Use of Irrigation Technologies for Production of Horticultural Crops in Florida

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Potential use of irrigation technologies and future research priorities

As outlined in this review, soil moisture sensor and ET based irrigation have shown strong potential for saving of irrigation water. In the past, soil moisture sensors have been used by growers with little adoption due to costs, the level of technical competence and sensor maintenance required to manage these systems. Continued restrictions aimed at reducing nutrient leaching and recent increases in energy costs has increased grower interest in use of improved technologies reviewed in this paper. However, more work is needed to develop irrigation scheduling recommendations and automated control systems that the majority of vegetable and fruit crop growers would rely on. Detailed analysis of sensor position in microirrigated crops, particularly plastic mulched vegetable systems are needed. The use of electrical conductivity (EC) probes to track fertilizer movement would aid growers in development of more effective irrigation management with the potential of reduced leaching. Relationship between EC probe readings and crop performance should be funded to meet this goal.

Advances in soil moisture sensors and irrigation controllers have made them easier to use and the cost of energy has made sensor a more viable alternative. Sensor-based automated irrigation control systems may become more attractive to growers in the near future, particularly if more demonstrations such as the one in a current program on vegetables were funded. Guidelines on commercial automatic soil moisture based irrigation controls should be developed for both vegetables and citrus. The grower guidelines should include number of sensors required and optimum placement relative to varying soil conditions of commercial production. Evaluation of grower acceptance and use of web tools, for both ET and soil moisture monitoring should be funded. Demonstrations of current ET based irrigation scheduling tools in citrus production need to be funded to encourage growers to adopt this technology. Currently, several projects aimed at determining feasibility of daily fertigation and required seasonally adjusted durations to obtain optimum tree growth and production with reduced leaching from applications of high quantities of dry fertilizer are just starting and should be encouraged. Funding of current work on vegetable crop ET to refine the K_c values under drip/mulched irrigation needs to continued and models useful for ET based vegetable irrigation scheduling should be a high priority.

An economic assessment of costs associated with and benefits derived from conversion of irrigation systems in vegetables from seepage to drip irrigation needs to be made to promote water conservation by vegetable growers in south Florida. Current work on the assessment of fertilizer application method and nutrient distribution uniformity in both vegetables and citrus at various rates is needed. Use of reclaimed water as an irrigation source has been well received by growers in general, citrus growers particularly. The processing, pipeline and distribution systems associated with distribution of reclaimed water to agricultural users are very expensive and the limiting factor in use of reclaimed water for agricultural irrigation. Further, food safety restrictions associated with reclaimed water use in vegetables limit use in this segment of the industry. Work on reclaimed water irrigation relative to food safety issues need increased funding.

Abstract. Major horticultural crops in Florida are vegetables (tomatoes, peppers, snap beans), small fruits and melons (strawberry and watermelon) and citrus. Approximately half of the agricultural acreage and nearly all of the horticultural crop land is irrigated. Irrigation systems include low volume microirrigation, sprinkler systems, and subsurface irrigation. This review details the relative irrigation efficiencies of these systems ranging from 80-95% fro microirrigation to 20-70% for seepage. Factors affecting irrigation uniformity such as design and maintenance are discussed. A wide range of soil moisture sensors (tensiometers, granular matrix, and capacitance) are currently being used in the state. The use of these sensors and ET estimation using weather information for the Florida Automated Weather Network in irrigation scheduling are discussed. Current examples of scheduling tools and automated control systems being used on selected crops in Florida are provided. Research data on the affect of irrigation scheduling and fertigation on nutrient, particularly nitrate, are reviewed. Concluding this review is a discussion of potential for adoption of irrigation scheduling and control systems by Florida growers and future research priorities.

Irrigation can be defined as the artificial application of water to the soil for assisting in growing crops and is considered one of the most important cultivation practices in dry or limited rainfall areas and during periods with no or little rainfall. The vegetable and fruit industries in the U.S. are some of the most important sectors of the American agriculture, representing about 30% of the U.S. cash receipts for crops (considering food grains, cotton and tobacco, oil seeds, etc.).

Florida is the top water user in the humid region of the U.S., ranking second in withdrawal of ground water for public supply in the United States and ranks thirteenth nationally for agricultural self-supplied water use (Solley et al., 1998). Agricultural self-supply accounts for 35% of Florida fresh ground water withdrawals and 60% of fresh surface water withdrawals. This category is the largest component of freshwater use with 45% of the total withdrawals in Florida (Marella, 1999). Due to the high water demand by plants in Florida, conservation of water has become a very important aspect of irrigation management.

An approach to conserving water is to maximize the irrigation efficiency and to minimize water loss. Irrigation efficiency is a measure of 1) the effectiveness of an irrigation system in delivering water to a crop, and/or 2) the effectiveness of irrigation in increasing crop yields. Good irrigation practices imply good irrigation efficiency and can be achieved by maintaining a good irrigation water application uniformity and improve water uptake efficiency of the irrigation water. Uniformity can be defined as the ratio of the volume of water used or available for use in crop production to the volume pumped or delivered for use. Crop uptake efficiency may be expressed as the ratio of crop yield or increase in yield over no irrigated production to the volume of irrigation water used. Irrigation efficiencies thus provide a basis for the comparison of irrigation systems from the standpoint of water beneficially used and from the standpoint of yield per unit of water used (Haman, et al., 2005). Irrigation system efficiency depends primarily on three components: 1) design, 2) installation and maintenance, and 3) management. A properly designed and maintained system can be inefficient if mismanaged.

The recommendations of the University of Florida/IFAS for irrigation management of vegetable crops include the following: using a combination of target irrigation volume; a measure of soil moisture to adjust this volume based on crop age and weather conditions; a knowledge of how much the root zone can hold; and an assessment of how rainfall contributes to replenishing soil moisture (Hochmuth, 2007). The remainder of this review will discuss 1) irrigation of horticultural crops in Florida, 2) factors affecting water use efficiency (ie system efficiency, uniformity and maintenance), 3) use of reclaimed water in Florida, 4) irrigation scheduling technologies, 5) irrigation control strategies, 6) use of fertigation in horticultural crops, 7) potential use of irrigation technology and future research priorities.

Irrigation of Horticultural Crops in Florida

Nationally, 53,329,607 acres of crop land are irrigated, Florida agriculture accounts for 3 percent (1,610,798). There are 3,715,257 acres of crop land in Florida (USDA, 2004a). In 2003, 49% (1,815,174 acres) of this land was irrigated and 62% of harvested crop land was irrigated in the same year (USDA, 2004b). In terms of irrigation, virtually all horticultural production is irrigated in Florida due to the economic value of these crops and relatively low water holding characteristics of the sandy soils. These crops include 748,362 acres of tree fruit crops (mostly citrus), 120,306 acres of vegetables (including 37,783 acres of tomatoes), 49,833 acres of potatoes, 14,630 acres of sweet corn, and 5,685 acres of berries (USDA, 2004b).

Although Florida ranks 11th in irrigated acreage nationally (Fig. 1), it is surpassed by only Arkansas in the Eastern U.S. (USDA, 2004b). Irrigated acreage in Florida has increased from approximately 400,000 acres in 1954 to the current level (Smajstrla and Haman, 1998; USDA, 2004b; Fig. 2).

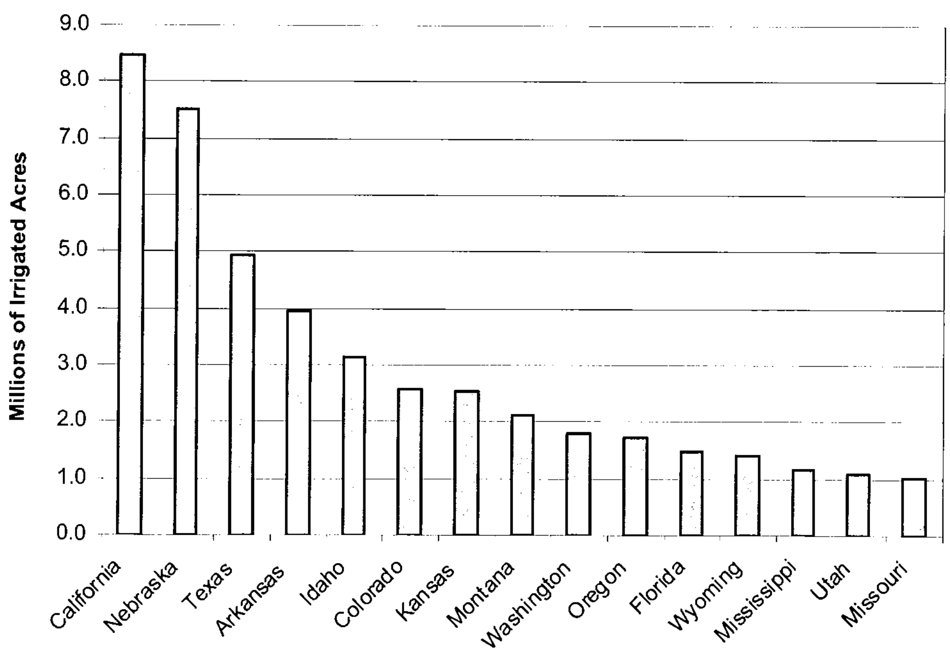

Figure 1. Irrigated acreage for states with more than 1,000,000 acres irrigated (from USDA, 2004b).

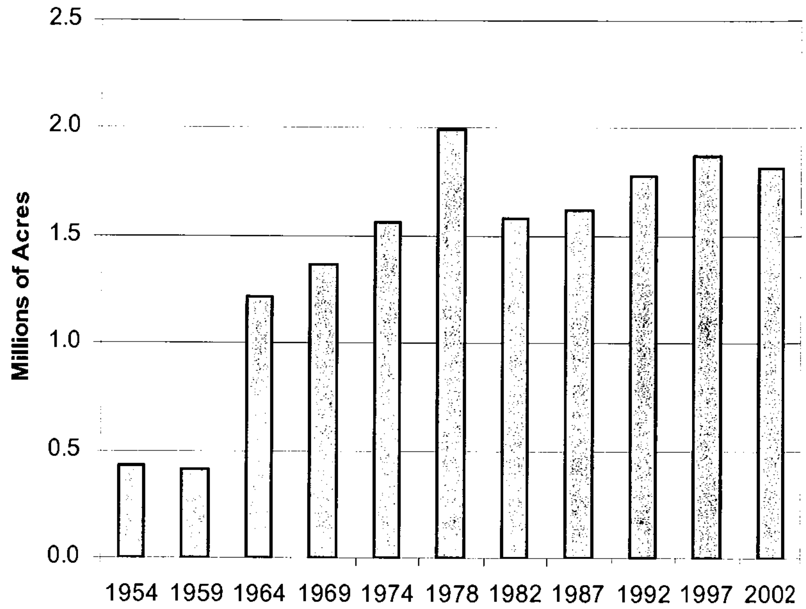

Figure 2. Irrigated land in Florida over time (from USDA, 2004b).

Irrigation Methods

Irrigated acreage in Florida spans a wide range of irrigation delivery systems depending on the type of crop and cultural conditions. Irrigation can be grouped into the following general categories: low volume (also known as microirrigation, trickle irrigation, or drip irrigation), sprinkler, surface (also known as gravity or flood irrigation), and seepage (also known as subsurface irrigation or water table control). Microirrigation and sprinkler irrigation accounts for 6% and 50%, respectively, on a national basis (USDA, 2004a). The largest fraction of irrigated land in Florida is microirrigation (45%, Fig. 3) which is largely due to microsprinkler irrigation of citrus, which accounts for the largest crop acreage in the state. Sprinkler irrigation accounts for 11% of the irrigated land. Florida irrigated agriculture is thus more water use efficient compared with U.S. agriculture in general due to greater application efficiency of microirrigation compared with sprinkler irrigation.

