Sensor-Based Automation of Irrigation on Bermudagrass, during Wet Weather Conditions

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Abstract: New technologies could improve irrigation efficiency of turfgrass, promoting water conservation and reducing environmental impacts. The objectives of this research were to quantify irrigation water use and to evaluate turf quality differences between (1) time-based scheduling with and without a rain sensor (RS); (2) a time-based schedule compared to a soil moisture sensor (SMS)-based irrigation system; and (3) different commercially available SMS systems. The experimental area consisted of common bermudagrass [*Cynodon dactylon* (L.) Pers.] plots (3.7 m × 3.7 m), located in Gainesville, Fla. The monitoring period took place from July 20 to December 14, 2004, and from March 25 to August 31, 2005. SMS-based treatments consisted of irrigating one, two, or seven days a week, each with four different commercial SMS brands. Time-based treatments with or without RS and a nonirrigated treatment were also implemented. Significant differences in turfgrass quality among treatments were not detected due to the sustained wet weather conditions during the testing periods. The treatment with the rain sensor resulted in 34% less water applied than that without the rain sensor (2-WORS) treatment. Most SMS brands recorded irrigation water savings compared to 2-WORS, ranging from 69 to 92% for three of four SMSs tested, depending on the irrigation frequency. Therefore, SMS systems represent a promising technology because of the water savings that they can achieve during wet weather conditions while maintaining acceptable turfgrass quality.

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Introduction

Turfgrass is the main cultivated crop in Florida with nearly four times the acreage as the next largest crop, citrus (Hodges et al. 1994; USDA 2005). Irrigation of residential, commercial, industrial, and recreational turf areas is commonly employed to ensure acceptable turf quality. As a consequence of problems related to droughts, coupled with the steadily increasing demand for water, the state of Florida has imposed restrictions on irrigation water use. The development of best management practices (BMPs) for irrigation water use in turf has become an undeniable strategic, economic, and environmental issue for the state. New landscape irrigation technologies could improve irrigation efficiency by promoting water conservation and reducing environmental impacts.

Florida receives an average of approximately 1,400 mm of rainfall a year, which varies depending on location in the state. Although rainfall, typically, exceeds evapotranspiration (ET), irrigation is required because total annual rainfall, typically, varies both geographically and temporally (USDA 1981; Carriker 2000; NOAA 2003), and lack of rainfall for even a few days causes depletion of moisture in the predominately sandy soils found in Florida (Carriker 2000; NRC 1996).

Florida has the second largest withdrawal of groundwater for public supply in the United States. In 1995, nearly 93% of the population in Florida used groundwater as a drinking water source (Solley et al. 1998). Moreover, Florida has a fast-growing population with a net inflow of more than 1,100 people a day, and is projected to be the third most populous state in the nation by 2025 (OEDR 2006; USCB 2004a). The USCB estimated that Florida accounted for approximately 11% of all new homes constructed in the United States in 2003, the largest amount in any single state (USCB 2004b); the majority of them with an in-ground irrigation system (TBW 2005; Whitcomb 2005). As urban populations swell, pressures on limited supplies of clean water are increasing. Saltwater intrusion in the Floridan aquifer has been found in coastal Hillsborough, Manatee, and Sarasota counties (SWFWMD 2006).

The primary use of residential outdoor water is irrigation. A study in the U.S. indicated that households that use automatic timers to control their irrigation systems use 47% more water outdoors than those without timers, homes with in-ground sprinkler systems use 35% more water outdoors than those without in-ground systems, and on average, 58% of household water is used outdoors (Mayer et al. 1999). In the Central Florida Ridge, the potable water used for landscape irrigation has been found to be as high as 74%, with an average of 64% (Haley et al. 2007), and even when irrigation is restricted to two days a week (SJRWMD 2006), typically, homeowners tended to overirrigate (Haley et al. 2007).

Overirrigation or underirrigation negatively can affect turf-

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grass quality. It has been reported that deeper and less-frequent irrigation improves turfgrass quality. Augustin and Snyder (1984) concluded that this practice tended to reduce N leaching in sandy soils, increasing N utilization, resulting in a better color rating (better quality). Bonos and Murphy (1999) reported an increase in a Kentucky bluegrass (*Poa pratensis L.*) cultivar root growth as drought stress was imposed. Jordan et al. (2003) found that bentgrass irrigated every 4 days produced a significantly larger and deeper root system, a higher shoot density, and higher overall plant health—resulting in greater turf quality—than that watered every 1 or 2 days (even under golf putting green management conditions). McCarty (2005) summarizes that drier soil conditions slow shoot growth, and increase root growth and leaf water content. Moreover, limitations to the establishment and survival of some turfgrass weeds (Colbaugh and Elmore 1985; Youngner et al. 1981), and reduction of some pathogen severity (Davis and Dernoeden 1991; Kackley et al. 1990) have been associated with deep, infrequent irrigation. Hence, better irrigation scheduling by homeowners may lead to improved turfgrass quality coupled with potential savings in irrigation water use.

Over the last decade, the soil moisture sensor (SMS) industry has advanced dramatically. Two basic reasons can explain this advancement. The first has been the major development of computer technology, with more powerful, smaller, and more economical integrated circuits. The second phenomenon has been the significant advances in the application of electromagnetic methods to the measurement of soil water content. These methods make use of the high relative permittivity (dielectric constant) of water in soil to estimate water content. The relative permittivity of water is about 80, whereas the other components in soil, including air, have relative permittivities in the range of 1–7. Hence, methods that measure the relative permittivity are effective for the measurement of the soil water content (Topp 2003). Combining computer technology and the soil dielectric concept has allowed manufacturers to design and produce a number of different types of inexpensive SMSs for soil moisture measurement.

Automation of irrigation systems, based on SMS technology, has the potential to provide maximum water use efficiency, by maintaining soil moisture between a desired range that is optimal or adequate for plant growth and/or quality; allowing irrigation only when necessary (Muñoz-Carpena and Dukes 2005). A wide range of applications to automatically control irrigation events has been investigated in coarse textured soils. In Florida, switching tensiometers have been studied for agricultural production (Smajstrla and Koo 1986; Clark et al. 1994; Smajstrla and Locascio 1994; Muñoz-Carpena et al. 2003; Muñoz-Carpena et al. 2005), and for maintaining bermudagrass turf (Augustin and Snyder 1984). Although water savings were found, these investigations suggest that tensiometers require calibration and frequent maintenance, up to twice per week. Consequently, this technology has not been adopted to automate irrigation in Florida.

