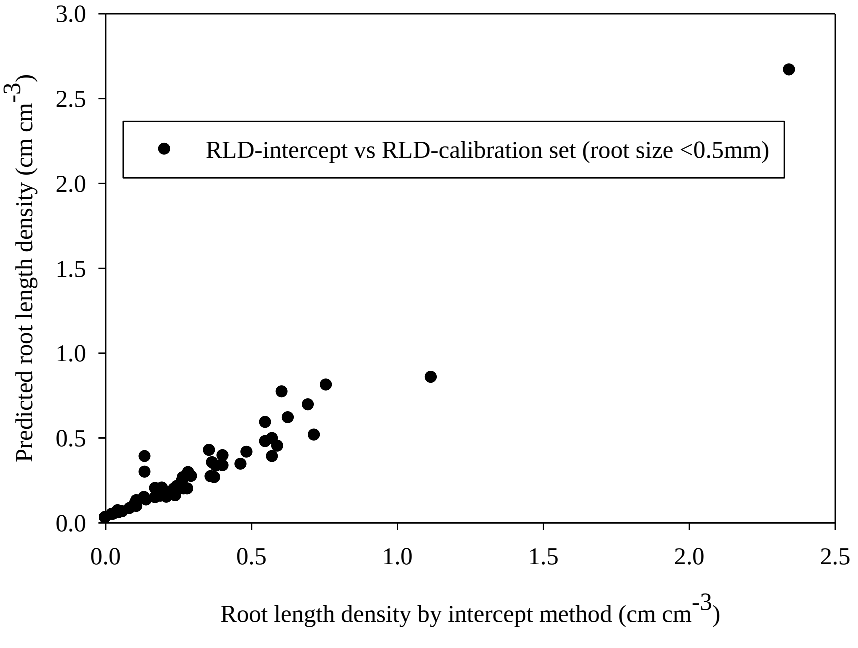
AVERAGE MONTHLY TEMPERATURE, RELATIVE HUMIDITY, RAINFALL, SOLAR RADIATION AND EVAPOTRANSPIRATION AT LAKE ALFRED SOURCED FROM THE FLORIDA AUTOMATED WEATHER NETWORK (HTTP://FAWN.IFAS.UFL.EDU/) FROM 2009 TO 2011

Month	Average temperature (^{o}C)	Minimum temperature (^{o}C)	Maximum temperature (^{o}C)	Relative Humidity (%)	Rainfall (mm)	Solar radiation (W m^{-2})	Evapotranspiration (mm d^{-1})
January	[§]13.8±1.3	-2.3±1.0	27.6±0.9	74.0±2.6	61.1±30.1	136.3±5.9	1.4±0.1
February	15.3±2.8	0.0±2.8	28.2±2.2	71.7±4.5	30.1±35.6	168.5±10.8	2.1±0.3
March	18.5±2.1	3.9±2.0	30.8±2.8	70.3±2.5	149.7±139.3	215.1±4.5	2.8±0.3
April	22.6±1.1	9.0±3.3	33.4±1.4	69.7±2.5	32.9±42.8	261.8±20.9	4.1±0.4
May	25.5±0.6	16.9±1.9	35.1±0.5	73.0±4.4	111.6±102.6	268.0±35.0	4.7±0.5
June	27.5±0.5	20.2±0.5	36.9±0.6	76.7±1.5	137.3±59.0	258.5±14.1	4.8±0.3
July	27.7±0.3	21.2±0.0	36.0±0.4	80.0±1.0	110.8±35.3	235.4±12.1	4.6±0.3
August	27.6±0.1	22.6±0.5	35.9±0.1	82.7±1.5	249.2±63.4	220.6±7.7	4.2±0.1
September	26.5±0.2	18.9±1.5	34.4±0.3	81.3±0.6	109.8±42.5	210.2±11.0	3.7±0.1
October	23.1±1.6	10.5±2.4	33.0±2.3	76.3±3.8	76.4±128.1	193.6±26.1	2.9±0.3
November	19.5±0.4	6.5±1.6	30.2±0.4	78.3±1.5	23.0±17.0	149.3±13.8	1.8±0.0
December	15.2±4.2	0.9±4.2	28.1±2.2	78.0±6.1	41.0±41.5	128.3±24.6	1.3±0.3