The USDA for many years has ranked gravity irrigation as very high in Florida; however, we believe this nomenclature is incorrect. Strictly speaking, gravity irrigation does not use an artificial power source (i.e. pump) to move water and relies on water infiltrating the ground from the surface. There are a few flood irrigation systems in Florida, the authors believe that gravity and seepage (i.e. subirrigation by USDA) categories refer to the same type of irrigation system where irrigation is primarily due to upward movement of water from capillarity due to an artificially maintained water table. This water table is typically maintained by water furrows where an outlet from a pressurized source is used to deliver water to the furrow (spaced every 60 ft) and thereby maintain the shallow water table. In contrast, gravity irrigation uses water diverted from surface canals to flood entire fields or to flood furrows and then relies on capillarity to move water laterally to the crop root zone. Descriptions of these irrigation methods and their relative efficiencies follow.

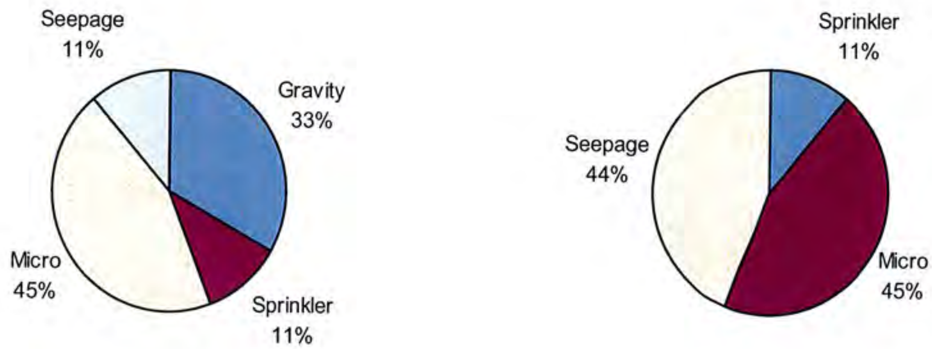

Figure 3. Percentage of total irrigated land by irrigation delivery method according to USDA (2004b) on left and authors' interpretation of USDA data as related to Florida irrigation systems on right. Note that USDA numbers were adjusted slightly to maintain a 100% total.

Sprinkler: Sprinkler systems are designed to use overlapping patterns to provide uniform coverage over an irrigated area. Sprinklers are normally spaced 50-60% of their diameter of coverage to provide uniform application in low wind conditions. Studies have shown that 1.5 to 7.6% of irrigated water can be lost due to wind drift and evaporation during application (Frost and Schwalen, 1960; Kohl et al., 1987). Application efficiencies of sprinkler systems are relatively low at less than 80% (Table 1). Because networks of pressurized pipelines are used to distribute water in these systems, the uniformity of water application and the irrigation efficiency is more strongly dependent on the hydraulic properties of the pipe network. Thus, application efficiencies of well-designed and well managed pressurized sprinkler systems are much less variable than application efficiencies of gravity flow irrigation systems, which depend heavily on soil hydraulic characteristics. Therefore, during water applications, sprinkler irrigation systems lose water due to evaporation and wind drift (Haman, et al., 2005). More water is lost during windy conditions than calm conditions. More is also lost during high evaporative demand periods (hot, dry days) than during low demand periods (cool, cloudy, humid days). Thus, sprinkler irrigation systems usually apply water more efficiently at night (and early mornings and late evenings) than during the day. It is not possible to apply water with perfect uniformity because of friction losses, elevation changes, manufacturing variation in components, and other factors. Traveling guns typically have greater application efficiencies than portable guns because of the greater uniformity that occurs in the direction of travel (Smajstrla et al., 2002). Periodic move lateral systems are designed to apply water uniformly along the laterals. No uniformity and low applications efficiencies occur when the laterals are not properly positioned between settings. Non-uniformity also occurs at the ends of the laterals where sprinkler overlap is not adequate (Smajstrala et al., 2002).

Microirrigation systems: Application efficiencies of microirrigation systems are typically high because these systems distribute water near or directly into the crop root zone, water losses due to wind drift and evaporation are typically small (Boman, 2002; Locascio, 2005). This highly efficient water system (90% to 95%) is widely used on high value vegetables and tree fruit corps. The advantages of microirrigation over sprinkler include: reduced water use, ability to apply fertilizer with the irrigation, precise water distribution, reduced foliar diseases, and the ability to electronically schedule irrigation on large areas with relatively smaller pumps.

If microsprinkler systems are operated under windy conditions on hot, dry days, wind drift and evaporation losses can be high. Thus management to avoid these losses is important to achieving high application efficiencies with these systems. Therefore, management to avoid these losses is important to achieve high application efficiency. The most common application of microirrigation in Florida is that of under-tree microsprinkler systems for citrus. Less efficiency has been found for microsprinkler system compared to drip irrigation system. Application efficiencies of drip and line source systems are primarily dependent on hydraulics of design of these systems and on their maintenance and management (Boman, 2002). It has been reported that drip irrigation gives the highest application efficiency (table 1) for vegetables in Florida compared with seepage and overhead irrigation systems (Simonne, et. al.,2007, Table 1).

Table 1: Application efficiency for water delivery system (Simonne et. al., 2007)

Irrigation system	Application efficiency
Overhead	60-80%
Seepage	20-70%
Drip	80-95%

Seepage/Flood Systems: Water is distributed by flow through the soil profile or over the soil surface. The uniformity and efficiency of the irrigation water applied by this method depends strongly on the soil topography and hydraulic properties (Boman, 2002). Florida's humid climate requires drainage on high water table soils, and field slope is necessary for surface drainage. But surface runoff also occurs because of field slope. Runoff reduces irrigation application efficiencies unless this water is collected in detention ponds and used for irritation at a later time (Smajstrala et al., 2002). Water distribution from seepage irrigation systems occurs below the soil surface. Therefore, wind and other climatic factors do not affect the uniformity of water application. Use of a well designed and well maintained irrigation system reduce the loss of water and thereby increase application efficiency as well as uniformity (Boman, 2002).

Irrigation of Vegetables and Melons

The estimated area planted with vegetables and melons in the United States in 2007 was greater than 1.94 million acres and the estimated value of the crop was 10.9 billion dollars nationwide (USDA, 2008). The four largest vegetable crops, in terms of US production, are onions, head lettuce, tomatoes and watermelons, which combined account for 65% of the total production. In particular, vegetable crop cultivation areas are concentrated in the West, Southeast, Northwest and Great Lakes regions of the U.S. (Fig.4) and the leading states in the order of acreage and dollar value are California, Florida, Georgia, Arizona and New York.

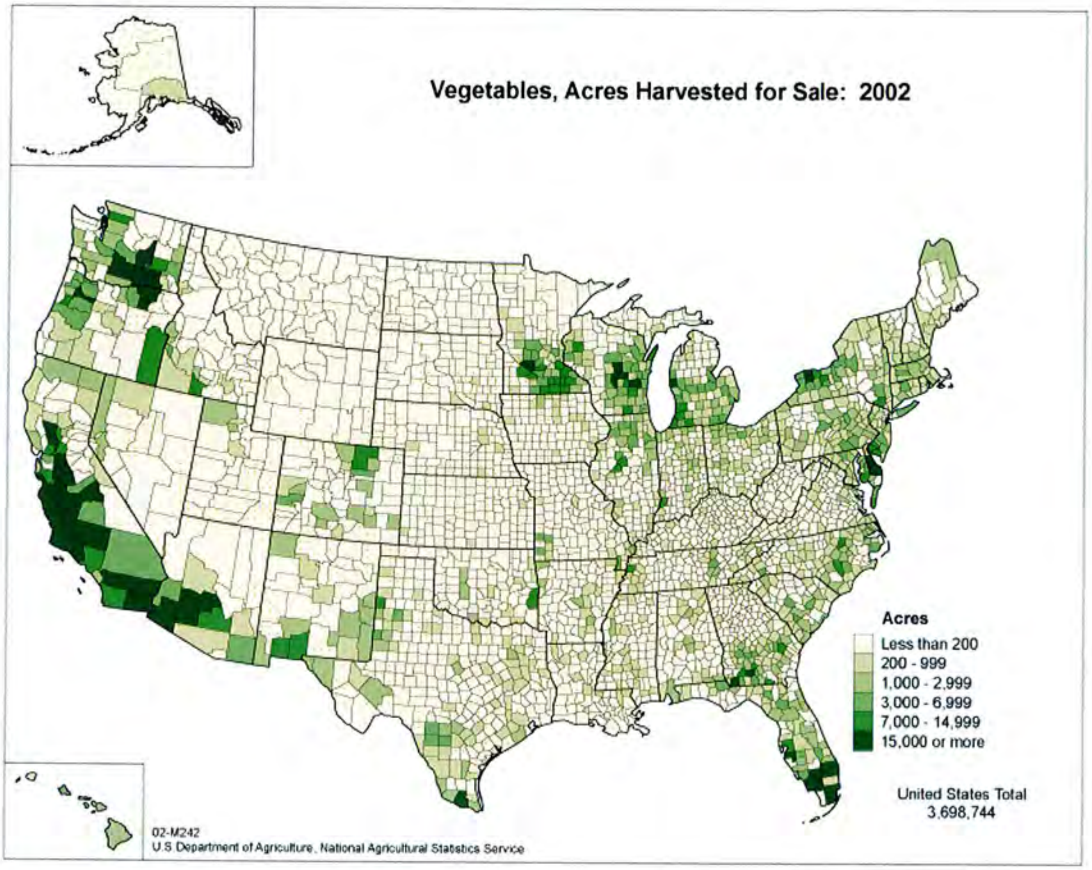

Fig. 4. Vegetable acreage harvested in 2002. Source: Prepared by Economic Research Service using data from USDA – National Agricultural Statistics Service, 2002, Census of Agriculture.

Florida is the most important center of production and distribution of vegetables in the Southeastern U.S. with 181,600 acres planted in 2006 and a crop value greater than 1.2 million dollars (USDA, 2008), (Figs. 5 and 6). Among the vegetable crops cultivated in Florida, tomatoes, bell peppers, sweet corn, strawberries, snap beans, cucumbers are economically the most important. **Tomato** is the most important vegetable commodity in Florida in terms of planted area and crop value. Between 1998 and 2006, the planted area with tomato averaged 42,600 acres, about 20% of the total vegetable area planted in the state. However, high crop value is attached to tomato production, as the average tomato crop value during the same period was 537 million dollars, representing 38% of the total crop value of all state vegetables (FDACS, 2007). South Florida has the largest number of tomato farms in the state and in this area there is a predominance of seepage irrigation. The counties of Collier, Manatee, Hendry, Palm Beach and Dade contain the main tomato production areas using seepage irrigation. The area corresponds to 31%, 25%, 11%, 7% and 6%, respectively, of the total area planted with tomato in the state. Other important production areas are Hillsborough and Gadsden Counties, with 11% and 5% of the state planted area with tomato. In this case, there is a predominance of drip irrigation.

