SOIL MOISTURE SENSOR LANDSCAPE IRRIGATION CONTROLLERS: A REVIEW OF MULTI-STUDY RESULTS AND FUTURE IMPLICATIONS

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ABSTRACT. *This is a review article with the objective of summarizing and relating the main findings of different research projects carried out in Florida that evaluated commercially available soil moisture sensor systems (SMSs) for residential irrigation control. The initial goal of the experiments cited was to find out if SMSs could reduce irrigation water application as compared to typical residential irrigation systems without sensor feedback. The effect of different threshold settings and irrigation frequencies on water application and turf quality was also evaluated. Other research goals included evaluating the consistency of different SMS units and their precision in measuring soil water content (θ). Results on turfgrass plots showed that a 7 days per week (d week^{-1}) irrigation frequency significantly reduced the water applied compared to 1 and 2 d week^{-1} scheduled frequencies. During rainy periods, the SMSs tested reduced irrigation by 42% to 72% on average, depending on specific testing conditions, while maintaining good turf quality. During dry periods, the average savings decreased to -1% to 64%, and the resultant turf quality was sometimes below the minimum acceptable level. Therefore, under sustained dry weather conditions or in dry climates, the run times, irrigation frequency, and/or low threshold settings should be carefully considered. Results showed that SMSs from Acclima and Rain Bird were more consistent and precise in measuring soil water content and saved more water than Water Watcher and Irrometer units. Under residential conditions, SMSs decreased the water application by 65% compared to homes with automated irrigation systems without sensor feedback. Overall research results clearly demonstrate that the use of SMSs in Florida, when properly installed, set, and maintained, could lead to significant irrigation water savings while maintaining turf quality at or above the minimum acceptable rating.*

Keywords. *Automation, FDR, Irrigation scheduling, Potable water, Residential irrigation, Soil moisture sensor controller, TDR, TDT, Turfgrass, Turf quality, Water use.*

The effects of increased population growth, industrial expansion, and agricultural irrigation withdrawals have led to concerns for the future availability and quality of groundwater. Nearly 80% of the population of Florida lives within 20 miles of the coast. Due to excessive pumping, saltwater intrusion in the Floridan aquifer (the primary source of drinking water for most cities in central and northern Florida) has been found in the coastal areas of Hillsborough, Manatee, Sarasota, Duval, and St. Johns counties (Spechler, 1994; SWFWMD, 2006).

Due to the low water holding capacity of the soils, in addition to the irregularity in frequency and depth of the rainfall events, irrigation of landscapes in Florida is commonly employed to ensure acceptable plant growth and quality. A study performed in the Central Florida Ridge found that homeowners tended to over-irrigate and that 64% of the total water use in households was attributed to landscape irrigation (Haley et al., 2007).

To cope with the increasing demand for potable water (aggravated by recurrent droughts), Florida has implemented several laws and ordinances related to landscapes and irrigation (Tampa Bay Water, 2005; SJRWMD, 2006), including restricting the proportion of turf area for new homes, day-of-the-week watering restrictions (on some occasions, completely banning irrigation for certain periods, and even restricting irrigation with recycled wastewater), requiring the use of rain-sensing shutoff devices on all automated irrigation systems, establishing incentives to increase the use of xeriscaping or to adopt smart irrigation technologies, etc. Another measure to satisfy the potable water demand included the construction of a seawater desalination plant in the Tampa Bay region (Tampa Bay Water, 2011).

An automated irrigation system that receives feedback from one or more soil moisture sensors is designed to main-

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tain a desired soil water content (θ) range in the root zone that is optimal or adequate for plant growth and/or quality, allowing irrigation only when necessary (Dukes, 2005). Recently developed soil moisture sensor systems (SMSs) for irrigation control include not only a sensor to be buried in the soil but also a user interface module (commonly called a controller) to be connected to the irrigation timer. This controller is a milestone in the development of the soil moisture sensor industry because it allows the operator to choose a desired θ threshold above which scheduled irrigation events are not allowed (Cardenas-Lailhacar and Dukes, 2010).

Early research carried out in Florida using switching tensiometers connected to irrigation timers resulted in water savings of 42% to 95% over conventionally irrigated bermudagrass turf plots (Augustin and Snyder, 1984). A 1997 study involving 21 residential sites in Colorado was performed using granular matrix sensors. Compared to the theoretical water requirement, the granular matrix sensors reduced water applied by an average of 27% (Qualls et al., 2001). In North Carolina, Grabow et al. (2008) showed that SMS-based systems applied about 30% less water than the standard time-based treatment while maintaining acceptable turf quality for most of the study period. During 2009, also in North Carolina, homes equipped with SMSs applied 44% less water and achieved significantly higher turf quality than homes with typical pre-set time clock schedules (Nautiyal et al., 2010).

The objective of this review article is to summarize and relate the main findings of research carried out in Florida, across multiple studies, evaluating commercially available SMSs for use on residential irrigation systems. The initial goal of the experiments cited was to find out if different SMSs could reduce irrigation water application as compared to typical residential irrigation systems without sensor feedback. The effect of different threshold settings and irrigation frequencies on water application and turf quality was also evaluated. Initial research was performed on controlled plots; afterwards, the SMSs were evaluated under residential landscape conditions. Other research goals included evaluating the consistency of different manufacturers' SMS units and their precision in measuring θ.

Testing Sites and Experiments

Research on SMSs was conducted in experimental plots at the University of Florida Department of Agricultural and Biological Engineering turfgrass testing facility in Gainesville, Florida, and at the Plant Science Research and Education Unit near Citra, Florida. Research under residential conditions was performed at Palm Harbor, in Pinellas County, Florida.