Other types of sensors have been adapted to automate irrigation based on soil moisture status in Florida. Nogueira et al. (2002) used time-domain reflectometer (TDR) sensors to maintain soil moisture within two preset limits (upper and lower soil moisture thresholds). Dukes and Scholberg (2005) and Dukes et al. (2003) reported 11 and 50% water savings—without diminishing yields—using TDR probes on sweet corn, and a commercially available dielectric sensor on green bell pepper, respectively. Granular matrix sensors (GMSs) have also been used to automatically irrigate agricultural crops (Muñoz-Carpena et al. 2003; Shock et al. 2002), and as with other solid-state sensors, do not require as much maintenance as tensiometers.

Although SMSs have been successfully demonstrated in agriculture, they have found limited use in residential landscape irrigation. A study using GMSs to control urban landscape irrigation in Colorado, applied 533 mm of water for irrigation compared to the theoretical requirement of 726 mm; a reduction of 27% (Qualls et al. 2001).

Since 1991 Florida law has required a rain sensor (RS) device or switch hooked up to all automatic lawn sprinkler systems (Florida Statutes, Chap. 373.62; http://www.leg.state.fl.us/Statutes/index.cfm?Mode=View%20Statutes&Submenu=1&Tab=statutes&CFID=8781381&CFTOKEN=75889146). A rain sensor is a piece of equipment designed to interrupt a scheduled cycle of an automatic irrigation timer when a specific amount of rainfall has occurred (Dukes and Haman 2002a). Benefits and advantages of its use are similar to those of SMSs, and have been summarized by Dukes and Haman (2002a). Even though RSs have been mandated on all automatic irrigation systems installed after 1991, and have been commercially available for many years, little evidence related to their usefulness and/or to quantify their water savings exists.

The goal of this research was to find out if different SMS systems (sensor with a proprietary controller) could reduce irrigation water application—while maintaining acceptable turf quality—compared to various time-based irrigation schedules to simulate common homeowner practices. The objectives of this experiment were to quantify irrigation water use and to evaluate turf quality differences between: (1) time-based scheduling with and without an RS; (2) a time-based schedule compared to an SMS-based irrigation system; and (3) different commercially available irrigation SMS systems.

Materials and Methods

The experimental area was located at the Agricultural and Biological Engineering Department research facilities, University of Florida, Gainesville, Fla.; on an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudult) (Thomas et al. 1985; USDA 2007). This soil has a field capacity of 7% (volumetric moisture content), as determined from dry-down experiments on repacked soil columns (Cardenas-Lailhacar 2006) and according to testing on intact cores as reported by Carlisle et al. (1981).

The site consists of 72 ($3.7 \text{ m} \times 3.7 \text{ m}$) plots on a field covered with well-established common bermudagrass [*Cynodon dactylon* (L.) Pers.]. Each plot was sprinkler irrigated by four quarter-circle, pop-up spray heads, with an average application rate of 38 mm/h at 172 kPa (Hunter 12A, Hunter Industries, Inc., San Marcos, Calif.). Plots were mowed twice weekly at a height of 5.5 cm. Agrochemicals were applied as needed to control weeds and pests, with no visual toxicity signs on the bermudagrass after the applications. Nutrient applications were made using ammonium sulfate (21–0–0), at an N rate of 50 kg/ha, in April and May of 2004, before the beginning of the experiment. Then, a granulated 16–4–8 controlled-release fertilizer (Professional Turf Fertilizer, TurfGro, Phoenix, Ariz.) was applied at an N–P–K rate of 180–45–90 kg/ha, in July 2004 and April 2005.

Four commercially available SMS systems were selected for evaluation: Acclima Digital TDT RS-500 (Acclima Inc., Meridian, Id.), Watermark 200SS-5 (Irrometer Company, Inc., Riverside, Calif.), Rain Bird MS-100 (Rain Bird International, Inc., Glendora, Calif.), and Water Watcher DPS-100 (Water Watcher, Inc., Logan, Utah), codified as AC, IM, RB, and WW, respectively. Each SMS system included a sensor to be buried in the soil and a controller, which could be adjusted to different soil water thresholds. All controllers were connected in series with typical residential irrigation timers. Cardenas-Lailhacar (2006) presented photographs of each SMS system and of the experimental site.

The IM controllers were set at Number 1 (equivalent to 10 kPa of soil tension according to the manufacturer), whereas the AC controllers were set on their display at a volumetric moisture content (VMC) of 7%, where a soil tension of 10 kPa and a VMC of 7% were taken as approximately field capacity (Cardenas-Lailhacar 2006). Following manufacturer recommendations to find a set point close to field capacity, the RB and WW controllers were set at their thresholds 24 h after a significant rainfall event (which happened on July 20, 2004, after four days of rain, with a total of 107 mm that filled the soil profile with water). The RB controllers have a scale from a dry (#1) to a wet (#9) condition, and their thresholds were found by moving and setting the knob at the driest point (#2.5, in this case) where it would bypass irrigation, as indicated by a light-emitting diode (LED). On the WWs, initially the threshold could not be set, since the soil moisture was below the measurement range of the controller. After discussion with the manufacturer, a 1,000Ω resistor was added between the solenoid valve port and the valve common port, which allowed the controller to read the low VMC at field capacity of this sandy soil. The calibration procedure consisted of setting the knob in the middle of the scale (dimensionless), and pushing the calibration button, which allowed its autoset point. It is important to note that following these methods the thresholds on the RB and WW controllers could not be associated with a specific soil VMC prior to the experiment. However, in order to find similar outcomes to those that homeowners would encounter, SMS systems were planned to be used directly "out of the box," following manufacturer recommendations for installation and set points; a circumstance that could not be immediately accomplished in the aforementioned WW case.

Treatments

Two basic types of treatments were defined: SMS-based treatments, and time-based treatments (Table 1). All four SMS brands were tested at three irrigation frequencies: one, two, and seven days per week (1, 2, and 7 day/week, respectively), resulting in 12 SMS/frequency combinations. The 1 and 2 day/week watering frequencies represent typical day of the week irrigation restrictions imposed in Florida (FDEP 2006; SJRWMD 2006). Within the time-based treatments, a frequency of 2 day/week was defined (the most common in Florida, and current watering restriction in the study area). To simulate requirements imposed on homeowners by Florida Statutes (Chap. 373.62), two time-based treatments were connected to a rain sensor: with-rain sensor (2-WRS) and deficit-with-rain sensor (2-DWRS). The rain sensor (Mini-click II, Hunter Industries, Inc., San Marcos, Calif.) was set at a 6 mm rainfall threshold. A without-rain-sensor treatment (2-WORS) was also included, in order to simulate homeowner irrigation systems with an absent or nonfunctional rain sensor. Finally, a nonirrigated treatment (0-NI) was implemented as a control for turfgrass quality. Experimental treatments were replicated four times, in a completely randomized design.