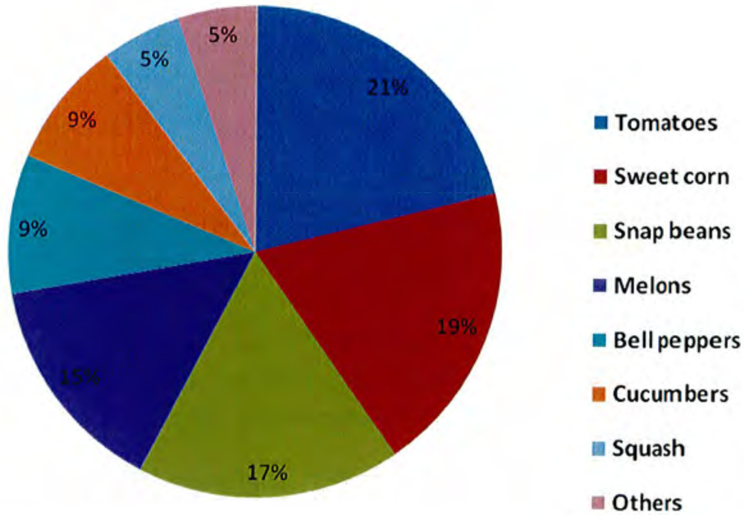

Fig. 5. Percentage of planted area with vegetables in Florida between 1998 and 2006, (USDA, 2008).

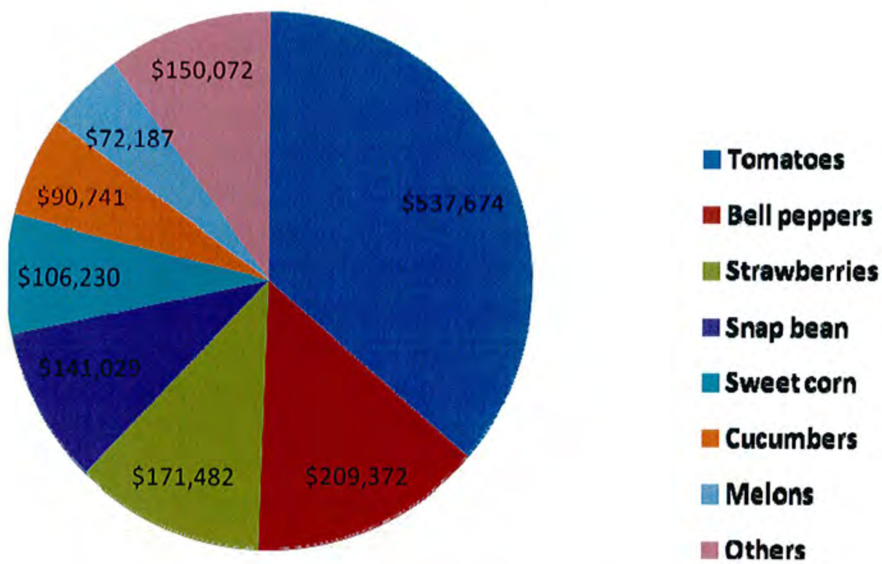

Fig. 6. Crop value in thousands of dollars (US vegetables in Florida between 1998 and 2006, (USDA, 2008).

Florida has around 39,000 acres of sweet corn planted annually, and the crop value is on the order of 108 million dollars. Sweet corn is predominantly grown in Palm Beach (68%) and Dade (13%) Counties and the irrigation management is mainly sprinkler sometimes combined with seepage irrigation.

Snap bean has about 33,000 acres planted annually in Florida. This crop is grown in several counties in Florida, the most important are Dade with 54% of the area planted with snap beans in the state, Hendry with 13%, and Palm Beach and Alachua with 8% each. Snap beans are typically irrigated by sprinklers in Dade and Alachua counties and seepage or drip irrigation in Hendry and Palm Beach Counties.

Watermelon is broadly cultivated in Florida, with around 23,000 acres planted in the state annually. The irrigation managements for this crop are drip irrigation and seepage irrigation, depending on the state region. The counties with drip irrigation are Suwannee with 9% of the total state area planted with watermelon, Manatee with 9%, Levy with 8%, Alachua with 7% and Marion with 4%. Watermelon is grown using seepage irrigation in Hendry Co. with 11%; Charlotte Co. with 7%, Collier and Desoto Co. with 6% each of the total state area planted with this crop.

Bell pepper is the second most important vegetable produced in Florida in terms of value. With a crop value of 209 million dollars, the average acreage annually planted with bell peppers in Florida is 18,500 acres. Palm Beach County has the largest area cultivated with bell pepper, more than 10,000 acres, corresponding to 62% of the area planted. Pepper production is also important in Collier and Hillsborough Counties, with 7% each of the total state planted area with this crop. The predominant irrigation management for pepper is seepage irrigation.

Strawberry is the most valuable crop per unit area in Florida. The average annual crop value is about 171 million dollars; however the area planted with this crop represents only 3% (6,700 acres) of the total area planted with vegetables in FL. Strawberry production is concentrated in Alachua, Pasco, Hillsborough and Polk Counties, and employs drip irrigation as well as sprinkler irrigation for frost protection. Approximately 80 percent of Florida strawberry acreage is drip-irrigated (Haman, 2005).

Irrigation of Tree Fruit Crops

World production of all Citrus varieties totaled 74.5 million metric tons in 2006/07 (FASS, 2007). Citrus production in the U.S. is in Florida (67%), California (28%), Texas (4%) and Arizona (1%) and totaled 9.4 million metric tons for a 13% of world production. Florida citrus production by variety in 2006/07 was oranges (80%), grapefruit (17%) and tangerines (3%). Citrus acreage in Florida was highest at over 941,471 acres in 1970 then declined to less than 625,000 acres in 1985 due to the effect of three successive freezes (FASS, 2007). Since the mid 1980s, Florida citrus acreage has rebound to nearly 857,687 acres in 1998. Citrus acreage has declined over the past 8 years to 621,373 acres due to control of citrus canker and greening diseases and urbanization. With a crop value of $1.362 billion in 2006/07, citrus is one of the most important horticultural crops in Florida. Just over 75% of Florida citrus production is on sandy Spodosols or Alfisols with a spodic or argillic horizon at less than 1 meter below the soil surface (FASS, 2007). These "flatwood soils" are found in the southwest flatwoods (Hendry, Collier, Desoto, Hardee and Hillsborough counties) and eastern flatwoods (St. Lucie, Indian River, Okeechobee and Martin counties) citrus production areas. Because these soils are sandy, nutrient and water holding capacities are quite low (Obreza et al., 1997; Obreza and Collins, 2002). Many of these soils have a confining soil horizon that may permit a perched water table and reduced risk of nutrient leaching. Drainage, the presence or absence of impermeable soil diagnostic horizons, and whether or not the citrus grove is bedded all have considerable influence on citrus root distribution. Because of drainage conditions, these soils are bedded for commercial citrus production, often with additional ditching to remove excess water. The shallow root system is restricted to the upper 12 to 18 inches of soil with approximately one third of the root system extending out to the edge of the bed (Bauer et al., 2005). The remainder of the root system is located toward the center of the bed.

The remaining citrus acreage (26%) of Florida citrus is grown in the central Florida ridge area (Polk, Highlands and Lake counties) on Entisols, which are characterized by uncoated sand with low organic matter content, therefore have very limited water and nutrient holding capacities (Obreza et al., 1997; Obreza and Collins, 2002). These "ridge soils" are deep and well drained, requiring little to no drainage. Root zones on these Entisols are not restricted by soil horizons and are typically 36 inches deep or greater (Morgan et al., 2007). Over the past 20 years, nearly all Florida citrus irrigation has been converted from high volume sprinkler to low volume under tree microsprinkler irrigation.

Tropical tree fruit crop Production (e.g. avocado, mango and etc.) is restricted to approximately 7,700 acres in Dade and Brevard counties (FASS, 2003). These tree fruit crops are typically irrigated with sprinkler or microsprinkler systems. Temperate fruit crops (e.g. peaches and blueberries) have been grown on as many as 4,000 acres in the 1960's. These fruit crops now account for approximately 500 acres (Ferguson et al., 2007a,b). Irrigation of these crops had been dominated by high volume impact sprinklers but these have been converted to water conserving microsprinkler systems.

Water Use Efficiency

Concerns about the environmental impact of water and fertilizer use by agriculture have dramatically increased in past few years. Crop production is linked to leaf photosynthesis and canopy size, and water stress drastically reduces both components (Kramer and Boyer, 1995). Adequate water supply is therefore critical in maximizing crop production, nutrient use efficiency and quality of most horticultural crops. Efficient water use may promote an increase in fertilizer retention in the effective root zone, maximizing crop production and minimizing the potential of groundwater degradation (e.g. nitrate leaching) (Scholberg et al., 2002). A simple goal of the ideal irrigation scheduling would be to increase crop production with the least amount of water, therefore minimizing water loss by deep percolation, runoff or evaporation. However, no irrigation system has the capability of completely avoiding water losses, although several irrigation methods and techniques can be adopted to minimize losses and increase the water use efficiency by crops.

Irrigation System Efficiency

In terms of irrigation efficiency, Florida has the second highest acreage of microirrigation in the U.S., which is encouraging because properly maintained and operated microirrigation systems are typically 80-90% efficient. However, approximately 44% of Florida acreage is seepage irrigated, most of this acreage is under high value crop production such as fresh market vegetables and potatoes. Unfortunately, this type of irrigation is no more than 50% efficient due to the large amount of water required to constantly maintain a shallow water table throughout the crop season. However, growers like this type of irrigation system due to its relative ease of operation (e.g. constant pumping during the season) and because the infrastructure costs are much lower than with systems such as drip irrigation. Thus, as water supplies become strained, one option to increase irrigation efficiency is conversion from seepage to drip irrigation.

How well a System is designed and managed has a great influence on irrigation system application efficiencies. Tables 2 and 3 contain reasonable values of irrigation efficiency for scheduling irrigation in typical Florida soil to meet the crop water requirement (Smajtrala et al., 2002). Application efficiencies are likely to be changed if irrigation systems are operated to apply water for other purposes, for examples, application efficiencies will be reduced if water is applied for leaching of salts, freeze protection, establishment of young plants, crop cooling, or other beneficial uses.

Table 2. Pressurized Irrigation system application efficiencies, Ea (%) in Florida (from Smajtrala et al., 2002).

System Type	Range	Average
Solid set Sprinkler systems	70-80	75
Portable guns	60-70	65
Traveling guns	65-75	70
Center pivot and lateral move systems	70-85	75
Periodic move lateral	65-75	70
Surface	70-90	85
Subsurface	70-90	85

Table 3. Gravity flow irrigation system application efficiencies, E_a (%) in Florida (from Smajtrala et al., 2002).

System type	Range (%)
Subirrigation (seepage systems)	
Flow through	20-70
Tailwater recycle	30-80
Semi-closed conveyance	
Flow through	30-70
Tailwater recycle	40-80
Subsurface conduit systems	40-80
Surface (flood) systems	
Crown flood systems	25-75
Continuous flood (paddy) systems	25-75

Application Uniformity

One important irrigation management factor is irrigation uniformity, which is how evenly water is distributed across the field. Non-uniform distribution of irrigation water may create zones of over- and/or under-irrigation which can lead to yield reduction due to excessive nutrient leaching or plant water stress.