Both the Gainesville and Citra facilities consist of 72 plots, each irrigated by four quarter-circle pop-up sprinkler spray heads. Rain Bird ESP modular irrigation timers (Rain Bird International, Inc., Glendora, Cal.) were used for irrigation scheduling at both sites. In all studies, SMS probes were buried in the root zone (7 to 8 cm), and the controllers were connected to the irrigation timers in a bypass mode operation. All treatments were programmed to apply the same amount of irrigation per week (except for a non-irrigated treatment). The irrigation schedule was adjusted every month, and the volume was set to replace the monthly historical net irrigation requirement, based on recommendations by Dukes and Haman (2002) for the area where the experiments were carried out.

Haley et al. (2007) found that homeowners in central Florida who followed this schedule with a functioning rain sensor applied 29% less water than typical homeowners who were monitored. Therefore, while this scheduling did not adjust for actual year-to-year weather differences, it provided a common comparison for all treatments. The without-sensor (WOS) treatment used in subsequent studies was meant to be used as a baseline irrigation schedule that mimics the relatively high amounts of irrigation observed at actual homes by Haley et al. (2007). Therefore, differences in water application among irrigated treatments were the result of SMSs bypassing scheduled irrigation cycles, rather than differing irrigation amounts between treatments.

Irrigation volumes applied to each plot were recorded by 20 mm × 190 mm pulse-type positive-displacement flowmeters (Elster AMCO Water, Inc., Ocala, Fla.). These flowmeters were connected to multiplexers and to a CR-10X datalogger (Campbell Scientific, Logan, Utah) to monitor daily water application. Weather data (air temperature, relative humidity, solar radiation, wind speed, wind direction, barometric pressure, and rainfall) were collected by automated weather stations (Campbell Scientific) located at each experimental site.

Turf quality was rated visually by the same person per site at least on a monthly basis. Evaluations were made using the National Turfgrass Evaluation Program (NTEP) procedures (Shearman and Morris, 1998). The ratings were on a 1 to 9 scale, with 1 representing dead or dormant grass, and 9 representing excellent grass. A quality rating of 5 was chosen as minimally acceptable for a homeowner lawn.

Statistical analyses for irrigation and turf quality data were performed using SAS (2003) with the general linear model procedure (proc GLM) and the mixed model procedure (proc MIXED). Analysis of variance was used to determine treatment effects, and Duncan's multiple range test was used to identify mean treatment differences. Differences were considered significant at an alpha level of 95% or higher ($p \leq 0.05$).

Gainesville

At the Gainesville testing site, 56 plots measuring 3.7 × 3.7 m each and covered with well established common bermudagrass [*Cynodon dactylon* (L.) Pers] were used to test the SMSs. The soil in the experimental area was an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudult) (Thomas et al., 1985). This soil has a field capacity of 7% (Cardenas-Lailhacar et al., 2008; Carlisle et al., 1981).

Four commercially available SMSs were selected for evaluation: Acclima Digital TDT RS-500 (Acclima Inc., Meridian, Ida.), Watermark 200SS-5 (Irrometer Company, Inc., Riverside, Cal.), Rain Bird MS-100 (Rain Bird International, Inc., Glendora, Cal.), and Water Watcher DPS-100

(Water Watcher, Inc., Logan, Utah), denoted as AC, IM, RB, and WW, respectively. The thresholds on all SMS controllers were set close to field capacity following the manufacturers' procedures. The experimental design included 1, 2, and 7 days per week (d week^{-1}) irrigation frequencies for the SMS treatments. The 1 and 2 d week^{-1} irrigation frequencies were used to emulate common day-of-the-week water restrictions in Florida, and the 7 d week^{-1} frequency was used to evaluate the complete automation of the irrigation system. Therefore, the SMS-based treatments were identified with a number (the irrigation frequency in d week^{-1}) and the brand abbreviation (e.g., 2-AC is a 2 d week^{-1} irrigation frequency and the Acclima system).

A non-irrigated treatment (0-NI) was used as a control for turf quality, and a treatment without sensor (2-WOS), with a 2 d week^{-1} irrigation frequency, was included to simulate homeowner irrigation systems with no sensor feedback (no rain sensor or SMS). Experimental treatments were replicated four times in a completely randomized design. Details and further information can be found in Cardenas-Lailhacar et al. (2008, 2010) and Cardenas-Lailhacar and Dukes (2010).

Data were collected from 20 July through 14 December 2004 and from 25 March through 31 August 2005. Treatments were resumed on 22 July and continued through 10 December 2006. From 25 March through 15 July 2006, a variation of the original experiment was carried out: all irrigation treatments were set at a 2 d week^{-1} frequency, and the IM controller thresholds were set at a dryer position (2 instead of 1). The objectives of this experiment were to analyze the consistency of three units within the same brand to control irrigation, and to compare the different brands against each other.

CITRA

Thirty-six 4.3 × 4.3 m plots of well established St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] were used in the Citra experiments. The soil is a loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudult (USDA, 2007), similar in physical characteristics to the Gainesville testing site.

There were four experimental periods: 22 April to 30 June 2006 (S06), 23 September to 15 December 2006 (F06), 1 May to 31 August 2007 (S07), and 1 September to 30 November 2007 (F07). As in the Gainesville experiments, there was a non-irrigated (0-NI) treatment for turf quality control and a treatment without sensor feedback (2-WOS) for water savings comparisons.

Two SMSs were tested in Citra: the Acclima Digital TDT RS-500 (AC), and the Lawn Logic LL1004 (LL) (Alpine Automation, Inc., Aurora, Colo.). Both systems were tested at three different θ thresholds: low (dry), medium, and high (wet). The Acclima systems were set on their display at 7%, 10%, and 13% volumetric soil water content (θ_V). The Lawn Logic system uses a site-specific auto-calibration method with relative setpoints from 1 (dry) to 9 (wet). Once the auto-calibration is performed, the controller equates the field capacity of the soil with setpoint 5. The setpoints used as experimental treatments levels were 2, 5, and 8 for S06, and 4, 5, and 6 for F06 and for all of 2007. All of these sensors were placed in the driest block of a randomized complete block design with four replications. The driest block was selected during intensive θ_V characterization of the site. Average field capacity based on soil sample analysis in this block was 11% θ_V. All of the SMS-based treatments had one sensor installed in this dry block to control the irrigation of all four replicates. Treatment AC-IP consisted of four plots, each with its own sensor, set at a 7% threshold, to study the effect of inherent moisture level variability on irrigation automation. More information and details are given by McCready et al. (2009).