The weekly irrigation depth was programmed to replace 100% of the monthly historical net irrigation requirement, based on recommendations by Dukes and Haman (2002b) for the area where this experiment was carried out (Table 2). All treatments were programmed to apply the same amount of irrigation per week, except for treatments 2-DWRS (60% of this amount), and 0-NI. Therefore, differences in water application among treatments would be the result of sensors bypassing scheduled irrigation cycles.

The irrigation cycles were programmed on two ESP-6, and three ESP-4Si model timers (Rain Bird International, Inc., Glendora, Calif.) set to start between 1 and 5 a.m., with the purpose of diminishing wind drift and decreasing evaporation, and to mimic water use restrictions where this study was carried out, that prohibit irrigation between 10 a.m. and 4 p.m. (SJRWMD 2006).

Table 1. Irrigation Treatment Codes and Descriptions

Treatment codes	Irrigation frequency (days/week)	Soil moisture sensor brand or treatment description
	(a) Time based	
2-WORS	2	Without rain sensor
2-WRS	2	With rain sensor
2-DWRS	2	Deficit with rain sensor, 60% of 2-WRS
	(b) SMS based	
1-AC	1	Acclima
1-RB	1	Rain Bird
1-IM	1	Irrometer
1-WW	1	Water Watcher
2-AC	2	Acclima
2-RB	2	Rain Bird
2-IM	2	Irrometer
2-WW	2	Water Watcher
7-AC	7	Acclima
7-RB	7	Rain Bird
7-IM	7	Irrometer
7-WW	7	Water Watcher
0-NI	0	No irrigation

Note: SMS=soil moisture sensor.

Table 2. Monthly Irrigation Depth to Replace Historical Net Irrigation Requirements (Adapted from Dukes and Haman 2002b)

Month	Irrigation depth (mm)
January	0
February	0
March	112
April	112
May	183
June	142
July	137
August	178
September	137
October	122
November	91
December	91
Total	1,305

Uniformity Testing

A uniformity test was conducted for each plot with 16 catch-cans on a 0.9 m × 0.9 m grid spacing. To minimize edge effects, this grid was positioned 0.4 m inside the plot boundaries. The cans had an opening diameter of 15.9 cm and a depth of 20.3 cm. Pressure at the two farthest plots was measured to ensure adequate sprinkler operation. The system was set to run for 35 min, to ensure that the average water application depth was at least 13 mm. Wind velocity during the test period was measured with a hand held anemometer. The American Society of Agricultural Engineers (ASAE) standards (ASAE 2000) allow uniformity testing with wind speeds up to 5 m/s. However, if wind was over 2.5 m/s or the distribution was affected by wind gusts, the test was discontinued.

The low-quarter irrigation distribution uniformity (DU_{lq}) was calculated with the following equation (Merriam and Keller 1978):

$$DU_{lq} = \frac{\bar{D}_{lq}}{\bar{D}_{tot}} \tag{1}$$

where $\bar{D}_{lq}$=mean of the lowest 25% of a group of catch-can measurements; and $\bar{D}_{tot}$=overall mean of a group of catch-can measurements.

The irrigation uniformity tests resulted in a wide range of DU_{lq} values across the plots (0.15–0.79), with an average of 0.52 that, according to the Irrigation Association (IA 2005) overall system quality ratings, is considered "fair." The very low values denoted some performance problems (partially or completely clogged nozzles, spray heads below the mowing height, spray heads misaligned, etc.) that were fixed after the test was run. Even when a new DU_{lq} test was not performed after the repairs, observations denoted a substantial improvement on the plots with low DU_{lq} values. As a comparison, Baum et al. (2005) performed uniformity tests on irrigation systems of homes in central Florida having spray heads, and found an average DU_{lq} of 0.41, with a range of 0.12–0.67. Thus, the irrigation uniformity of the experimental plots was representative of actual homes. In addition, Dukes et al. (2006) reported that catch-can DU_{lq} as low as 0.40 did not result in reduced soil water DU_{lq} of approximately 0.75. The writers concluded that the soil system and plant canopy can buffer low catch-can DU_{lq} values resulting in a higher effective irrigation uniformity.

Soil Moisture Sensor Installation

According to manufacturer recommendations, the SMSs should be buried in the driest zone of a multiple-zone system. Accordingly, to identify the driest and wettest plots in the experimental area, a volumetric soil moisture survey assessment was carried out on each plot. In addition, because 64 plots were required, this analysis was used to discard eight plots from a pool of 72 plots available. On March 12, 2004, after 14 days without rainfall, a relatively "dry" soil moisture condition was evident. The volumetric moisture content was measured in each plot by means of a hand held TDR device, which measured the moisture in the top 20 cm (Field Scout 300, Spectrum Technologies, Inc., Plainfield, Ill.). Measurements were taken at five locations in the center 1 m × 1 m of each plot and averaged. On March 17, 2004, 24 h after a 23 mm rainfall filled the soil profile, the volumetric moisture content in a "wet" condition was measured as well. Two plots had significantly higher VMC, under both the wet and the dry condition, so they were discarded. Six plots were also discarded because they had the absolute lowest VMC values of all plots, even when they were not statistically different ($P > 0.95$), coupled with a comparatively lower turfgrass quality before the beginning of the experiment. An analysis of variance (ANOVA) on the remaining 64 plots, indicated that only two plots were significantly wetter than the rest ($P > 0.95$) in the wet condition, so they were discarded as locations for SMS placement. In the dry condition, there were not statistical differences ($P > 0.95$) in the soil moisture levels. Thus, the plots selected to bury the SMSs were the absolute driest ones and/or the most convenient for sensor installation. Moreover, in the dry condition, the soil moisture content (5.2–6.8%) was not significantly different ($P > 0.999$) across sensor control plots. In all cases, SMSs were installed in the center of the plots, in the top 7–10 cm of the soil, where most of the roots were observed. The plots with the sensors were used to control irrigation in three other plots for a total of four replications for each treatment.

Irrigation Management and Data Collection

Data were obtained from July 20 to December 14 of 2004 and from March 25 to August 31 of 2005. Water application data were collected independently for each plot. Pulse-type positive displacement flowmeters (PSMT 20 mm × 190 mm, Amco Water Metering Systems, Inc., Ocala, Fla.) were connected to nine AM16/32 multiplexers (Campbell Scientific, Logan, Utah), which were hooked up to a CR 10× model datalogger (Campbell Scientific, Logan, Utah), to continually record the irrigation date and volume applied to each plot. In addition, flowmeters were read manually each week to verify automatically acquired data.