For a sprinkler irrigation system the uniformity of application can be evaluated by placing containers in a geometric configuration and measuring the amount of water caught in each container. Dukes (2006) utilized this type of testing to show that effect of pressure and wind speed on operating performance of two types of center pivot sprinkler system nozzle packages. Furthermore, Dukes and Perry (2006) showed that uniformity of a variable rate control system was not different than a traditional control system on two typical center pivot/linear move irrigation systems used in the Southeast U.S. However, the problem of sprinkler systems is that the water application pattern is susceptible to distortion by the wind. While wind speed and direction are not controlled variables, their effect on irrigation uniformity is significant, so that sprinkler system design must be done with anticipated wind conditions. Under windy conditions, reduce the spacing between laterals when possible to optimize the application uniformity. Maintenance of adequate water pressure through the entire systems, repairing leaks and replacing malfunctioning sprinklers, is also a way to improve the irrigation uniformity.

Drip irrigation systems are very efficient in terms of water distribution and reduction of water losses. The uniformity is directly related to the pressure variation within the entire system and the variability of the emissions of each individual emitter. Several factors contribute to reduce the uniformity of water application such as excessive length of laterals, excessive pressure losses due to changes in elevation along the laterals, emitter clogging and soil characteristics. Specifically for drip irrigation where the number of point sources of water (emitters) is limited, the uniformity of application can be compromised by the soil characteristics, leading to a very intense water percolation during long irrigation events. The water holding capacity of sandy soils is very low because of the large spaces between soil particles (macro pores with diameter higher than 0.06 mm), through which water can pass rapidly.

Conversely for finer texture soils, smaller pore sizes are dominant and due to capillarity higher lateral movement is expressed. The important aspect of such flow in sandy soils (most of Florida soils) is that water and nutrients (particularly nitrate) can infiltrate downward through soil profile much faster than finer soils. It is also important to point out that preferential pathways lead to dramatic reduction in wetted soil volume and increase of nutrient leaching which can be crucial for root development, plant growth and yield on many vegetables. The limited lateral water movement in sandy soils under drip irrigation drastically affects the root distribution (Zotarelli et al., In Press) and nutrient interception in the sides of the raised bed (Fig 7).This could be a problem for double row crops like peppers and squash when a single drip tape in center of the bed is placed.

Fig. 7 Picture of lateral movement of irrigated water for pepper in a sandy soil after a hour of irrigation event. (A) left side of the bed and (B) right side of the raised bed. (Photo: L. Zotarelli, University of Florida, Plant Science Research Unit, Citra. FL. Oct. 2007)

Non-uniform distribution of water in the bed may also compromise the acquisition of nutrients by the root system. Since nitrate is a highly mobile, non-adsorbing ion, low rooting densities may not be sufficient for nitrate acquisition, and a larger fraction of the N applied through fertigation can escape below the root zone. The basis for this lies in previous field observations which demonstrated that the displacement of irrigation water and nutrients is primarily vertical and confined to a 12-15 inch wide zone, due to the extremely high hydraulic conductivity of our sandy soils (Zotarelli et al., unpublished data). With the use of conventional irrigation practices such as single application, water and nutrients are thus displaced up to 3-4 feet within one week, while the effective vegetable rootzone may only be 1-2 feet deep. The use of appropriate irrigation scheduling facilitates more frequent applications of small volumes of water and improves matching of water supply and crop water demand which is critical to reduce potential crop water stress and leaching losses in sandy soils (Zotarelli et al. 2008a,b; Zotarelli et al., in press). Since applying frequent small volume irrigation with conventional systems tends to be labor intensive and/or technically difficult to employ, sensor-based irrigation systems may facilitate the successful employment of low volume-high frequency irrigation systems in commercial vegetable systems. In addition, reduction in emitter spacing and also the use of double drip tapes placed closer to the crop rows may improve the uniformity of water and nutrient distribution along the beds, while reducing the amount of water required. However, there is a lack of information about the effectiveness of this system for double row crops.

Irrigation System Maintenance

Microirrigation systems are technically more complex than overhead sprinkler or flood irrigation systems. Low volume irrigation systems require significant maintenance to assure maximum operational efficiency. The performance of a micro-irrigation system may rapidly deteriorate if it is not routinely maintained Properly (Obreza, 2004). Maintenance to improve system uniformity includes checking for leaks, backwashing and cleaning filters, periodic line flushing, chemical injection (e.g. chlorinating and acidifying), and cleaning or replacing plugged emitters. Proper maintenance of a micro-irrigation system will extend system life, improve performance, minimize down-time, reduce the probability of non-uniform water and fertilizer applications due to emitter plugging, reduce operating costs, save water and fertilizer.

Reclaimed Water Use in Florida

Florida is recognized as a national leader in the water reuse totaling over 1.1 billion gallons per day or about 52 percent of the state's total domestic wastewater treatment plant capacity in 2001 (Water Reuse Work Group, 2003). Currently there are 440 reclaimed water reuse systems in Florida irrigating 92,345 ha with 2,385 million liters of reclaimed water per day (Florida DEP, 2005). The majority of these systems irrigate golf courses, public right-of-ways, and home landscapes. However, 6,144 ha of production agriculture are currently irrigated with reclaimed water, with citrus orchards accounting for all but 364 ha (table 4).

Table 4. Florida's use of reclaimed water

Reuse Type	% of Reclaimed Water Used
Landscape Irrigation	44%
Agricultural irrigation	19%
Ground water recharge	16%
Industrial activities	15%
Wetland and other activities	16%
Total	100%

In 1998, 88 mgd of reclaimed water was used to irrigate about 33,500 acres of agricultural land. Although most of this reclaimed water was used to irrigate feed and fodder crops, 20 mgd was used to irrigate over 15,200 acres of edible crops. The permitted reuse capacity of all edible crop systems was 41 mgd. While citrus represents the primary edible crop irrigated with reclaimed water, a wide range of other edible crops (e.g. tomatoes, cabbage, peppers, watermelon, corn, eggplant, strawberries, peas, beans, herbs, squash, and cucumbers) also are irrigated with reclaimed water (York et al. undated).

The legislature of Florida has established a rule in 1989 regarding the use of reclaimed water to irrigate edible crops. This rule prohibits direct contact application methods (spray irrigation), if reclaimed water is to be used to irrigate crops that will not be peeled, skinned, cooked, or thermally processed before human consumption (the so-called "salad crops"). Indirect contact methods (drip, subsurface, and ridge and furrow irrigation) may be used to irrigate the salad crops. Any type of irrigation system may be used to irrigate tobacco, citrus, and any crop that will be peeled, skinned, cooked, or thermally processed before human consumption.

Experiments on 'Marsh' grapefruit trees conducted near Vero Beach found that trees receiving reclaimed wastewater tended to have higher leaf K and B levels than the control trees; however, B levels were not in the toxic range. Leaf P, Mg, Cu, Mn, and Zn levels were similar for all trees.

All reclaimed wastewater treatments caused significantly greater weed growth than the control treatment. Therefore, reclaimed wastewater can be effectively used to irrigate resets with no deleterious effects provided that weed growth is controlled (Maurer et al., 1995).

Conserv II provides reclaimed water for agricultural irrigation to portions of Orange and Lake Counties near Orlando. The project currently delivers approximately 133,000 cubic meters of reclaimed water per day (cmd) (275,000 cmd maximum flow) about 20 miles west from Orlando and is used to irrigate about 10,035 acres of citrus groves, 7 foliage and landscape nurseries, 2 tree farms, 3 ferneries, and 2 golf courses. The capacity of the system is 65.5 mgd. About 20.0 mgd of reclaimed water was used for irrigation and 16.7 mgd was used for ground water recharge in 2000 (Cross and Lathrop, 2000). The reclaimed water meets a number of drinking water standards (Table 5), is low in heavy metal concentrations, and has no odor or color.

Studies were conducted to determine if citrus could tolerate high application rates of reclaimed water (Parsons and Wheaton, 1992). In research plantings, very high rates of up to 100 inches/year were applied to two citrus varieties, Hamlin orange and Orlando tangelo, on four rootstocks. Application of 100 inches of reclaimed water significantly increased canopy volume and fruit yield compared to 16-inch applications of ground water and reclaimed water.

Weed growth can be controlled with proper herbicide use and mowing and is not as great a problem in mature groves. Irrigation with reclaimed water increased soil and leaf phosphorus, calcium, and sodium content. Leaf levels of sodium, chloride, and boron were elevated but remained below toxic levels (Parsons and Wheaton, 1996, Morgan et al., 2008). Annual energy savings from eliminating irrigation pumping costs can be as much as $128/acre (Cross and Lothrop, 2000).

In an evaluation of the nutritional value of this reclaimed water, trees that were given no fertilizer and irrigated only with reclaimed water took two to five years to show nutrient deficiency symptoms and yield declines. In experimental plots, high application rates of reclaimed water maintained yields for one year, but yields declined in the second year without additional fertilizer application (Wheaton, et al., 1998). Although reclaimed water provides all the phosphorus, calcium, and boron required by trees in central Florida, this water cannot supply sufficient nitrogen, even if it is applied at high [100 inches/year] rates (Parsons, et al., 1999). A survey of commercial orchards receiving either reclaimed or well water over a ten year period indicated no detrimental increase in soil or leaf nutrient concentrations over time (Morgan et al., 2008).

Irrigation Scheduling

Irrigation scheduling consists simply of applying water to crops at the "right" time and in the "right" amount. Scheduling often consists of grower judgment or a calendar based schedule of irrigation events based on previous seasons. Several factors such as plant evaporative demand, soil characteristics and root distribution are taken into account as well, in order to establish proper irrigation scheduling (Locascio 2005). The simplest form of scheduling is the "feel" method as outlined by the USDA NRCS (1998). A wide range of irrigation scheduling methods is used in Florida with corresponding levels of water managements. The recommended method for schedule irrigation (drip or overhead) for vegetable crops is to use together, (1) the crop water requirement method that takes into account plant stage of growth; (2) a measurement of soil water status; and (3) guidelines for splitting irrigation (Simonne et al., 2007).

Table 5. Maximum allowable contaminate limit (MACL) for Florida drinking water and Conserv II reclaimed water, and typical Water Conserv II reclaimed water concentrations. All values are in mg L^{-1} except for pH and EC (from Morgan et al., 2008).

	Drinking water MACL	Well water typical concentrations	Conserv II reclaimed water MACL	Typical Conserv II reclaimed water concentrations
		---mg L^{-1}---		
Arsenic	0.05	--	0.10	<0.005
Barium	2	--	1	<0.01
Beryllium	0.004	--	0.10	<0.003
Bicarbonate	--	--	200	105
Boron	--	0.02	1.0	<0.25
Cadmium	0.005	--	0.01	<0.002
Calcium	--	39	200	42
Chloride	250	15	100	75-81
Chromium	0.1	--	0.01	<0.005
Copper	1	0.03	0.20	<0.05
EC (µmhos)	781	360	1100	720
Iron	0.3	0.02	5	<0.4
Lead	0.015	--	0.1	<0.003
Magnesium	--	16	25	8.5
Manganese	0.05	0.01	0.20	<0.04
Mercury	0.002	--	0.01	<0.0002
Nickel	0.1	--	0.20	0.01
Nitrate-N	10	3	10	6.1-7.0
pH	6.5-8.5	7.8	6.5-8.4	7.1-7.2
Phosphorus	--	0.01	10	1.1
Potassium	--	6	30	11.5
Selenium	0.05	--	0.02	<0.002
Silver	0.1	--	0.05	<0.003
Sodium	160	18	70	50-70
Sulfate	250	23	100	29-55
Zinc	5	0.02	1	<0.06

Soils hold different amounts of water depending on their pore size distribution and their structure. The upper limit of water holding capacity is often called "field capacity" (FC) while the lower limit is called the "permanent wilting point" (PWP). The total amount of water available for plant uptake is the "available water" (AW) which is the difference between FC and PWP (Fig. 8) and is often expressed a percent by volume (volume of water/volume of sample). The "plant available water" (PAW) is determined by multiplying the AW (in units of water depth) by the root zone depth where water extraction occurs. Depletion of the water content to PWP adversely impact plant health and yield. Thus for irrigation purposes, a "maximum allowable depletion" (MAD) or fraction of PAW representing the plant "readily available water" (RAW) is essentially the operating range of soil water content for irrigation management. Theoretically irrigation scheduling consists of irrigating at a low threshold corresponding to a water content at a given MAD and irrigating until the depleted water has been replaced to but not more than the FC level, otherwise drainage and or deep percolation will occur.