PINELLAS

In the Pinellas study, 58 cooperating homes were recruited, all of them with an automated in-ground irrigation system that used potable water. The objective of this study was to determine if SMSs connected to automated irrigation systems could reduce the irrigation water application in a residential setting while maintaining acceptable turfgrass quality. At each home, a dedicated positive-displacement flowmeter (25.4 mm C-700, Elster AMCO Water, Inc., Ocala, Fla.) was installed to measure the irrigation water applied. Automatic meter reading (AMR) devices (Datamatic, Ltd., Plano, Tex.) were mounted on the flowmeters to record the hourly water use. Due to the encouraging and consistent results obtained with the Acclima Digital TDT RS-500 SMSs in the Gainesville and Citra experiments, 12 Acclima systems were installed at different homes and set at 10% θ_V. The already programmed irrigation frequencies and run times were not modified for any home. As a result, the comparison treatment (without sensor feedback) corresponded to actual homeowner practices. After installing the SMSs, and to obtain results from a non-controlled environment, project personnel purposefully limited interaction with all cooperators. As a consequence, turf quality was evaluated at a lower frequency than in the plot experiments but was rated at least once per season (e.g., four times per year minimum). Data reported here were obtained from November 2006 through December 2008. Further details can be found in Haley and Dukes (2012).

PRECISION OF SMSS

At Gainesville, a frequency domain reflectometry probe (20 cm ECH2O, Decagon Devices, Inc., Pullman, Wash.) was buried in every plot, diagonally, between 7 and 10 cm from the surface and 30 cm from the SMS probes that were controlling irrigation. Previously, ECH2O probes were calibrated gravimetrically, and individual R^2 values ≥0.97 were obtained through regression analysis. The ECH2O sensors were connected to HOBO micro-loggers (Onset Computer Corp., Bourne, Mass.), and θ_V readings were recorded every 15 min. Part of the objective of this research was to determine the θ_V at which the scheduled irrigation cycles were allowed or bypassed by the SMSs and to assess the precision of the SMSs in measuring θ. Data were collected from 21 July through 14 December 2004. Further details can be found in Cardenas-Lailhacar and Dukes (2010).

Table 1. Total rainfall and crop evapotranspiration (ET_c) for Gainesville, Citra, and Pinellas during the different testing periods (after Cardenas-Lailhacar et al., 2008, 2010; McCready et al., 2009; and Haley and Dukes, 2012).

	Testing Period		Total Rainfall	ET_c (mm)
Gainesville				
	2004	Measured (mm)	944	375
		Historical (mm)	508	
		Difference	86%	
	2005	Measured (mm)	732	578
		Historical (mm)	649	
		Difference	13%	
	2006, First half	Measured (mm)	323	445
		Historical (mm)	523	
		Difference	-38%	
	2006, Second half	Measured (mm)	567	424
		Historical (mm)	517	
		Difference	10%	
Citra				
	S06	Measured (mm)	138	296
		Historical (mm)	298	
		Difference	-54%	
	F06	Measured (mm)	92	142
		Historical (mm)	188	
		Difference	-51%	
	S07	Measured (mm)	287	453
		Historical (mm)	636	
		Difference	-55%	
	F07	Measured (mm)	347	193
		Historical (mm)	258	
		Difference	34%	
Pinellas				
	Nov. 2006 to Dec. 2008	Measured (mm)	1043	1025
		Historical (mm)	1259	
		Difference	-17%	

RESULTS AND DISCUSSION

GAINESVILLE

Weather Conditions

During the testing periods of 2004 and 2005, both frequent rainfall and a large amount of cumulative precipitation occurred, which is common in this region (NOAA, 2010). During the 2005 experimental period, 40% of the days had rainfall events, resulting in cumulative precipitation of 13% more than the historical average (1970-2000). Rainfall events were less frequent in 2004 (31% of the days, compared to a normal of 34%), but the cumulative rainfall for the experimental period was 86% more than historical (table 1). Consequently, normal to wet weather conditions could be considered prevalent during the 2004 and 2005 testing periods. During the second half of the 2006 testing period, even though the cumulative rain was 10% higher than a normal year, 76% of the rain fell in only six days (4% of the experimental days), a very low rainfall frequency compared to a normal year, resulting in relatively dry testing conditions.

Irrigation Water Savings

For the normal/wet testing period, the SMS-based treatments reduced the amount of irrigation scheduled to be applied by 72% on average, with a range of 27% to 92%, compared to 2-WOS (table 2, comparison A). Results for the dry period also showed a significant difference in water savings by the SMS-based treatments compared to 2-WOS, ranging from 9% to 83% with an average of 54%. These results are consistent with but lower than the normal/wet weather conditions, due to the low frequency of rainfall.

For both testing periods, an interaction between irrigation frequency and sensor brand was found. Within the different frequencies tested, the 7 d week^{-1} frequency always resulted in a significantly lower depth applied, although a wide range of variation was apparent across the sensor brands. This trend appears to be because the soil is kept closer to field capacity under high-frequency irrigation schedules (with lower amounts applied for a given irrigation event), so even a small amount of rainfall may result in bypassing a scheduled irrigation cycle. Thus, under frequent rainfall, it is more likely that scheduled events would be bypassed. Consequently, programming the timers to run every day and letting the SMS decide when to irrigate

Table 2. Average weekly irrigation depth applied by treatment and water savings compared to treatment 2-WOS during normal/wet and dry weather conditions at Gainesville (after Cardenas-Lailhacar et al., 2008, 2010).