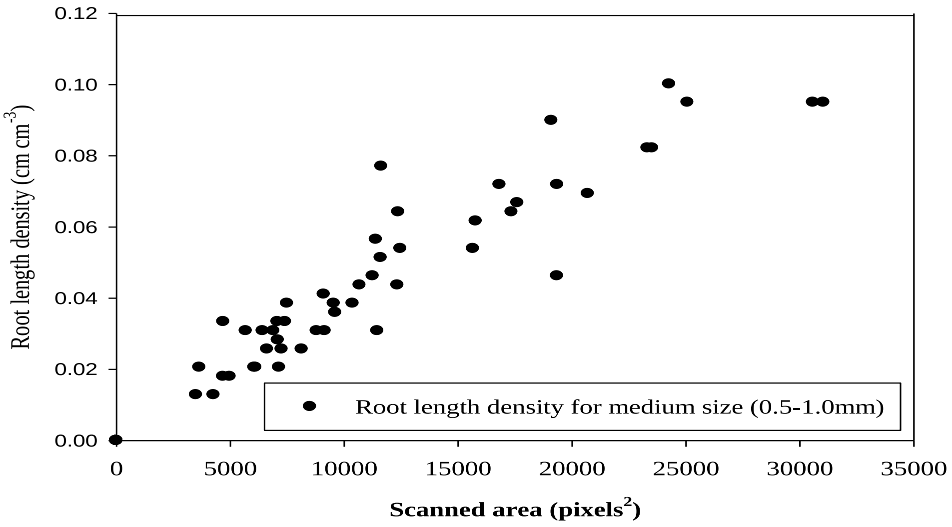
[§] Mean ± 1 standard deviation

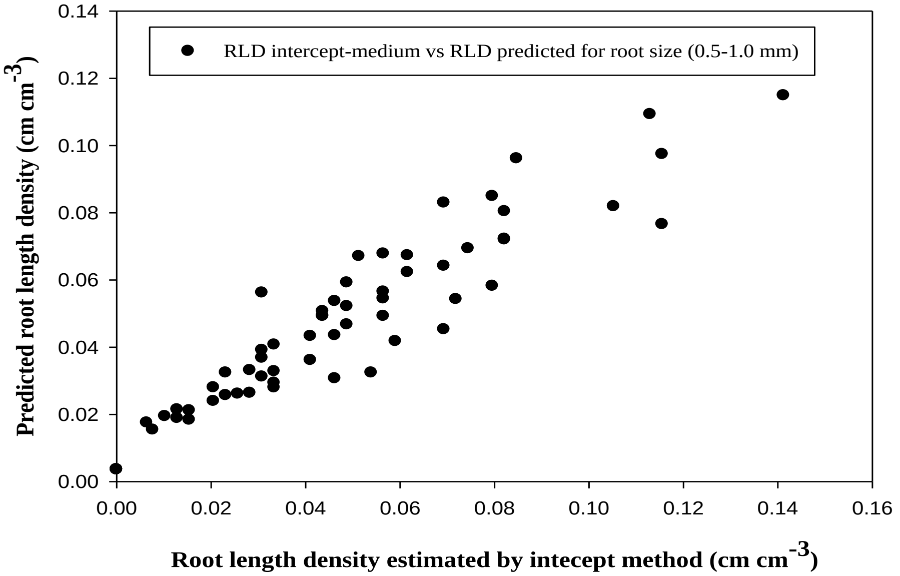
APPENDIX F
CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT CREC FOR ROOT DIAMETER LESS THAN 0.5 MM





CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT CREC FOR ROOT DIAMETER 0.5-1.0 MM