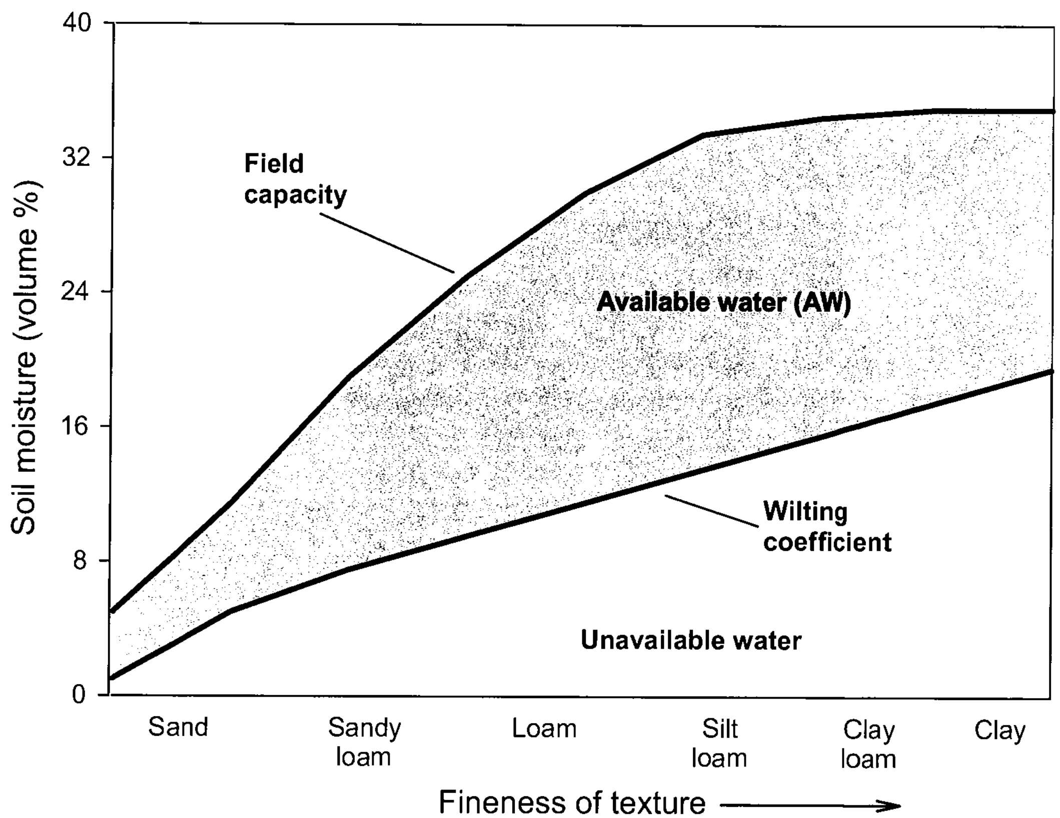

Fig. 8. General relationship between soil moisture characteristics and soil texture. Adapted from Brady, 1990.

Soil Moisture Measurement

Soil moisture (*water content*) can be measured directly by the gravimetric method. This entails sampling the soil with a core sampler, weighing the moist soil, then drying it in an oven, and then weighing the dry soil. However, this method is destructive (i.e., it is not possible to measure in the same location twice, and it does not yield instantaneous results) (Muñoz-Carpena et al., 2005b). Many sensors are available to determine the approximate *in situ* water content including time domain reflectometry (TDR), neutron probe, frequency domain sensor, capacitance probe, electrical resistivity tomography, and others that are sensitive to the physical properties of water.

Accurate determination of soil moisture status is the prime factor of a good irrigation management practice. There are different direct or indirect methods to measure the soil moisture content. The following are common methods and sensors used to determine soil water content.

Feel and appearance method: This method is the quickest and simplest way to measure soil moisture in the field. This method involves collecting soil samples from near the tree's drip line in an area watered by the irrigation system. However, this method needs a good experience and judgment of the sampler to get maximum accuracy in determining soil water status (USDA-NRCS, 1998).

Gravimetric soil moisture determination: Gravimetric analysis is the most widely used technique to standardize soil moisture sensors. Samples are collected, weighed and oven-dried at 105^0C. Water content can be determined on the basis of weight loss. Although this gives an accurate measurement, this technique has a number of disadvantages. Laboratory equipment, sampling tools, and 24 to 48 hours of drying time are required. Besides, it is impossible to measure soil water at exactly the same point at a later date.

Tensiometers: These devices measure the soil water content indirectly by measuring the energy exerted by a plant to extract water. Tensiometers indicate the soil water status for soils as they become drier in response to crop use and as they receive water from rainfall or irrigation. Frequent servicing is needed when air bubble accumulate in the tube of the tensiometer. Freezing temperatures can damage the vacuum gauge, the most expensive part of a tensiometer. This device needs to be in an area wetted by the micro- irrigation system to provide best information (Boman and Persons, 2002).

Granular Matrix Sensors: Similar to tensiometers, these sensors are made of a porous material that reaches equilibrium with the soil moisture tension, which is correlated with a measurement of resistance (Irmak and Haman, 2001). These sensors have been used in a wide range of applications to initiate automatic irrigation from onion and potato (Shock et al., 2002) to urban landscapes (Qualls et al., 2001). Generally, these sensors have been found to require less maintenance than traditional tensiometers. Similar to many of the automatic tensiometer controlled irrigation systems, Shock et al. (2002) described a system that used GMS to initiate a timed irrigation event.

Resistive sensors: these electromagnetic sensors depend on the effect of water on the electrical properties of a soil. Soil resistivity depends on water content. The most common method of estimating matrix potential is with gypsum or porous blocks. They are insensitive to small change in water content; however, they are sensitive to soil water salinity (Boman and Persons, 2002). These blocks are economical, easy to install, allows continuous soil water measurement and require less calculations. The major disadvantage of gypsum blocks are they deteriorate with time and each block has somewhat different characteristics and should be calibrated individually. Besides, gypsum blocks do not work well in sandy soils and they are sensitive to temperature and salts in soil. There fore, use of this method in sandy Florida soil with less water holding capacity is not recommended (Boman and Persons, 2002).

Capacitive sensors: in this method, volumetric soil water content is determined by measuring the capacitance between two electrodes implanted in the soil and must be calibrated to produce accurate moisture measurements (Morgan et al., 1999). These sensors rely on the fact that water has much higher dielectric constant than air or dry soil. Two types of devices are available: portable sensor with an access tube, and permanently installed with numerous sensors connected to a data logger. Unlike gypsum blocks, these sensors are sensitive to salts and water content can be measured at any depth. They provide high accuracy; no hazard is associated with their use. However, determining the water content of a soil by this method needs a complex calibration method. High cost is the major disadvantage of this method.

Time-Domain Reflectometry (TDR): TDR measures the movement of electromagnetic waves or signals through soil. The advantage is that they can make relatively accurate measurements and they are not sensitive to salt. Disadvantages include the cost of the instrument.

Remote Sensing Techniques: The remote sensing of soil water depends on the measurement of the electromagnetic energy that has been reflected or emitted from the soil surface. Satellite remote sensing method: satellite microwave remote sensing is used to estimate soil moisture based on the large contrast between the dielectric properties of wet and dry soil. The data from microwave remote sensing satellite such as WindSat, AMSR-E, RADARSAT, ERS-1-2 are used to estimate surface soil moisture (Dingman, 2002).

Other sensing technologies that are being researched for irrigation scheduling include microwave and infrared technologies used to determine soil water content. Typically, these technologies are deployed via aircraft and are intended to survey large areas. Thus, they are much more expensive than other sensor technologies; however, they can be used to determine soil moisture status over large areas very quickly. Another disadvantage is that they do not penetrate the soil more than several centimeters, making them inadequate for irrigation scheduling.

Among all the above mentioned devices used for determining soil moisture content in Florida, tensiometers are the instruments most commonly used for scheduling irrigations. Gypsum blocks are also used on a limited basis, but they are not very effective in the range required for irrigation scheduling on typical Florida sandy soils. (Smajstrla et al, 2004). Both of these instruments register the status of water in the soil, in terms of soil-water tension, at the depth at which the device is placed. When placed in the plant root zone, they indicate the soil water status that the plants are experiencing. Disadvantages of soil moisture sensors include their cost, labor requirements for reading and servicing, and the need for periodic calibration. Sensors also measure soil water status at a point rather than for the whole field, thus many instruments may need to be installed to accurately represent a given field (Smajstrla et al, 2006).

Evapotranspiration Measurement

Many field calibrated evapotranspiration (ET) models meet the objective of forecasting irrigation dates with continuous weather updating. However, a major problem still exists in determining the proper amount of water to apply to irrigated fields (Thomson and Ross, 1996). Over the years, some sensor-based scheduling methods have been used to indicate how much water to apply. These methods observed sensor responses to wetting to adjust subsequent water amounts (Stolzy et al., 1959; Fischbach and Schleusener, 1961; Skinner, 1976). Use of crop ET (ET_c) is currently being used in citrus irrigation but not vegetables.

Allen et al. (1998) proposed that ET_c can be derived from a reference ET (ET_o) as follows:

$$ET_c = (ET_o)(K_c)(K_s)$$

Where: ET_c = Crop evapotranspiration (mm d^{-1});
ET_o = Potential evapotranspiration (mm d^{-1});
K_c = Crop coefficient;
K_s = Soil water depletion coefficient.

The crop coefficient (K_c) is defined as the ratio of ET_c to ET_o when soil water availability is non-limiting. In this case, the soil water depletion coefficient (K_s) is assumed to be equal to unity. K_c is indicative of climatic and/or developmental effects on ET_c compared with ET_o. Estimates of K_c for a wide range of citrus tree sizes span from 0.6 in the fall and winter to 1.2 during the summer months (Boman, 1994; Fares and Alva, 1999; Martin et al., 1997; Rogers et al., 1983). As soil water content (WC) decreases, soil water potential (WP) also decreases, resulting in lower plant soil water uptake and thus lower ET_c/ET_o ratios.

Allen et al. (1998) suggested that for most soils, a value of WP less than FC exists where water uptake is not limited by WP. They referred to the range of WC above a critical threshold value 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 (Fig. 1).

$$K_s = \frac{[TAW - (\theta_{FC} - \theta)]}{TAW - RAW} = \frac{\theta - \theta_{WP}}{\theta_t - \theta_{WP}}$$

Where: K_s = Soil water depletion coefficient ($K_s \leq 1$);
TAW = θ_{FC} - θ_{WP} = Total available water ($cm^3\ cm^{-3}$);
θ_{WP} = Permanent wilting point soil water content ($cm^3\ cm^{-3}$);
θ = Soil water content ($cm^3\ cm^{-3}$);
θ_{FC} = Field capacity soil water content ($cm^3\ cm^{-3}$);
RAW = θ_{FC} - θ_t = Readily available water ($cm^3\ cm^{-3}$).