		Normal/Wet Conditions					Dry Conditions				
Treatment		Average Depth (mm week^{-1})	Comparisons[a] A	B	C	Water Savings (%)	Average Depth (mm week^{-1})	Comparisons[a] A	B	C	Water Savings (%)
2-WOS		35	a	-	-	0	33	a	-	-	0
SMS-based	1-AC	6	-	-	b	81	9	-	-	b	73
	1-RB	6	-	-	b	81	24	-	-	a	28
	1-IM	18	-	-	a	48	24	-	-	a	27
	1-WW	7	-	-	b	79	NA[b]	-	-	-	NA[b]
	1 Average	10	-	b	-	72	19	-	a	-	43
	2-AC	8	-	-	b	77	8	-	-	b	75
	2-RB	4	-	-	d	88	6	-	-	b	81
	2-IM	25	-	-	a	27	30	-	-	a	9
	2-WW	6	-	-	c	82	NA[b]	-	-	-	NA[b]
	2 Average	11	-	a	-	68	15	-	b	-	55
	7-AC	3	-	-	c	92	6	-	-	c	83
	7-RB	3	-	-	c	90	7	-	-	b	79
	7-IM	16	-	-	a	53	22	-	-	a	32
	7-WW	11	-	-	b	69	NA[b]	-	-	-	NA[b]
	7 Average	8	-	c	-	76	12	-	c	-	64
SMS average		10	b	-	-	72	15	b	-	-	54

[a] A = treatment without sensor feedback versus SMS-based treatments, B = between irrigation frequency averages, and C = between brands within the same irrigation frequency. Different letters within a column indicate statistical difference at $p < 0.001$ (Duncan's multiple range test).

[b] NA = treatments where the irrigation system was malfunctioning and were not considered for water application analyses.

could lead to complete automation of the irrigation system and could result in higher water savings than current day-of-the-week water restrictions.

During dry weather conditions, the AC systems tended to save more water than the RB systems. Brand IM allowed more water to be applied compared to the other brands at every frequency and weather condition tested, even during the dry testing period when the IM controllers were set at position 2 (instead of 1), which should have kept the soil moisture in a dryer condition. (The threshold for the IM controllers was set at 6 for short periods to verify that the systems were functional.) It was hypothesized that this behavior was due to the reported slow response time of the granular matrix sensors used by the IM systems, their hysteretic behavior, the high variability of measurements, 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).

Turf Quality

During 2004 and 2005, turf quality always exceeded the minimal acceptable level in all treatments (including non-irrigated plots), and turf quality ratings were not statistically different (data not shown, see Cardenas-Lailhacar et al., 2008). This is explained by the relatively frequent rainfall throughout most of this testing period, which favored the growth of bermudagrass, and by the drought-tolerant characteristics of this grass, which helped maintain good quality during the short dry periods. It was concluded that irrigation was not necessary during this experimental period to maintain an acceptable turf quality.

Conversely, figure 1 shows the relationship between the average irrigation depth applied by treatment and the resultant turf quality by 20 October 2006, after 36 days with no rainfall. The non-irrigated treatment (0-NI) resulted in turf quality of 3.3, which is below the minimum acceptable level of 5.0; therefore, supplemental irrigation was necessary to maintain acceptable turf quality during this period. The treatment without sensor feedback (2-WOS) resulted in high average turf quality (7.0). No significant differences in average turf quality were found between the irrigation frequencies, even when they allowed significantly different amounts of water to be applied (table 2, dry conditions, comparison B). Turfgrass quality ratings for the IM systems, which applied more water than the other brands, ranged between 6.0 and 6.8, with an average of 6.4, which was significantly higher than the AC and RB averages (5.3 and 5.3, respectively). Statistical differences were found in turf quality ratings between the SMS-based treatments, where the lowest turf quality was found for 2-RB because of a hardware malfunction by the middle of the testing season. Treatment 7-RB maintained minimum acceptable turf quality, while the AC treatments resulted in turf qualities between 5.0 and 5.5. Considering these results, the set-points and/or run times for these systems were possibly at the lower limit for sustained dry weather conditions.

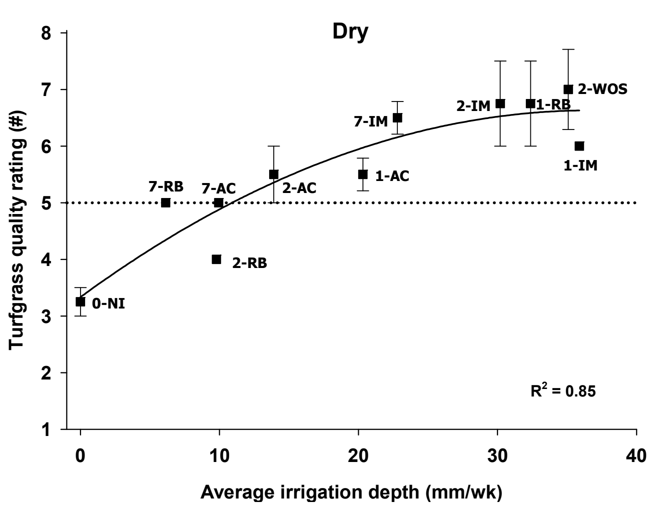

Figure 1. Relationship between average irrigation depth applied and resultant turf (bermudagrass) quality by 20 October 2006 after 36 days with no rainfall at Gainesville (after Cardenas-Lailhacar et al., 2010). The SMS treatments were set at 1, 2, and 7 d week^{-1} irrigation frequencies. Bars represent the standard error of the mean (*n* = 4); the dotted line indicates the minimum acceptable turfgrass quality.