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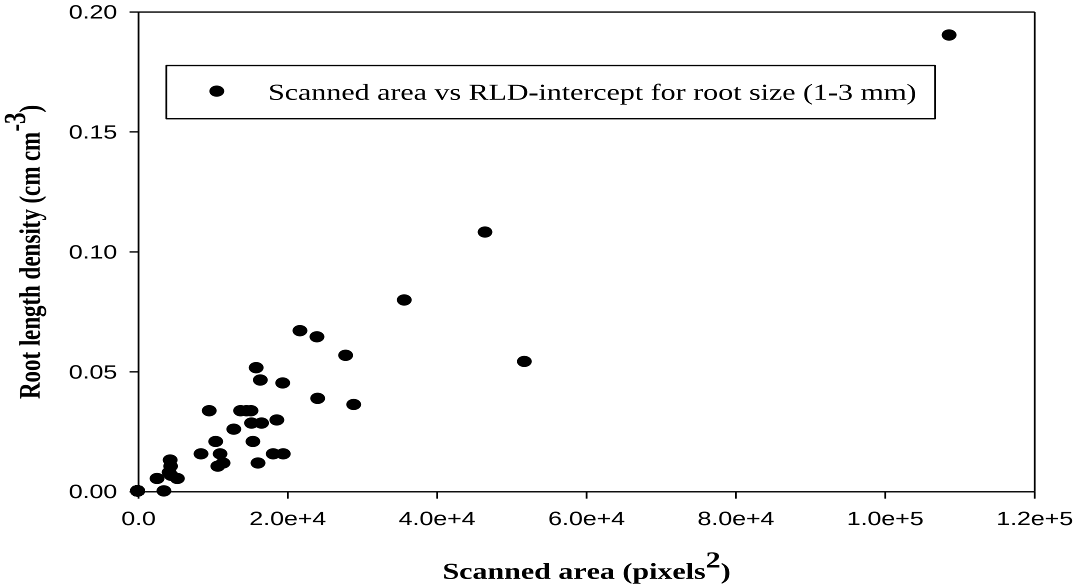
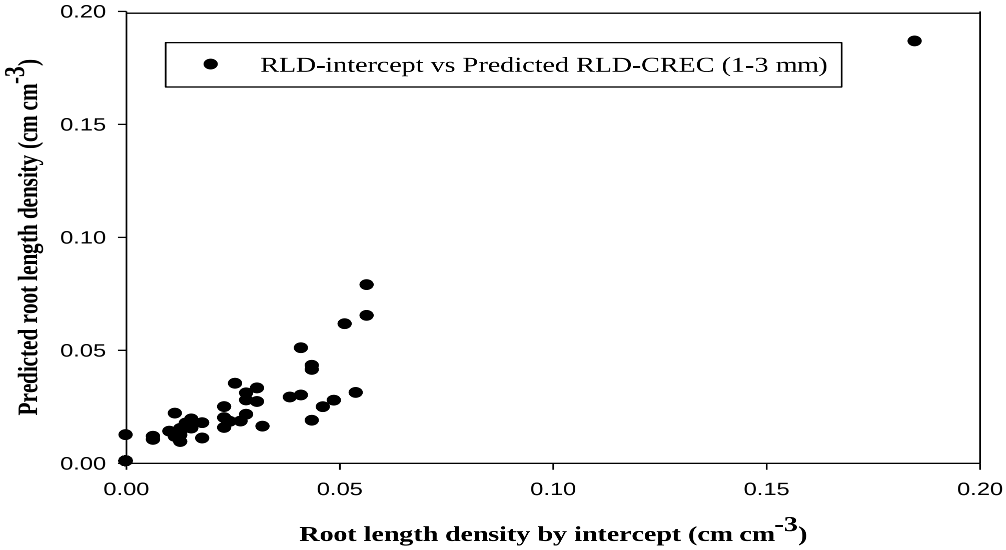
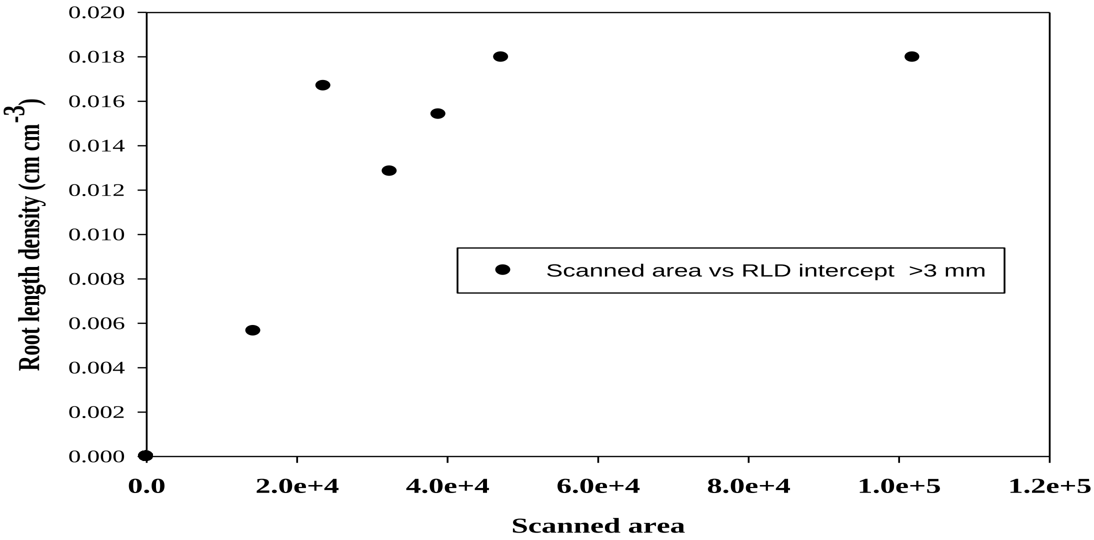
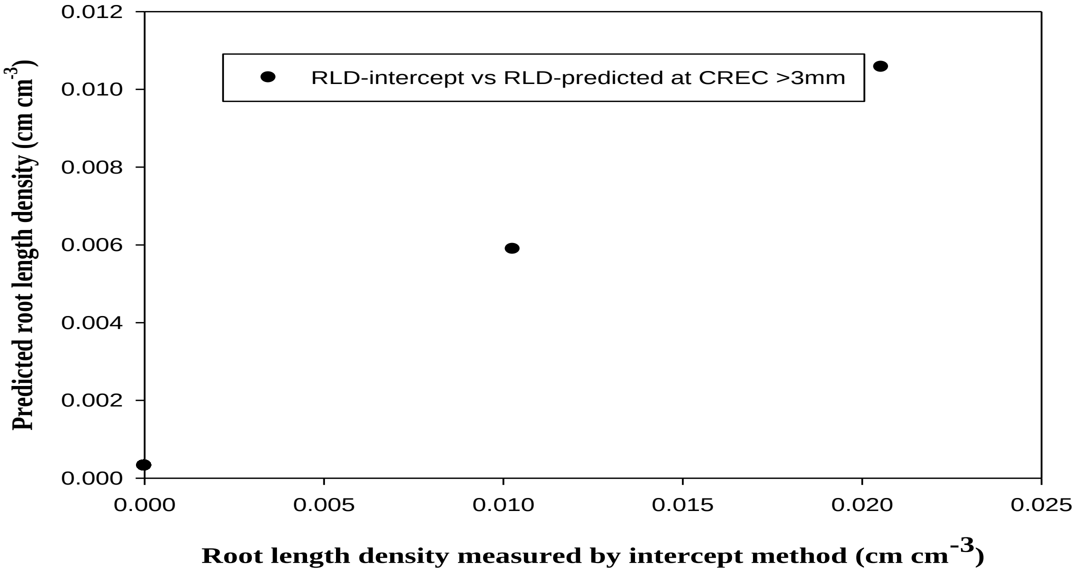