Weather data were collected by an automated weather station (Campbell Scientific, Logan, Utah), located beside the experimental site. Measurements, made every 15 min, included air temperature, relative humidity, wind speed, wind direction, solar radiation, barometric pressure, and soil heat flux. Rainfall was recorded continuously by a manual rain gauge during 2004 and 2005, and also by a tipping bucket rain gauge in 2005. Both methods agreed well (R^2=0.99) when measured over a period of 212 days, encompassing 73 rain events that ranged from 0.3 to 50.3 mm.

Turfgrass quality was visually assessed and rated using a scale of 1–9, where "1" represents brown, dormant, or dead turf, and "9" represents the best quality (Skogley and Sawyer 1992). A rating of 5 was considered the minimum acceptable turf quality for a lawn turfgrass. Ratings were carried out by the same person in July, October, and December of 2004, and in April, May, and July of 2005.

Statistical data analyses were performed using the general linear model (GLM) procedure of the Statistical Analysis System software (SAS 2003). Analysis of variance was used to determine treatment differences for a completely randomized design and Duncan's multiple range test was used to identify mean differences.

Results and Discussion

Environmental Conditions

Table 3 summarizes the monthly mean average air temperature, relative humidity, wind speed, total rainfall, and crop evapotrans-

Table 3. Weather Conditions and Estimated Turfgrass Evapotranspiration (ET_c) at the Experimental Site during July 20 to December 14, 2004, and from March 25 to August 31, 2005

Month	Mean air temperature (°C)	Mean relative humidity (%)	Mean wind speed (m/s)	Total rainfall (mm)	ET_c[a] (mm)
(a) 2004					
July (20–31)	27.4	75	2.2	22	46
August	26.2	82	2.5	299	97
September	24.9	79	4.1	495	83
October	22.6	79	2.3	68	71
November	18.3	78	2.7	49	56
December (1–14)	14.3	75	2.7	13	22
Total				944	375
(b) 2005					
March (25–30)	20.1	76	3.8	31	19
April	18.4	66	3.4	114	109
May	22.7	73	2.7	109	112
June	25.8	82	2.9	198	104
July	27.6	77	3.3	126	128
August	27.5	81	2.2	154	105
Total				732	578

[a]Crop evapotranspiration (ET_c) calculated from reference evapotranspiration (ET_o) and specific crop coefficient (K_c) values ($ET_c = ET_o * K_c$). ET_o was calculated from the Penman–Monteith equation, with a crop coefficient $K_c = 0.85$ for established bermudagrass, as described in FAO-56 by Allen et al. (1998).

piration during the experiment period. In general, favorable conditions prevailed for the growth and development of the bermudagrass. However, in December of 2004 the average air temperature began to gradually decline and, on December 15, 2004, the bermudagrass went dormant. The irrigation treatments were discontinued until the bermudagrass greened up again, on March 24, 2005.

Both 2004 and 2005 were rainy years (Figs. 1 and 2), with high frequent rainfall and a large amount of cumulative precipitation, which is not uncommon in this region. During 2004, a tropical storm and two hurricanes—Frances and Jeanne—passed over the research area during the experiment. Even while 2005 broke all records for the number of hurricanes and named tropical storms in the United States, none of them directly hit the experiment site. Nonetheless, during the 2005 data collection period, 40% of the days had rainfall events, totaling 732 mm (13% more than historical rainfall for this time period), and averaging 135 mm/month. In 2004, even though it rained less frequently (31% of the days), the cumulative rainfall for the experimental period was even larger, with 944 mm (88% more than historical rainfall), and more than 190 mm/month on average. However, most of this rainfall (56%) occurred during the tropical storm and the two hurricanes. If these events were not considered, a total of 414 mm with an average of 84 mm/month fell during 2004.

Time-Based Treatments

In Table 4, Comparison A shows that the three time-based treatments (2-WORS, 2-WRS, and 2-DWRS) were significantly different ($P < 0.0001$) from each other during this study. Treatment 2-WRS (2 day/week, with a rain sensor) was established to mimic a homeowner complying with irrigation regulations and setting the timer according to recommended practices. This treatment accounted for 995 mm of water, or an equivalent of 98 mm/month. A recent study, carried out by Haley et al. (2007) in Central Florida, within the St. Johns River Water Management District, found that homeowners with automatic irrigation systems applied 149 mm/month on average. Therefore, the comparisons made here may be considered conservative and differences in the results for actual homeowners could be larger.

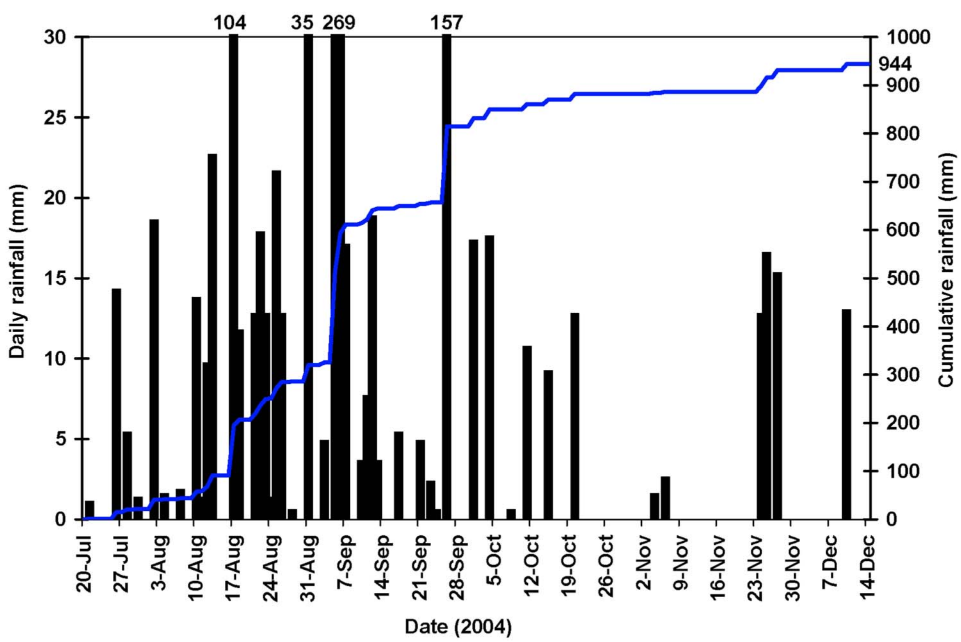

Fig. 1. Daily and cumulative rainfall in 2004. Note: rainfall for September 5 (188 mm) and September 6 (81 mm) are shown as a cumulative total (269 mm).