Brand Consistency

During the first half of 2006, a variation of the original experiment was carried out: all irrigation treatments were set at a 2 d week^{-1} frequency to analyze the consistency of the three tested units of a brand at controlling irrigation, and to directly compare the different brands against each other. During this experiment, rainfall occurred on 18% of the days, compared to a normal of 35%. The cumulative precipitation was 38% below a normal year (table 1), and 77% of this amount fell in only five rain events. Therefore, this was considered a very dry period.

The average savings of the SMS-based treatments compared to 2-WOS was 33% (table 3), which was less than that achieved at Gainesville during the normal/wet period (72%) and even less than the dry period of the second half of 2006 (54%) and was not statistically different from treatment 2-WOS (table 3, comparison A). These lower savings were mainly caused by brands IM and WW, which applied significantly more water than the other brands, resulting in modest water savings (8% and 16%, respectively). It should be noted that the IM controllers were set at a dryer threshold (2 instead of 1) during this testing period. Differences between mean weekly treatment depths and 2-WOS translated into significant savings of 54% and 56%

Table 3. Average weekly irrigation depth applied by treatment and water savings compared to treatment 2-WOS during dry weather conditions on the first half of the 2006 testing period at Gainesville (after Cardenas-Lailhacar et al., 2010).

Treatment		Average Depth (mm week^{-1})	Comparisons[a] A	Comparisons[a] B	Water Savings (%)
2-WOS		38	a	a	0
SMS-based	AC	17	-	b	54
	RB	17	-	b	56
	IM	35	-	a	8
	WW	32	-	a	16
SMS average		25	a	-	33

[a] A = treatment without sensor feedback versus SMS-based treatments, and B = between all irrigation treatments. Different letters within a column indicate statistical difference at $p < 0.05$ (Duncan's multiple range test).

for brands AC and RB, respectively, which is remarkable considering the dry weather conditions that prevailed during this experiment.

Throughout this experiment, the different units of each brand (AC, WW, and RB) tended to respond in the same way over time and with similar cumulative amounts of water applied by the end of the data collection period (data not shown). However, the IM units showed variability, which is consistent with the high variability of readings between units that has been reported for coarse-textured soils (Taber et al., 2002; Intrigliolo and Castel, 2004).

Turf quality in treatment 0-NI declined to unacceptable levels by July 2006 (fig. 2) and was statistically different from both the 2-WOS and the average of the SMS-based treatments, which remained above the minimum quality ratings. No significant differences were found between 2-WOS and the average of the SMS-based treatments. Although turf quality varied across treatments, all SMS-based treatments resulted in average quality that was above a 5.7 rating. However, some AC and RB replications, which were the treatments that saved the most water, were just at the acceptable quality level (5.0) or slightly above, similar to previously mentioned results from the dry experimental period during the second half of 2006. These results show that these low thresholds and run times can save more water, but that they were at the lower limit required to maintain acceptable quality during sustained dry weather conditions. It should also be noted that these plots were planted with common bermudagrass, which is considered a more drought-tolerant turfgrass compared to the more common St. Augustinegrass in Florida.

CITRA

Weather Conditions

The consecutive testing periods S06, F06, and S07 were considered dry. There were 49 days with rain events greater than 2.5 mm, compared to 78 days of the historical average (1970-2000), and the total rainfall depths for each partial testing period were less than half of the historical average (table 1) for these treatment periods (McCready et al., 2009; NOAA, 2010). Conversely, the testing period F07 could be considered wet, with 19% more rain events and a cumulative rainfall depth 35% higher than historical (NOAA, 2010).

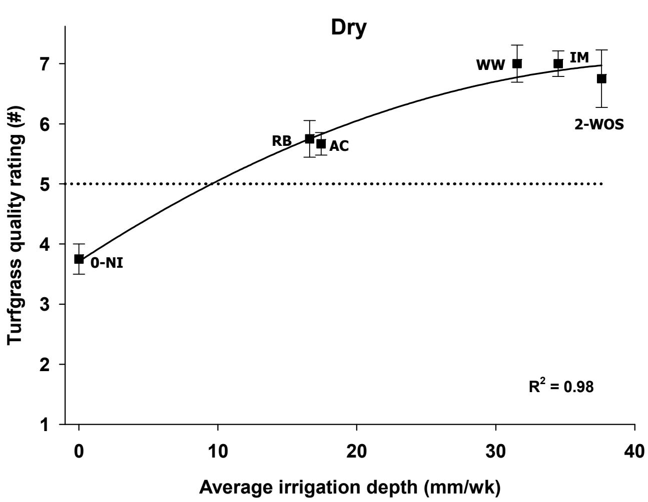

Figure 2. Relationship between average irrigation depth applied and resultant turf (bermudagrass) quality by July 2006 during sustained dry weather conditions at Gainesville (after Cardenas-Lailhacar et al., 2010). Irrigated treatments were all set at a frequency of 2 d week^{-1}. Bars represent the standard error of the mean (*n* = 4); the dotted line indicates the minimum acceptable turfgrass quality.

Irrigation Water Savings and Turf Quality

Table 4 shows the average irrigation depth applied by treatment and the water savings compared to 2-WOS, and figures 3 and 4 show the resultant average turf quality for wet and dry conditions, respectively. The highest overall water savings from the SMS-based treatments occurred during wet weather conditions, with an average of 42% and a range between 11% and 72%. Conversely, during dry weather conditions, the SMS-based treatments tended to apply more water and, therefore, the water savings were less, averaging 27% and ranging from -1% to 64%. The wet testing period was the only period in which all SMS-based treatments applied significantly less irrigation than 2-WOS and produced good turf quality (5.9 and above). As in the Gainesville site experiments, even the non-irrigated plots averaged minimum acceptable turf quality (5) during wet weather conditions. Turf quality tended to increase with supplementary irrigation applied (fig. 3), but it was not statistically different between the irrigated treatments. Therefore, during wet weather conditions, an increase of the threshold setpoints and/or the irrigation depth applied might not result in better turf quality.