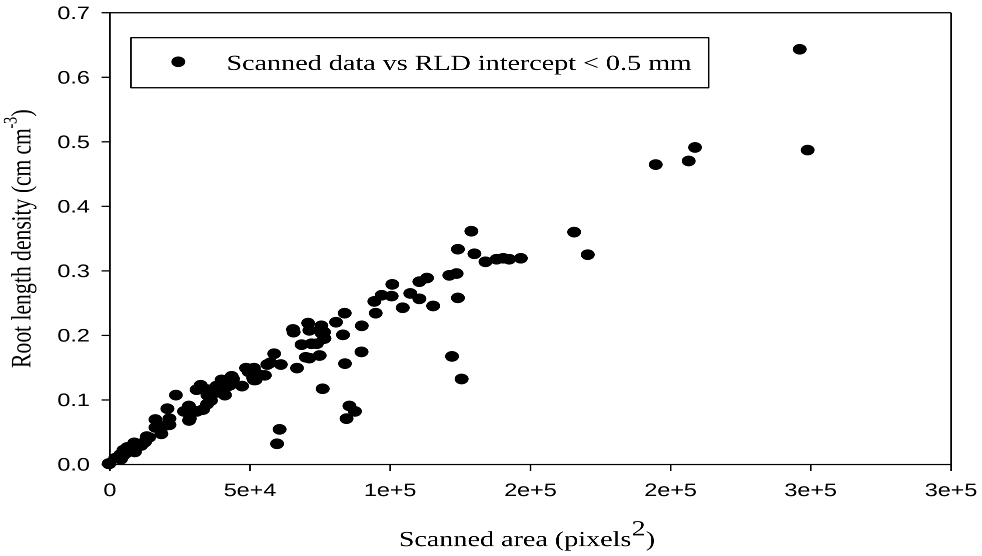


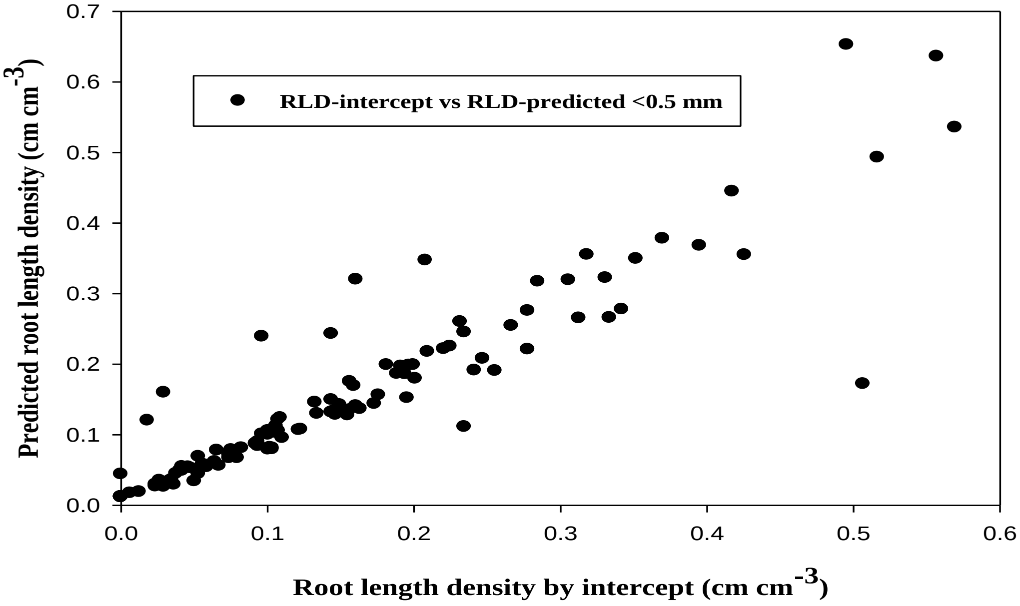
CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT CREC FOR ROOT DIAMETER GREATER THAN 3.0 MM



