Best management practices for irrigation and fertilization of vegetable crops in Florida

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ABSTRACT
Major horticultural crops in Florida are vegetables, small fruits, melons and citrus. Approximately half of the agricultural area and nearly all of the horticultural crop land is irrigated. Irrigation systems include low volume microirrigation, sprinkler systems, and subsurface irrigation. The present manuscript provides an overview of irrigation methods used in Florida. Factors affecting irrigation efficiency and uniformity such as design and maintenance are discussed. A wide range of soil moisture sensors (e.g. tensiometers, granular matrix, and capacitance) are currently being used in the state for soil moisture monitoring. Current examples of scheduling tools and automated control systems being used on selected crops in Florida are provided. Research data on the effect of irrigation scheduling and fertigation on nutrient movement, particularly nitrate, are reviewed.

RESUMO
Os principais produtos agrícolas produzidos na Flórida são olerícolas, melões, pequenas frutas e citrus. Aproximadamente metade da área agrícola do estado, e praticamente toda a área cultivada com hortaliças depende de irrigação. Os sistemas de irrigação utilizados incluem aspersão, gotejamento, e irrigação de subsuperfície. O presente manuscrito descreve os métodos de irrigação utilizados na Flórida, fatores que afetam a eficiência de irrigação e uniformidade, planejamento e manutenção. Sensores de umidade do solo tem sido utilizados (exemplo: tensiômetros, matriz granular e capacitância) para monitoramento da umidade do solo. Exemplos de ferramentas de manejo e automatização da irrigação para algumas culturas são relatados no presente manuscrito, bem como, resultados de pesquisa sobre lixiviação de nitrato.
INTRODUCTION

Irrigation can be defined as the artificial application of water to the soil to supplement rainfall in crop growth and is considered one of the most aspects of agricultural management in dry or limited rainfall areas and during periods with no or little rainfall. Florida is currently ranking second in withdrawal of ground water for public supply in the United States and ranking thirteenth nationally for agricultural self-supplied water use (Solley et al., 1998). About 35% of Florida fresh ground water withdrawals and 60% of fresh surface water withdrawals are used for agricultural purposes. Agricultural water use is still the largest single category of water use in Florida; however, as population pressure continues to grow, irrigation water users are being forced to become more efficient.

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 good irrigation water application uniformity and improving water uptake efficiency of the irrigation water. Uniformity can be defined as the ratio of the volume of water 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 non-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 (Howell, 2001). 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, Institute of Food and Agricultural Sciences for irrigation management of horticultural 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; knowledge of how much the root
zone can hold; and an assessment of how rainfall contributes to replenishing soil moisture.

IRRIGATION IN FLORIDA

There are 1,503,512 ha of crop land in Florida (USDA, 2004a). In 2003, 49% (734,575 ha) 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 capacity of the sandy soils. These crops include 302,851 ha of tree fruit crops (mostly citrus), 48,686 ha of vegetables (including 15,290 ha of tomatoes), 20,166 ha of potatoes, 5,920 ha of sweet corn, and 2,300 ha of berries (USDA, 2004b).

Irrigated area 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 (a variation on subsurface irrigation or water table control in other parts of the U.S.). 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%) which is largely due to microsprinkler irrigation of citrus, which accounts for the largest crop area 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 to sprinkler irrigation. Seepage irrigation or subirrigation refer to 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.

IRRIGATION OF VEGETABLES AND MELONS
Florida is the most important center of production and distribution of vegetables in the Southeastern U.S. with 73,500 ha planted in 2006 and a crop value greater than 1.2 million dollars (USDA, 2008b). Among the vegetable crops cultivated in Florida, tomatoes (*Lycopersicon esculentum* Mill.), bell peppers (*Capsicum annuum* L.), sweet corn (*Zea mays* L.), strawberries (*Fragaria ananassa*), snap beans (*Phaseolus vulgaris* L.), cucumbers (*Cucumis* sp.) 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 17,240 ha, 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. Other important production areas are found in the southwest Florida where there is a predominance of drip irrigation. Sweet corn in Florida has around 15,700 ha planted annually, and the crop value is about 108 million dollars. Sweet corn is predominantly grown in South Florida and the irrigation management is mainly sprinkler sometimes combined with seepage irrigation. 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 area annually planted with bell peppers in Florida is 7,500 ha. The predominant irrigation management for pepper is seepage irrigation, however, several farms have adopted drip 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% (2,700 ha) of the total area planted of fruits and vegetables in Florida. Strawberry production is concentrated in Southwest Florida, and employs drip irrigation as well as sprinkler irrigation for frost protection. Approximately 80% of Florida strawberry area is drip-irrigated (Haman *et al*., 2005).