The threshold settings were important to the effectiveness of the SMS controllers in reducing water applied while producing acceptable turfgrass quality. In general, the SMS-based treatments resulted in higher water savings when set at low thresholds, compared to the medium and high thresholds. As a consequence of the low precipitation during the dry testing period, the 0-NI treatment resulted in a very low turf quality (1.1) and needed to be re-sodded twice. The establishment periods after re-sodding these plots was more than 75 days each time. Treatment LL-Low, which had a threshold setting of 2, produced high water savings but an average turf quality rating (4.2) below acceptable. The threshold of LL-Low was increased from 2 to

Table 4. Average weekly irrigation depth applied by treatment and water savings compared to treatment 2-WOS during normal/wet and dry weather conditions at Citra (after McCready et al., 2009).

Treatment	Normal/Wet Average Depth[a] (mm week^{-1})	Normal/Wet Water Savings (%)	Dry Average Depth[a] (mm week^{-1})	Dry Water Savings (%)
2-WOS	30 a	0	31 a	0
SMS-based				
AC-IP	8 e	72	18 d	44
AC-Low	9 e	69	19 cd	39
AC-Med	14 d	51	25 bc	21
AC-High	26 b	14	29 ab	6
LL-Low	16 d	45	11 e	64
LL-Med	20 c	33	25 bc	20
LL-High	26 b	11	32 a	-1

[a] Within a column, values followed by different letters are statistically different at $p < 0.001$ (Duncan's multiple range test).

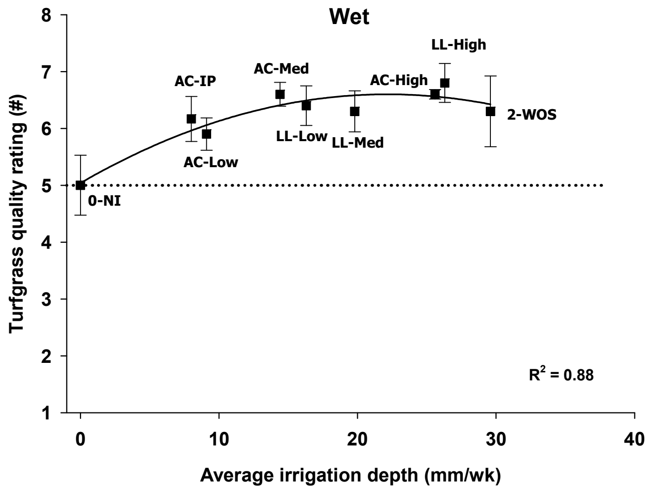

Figure 3. Relationship between average irrigation depth applied and resultant turf (St. Augustinegrass) quality during wet weather conditions at Citra (after McCready et al., 2009). Bars represent the standard error of the mean (*n* = 4); the dotted line indicates the minimum acceptable turfgrass quality.

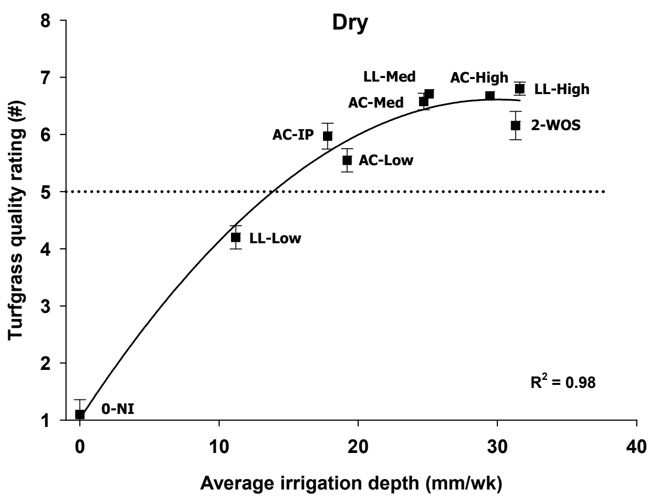

Figure 4. Relationship between average irrigation depth applied and resultant turf (St. Augustinegrass) quality during dry conditions at Citra (after McCready et al., 2009). Bars represent the standard error of the mean (*n* = 4); the dotted line indicates the minimum acceptable turfgrass quality.

4 at the end of the first partial dry period (S06) until the end of the experiment. However, during the second partial dry period (F06), additional irrigation was necessary for this treatment, and in the third partial period (S07) treatments 0-NI and LL-Low were ended early, again, to prevent death of the turfgrass due to lack of water, and additional irrigation was supplied. Conversely, during the wet period, both the 0-NI and LL-Low treatments resulted in acceptable average turf quality (5.0 and 6.2, respectively). This suggests that the setpoint of 4 on the LL systems is adequate during normal/wet years but is too low for extremely dry weather conditions.

During the first partial dry period (S06), the average turf quality for the AC-Low treatment was acceptable (5.1). However, by the end of June 2006, the turf quality rating was only 4.3, and some areas of the AC-Low plots required re-sodding. The controller of the AC-Low treatment bypassed irrigation when the θ_V values were greater than or equal to 7%, with the exception of one irrigation event (data not shown, see McCready et al., 2009). Thus, the controller was bypassing irrigation based on the threshold setting; however, the decline in turf quality indicates that this threshold was too low for the site conditions during dry weather. This is consistent with the Gainesville site during the dry testing period, when the AC treatments (also set at 7% θ_V) resulted in turf quality at or slightly above acceptable (fig. 1). Therefore, the 7% θ_V setpoint on these systems appears to be too low for these sandy soils under sustained dry weather conditions.