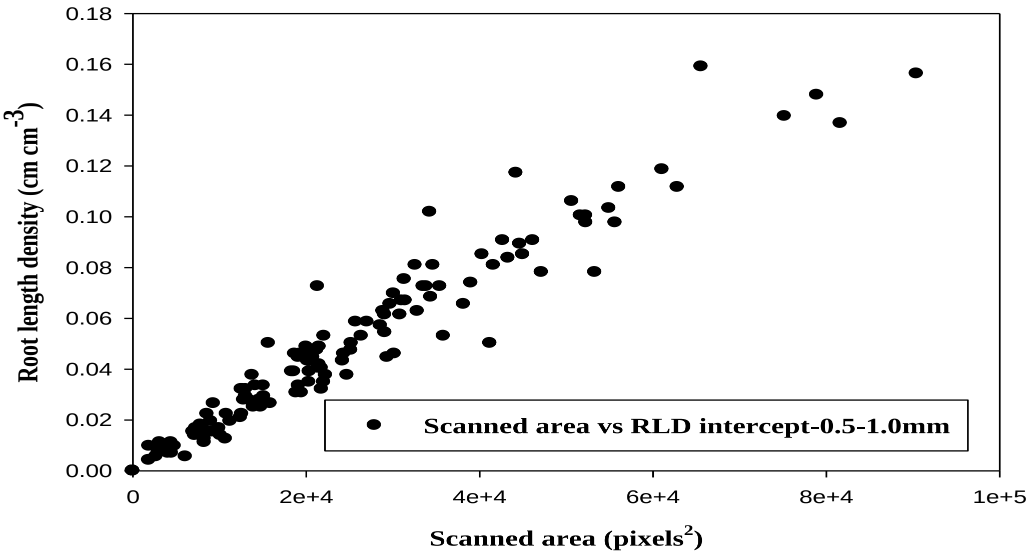


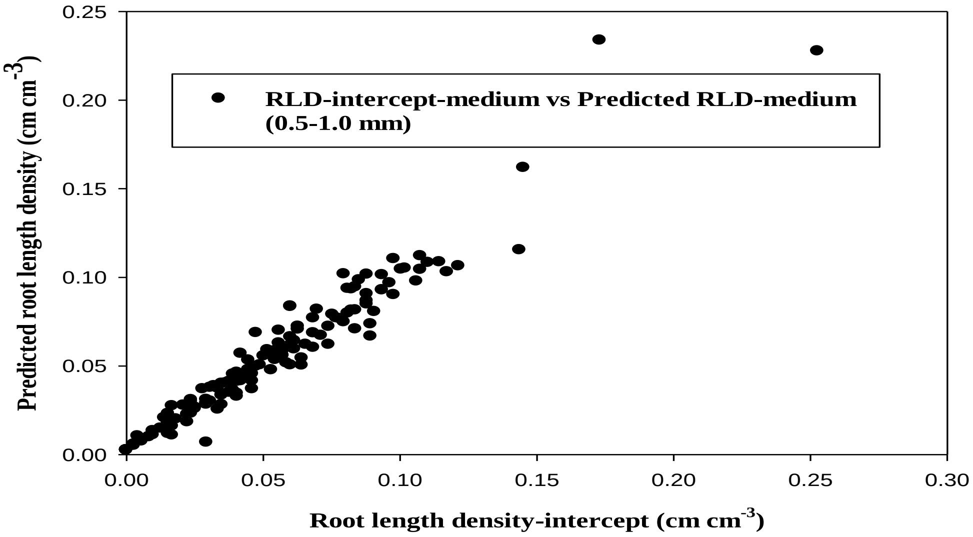
CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT SWFREC FOR ROOT DIAMETER LESS THAN 0.5 MM