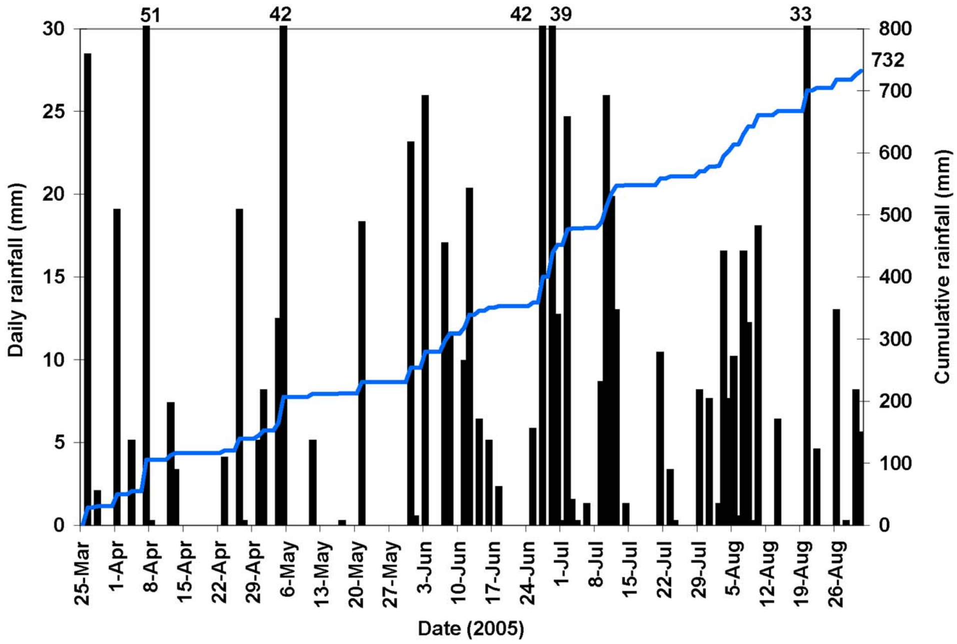

Fig. 2. Daily and cumulative rainfall in 2005

The well-managed or water conservative homeowner profile, imitated by treatment 2-DWRS (2 day/week, with a rain sensor, and 60% of 2-WRS), applied 63% of the water applied by 2-WRS, close to the target of 60%. The total depth was 623 mm, or an equivalent of 61 mm/month.

The treatment simulating an irrigation system with an absent or nonfunctional rain sensor (2-WORS) accounted for 1514 mm, or 148 mm/month. Thus, this treatment applied 52% more water than the treatment with a functional rain sensor (2-WRS), whereas 2-WRS saved 34% of the water applied by 2-WORS. These results demonstrate the importance of a functional and well-maintained rain shut-off device on all automated irrigation systems in Florida; where rainy weather is common (NOAA 2003). Moreover, as the study prepared by Whitcomb (2005) recently found, just 25% of the surveyed homeowners in Florida with automatic irrigation systems reported having a rain sensor, and the author speculated that they are often incorrectly installed. Therefore, appropriately installed and properly working rain sensors could signify not only substantial water savings to homeowners, but could also lead to sound environmental and economic benefits to the state. Moreover, Cardenas-Lailhacar and Dukes (2008) found that rain sensors under the climate conditions of this study have a payback period of less than a year when set at thresholds of 13 mm or less.

Time-Based Treatments versus SMS-Based Treatments. Table 4 (Comparison B) shows that there was a significant ($P < 0.0001$) difference between the averages of time-based and SMS-based treatments; with 1,044 and 420 mm of cumulative irrigation depth, respectively. Thus, the SMS-based treatments, on average, significantly reduced the amount of irrigation water applied compared to the time-based treatments, even when an operative rain sensor was an important component on two of the three time-based treatments. Moreover, 72% of the water applied by 2-WORS was saved on average by the SMS-based treatments.

Table 4. Total Cumulative Irrigation Depth Applied to Treatments, Statistical Comparisons, and Percent Water Savings Compared to 2-DWRS, 2-WRS, and 2-WORS

Treatment	Cumulative depth (mm)	Comparisons[a]			Water savings (%)		
		A	B	C	2-DWRS	2-WRS	2-WORS
(a) Time based							
2-WORS	1514	*a*[b]			−143	−52	0
2-WRS	995	*b*			−60	0	34
2-DWRS	623	*c*			0	37	59
Time-Avg	1044		a				
(b) SMS based							
1-AC	283				55	72	81
1-RB	281				55	72	81
1-IM	793				−27	20	48
1-WW	323				48	68	79
1-Avg	420			*b*			
2-AC	348				44	65	77
2-RB	188				70	81	88
2-IM	1105				−77	−11	27
2-WW	270				57	73	82
2-Avg	478			*a*			
7-AC	122				80	88	92
7-RB	147				76	85	90
7-IM	715				−15	28	53
7-WW	463				26	54	69
7-Avg	362			*c*			
SMS-Avg	420		b				
CV (%)[d]		2.6	57.4	6.0			

Note: SMS=soil moisture sensor, and CV=coefficient of variation determined by the overall ANOVA model.

[a]A=between time-based treatments; B=time-based treatments versus SMS-based treatments; and C=between irrigation frequency averages.

[b]Different letters within a column indicate statistical difference at $P < 0.05$ (Duncan's multiple range test).

Comparisons between SMS-Irrigation Frequencies

When the averages of the three different SMS irrigation frequencies were analyzed (Table 4, Comparison C), the 2 day/week frequency applied significantly ($P < 0.0001$) more water, followed by the 1 day/week frequency, with 478 and 420 mm of total cumulative water depth, respectively. Although a wide range of variation was apparent across the sensor brands, the 7 day/week frequency resulted in a significantly lower depth applied of all three frequencies, with an average of 362 mm, because two of four 7 day/week treatments (7-AC and 7-RB) bypassed more scheduled irrigation events due to frequent rainfall (Figs. 1 and 2).

Water Savings

Table 4 shows the water savings (%) of each treatment compared to the time-based treatments 2-DWRS, 2-WRS, and 2-WORS. Treatments 7-AC and 7-RB achieved the highest amounts of water savings throughout this experiment and, as expected, 2-WORS applied more water than all the other treatments. On the other hand, the IMs always allowed more water to be applied compared to the other brands in every frequency tested. This could be due to their reported limitations to timely sense differences in soil water content, their hysteretic behavior, the high variability of readings, and their limitations in sandy soils, where low tension values are necessary to prevent plant stress (Irmak and Haman 2001; Taber et al. 2002: Intrigliolo and Castel 2004; McCann et al. 1992).