The greater the RAW for a given soil, the longer water can be withdrawn from it before ET_c is limited. Thus, K_s is a measure of the reduction in ET_c caused by reduced soil water uptake due to decreased WC and WP. However, our experience in Florida has suggested that RAW in sandy citrus soils is much smaller than the relative amount suggested by Allen et al. (1998). If one assumes that K_c is constant over relatively short time periods, then the reduced ET_c/ET_o ratios must be a result of lower K_s values. Therefore, the correction coefficient used to estimate ET_c from ET_o is a product of K_c and K_s [(K_c)(K_s)].

When managing water for citrus production, WC must be maintained within a range that allows sufficient water uptake for optimum growth while simultaneously preventing nutrient leaching below the root zone. While the upper limit of WC is typically defined as FC, the soil water content at which redistribution of water essentially ceases after free drainage occurs (Hillel, 1998), the lower limit (PWP) is harder to define and depends greatly on soil physical characteristics. If the effects of soil physical characteristics on soil water availability are understood, water can be maintained within appropriate limits and the potential for both crop water stress and agrichemical leaching will be minimized.

Irrigation Control Strategies

Irrigation control strategies utilize one or a combination of two basic methods. These methods are use of soil moisture sensors and or crop ET. Regardless of the methods used the goals of providing optimum soil moisture for plant growth and productivity, and reduction of fertilizer nutrient leaching are the same. The flowing sections describe these two irrigation scheduling options and the technologies involved in each.

Soil Moisture Sensor Based Irrigation Control

There are two fundamental types of irrigation control when sensors are used, on-demand and bypass (Dukes and Munoz-Carpena, 2005). On demand irrigation control consists of a control system that irrigates in response to soil moisture measurements in the irrigated zone to maintain soil moisture content within low and high thresholds (i.e. to maintain soil water content within RAW). Thus, this type of control system must determine when to start and when to terminate irrigation. This type of control system has been used on sweet corn research in Florida (Dukes and Scholberg, 2005), on green bell pepper (Dukes et al., unpublished data), and is currently being used with promising results on golf course fairway irrigation control (Dukes et al., unpublished data). On demand control is controller and sensor intensive. That is to say that there is little room for error in the control system or sensor performance. Alternatively, bypass control simply bypasses timed irrigation events when measured soil moisture exceeds preset thresholds (e.g. MAD as upper limit). This type of control is simpler from a controller standpoint; however, the user must program the number and length of irrigation events to correspond to plant water requirements. Bypass control has a long history in Florida irrigation research starting in the 1980's on vegetables and turfgrass research with switching tensiometers. Bypass control is currently being researched in Florida on tomato, green bell pepper, turfgrass and landscapes with capacitance based soil moisture sensor irrigation controllers (Dukes et al., unpublished).

As an irrigation scheduling method, sensors have been promoted for many years and have been used to some extent in various types of agriculture. Munoz-Carpena et al. (2005a) provided a comprehensive review of types of sensors used to measure soil moisture content. Generally, there are two types of sensors that are used for irrigation scheduling, those that measure soil water potential (also called tension or suction) and those that measure volumetric water content directly. Dukes and Munoz-Carpena (2005) summarized some advantages and disadvantages of both types of sensors. Within the category of volumetric sensors, capacitance based sensors have become common in recent years due to a decrease in cost of electronic components and increased reliability of these types of sensors. However, several sensors available on the market have substantially different accuracies, response to salts, and cost.

Vegetable production using sensor based irrigation control

Increase in crop production with reduced soil moisture tension using tensiometers has been documented (Clark et al., 1991). Simple soil water status sensors (e.g. tensiometers) have been used for many years as devices used to give growers feedback on when to irrigate. Tensiometers are viable devices for this purpose; however, they require constant maintenance to keep them refilled and to maintain water within the water column free of dissolved air.

Many researchers have examined the use of sensor-based control systems in vegetable production (Table 6). Smajstrla and Koo (1986) documented the extensive problems with maintaining a tensiometer based automatic control system in working order. For these reasons, tensiometer based automatic control is not practiced in Florida vegetable or citrus production and use of tensiometers for manual irrigation is limited. The first attempts at irrigation automation used switching tensiometers that have a magnetic switch that opens the irrigation control circuit bypassing timed events when the measured tension exceeds the switch set point. Smajstrla and Locascio (1996) used switching tensiometers to control drip irrigation of fresh market tomato. Granular matrix sensors were designed as tensiometer replacements that do not require extensive maintenance. Smajstrla and Locascio (1996) used switching tensiometers to automatically initiate up to three daily irrigation events on fresh market tomato (i.e. bypass control). Irrigation durations were determined by half pan evaporation the previous week and events varied from 30 min to 90 min as environmental demands increased throughout the season. The highest yields in a four year study were achieved with a 10 kPa tensiometer set point which is equivalent to 10% volumetric water content for the Arredondo fine sand at the study site. Irrigation applied at this threshold was reported as ranging from approximately 160 mm to 225 mm depending on study year. Problems associated with tensiometers for use in automated irrigation systems have been reported as needing frequent maintenance as well as clogging due to algae growth (Smajstrla and Koo 1986).

Table 6. Literature summary of automatic control systems used in Florida citrus and vegetable research.

Author	Crop	Automatic Irrigation Control System (AICS)	Research Findings
Smajstrla and Locascio, 1996	Tomato	Switching tensiometers	Reduced irrigation requirements of tomatoes by 40% to 50% without reducing yields compared to fixed schedule (3 to 5 times per/week
Smajstrla and Koo, 1986	Citrus	Switching tensiometers	Efficient use to schedule irrigation application based on soil water potential. Maintenance and periodic inspections are required and tensiometers were subjected to damage when exposed to freezing temperatures
Dukes et al., 2003	Pepper	Capacitance based soil moisture probe, time domain transmission (TDT)	Use of 50% less irrigation water, similar yields compared to a daily based on Class A pan evaporation irrigation method
Nogueira et al., 2003	Sweet corn	Time domain reflectometry (TDR) soil moisture probes	Permits the control of the water application showing potential for automatic irrigation management
Dukes and Scholberg, 2005	Sweet corn	Time domain reflectometry (TDR) soil moisture probes	Up to 11% of reduction in water use using AICS with subsurface drip irrigation compared to sprinkler irrigation without affecting yields
Munoz-Carpena et al., 2005	Tomato	switching tensiometers and granular matrix sensor based irrigation controllers	Switching tensiometers at the 15 kPa set point resulted to up to 73% reduction in water use when compared to the control
Dukes et al., 2006	Pepper	Commercially available dielectric sensor	50% of reduction in water use compared to manually irrigated once a day, similar yields
Munoz-Carpena et al., 2008	Tomato	Capacitance based soil moisture probe, time domain transmission (TDT)	Savings up to 74% in water use compared to the fixed time irrigation; 61% of savings compared to the evapotranspiration based water application
Zotarelli et al., 2008a	Zucchini	Capacitance based soil moisture probe, time domain transmission (TDT)	Reduction in water use by 30-80% compared to the single daily fixed time irrigation, significant reduction in N leaching, increase in yield and N use efficiency
Zotarelli et al. 2008, In press	Tomato	Capacitance based soil moisture probe, time domain transmission (TDT)	Irrigation water savings superior to 67% compared to the control, yield increment of 11-26%

Granular matrix resistance sensors have been manufactured for a number of years as a tensiometers replacement. However, these sensors have been shown to require a special calibration for coarse Florida soils (Irmak and Haman, 2001). When used for vegetable irrigation control on gravelly loam soil in South Florida, granular matrix sensors performed erratically and did not reduce water application compared to a time-based schedule (Munoz-Carpena et al. 2005b). Similarly, Cardenas-Lailhacar et al. (2008) found that granular matrix sensor based irrigation controllers were no more effective than a rain sensor for turfgrass irrigation control on a fine sand. These sensors have been used successfully to irrigate onion and potato on moderately heavy soil types (Shock et al., 2002).

Capacitance (e.g. time domain reflectometry (TDR) and frequency domain reflectometry) based soil moisture measurement devices have been shown to have relatively accurate soil moisture measurement in sandy soils common to Florida (Irmak and Irmak, 2005). Dukes and Scholberg (2005) installed an automatic irrigation control system based on research grade TDR soil moisture probes and microcontrollers for irrigation of sweet corn. Irrigation was initiated based on preset low soil moisture thresholds and terminated based on an upper threshold. This control system was coupled with a subsurface drip irrigation system with drip tube buried under each row at 23 and 33 cm in two different treatments. The 23 cm deep treatment under automatic control reduced irrigation 11% relative to sprinkler irrigation typically used by growers. Dukes et al. (2003) used a simple soil moisture based control system to automatically maintain a relatively constant soil moisture content in the root zone of green bell pepper through high frequency irrigation based on soil moisture measurements by the control system. Compared to manual irrigation treatments with one or two irrigation events per day with similar yield, irrigation amount was reduced by approximately 50%. Capacitance based soil moisture sensors do not require maintenance once installed, contrasted with tensiometers that require weekly (Munoz-Carpena et al. 2005a) or bi-weekly maintenance (Smajstrla and Locascio 1996) to maintain accuracy. Soil moisture sensor irrigation control has been used on drip irrigated zucchini squash to increase yield by 35%, irrigation water use efficiency by 274%, and nitrogen use efficiency by 40% relative to single daily timed irrigation representative of grower practices (Zotarelli et al. 2008a). In general, this study found that a simple and inexpensive irrigation controller coupled with commercially available soil moisture probes (Munoz-Carpena et al. 2008) was effective at reducing both irrigation water application and nitrogen leaching under several drip irrigation configurations. Zotarelli et al. (In press) reported irrigation savings of 40% to 65% less than typical grower based time irrigation scheduling while increasing tomato yield 11% to 45%. Similar results reducing irrigation application and drainage while maintaining green bell pepper yields on sandy soils have been reported for Florida conditions (Dukes et al. 2006).

A number of researchers have shown that excessive irrigation on vegetables may cause yield decreases relative to optimum irrigation amounts as determined by soil moisture sensor control on green bell pepper (Dukes et al. 2003), as determined by pan evaporation for a yield decrease in high irrigation rates on fresh market tomato in one of two seasons (Locascio et al. 1989), and as shown on fresh market tomato in south Florida (Munoz-Carpena et al. 2005b).

Water budget irrigation management

Supplemental irrigation of citrus in Florida came into use in the 1940s. Various irrigation methods were used, including water wagons, surface flood, sub-irrigation, sprinkler, and micro-irrigation systems. Microsprinkler irrigation systems have become the standard for Florida citrus. Compared with overhead sprinklers, low volume systems can save water if they are properly managed. Because these systems usually operate at lower pressures than conventional overhead systems, there can also be appreciable savings from reduced energy costs.

Citrus water requirements vary with climatic conditions and variety (Rogers and Bartholic, 1976; Boman, 1994; Fares and Alva, 1999). Florida citrus ET_c typically ranges between 820 and 1280 mm yr^{-1} (Rogers et al., 1983). In addition to tree uptake, soil water content can be reduced by evaporation from the soil surface and transpiration from non-crop species (Allen et al., 1998).