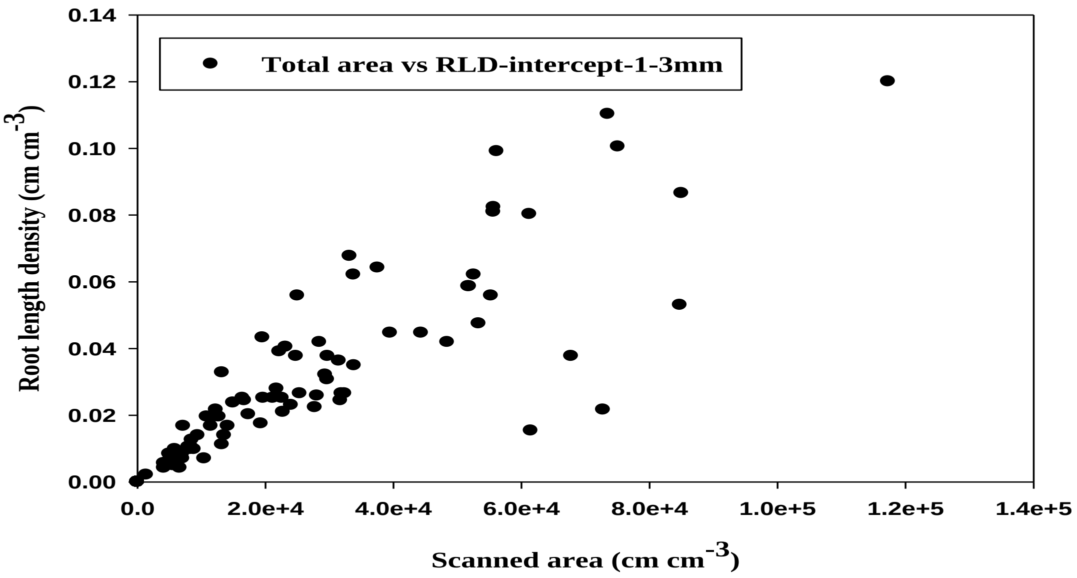


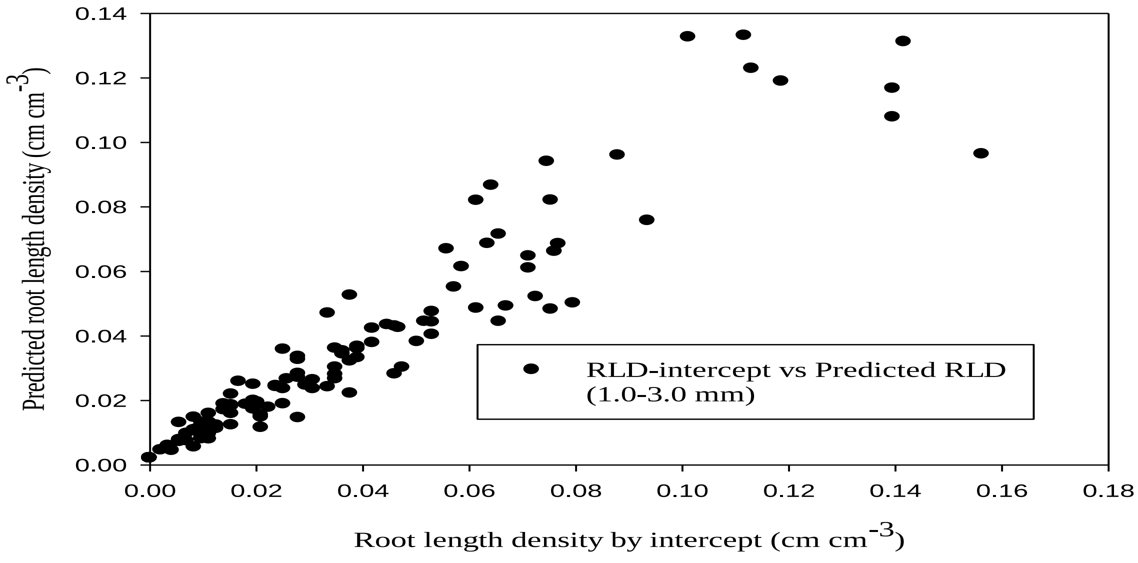
CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT SWFREC FOR ROOT DIAMETER 0.5-1.0 MM