The irrigation of vegetable crops in Florida is classified in sprinkler, microirrigation systems and seepage irrigation. Sprinkler systems are designed to use overlapping patterns to provide uniform coverage over an irrigated area. These types of
systems have been frequently used under row vegetable crops such as sweet corn, potato, snap beans and vegetable crops not cultivated with plastic mulch. 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 typically less than 80%. 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 seepage or surface 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 (Smajstrla et al., 2002).

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 crops. 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 smaller pumps relative to sprinkler systems. 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. 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 is thought that drip irrigation gives the higher application efficiency for vegetables in Florida (80-90%) compared with seepage (20-50%) and overhead irrigation systems (60-80%) (Simonne, et al., 2007).

In seepage or 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 irrigation 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).

Approximately 44% of Florida irrigated area uses seepage irrigation; most of this area is under high value crop production such as fresh market vegetables and potatoes. Unfortunately, this type of irrigation has very low efficiency due to the large amount of water required to constantly maintain a shallow water table throughout the crop season, which may cause nutrient leaching (Pandey et al., 2007). 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.

STRATEGIES TO IMPROVE WATER AND NUTRIENT USE EFFICIENCY

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).

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. 1) 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.

**Irrigation Control for Vegetable Crops**

Irrigation control strategy goals of providing optimum soil moisture for plant growth, productivity, and reduction of fertilizer nutrient leaching. The flowing section describes irrigation control 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 & Muñoz-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 readily-available water (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 & Scholberg, 2005), on green bell pepper (Dukes *et al.* 2007a), 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. field capacity as the 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, zucchini, green bell pepper (*Zotarelli, et al.*, 2008a; 2009), turfgrass and landscapes (*Dukes et al.*, 2007b) with capacitance based soil moisture sensor irrigation controllers.

As an irrigation scheduling method, sensors have been promoted for many years and have been used to some extent in various types of agriculture. Muñoz-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 & Muñoz-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, a variety of sensors are available on the market that 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 1). Due to documented maintenance issues (e.g. Smajstrla & Koo 1986), 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. These switching tensiometers automatically initiated up to three daily irrigation events. Irrigation durations were determined by half pan evaporation of 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 & Koo 1986).

Granular matrix resistance sensors have been manufactured for a number of years as a replacement for tensiometers. However, these sensors have been shown to require a special calibration for coarse Florida soils (Irmak & 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 (Muñoz-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 soil. These sensors have been used successfully to irrigate onion and potato on moderately heavy soil (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 & Irmak, 2005). Dukes & 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 in contrast to tensiometers that require weekly (Muñoz-Carpena et al. 2005a) or bi-weekly
maintenance (Smajstrla & 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 (Muñoz-Carpena et al. 2008) was effective at reducing both irrigation water application and nitrogen leaching under several drip irrigation configurations. Zotarelli et al. (2009) 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 (Muñoz-Carpena et al. 2005b).

**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 & Scholberg, 2005; Zotarelli et al., 2008b; Zotarelli et al. 2009). Appropriate irrigation scheduling and matching irrigation amounts with the water holding capacity of the effective root zone thus may provide ways to minimize the incidence of excess N leaching associated with over-irrigation.
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.

**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 & 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, the spacing between laterals when possible should be reduced 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., 2009) and nutrient interception in the sides of the raised bed. 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.