For all treatment periods, the high threshold treatments produced good turf quality (6.3 to 6.8) but little or no water savings (-1% to 14%). The medium threshold treatments, on the other hand, produced turf qualities between 6.3 and 6.7 and water savings between 20% and 51%. The turf quality ratings for the medium thresholds were not significantly different from those for the high threshold settings, even when most of the time they applied significantly less water, indicating that the high thresholds treatments over-irrigated during the testing periods.

For treatments AC-Low, AC-Med, and AC-High, one sensor was used to control the irrigation of all four plots in the treatment. Conversely, treatment AC-IP (threshold setting of 7% θ_V) had one sensor buried in all four plots. Results showed that the average water applied was not significantly different between the AC-IP and AC-Low treatments (same moisture threshold setting) and produced similar average turf quality ratings. Thus, a single sensor buried in a dry plot to control irrigation on four plots produced similar outcomes as the treatment with one sensor in each of four individual plots.

PINELLAS

In the Pinellas study, the total rainfall was 17% less than the 31-year (1970-2000) historical normal (1,043 vs. 1,259 mm, respectively), and 15 of the 26 months in the study had less than normal rainfall (table 1). Throughout the study, the SMSs bypassed unneeded irrigation events during rainy periods as well as during dry times with intermittent rainfall, for an average of 2.3 irrigation events per month. In comparison, the treatment without sensor feedback applied an average of 6.0 irrigation events per month, even when a 1 d week^{-1} watering restriction ordinance was in effect for most of the testing period.

The average irrigation water depth applied by the treatment without sensor feedback was 15 mm week^{-1}, while the SMS treatment applied 5 mm week^{-1} (65% less water use). These application rates appear to be lower than in the plot experiments. However, compared to a calculated net irrigation requirement, all treatments resulted in some under-irrigation relative to the theoretical estimate, with the SMS treatment expressing the greatest under-irrigation (Haley and Dukes, 2012). In addition, in this study, the grass did not go dormant during the winter seasons, so not all homeowners suspended their irrigation (contrary to the Gainesville and Citra testing sites, with 3 to 4 months of grass dormancy and no irrigation application). In spite of this

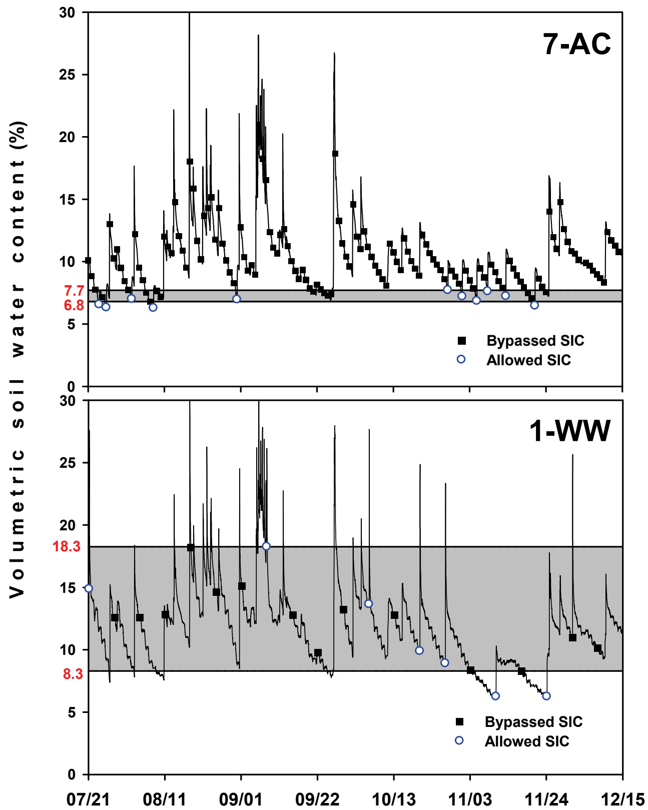

Figure 5. Volumetric soil water content of treatments 7-AC and 1-WW through the experimental period in 2004 at Gainesville (measured through an independent field-calibrated ECH2O sensor) showing results of the scheduled irrigation cycles (SICs). AC controllers were set at 7% θ_V, while the threshold for the WW controllers was set using the auto-calibration feature. Square symbols represent bypassed SICs, and circle symbols represent allowed SICs. Irrigation was always bypassed at values above the shaded area and always allowed at values below the shaded area. When an increment in volumetric soil water content does not have a circle on the bottom of the curve, a rainfall event occurred (after Cardenas-Lailhacar and Dukes, 2010).

lower application rate, no significant differences in average turf quality were detected among treatments, which always remained above the minimum acceptable level throughout the study (data not shown).

Data continued to be collected at these homes after the study results were published. As of November 2010, four years after the SMSs were installed, the water savings of the SMS treatments remained at 65% on average, compared to the houses with no sensor feedback. These results are very similar to those found in the preliminary studies under controlled plots at Gainesville and Citra. Therefore, the use of SMS devices on residential automated irrigation systems could lead to important water savings in Florida. These results promote the adoption of this technology not only in Florida but also in areas where rainfall normally supplies an important part of landscape irrigation needs. In addition, these SMSs could curb over-irrigation by regulating inappropriate timer scheduling.

Precision of SMSs

To quantify the effectiveness of the SMSs to control irrigation, it was important to detect when the scheduled irrigation cycles (SICs) were allowed or bypassed, and the associated θ_V. Figure 5 shows θ_V over time for treatments 7-AC and 1-WW at the Gainesville testing site. The SICs were always bypassed at values above the shaded area of figure 5 and always allowed at values below the shaded area. Most of the systems were not found to be precision instruments (repeatability of a measurement), which was evidenced when, within the shaded area, different SMSs sometimes bypassed SICs and sometimes did not, even when reading the same or a lower θ_V.

Table 5. Range of volumetric soil water content (θ_V) over which the different soil moisture sensor system brands always allowed or always bypassed irrigation at Gainesville (after Cardenas-Lailhacar et al., 2010).