Soils lose their ability to conduct water to the surface as they dry (Hillel, 1998). Likewise, citrus ET_c decreases as the fraction of the soil surface receiving full sunlight decreases and the canopy shades an increasingly larger ground area (Castel and Buj, 1992). Conversely, soil water use or apparent ET_c increases with increased ground coverage by non-crop species (Smajstrla et al., 1986). The above factors combine to limit ET_c for a given crop under specific conditions.

In a three year study, Morgan et al. (2006a) found that ET_0 totaled 1378 mm per year. Average daily ET_0 ranged from a low of 1.8 mm d^{-1} in December, to a high of 5.7 mm d^{-1} in June. Monthly standard deviations for ET_0 were 0.4 mm d^{-1} or less except for transition months between seasons (February and March in the spring, and August and September in the fall), indicating relative stability of the climate within most months. Maximum, minimum, and mean daily ET_0 and ET_c were not significantly different within corresponding months between the two cycles.

Daily ET_c was lower than or equal to or slightly higher than ET_0 and followed a similar seasonal fluctuation. ET_c approached ET_0 from June through August, but only when the soil was at or near field capacity. Mean daily ET_c ranged from a low of 1.3 mm d^{-1} in December, 2000 and December, 2001 to a high of 4.6 mm d^{-1} in June, 2001. Monthly standard deviations were slightly greater for ET_c (0.4 mm d^{-1}) compared with ET_0. The citrus ET_c values compared closely with those measured in humid climates by other researchers (Boman, 1994; Castel et al., 1987; Doorenbos and Pruitt, 1977; Rogers et al., 1983). For example, during a 3-yr period, Castel et al. (1987) measured monthly ET_c between 1.3 and 5.5 mm d^{-1} in a mature orange orchard in Spain. In contrast to the current study, Martin et al. (1997) reported an ET_c range of 1.1 to 10.6 mm d^{-1} for citrus in Arizona under arid conditions, indicating similar minimum but higher maximum daily ET_c compared with humid conditions in Florida.

Ratios of mean monthly ET_c to ET_0 as an estimate of $(K_c)(K_s)$ ranged from 0.65 to 0.91 and were similar to the flatwood K_c range of 0.61 to 0.92 and ridge K_c of 0.55 to 0.89 estimated by Jia et al. (2007) and lower than the range of 0.72 to 1.11 reported by Rogers et al. (1983) for a Florida citrus orchard. Reported K_c values for central Florida citrus ranged from about 0.6 in winter to 1.1 in summer (Boman, 1994; Fares and Alva, 1999; Rogers et. al., 1983). Mean daily K_c ranged between 0.55 and 1.2 for citrus under semi-arid to arid conditions (Doorenbos and Pruitt, 1977; Hoffman et al., 1982; Martin et al., 1997; and Wiegand et al., 1982). Theoretically, K_s should be 1 when soil water content is at or close to field capacity. Therefore, the ET_c:ET_0 ratio should approximate K_c at field capacity. The ET_c:ET_0 ratio when water content in the irrigated zone was at field capacity in the top 1 m of soil ranged from 0.7 in January to 1.1 in June (Fig.9).

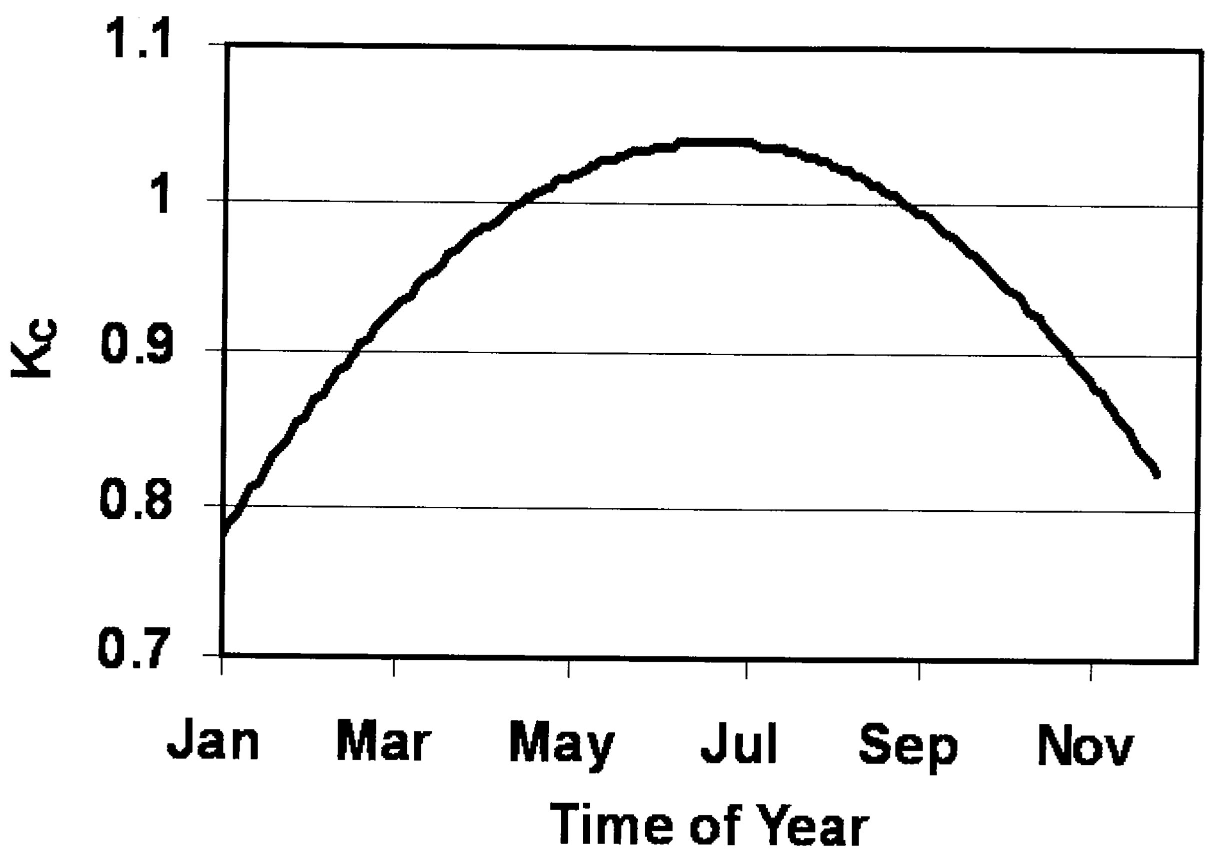

Figure 9. Temporal citrus crop coefficient (K_c) for mature trees as a function of month (from Morgan et al., 2006a).

The ET_c:ET_o ratio when soil field capacity is less than field capacity approximates K_s, assuming K_c equals 1. Since we found that K_c varied between about 0.8 and 1.1 during the course of a season, daily ET_o was multiplied by the appropriate K_c estimated for the DOY. ET_c:[(ET_o)(K_c)] ratios were calculated to approximate K_s and were plotted against soil water depletion (Fig. 10).

A region of readily-available water exists between field capacity and approximately 30 to 50% of available soil water depletion (ASWD) for loam and loamy clay soils where essentially no crop water stress occurs (Allen et al., 1998). However, the region of readily available water (RAW) is considerably reduced for sandy soils. Linear regression analysis determined the range of RAW to be less than 1% of ASWD in the upper 1 m of the total soil voume within the tree allocated space (Fig. 10). Estimates for K_s decreased from unity at 1% ASWD to approximately 0.5 at 50% ASWD for all soil volumes. A K_s value of 0.5 translates to a reduction of 50% in ET_c between field capacity and 50% depletion of AW (DAW).

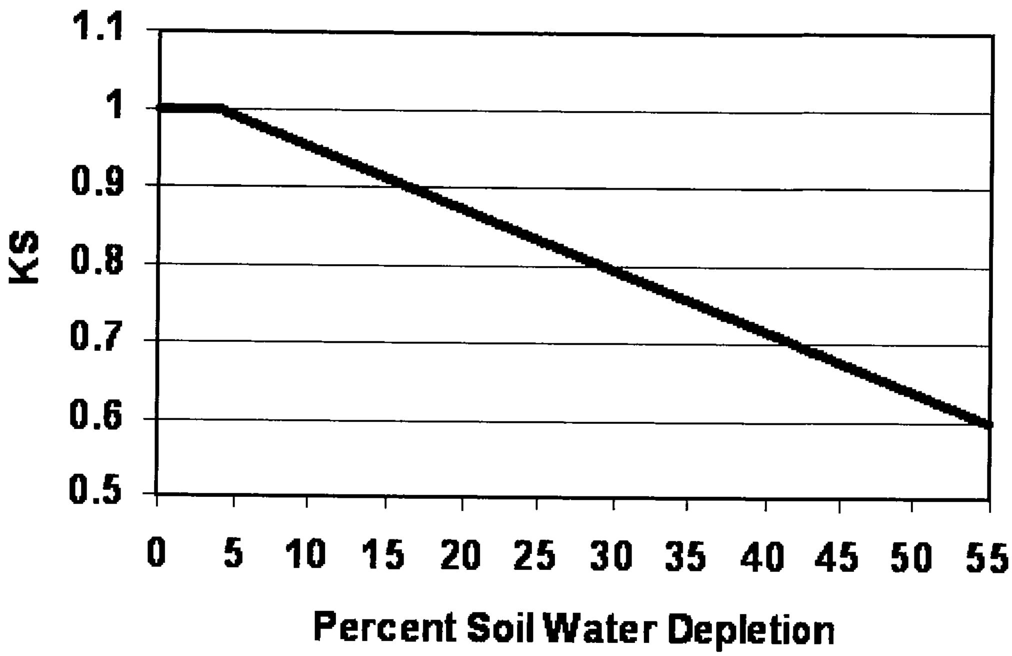

Figure 10. Soil depletion coefficient (K_s) as a funtion of soil water depletion (from Morgan et al., 2006a).

The reduction in ET_c reflected by K_s decreasing from 1 to 0.5 as DAW increased from 1 to 50% seems rather extreme. However, Rogers et al. (1983) suggested that lower estimated K_c values in the spring were caused by low rainfall and low soil moistrue outside the irrigated zone. Their reported K_c values of 0.77, 0.72, and 0.95 for March, April and May are 84, 76, and 92% of the estimated K_c values (Fig. 9). K_c values for the rainy season months of June and July were 101 and 97% of our values, indicating that estimating K_c from weekly water balances can lead to lower values during periods of low rainfall and high evaporative demand.

Stress associated with DAW greater than 33% during periods of bloom, fruit set, and rapid vegetative growth in the spring was found to reduce yield of overhead irrigated citrus grown on sandy soils under Florida climatic conditions (Koo,1963; 1978). Koo also determined that DAW of 66% could be tolerated during summer, fall and winter months. Thus, the potential onset of crop water stress associated with K_s of 0.7 from February through June and 0.4 from June through January should be used to schedule irrigation to maximize yields while minimizing water use.

Morgan et al. (2007) described temporal and spatial citrus root density distribution as a function of increase in tree canopy. Citrus tree roots were concentrated in the top 30 cm of soil under the canopy and decreased with soil depth. Root densitis at selected depths and loctions under the tree canopy were estimated and used to evaluate the water use uptake data. The daily rate of soil water uptake decreased with increased soil depth. Estimated ET_c per unit soil depth was determined by dividing layer ET_c by the layer depth. Maximum depth-adjusted ET_c at weighted θ near field capacity followed seasonal ET_0 trends. The months of May and December were chosen to illustrate periods of the growing season with high (5.2 mm d^{-1}) and low (1.8 mm d^{-1}) mean daily ET demand, respectively. Depth-adjusted layer ET_c at θ near field capacity from four measured depths were plotted for each of the three distances from the tree trunk for the months of May and December. Daily depth-adjusted uptake rates at all depths and distances followed the root length density distribution, indicating that soil water uptake was proportional to root length density. Water uptake per unit depth from each soil layer decreased proportionally with layer soil moisture less than field capacity similar to the relationship of K_s to soil moisture depletion.