When compared to the water conservative 2-DWRS treatment, brands AC, RB, and WW showed water savings that ranged from 44 to 80%, 55 to 76%, and 26 to 57%, respectively. On the other hand, all IM frequencies applied more irrigation than 2-DWRS, with values that ranged from 15 to 77% more water.

Treatment 2-IM was the only SMS-based treatment that applied more water than the time-based 2-WRS (11%). Conversely, 1-IM and 7-IM reduced water application 20 and 28%, respectively, compared to 2-WRS. However, these last proportions were far from the water savings achieved by the other SMS-based treatments, when compared to 2-WRS: AC sensors recorded irrigation water savings ranging from 65 to 88%, RBs from 72 to 85%, and WWs from 54 to 73%, depending on the irrigation frequency tested. It is important to remark that these water savings were on top of those already achieved by 2-WRS. Therefore, these results show that, in general, SMSs can also act as rain shut-off devices, although with a superior performance than rain sensors in terms of water savings.

When the irrigation treatments were compared to more than 75% of the surveyed homeowners in Florida (Whitcomb 2005), with a nonfunctional or absent rain sensor (2-WORS), the difference in water savings increased, ranging from 77 to 92% for ACs, 81 to 90% for RBs, 69 to 82% for WWs, and 27 to 53% for IMs. Even 2-IM (which applied 11% more water than 2-WRS) showed water savings (27%) with respect to 2-WORS, indicating that this sensor was operative but did not bypass as many scheduled irrigation cycles as other SMS-based treatments.

These results clearly demonstrate that the use of SMSs (along with traditional timers in residential irrigation systems) could lead to water savings more than twice as much as a rain sensor device alone, even when the time schedule is programmed to provide 60% of net irrigation requirements.

Automation of Irrigation Systems

Complete automation of a residential irrigation system, based on SMSs, could be achieved by programming the timer to run every day as a scheduling strategy. Then, SMSs will allow the system to initiate the scheduled irrigation cycles only when it is actually needed by the turfgrass (or other irrigated plant type), and override cycles when the sensed water content is over a preset threshold. In this experiment, this type of control was confirmed when the 7 day/week irrigation frequency applied significantly less water than the other frequencies (Table 4, Comparison C), and when two of the SMS-based treatments, programmed to run 7 day/week, consistently applied the smallest amount of water. In effect, treatments 7-AC and 7-RB recorded total water savings of 85% or more, when compared to 2-WRS, and 90% or more when compared to 2-WORS.

This concept (with a potential irrigation frequency of seven days a week) seems contradictory to the water use regulations and restrictions imposed by the Water Management Districts and/or municipalities in Florida (where irrigation is allowed only one or two days per week). However, during wet weather conditions these results suggest that setting the correct threshold, and programming the automatic irrigation system to run everyday for a short period of time (allowing the SMS to decide whether to irrigate), could save large amounts of water and may be a more effective water conservation strategy than day of the week watering windows. Moreover, this concept is not in opposition to the general recommendation for deeper and less frequent irrigation for turfgrass, because these treatments (7-AC and 7-RB) overrode almost every scheduled irrigation cycle, resulting in a low actual irrigation frequency, which was supplemented by large and/or frequent rainfall events that filled the profile (Figs. 1 and 2). Nonetheless, it is important to note that this technology and frequency needs to be evaluated during dry weather conditions to be sure that turfgrass quality does not decline due to reduced irrigation application.

Turfgrass Quality

Differences in turfgrass quality, including nonirrigated plots, were not detected among treatments, and always exceeded the minimum acceptable rating of 5. This result is explained in part by the generally wet weather conditions that prevailed through most of the experiment, which favored the growth and development of the bermudagrass (Table 3, and Figs. 1 and 2). Another factor contributing to the general good turf quality observed, even during the short "dry" periods, could be found in the species itself. Common bermudagrass is known as a more drought-tolerant grass compared to the pervasive St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] found in north-central Florida landscapes (Harivandi et al. 2001; Baldwin et al. 2006; Turgeon 2005). As a result, the treatment effects were buffered with respect to the turfgrass quality parameters, and it could be concluded that no irrigation was necessary to maintain an acceptable turf quality during the experiment time period. Jordan et al. (2003) obtained similar results working with bentgrass, when frequent rainfall coupled with high relative humidity conditions overrode the effects of the irrigation frequency treatments on turf quality.

Conclusions

High-frequency rainfall events and a large amount of cumulative precipitation, coupled with favorable environmental conditions, favored the growth and development of the bermudagrass during the timeframe of this research.

The three time-based treatments (2-WORS, 2-WRS, and

2-DWRS) were significantly different from each other during the study period. The treatment with a functional rain sensor (2-WRS), at a 6 mm threshold, applied significantly less water (34%) than the without rain sensor treatment (2-WORS), showing the importance of a well-maintained rain shut-off device in all automated irrigation systems in Florida. On the other hand, treatment 2-DWRS, applied close to the desired 60% of the water applied by 2-WRS. These time-based treatments were established to mimic the operation of irrigation systems carried out by different homeowner profiles. However, according to the results of this research, these treatments were fairly well managed compared to homeowners' actual operation practices in the Central Florida Ridge. Therefore, results in water use from this experiment can be considered conservative and differences for actual homeowners could be even larger.

For the SMS treatments, all three irrigation frequencies tested (1, 2, and 7 day/week) were significantly different. The 2 day/week frequency applied the highest volume of water, followed by the 1 day/week frequency, and the 7 day/week was the one that applied the least amount of water. These results suggest that scheduling high-frequency irrigation cycles (7 day/week) in closed control loop irrigation systems appears to be a viable strategy regarding water conservation for turfgrass irrigation in Florida's sandy soils during rainy periods. Moreover, it was concluded that irrigation was not necessary to maintain acceptable turf quality during the experimental period, which was evidenced by acceptable quality in nonirrigated plots.

The results showed that, on average, the SMS-based treatments were significantly more efficient as a means to save water than the time-based treatments. However, not all SMS treatments tested performed the same. The 2-IM treatment was the only SMS-based treatment that applied significantly more water than 2-WRS (11%). The other two IM treatments, 1-IM and 7-IM, applied less water than 2-WRS (20 and 28%, respectively), but always applied more water than the other brands/treatments in every frequency tested. The other brands (AC, RB, and WW) resulted in irrigation water savings compared to 2-WRS, which ranged from 54 to 88%, depending on the irrigation frequency. These results showed that most SMSs can also act as rain sensors, with superior performance in terms of water savings. When these last brands were compared to 2-WORS, the differences in water savings increased, and ranged from 69 to 92% over the 308-day study period.