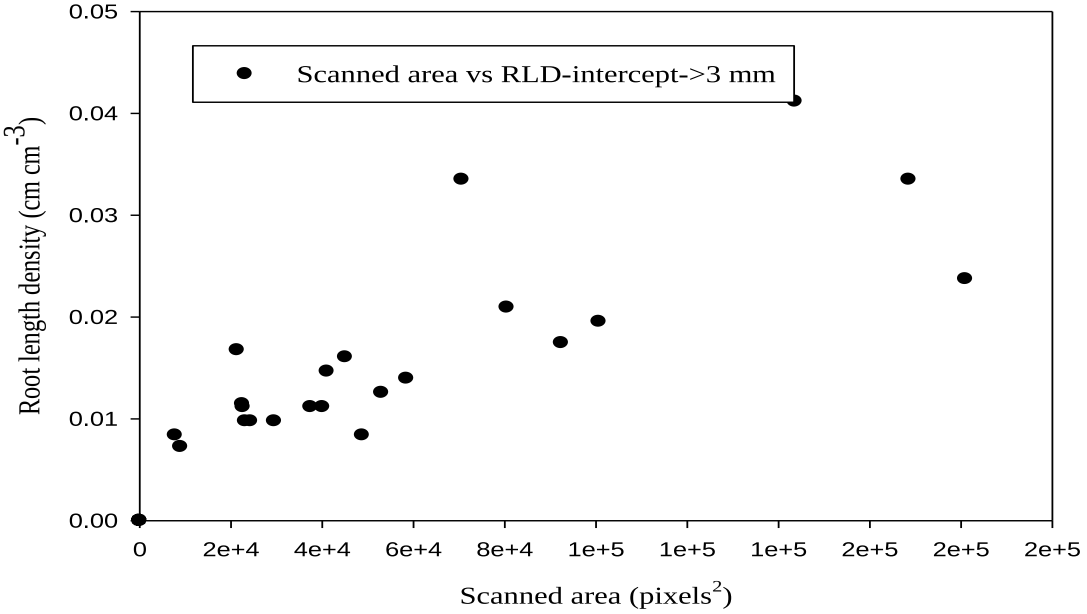


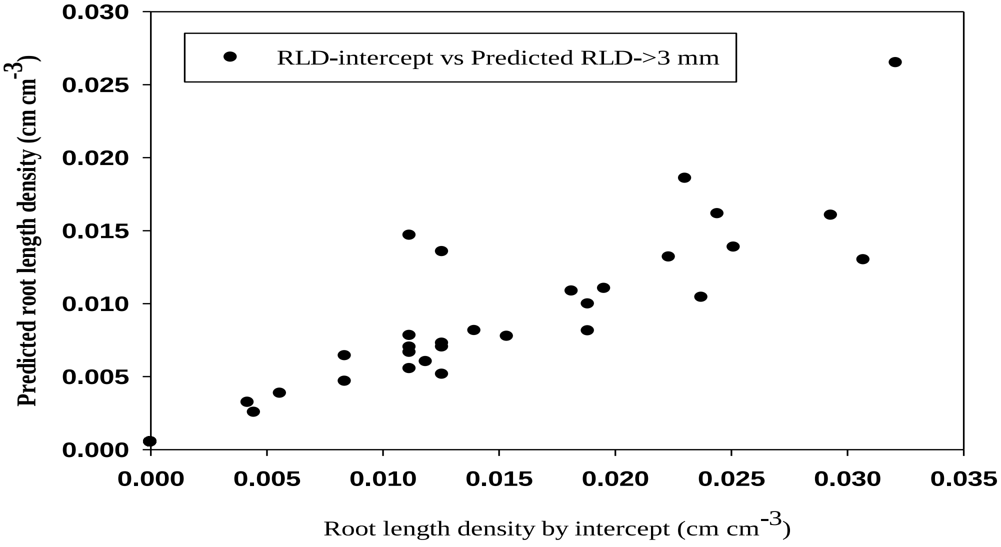
CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT SWFREC FOR ROOT DIAMETER 1.0-3.0 MM





CORRELATIONS BETWEEN RLD MEASURED BY LINE INTERSECTION METHOD AND PREDICTED RLD BY SCANNING METHOD AND SCANNED AREA AT SWFREC FOR ROOT DIAMETER GREATER THAN 3.0 MM





APPENDIX G
EXPERIMENTAL SET UP FOR THE SORPTION STUDY

Ion/Element	Co_1, µg/mL	Co_2, µg/mL	Co_3, µg/mL
P[¶]	10	25	50
P[§]	10	25	50
P[§§]	5	25	50
K^+	6	32	63
NH_4^+	6	32	64

[¶] Case A: In 20mL of 0.01M KCl

[§] Case B: In 20mL of 0.005M $CaCl_2$

[§§] Case C: In 20mL of fertilizer mixture

APPENDIX H
SORPTION COEFFICIENTS FOR NH_4^+ AND K^+ ON IMMOKALEE AND CANDLER FINE SAND USING FERTILIZER MIXTURE IN TAP WATER

Soil	Depth (cm)	NH_4^+		K^+	
		K_D	R^2	K_D	R^2
Immokalee	0-15	1.00	0.98	1.35	0.98
Immokalee	0-15	1.16	0.98	0.69	0.99
Immokalee	0-15	1.19	0.98	0.70	0.99
Immokalee	15-30	1.95	0.94	1.70	0.99
Immokalee	15-30	1.62	0.96	0.65	0.95
Immokalee	15-30	1.35	0.99	0.26	0.93
Candler	0-15	1.52	0.98	2.08	0.99
Candler	0-15	2.04	0.98	1.01	0.95
Candler	0-15	1.41	0.97	1.85	0.90
Candler	15-30	2.20	1.00	1.05	0.99
Candler	15-30	1.64	0.98	1.13	0.89
Candler	15-30	1.44	0.97	0.61	0.99