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 30-40 cm wide zone, due to the extremely high hydraulic conductivity of our sandy soils.
With the use of conventional irrigation practices such as single application, water and nutrients are thus displaced up to 100 cm within one week, while the effective vegetable rootzone may only be 30-60 cm 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. 2008abc). 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. For example, irrigation water which contains sand, a sand separator should be used. Clogging may occur when no filter or the incorrect type of filter is used resulting in poor water distribution uniformity and crop loss. 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, and reduce operating costs, save water and fertilizer.

**POTENTIAL USE OF IRRIGATION TECHNOLOGIES AND FUTURE RESEARCH PRIORITIES**
As outlined in this paper, soil moisture sensor based irrigation of vegetable crops has shown strong potential for saving irrigation water. 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. In the past, soil moisture sensors have not been used widely by growers due to costs, the level of technical skill required and sensor maintenance required. Continued restrictions aimed at reducing nutrient leaching and recent increases in energy costs have 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 crop growers would use. 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 and/or fertigation management with the potential of reduced nutrient leaching.

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**Figure 1.** General relationship between readily available water, soil field capacity, permanent wilting point, soil unavailable water and soil texture class.

**Figura 1.** Relação entre água disponível, capacidade de campo, ponto de murcha permanente, água indisponível no solo com a classe textural do solo.
Table 1. Literature summary of automatic irrigation control systems used in Florida vegetable research.

<table>
<thead>
<tr>
<th>Author</th>
<th>Crop</th>
<th>Automatic Irrigation Control System</th>
<th>Research Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smajstrla and Locascio, 1996</td>
<td>Tomato</td>
<td>Switching tensiometers</td>
<td>Reduced irrigation requirements of tomatoes by 40% to 50% without reducing yields when compared to fixed schedule (3 to 5 times per/week)</td>
</tr>
<tr>
<td>Dukes et al., 2003</td>
<td>Pepper</td>
<td>Capacitance based soil moisture probe, time domain transmission (TDT)</td>
<td>Use of 50% less irrigation water, similar yields compared to a daily based on Class A pan evaporation irrigation method</td>
</tr>
<tr>
<td>Nogueira et al., 2003</td>
<td>Sweet corn</td>
<td>Time domain reflectometry (TDR) soil moisture probes</td>
<td>Permits the control of the water application showing potential for automatic irrigation management</td>
</tr>
<tr>
<td>Dukes and Scholberg, 2005</td>
<td>Sweet corn</td>
<td>Time domain reflectometry (TDR) soil moisture probes</td>
<td>Up to 11% of reduction in water use using AICS with subsurface drip irrigation compared to sprinkler irrigation without affecting yields</td>
</tr>
<tr>
<td>Muñoz-Carpena et al., 2006</td>
<td>Tomato</td>
<td>Switching tensiometers and granular matrix sensor based irrigation controllers</td>
<td>Switching tensiometers at the 15 kPa $^{-3}$ set point resulted to up to 73% reduction in water use when compared to the control</td>
</tr>
<tr>
<td>Dukes et al., 2006</td>
<td>Pepper</td>
<td>Commercially available dielectric sensor</td>
<td>50% of reduction in water use compared to manually irrigated once a day, similar yields</td>
</tr>
<tr>
<td>Muñoz-Carpena et al., 2008</td>
<td>Tomato</td>
<td>Capacitance based soil moisture probe, time domain transmission (TDT)</td>
<td>Savings up to 74% in water use compared to the fixed time irrigation; 61% of savings compared to the evapotranspiration based water application</td>
</tr>
<tr>
<td>Zotarelli et al., 2008a</td>
<td>Zucchini</td>
<td>Capacitance based soil moisture probe, time domain transmission (TDT)</td>
<td>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</td>
</tr>
<tr>
<td>Zotarelli et al., 2009</td>
<td>Tomato</td>
<td>Capacitance based soil moisture probe, time domain transmission (TDT)</td>
<td>Irrigation water savings superior to 67% compared to the control, yield increment of 11-26%</td>
</tr>
<tr>
<td>Zotarelli et al., 2011</td>
<td>Pepper</td>
<td>Commercially available dielectric sensor</td>
<td>7 to 62% of reduction in water use compared to manually irrigated once a day, similar yields</td>
</tr>
</tbody>
</table>