Brand	Treatment	θ_V (%) When Irrigation Was Always: Allowed	Bypassed	Diff.	Average Diff.[a]
Acclima	1-AC	6.7	7.1	0.4	1.4 b
	2-AC	8.3	11.2	2.9	
	7-AC	6.8	7.7	0.9	
Irrometer	1-IM	8.5	12.3	3.8	7.8 a
	2-IM	9.8	17.8	8.0	
	7-IM	7.2	18.9	11.7	
Rain Bird	1-RB	5.5	9.4	3.9	3.2 ab
	2-RB	7.0	8.9	1.9	
	7-RB	3.5	7.3	3.8	
Water Watcher	1-WW	8.3	18.3	10.0	7.4 a
	2-WW	7.8	11.8	4.0	
	7-WW	8.8	16.9	8.1	

[a] Values followed by different letters are statistically different at $p < 0.05$ through the least significant difference (LSD) test.

A smaller θ_V range between the upper and lower limits of the shaded area suggests that a system is more precise in estimating θ_V, and vice versa. A summary of the θ_V range over which irrigation cycles were always allowed or always bypassed is shown in table 5. Brand AC resulted in the narrowest average range, followed by RB (1.4 and 3.2 percentile points, respectively), suggesting that these systems were more consistent and precise in measuring θ_V than brands WW and IM (which resulted in average ranges of 7.4 and 7.8 percentile points, respectively). These results support the water savings achieved by these brands (tables 2 and 3), where AC and RB saved significantly more water than WW and IM.

Conclusions

Threshold settings were important to the effectiveness of the SMSs on turfgrass plots established on sandy soils with field capacities of around 7% to 11%. The medium thresholds (around 80% of field capacity) on the SMS-based treatments resulted in good turf quality (6.3 and above) during all treatment periods. In general, the high threshold treatments (at field capacity or above) applied significantly more water than the medium threshold treatments but did not increase the turf quality significantly, indicating that they over-irrigated. Conversely, the low (dry) threshold settings resulted in poor to unacceptable turf quality (below 5.0) during dry weather conditions. Therefore, the medium threshold settings (close to field capacity) appear to be adequate in these sandy soils to balance turf quality and water conservation.

Within the different frequencies tested, the 7 d week^{-1}

frequency always resulted in a significantly lower depth applied. This trend appears to be because the soil is kept closer to field capacity under high-frequency irrigation schedules (with lower amounts applied for a given irrigation event), so even a small amount of rainfall may result in bypassing a scheduled irrigation cycle. Thus, under frequent rainfall, it is more likely that scheduled events would be bypassed. Consequently, programming the timers to run every day and letting the SMS to decide when to irrigate could lead to a complete automation of the irrigation systems and could result in a better strategy and higher water savings than day-of-the-week water restrictions.

Results during normal to wet weather conditions, which are fairly common in Florida and other parts of the southeast, showed that commercially available SMSs can significantly reduce irrigation water application when compared to typical residential irrigation systems with no sensor feedback, without reduction in turf quality. The SMSs tested reduced irrigation by 42% to 72% on average, depending on the testing site and experiment, with turf quality ratings always above 6. Even the non-irrigated treatments remained at the minimum acceptable level (5) or above during normal/wet conditions.

Conversely, during dry weather conditions, every SMS-based treatment resulted in lower water savings, ranging from -1% to 64%. The non-irrigated plots always resulted in turf quality below the minimum acceptable level (5) and, in some cases, even death. The turf quality of some irrigated treatments was sometimes at or below the minimum acceptable level, suggesting that their settings were at the lower limit for dry weather conditions. Therefore, the irrigation frequency, run time, and/or threshold setting should be carefully considered in sustained dry weather conditions.

Results for residential conditions show that the homes with SMSs applied 65% less water than the homes with automated irrigation systems without sensor feedback, which is remarkable considering the mostly dry weather conditions that prevailed. Even with these water savings, no significant differences in average turf quality were detected among treatments throughout the study. Furthermore, the homes with SMS control systems averaged fewer irrigation events (2.3 times per month) than the potential number of events with local watering restrictions (4 irrigation events per month). Therefore, SMSs could curb over-irrigation by regulating inappropriate timer scheduling.

Complementary research showed that brands AC and RB were more consistent and precise than brands WW and IM in measuring θ_V. The brands with higher precision also saved significantly more water than the less precise brands. Even though the models tested from brands LL, WW, and RB are no longer available in the market, and in spite of some treatment limitations, most of the SMS-based treatments bypassed the majority of the SICs during rainy periods and responded to dry periods by allowing irrigation to occur, independent of the experimental setting.

Overall research results are very consistent and clearly demonstrate that the use of SMSs in Florida (and likely in other locations with substantial rainfall that contributes to irrigation needs), when properly installed, set, and maintained, could lead to important irrigation water savings while maintaining turf quality at or above the minimum acceptable rating.

Since the beginning of these experiments, the prices of SMSs have dropped continuously. In 2004, prices approaching $500 USD per unit were common. By 2011, some of the tested units could be purchased for less than $200 USD. Considering the high price of potable water in some localities of Florida, and the potential water savings when using an SMS, the payback period for these units, in an average single-family home, could be two years or less.

Testing SMSs under residential conditions for a longer term and in greater numbers (such as an entire subdivision) could lead to definitively confirming the water savings potential of this technology.

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Nomenclature

AC = Acclima
F06 = 23 September to 15 December 2006
F07 = 1 September to 30 November 2007
IM = Irrometer
LL = Lawn Logic
NI = non-irrigated
RB = Rain Bird
S06 = 22 April to 30 June 2006
S07 = 1 May to 31 August 2007
SIC = scheduled irrigation cycle
SMS = soil moisture sensor system
WOS = without sensor
WW = Water Watcher
θ = soil water content
θ_V = volumetric soil water content