The maximum water uptake per unit root length of 1.3 $mm^3\ mm^{-1}\ d^{-1}$ occurred at field capacity. Water uptake rate decreased rapidly to 0.5 $mm^3\ mm^{-1}\ d^{-1}$ as θ decreased to approximately 50% DAW, then gradually decreased to 0.2 $mm^3\ mm^{-1}\ d^{-1}$ as θ decreased below 65% DAW. The maximum root water uptake rate observed in this study was substantually less than the 4.0 to 5.0 $mm^3\ mm^{-1}\ d^{-1}$ range reported for agronomic crops (Hamblin and Tennant, 1987; Bland and Dugus, 1989; Zaongo et al., 1994), which is somewhat surprising considering the differences in root morphology of annual versus perennial crops. Soil water uptake rate was closely related to root length density, thus soil regions containing higher root length density will dry out at a proportionally higher rate. Hence, a model of soil water uptake and depletion based on root length density would be appropriate for citrus.

Smajstrla et al. (1986) measured 46 to 105% higher annual citrus ET_c in orchards with full grass cover compared with those having bare soil. Similarly, Stewart et al. (1969) measured citrus ET_c rates that were 68 and 92% of full sod cover for bare and two-thirds sod cover, respectively. A portion of the increase in water uptake can be explained by exposure of the soil surface to direct sunlight. An example of the effect of soil surface shading was cited by Castel and Buj (1992), who reported a decrease in water uptake as ground shading by young Clementine trees increased during a 4-yr period.

Water use by vegetable crops has been determined for some crops gown with plastic mulch (Clark and Stanley, 1995; Stanley, 2004). Crop coefficients have been determined for some vegetable crops under drip (Clark et al., 1996) and seepage (Jaber et al., 2006) irrigation. Currently, few models for vegetable irrigation scheduling in Florida are available for growers.

Water balance-based irrigation scheduling

Generic tables and water budget models are examples of systems that will improve the likelihood of obtaining the irrigation goals of reduced leaching and improved nutrient uptake. Generic irrigation schedules have been reduced to a tabular format and are available in publications (Parsons and Morgan, 2002) and on the FAWN program website. These tables are used to schedule microsprinkler irrigation for young trees and mature ridge or flatwoods trees. In cases of high ET, additional water may be necessary to reduce stress on the trees and frequent irrigation would be more beneficial rather than lengthening the duration of irrigation.

The second method is the use of water budget models. Two models have been developed for Florida citrus production (Morgan et al., 2006b). An ET_0 can be used as a basis for estimating the citrus grove ET_c or irrigation demand. Reference ET is calculated on a daily basis using weather data or is available for the nearest FAWN site. However, once the crop ET is estimated, irrigation interval and duration can be calculated based on irrigation application rates and allowable soil water depletion. The UF/IFAS recommendation is to allow 25 to 33 percent soil-water depletion during February through May, and 50 to 66 percent depletion during June through January. These allowable depletions provide increased soil water in the spring of the year for blooming, fruit set, and growth flushes. The increased allowable soil water depletion in the summer and fall allows for the use of rainfall during our rainy season and adequate water for fruit expansion. Rooting depth adds another layer of precision to this irrigation budget model.

Two models have been developed and validated using weather station data and water uptake at six mature citrus orchards in central Florida (Morgan, unpublished data). One model is available on the FAWN website and provides seasonally adjusted irrigation intervals and durations based on user site inputs and FAWN ET_o. The second model determines day of the week irrigation schedules on a site specific basis for multiple irrigation blocks.

Nitrogen leaching: fertigation vs. irrigation

Fertigation is the application of nutrients through the irrigation system. Fertigation is a widespread practice for microirrigated vegetable and fruit crops in Florida, providing growers with the opportunity to apply nutrients more frequently in quantities that closely match short-term crop nutrient requirements.

This results in higher fertilizer use efficiency by the crop as well as a reduction of nutrient leaching below the plant root zone. However, in soils with poor water retention, such as sandy soils, application of excess water may promote displacement of nutrients before complete uptake has occurred (Dukes and Scholberg, 2002; Zotarelli et al., 2008b; Zotarelli et al. in press). Appropriate irrigation scheduling and matching irrigation amounts with the effective water holding capacity of the effective rootzone thus may provide ways to minimize the incidence of excess N leaching associated with over-irrigation. Figure 11 shows the effectiveness of appropriated irrigation scheduling (top) to reduce the volume of water percolated in the soil profile compared to fixed time of irrigation (bottom).

As described in the previous section, uniformity of water application also drives the uniformity of the fertilizer application. Therefore, high water application uniformity is essential for proper fertigation. The drip system needs to be completely pressurized before the fertigation begins, in order to avoid uneven application rates. In addition, the fertilizer used must be completely soluble in water, and pass through the filters to ensure that any undissolved fertilizer particles are filtered out of the drip system. Injecting N fertigation towards the end of the irrigation cycle may also prevent immediate N displacement below the soil region with highest root concentration (Scholberg, 1996). Alternatively, monitoring of soil electrical conductivity sensors (EC) has the potential for estimating variation in nutrient displacement in the crop root zone in order to improve fertigation and irrigation management. However, little information is available on the effectiveness of EC sensors on irrigation/fertigation management for vegetable crops in Florida.

Seemingly contradictory results have been found in studies looking at the effect of fertigation on citrus N use efficiency. Schumann et al. (2003) found highest yields were obtained by fertigation with lower N application rates compared with both dry granular fertilizer and controlled-release fertilizers. Leaf N values were higher per unit of applied N in the fertigated plots indicating more efficient uptake. The authors concluded that fertigation was the most efficient method of N application in this study, probably due to optimal placement and multiple applications. Alva et al. (1998) found yield was slightly greater and loading of groundwater nitrate-N was lower using fertigation compared with dry soluble fertilizers. Leaf nutrient concentration and fruit quality were not affected by the treatments. Conversely, Alva and Paramasivam (1998) found no significant interaction between rate and method in a separate study indicating that the dry soluble fertilizer, controlled release fertilizer, and fertigation were equally effective.

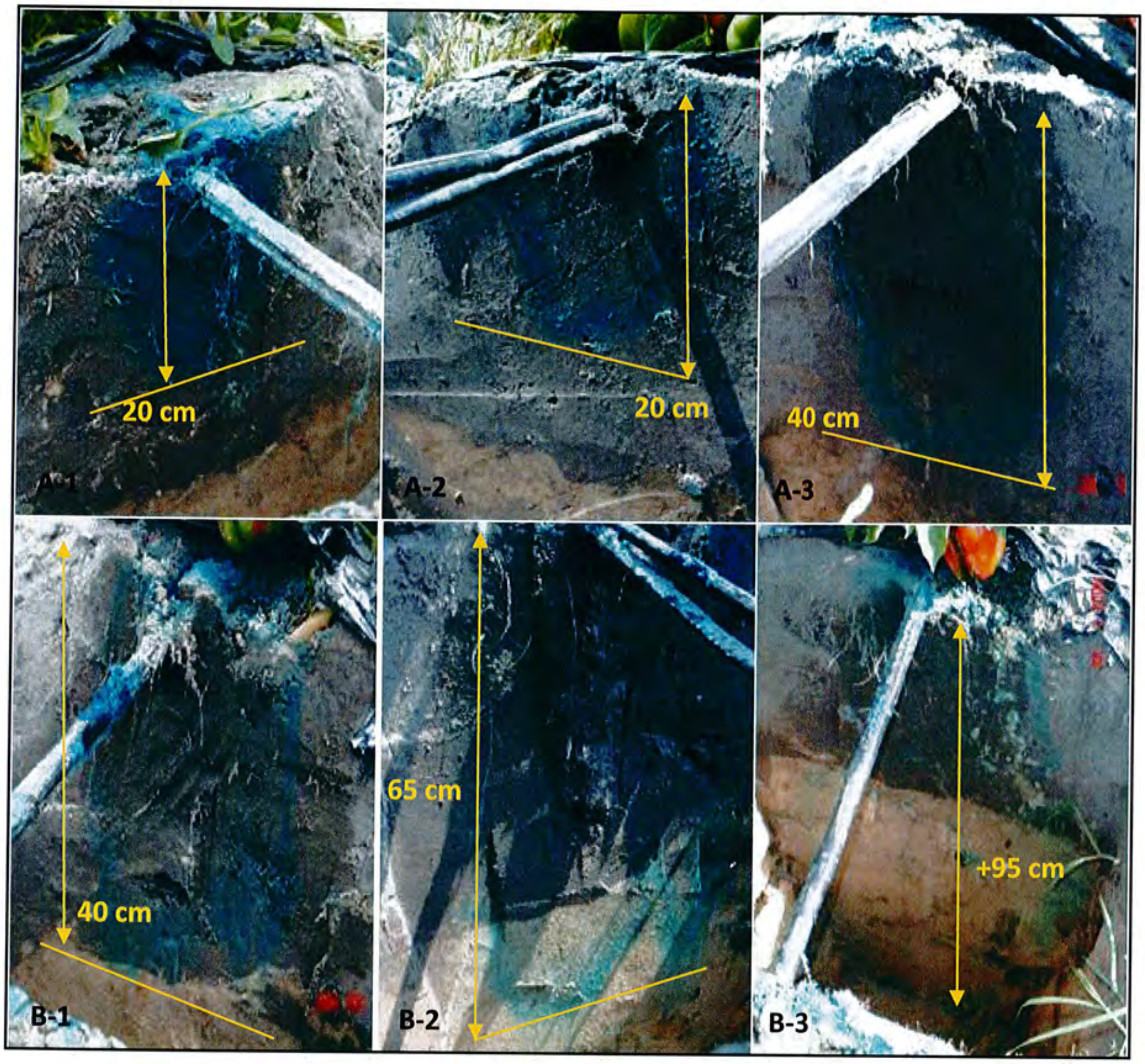

Fig.11. Demonstration of the effectiveness of soil moisture sensor based irrigation systems in enhancing nutrient retention for soil moisture sensor irrigation (top row) due to small frequent irrigation events compared to fixed time irrigation schedule with single daily large irrigation events (bottom row) applying dye through the fertigation drip lines. (A) soil moisture sensor irrigation; (B) fixed time irrigation schedule; (1) after 24 hours, (2) after 3 days and (3) after 7 days of the injection of dye.

Several field studies have determined the importance of proper irrigation scheduling on citrus growth and production on the low water-holding nutrient-retention soils of central Florida (Boman 1994; Parsons et al., 2001; Scholberg et al., 2002; Morgan et al., 2006a). A field-scale fertilizer and irrigation rate study was conducted on trees over a 10 year period (Morgan, unpublished). Leaf N and fruit soluble solids concentrations of trees less than 6 yrs old decreased with increased irrigation rate. Irrigation and N rate were both important factors for trees 8 to 10 years old. Canopy size and yield were highest at the moderate irrigation level compared with the low irrigation rate. As with the young tree study, fruit soluble solids significantly decreased with increased irrigation, but total soluble solids per hectare were greater with high the irrigation rate. these results would indicate that high, but not excessive irrigation is required in addition to proper N rate for optimum tree growth.

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