It should be noted that the specific performance of the individual sensors largely depends on the threshold setting and the sensor burial depth. Even when sensor burial depths were as similar as practically possible in this experiment, the sensor thresholds might have varied slightly, hence, affecting the results to some extent. In any case, soil moisture sensor systems appear to be a promising technology that could lead to a complete automation of residential irrigation systems, to substantial savings in irrigation water, and to sound environmental and economic benefits to the state. Testing this technology with actual irrigation systems on homes is recommended to validate these results.

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References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration: Guidelines for computing crop requirements." *Irrigation and Drainage Paper No. 56*, FAO Food and Agriculture Organization, Rome.

American Society of Agricultural Engineers (ASAE). (2000). "Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles." *American Society of Agricultural Engineers standards, ANSI/ASAE S436.1*, 48th Ed., ASAE, St. Joseph, Mich.

Augustin, B. J., and Snyder, G. H. (1984). "Moisture sensor-controlled irrigation for maintaining bermudagrass turf." *Agron. J.*, 76(5), 848–850.

Baldwin, C. M., Liu, H., McCarty, L. B., Bauerle, W. L., and Toler, J. E. (2006). "Response of six Bermudagrass cultivars to different irrigation intervals." *HortTechnology*, 16(3), 466–470.

Baum, M. C., Dukes, M. D., and Miller, G. L. (2005). "Analysis of residential irrigation distribution uniformity." *J. Irrig. Drain. Eng.*, 131(4), 336–341.

Bonos, S. A., and Murphy, J. A. (1999). "Growth responses and performance of Kentucky bluegrass under summer stress." *Crop Sci.*, 39(3), 770–774.

Cardenas-Lailhacar, B. (2006). "Sensor-based automation of irrigation of bermudagrass." MS thesis, Agricultural and Biological Engineering Dept., Univ. of Florida, Gainesville, Fla.

Cardenas-Lailhacar, B., and Dukes, M. D. (2008). "Expanding disk rain sensor performance and potential irrigation water savings." *J. Irrig. Drain. Eng.*, 134(1), 67–73.

Carlisle, V. W., Hallmark, C. T., Sodek, F., Caldwell, R. E., Hammond, L. C., and Berkheiser, V. E. (1981). "Characterization data for selected Florida soils." *Soil Science Research Report No. 81-1*, Institute of Food and Agricultural Sciences, Dept. of Soil Science Univ. of Florida, Gainesville, Fla.

Carriker, R. R. (2000). "Florida's water: Supply, use, and public policy." *Rep. FE 207*, Dept. of Food and Resource Economics, Univ. of Florida, Gainesville, Fla.

Clark, G. A., Stanley, C. D., and Maynard, D. N. (1994). "Tensiometer control versus tomato crop coefficients for irrigation scheduling." *ASAE Meeting Paper 94-2118*, American Society of Agricultural Engineers, St. Joseph, Mich.

Colbaugh, P. F., and Elmore, C. L. (1985). "Influence of water on pest activity." *Turfgrass water conservation*, V. A. Gibeault and S. T. Cockerham, eds., Cooperative Extension, University of California, Calif., 113–129.

Davis, D. B., and Dernoeden, P. H. (1991). "Summer patch and Kentucky bluegrass quality as influenced by cultural practices." *Agron. J.*, 83(4), 670–677.

Dukes, M. D., Haley, M. B., and Hanks, S. A. (2006). "Sprinkler irrigation and soil moisture uniformity." *Proc., 27th Int. Irrigation Show* (CD-ROM), San Antonio.

Dukes, M. D., and Haman, D. Z. (2002a). "Residential irrigation system rainfall shutoff devices." *Rep. ABE325*, Institute of Food and Agricultural Sciences, Univ. of Florida, Gainesville, Fla.

Dukes, M. D., and Haman, D. Z. (2002b). "Operation of residential irrigation controllers." *Rep. CIR1421*, Institute of Food and Agricultural Sciences, Univ. of Florida, Gainesville, Fla.

Dukes, M. D., and Scholberg, J. M. (2005). "Soil moisture controlled subsurface drip irrigation on sandy soils." *Appl. Eng. Agric.*, 21(1), 89–101.

Dukes, M. D., Simonne, E. H., Davis, W. E., Studstill, D. W., and Hochmuth, R. (2003). "Effect of sensor-based high-frequency irrigation on bell pepper yield and water use." *Proc., 2nd Int. Conf. on Irrigation and Drainage*, Phoenix, 665–674.

Florida Department of Environmental Protection (FDEP). (2006). "Chapter 62-40.411: Water shortage." ⟨http://www.dep.state.fl.us/legal/Rules/shared/62/40.pdf⟩ (Dec. 4, 2006).

Haley, M. B., Dukes, M. D., and Miller, G. L. (2007). "Residential irrigation water use in Central Florida." *J. Irrig. Drain. Eng.*, 133(5), 427–434.

Harivandi, M. A., Gibeault, V. A., Henry, M. J., Wu, L., Geisel, P. M., and Unruh, C. L. (2001). "Turfgrass selection for the home landscape." *Publication 8035*, Division of Agriculture and Natural Resources, Univ. of California at Davis, Davis, Calif.

Hodges, A. W., Haydu, J. J., van Blokland, P. J., and Bell, A. P. (1994). "Contribution of the turfgrass industry to Florida's economy, 1991–1992: A value-added approach." *Economic Rep. ER 94-1*, Institute of Food and Agricultural Sciences, Univ. of Florida, Gainesville, Fla.

Intrigliolo, D. S., and Castel, J. R. (2004). "Continuous measurement of plant and soil water status for irrigation scheduling in plum." *Irrig. Sci.*, 23(2), 93–102.

Irmak, S., and Haman, D. Z. (2001). "Performance of the Watermark granular matrix sensor in sandy soils." *Appl. Eng. Agric.*, 17(6), 787–795.

Irrigation Association (IA). (2005). *Landscape irrigation scheduling and water management*, Water Management Committee, Falls Church, Va.

Jordan, J. E., White, R. H., Vietor, D. M., Hale, T. C., Thomas, J. C., and Engelke, M. C. (2003). "Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars." *Crop Sci.*, 43(1), 282–287.

Kackley, K. E., Grybauskas, A. P., Dernoeden, P. H., and Hill, R. L. (1990). "Role of drought stress in the development of summer patch in field inoculated Kentucky bluegrass." *Phytopathology*, 80(7), 655–658.

Mayer, P. W., DeOreo, W. B., Opitz, E. M., Kiefer, J. C., Davis, W. Y., Dziegielewski, B., and Nelson, J. O. (1999). *Residential end uses of water*, American Water Works Association, Denver.