APPENDIX I
SORPTION COEFFICIENTS FOR P ON IMMOKALEE AND CANDLER FINE SAND

Soil	Electrolyte	Depth (cm)	K_f (mg^{1-N} kg^{-1} L^N)	N	†K_D (L kg^{-1})	R^2
Immokalee	0.01 M KCl	0-15	2.60	0.47	0.62	0.99
Immokalee	0.01 M KCl	0-15	1.36	0.56	0.41	0.99
Immokalee	0.01 M KCl	0-15	3.98	0.28	0.57	0.99
Immokalee	0.01 M KCl	15-30	1.56	0.55	0.46	0.98
Immokalee	0.01 M KCl	15-30	2.24	0.30	0.34	0.93
Immokalee	0.01 M KCl	15-30	2.79	0.49	0.70	0.99
Candler	0.01 M KCl	0-15	9.01	0.61	3.13	0.99
Candler	0.01 M KCl	0-15	7.41	0.58	2.38	0.96
Candler	0.01 M KCl	0-15	11.70	0.51	3.10	0.97
Candler	0.01 M KCl	15-30	19.33	0.48	4.73	0.98
Candler	0.01 M KCl	15-30	15.66	0.46	3.63	0.99
Candler	0.01 M KCl	15-30	13.04	0.46	3.02	0.97
Immokalee	0.005 M $CaCl_2$	0-15	5.00	0.36	0.88	0.91
Immokalee	0.005 M $CaCl_2$	0-15	3.25	0.45	0.73	0.98
Immokalee	0.005 M $CaCl_2$	0-15	2.18	0.54	0.63	0.96
Immokalee	0.005 M $CaCl_2$	15-30	3.56	0.42	0.74	0.99
Immokalee	0.005 M $CaCl_2$	15-30	1.85	0.45	0.42	0.94
Immokalee	0.005 M $CaCl_2$	15-30	3.97	0.51	1.05	0.95
Candler	0.005 M $CaCl_2$	0-15	29.85	0.21	3.51	0.97
Candler	0.005 M $CaCl_2$	0-15	18.04	0.31	2.78	0.97
Candler	0.005 M $CaCl_2$	0-15	30.31	0.26	4.09	0.99
Candler	0.005 M $CaCl_2$	15-30	31.02	0.23	3.86	0.99
Candler	0.005 M $CaCl_2$	15-30	35.69	0.25	4.68	1.00
Candler	0.005 M $CaCl_2$	15-30	33.39	0.28	4.75	0.96
Immokalee	Fertilizer mixture	0-15	NA	NA	0.56	1.00
Immokalee	Fertilizer mixture	0-15	NA	NA	0.41	0.95
Immokalee	Fertilizer mixture	0-15	NA	NA	0.38	0.99
Immokalee	Fertilizer mixture	15-30	NA	NA	0.26	0.91
Immokalee	Fertilizer mixture	15-30	NA	NA	0.37	0.86
Immokalee	Fertilizer mixture	15-30	NA	NA	0.65	0.98
Candler	Fertilizer mixture	0-15	5.17	0.57	1.61	0.95
Candler	Fertilizer mixture	0-15	7.84	0.43	1.67	0.94
Candler	Fertilizer mixture	0-15	15.22	0.23	1.89	0.91
Candler	Fertilizer mixture	15-30	2.73	0.69	1.18	0.98
Candler	Fertilizer mixture	15-30	14.22	0.28	2.02	0.94
Candler	Fertilizer mixture	15-30	14.6	0.41	2.95	0.99

†K_D-Linearized K_D estimated using a C_{max} of 15 mg L^{-1} for Immokalee and Candler fine sand

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BIOGRAPHICAL SKETCH

Davie Kadyampakeni was born in 1979 in Dedza district in central Malawi. He is a 5th born in a family of 5 sons and 3 daughters. He pursued his primary education (elementary education) at Dzenza Primary School and Kasina Preparatory Seminary in the same district between 1984 and 1993. Davie completed his junior secondary education (middle school) at St. Kizito Seminary in Dedza district (1993-1995) and completed his senior secondary education at Ntcheu Secondary School (High School) from 1996 to 1997. Upon completion of high school education as the best student of that year, Davie was selected to the University of Malawi in April 1998 to pursue a Bachelor of Science in Agriculture at Bunda College of Agriculture, specializing in Agricultural Engineering. He completed his first degree in June 2002, receiving several Dean's Honor Awards and was immediately awarded the Regional Universities' Forum for Capacity Building in Agriculture (RUFORUM) Fellowship to pursue a Master of Science (MS) in agronomy at the same college starting in October 2002. Davie completed his MS degree in September 2004 and joined the Malawi Ministry of Agriculture and Food Security as an Irrigation Agronomist in the Department of Agricultural Research Services at Kasinthula Experiment Research Station, Chikwawa, Malawi in October of the same year. In January 2007 he joined the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Chitedze Agricultural Research Station, Lilongwe, Malawi working as a Regional Scientific Officer for Malawi and Tanzania up to December 2007. From January 2008, he worked for the World Bank-IFAD funded Irrigation, Rural Livelihoods and Agricultural Development Project in Zomba, Malawi until August 2008 when he enrolled in the Ph.D. in Soil and Water Science program at the University of Florida. Davie is married to Iness Mhango and they are blessed with a son Atikonda who was born in the final stages of his doctoral program on October 16, 2011 in Naples, Florida. Upon completion and graduation, Davie plans to publish his work in refereed journals before joining the Consultative Group of International Agricultural Research Centers as a Scientist to solve food security problems and poverty in developing countries through soil fertility amelioration and improved irrigation management.