McCann, I. R., Kincaid, D. C., and Wang, D. (1992). "Operational characteristics of the watermark model 200 soil water potential sensor for irrigation management." *Appl. Eng. Agric.*, 8(5), 603–609.

McCarty, L. B. (2005). *Best golf course management practices*, Prentice-Hall, Upper Saddle River, N.J.

Merriam, J. L., and Keller, J. (1978). *Farm irrigation system evaluation: A guide for management*, Dept. of Agricultural and Irrigation Engineering, Utah State Univ. Logan, Utah.

Muñoz-Carpena, R., Bryan, H., Klassen, W., and Dukes, M. D. (2003). "Automatic soil moisture-based drip irrigation for improving tomato production." *Proc., Florida State Horticultural Society*, 116(2003), 80–85.

Muñoz-Carpena, R., and Dukes, M. D. (2005). "Automatic irrigation based on soil moisture for vegetable crops." *Rep. ABE356*, Institute of Food and Agricultural Sciences, Univ. of Florida, Gainesville, Fla.

Muñoz-Carpena, R., Dukes, M. D., Li, Y., and Klassen, W. (2005). "Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato." *HortTechnology*, 15(3), 584–590.

National Oceanic and Atmospheric Administration (NOAA). (2003). "Monthly station normals of temperature, precipitation, and heating and cooling degree days 1971–2000; 08 Florida." *Climatography of The United States No. 81*, ⟨http://hurricane.ncdc.noaa.gov/climatenormals/clim81/FLnorm.pdf⟩ (Dec. 4, 2006).

National Research Council (NRC). (1996). *A new era in irrigation*, National Academies Press, Washington, D.C.

Nogueira, L. C., Dukes, M. D., Haman, D. Z., Scholberg, J. M., and Cornejo, C. (2002). "Data acquisition and irrigation controller based on CR10X datalogger and TDR sensor." *Proc., Soil Crop Science Society of Florida*, 62(2002), 38–46.

Office of Economic and Demographic Research (OEDR). (2006). "Demographic estimating conference: Florida demographic forecast." ⟨http://edr. state. fl. us/conferences/population/demographic. htm⟩ (Dec. 4, 2006).

Qualls, R. J., Scott, J. M., and DeOreo, W. B. (2001). "Soil moisture sensors for urban landscape irrigation: effectiveness and reliability." *J. Am. Water Resour. Assoc.*, 37(3), 547–559.

Shock, C. C., Feibert, E. B. G., Saunders, L. D., and Eldredge, E. P. (2002). "Automation of subsurface drip irrigation for crop research." *Proc., World Congress of Computers in Agriculture and Natural Resources*, Iguacu Falls, Brazil.

Skogley, C. R., and Sawyer, C. D. (1992). "Field research." *Turfgrass*, D. V. Waddington, R. N. Carrow, and R. C. Shearman, eds., *Agronomy Monograph 32*, Madison, Wis. 589–614.

Smajstrla, A. G., and Koo, R. C. (1986). "Use of tensiometers for scheduling of citrus irrigation." *Proc., Florida State Horticultural Society*, 99(1986), 51–56.

Smajstrla, A. G., and Locascio, S. J. (1994). "Irrigation cutback effects on drip-irrigated tomato yields." *Proc., Florida State Horticulture Society*, 107(1994), 113–118.

Solley, W. B., Pierce, R. R., and Perlman, H. A. (1998). "Estimated use of water in the United States in 1995." *U.S. Geological Survey Circular 1200*, U.S. Geological Survey, Reston, Va.

Southwest Florida Water Management District (SWFWMD). (2006). "Southern water use caution area recovery strategy." *Final Rep.*, ⟨http://www.swfwmd.state.fl.us/waterman/swuca/SWUCA.htm⟩ (Dec. 4, 2006).

St. John's River Water Management District (SJRWMD). (2006). "Irrigation rule." ⟨http://sjrwmd. com/programs/outreach/conservation/irrigation_rule/index. html⟩ (Dec. 4, 2006).

Statistical Analysis System (SAS). (2003). *SAS/STAT user's guide, Ver. 9.1*, SAS Institute, Inc., Cary, N.C.

Taber, H. G., Lawson, V., Smith, B., and Shogren, D. (2002). "Scheduling microirrigation with tensiometers or Watermarks." *Int. Water Irrig.* 22, 22–26.

Tampa Bay Water (TBW). (2005). "Evaluating implementation of multiple irrigation and landscape ordinances in the Tampa Bay region." ⟨http://www.tampabaywater.org/conservation/reportsdocs.aspx⟩ (Dec. 4, 2006).

Thomas, B. D., Cummings, E., and Whittstruck, W. H. (1985). *Soil survey of Alachua County*, Florida, Institute of Food and Agricultural Sciences, Soil Science Dep. and the Florida Dep. of Agriculture and Consumer Services, Univ. of Fla., Gainesville, Fla.

Topp, G. C. (2003). "State of the art of measuring soil water content." *Hydrolog. Process.*, 17(14), 2993–2996.

Turgeon, A. J. (2005). *Turfgrass management*, Prentice-Hall, Upper Saddle River, N.J.

United States Census Bureau (USCB). (2004a). "Population estimates." ⟨http://www.census.gov/popest/estimates.php⟩ (Dec. 4, 2006), USCB, Washington, D.C.

United States Census Bureau (USCB). (2004b). "Housing unit estimates." ⟨http://www.census.gov/popest/housing/⟩ (Dec. 4, 2006), USCB, Washington, D.C.

United States Department of Agriculture (USDA). (1981). "Land resource regions and major land resource areas of the united states." *Soil conservation service handbook 256*, USDA, Washington, D.C.

United States Department of Agriculture (USDA). (2005). "Florida State agriculture overview—2005." ⟨http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_FL.pdf⟩ (Dec. 4, 2006), National Agricultural Statistics Service, Washington, D.C.

United States Department of Agriculture (USDA). (2007). "Official soil series descriptions." ⟨http://soils.usda.gov/technical/classification/osd/index.html⟩ (Dec. 4, 2006), Natural Resource and Conservation Service, Washington, D.C.

Whitcomb, J. B. (2005). "Florida water rates evaluation of single-family homes." ⟨http://www.swfwmd.state.fl.us/documents/reports/water_rate_report.pdf⟩ (Dec. 4, 2006), Southwest Florida Water Management District.

Youngner, V. B., Marsh, A. W., Strohman, R. A., Gibeault, V. A., and Spaulding, S. (1981). "Water use and turf quality of warm-season and cool-season turfgrasses." *Calif. Turfgrass Cult.*, 31(3–4), 1–4.