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Turfgrass Irrigation Controlled by Soil Moisture Sensor Systems

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Abstract

More than 15% of all new homes in the U.S. were built in Florida between 2005 and 2006, most of them with an automatic irrigation system, resulting in an increase in the demand for limited potable water resources. Soil moisture sensor (SMS) irrigation control systems have recently been released to the market, which could help prevent excess irrigation. The objectives of this research were to: 1) analyze the performance of SMS systems relative to actual soil moisture content, and 2) quantify irrigation water use and assess turf quality differences between a) a time-based scheduling system with and without a RS, b) a time-based scheduling compared to a SMS-based irrigation system, and c) different commercial irrigation SMS systems. The experimental area consisted of common bermudagrass [*Cynodon dactylon* (L.) Pers] plots (3.7 x 3.7 m), in a completely randomized design, located in Gainesville, Florida. Treatments consisted of four different commercial SMS brands (Acclima, Rain Bird, Irrometer, and Water Watcher) compared to time-based treatments (with rain sensor, without rain sensor). All of these treatments were scheduled at a two days a week irrigation frequency. Non-irrigated treatments were also implemented. Significant differences in turfgrass quality among treatments were not detected, including the non-irrigated plots, due to frequent rain during the 308-day study period. Including a rain sensor in the irrigation system resulted in 34% water savings. Among the SMS-based treatments, brands Acclima, Rain Bird, Irrometer, and Water Watcher, reduced irrigation

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water application by 77%, 88%, 27%, and 82%, respectively, compared to the time-based treatment without rain sensor. Therefore, SMS-systems represent a promising technology for water conservation on turfgrass irrigation in the humid region.

Introduction

Historically, Florida exhibits dry and warm weather in the spring and fall, as well as frequent rain events in summer (National Oceanic and Atmospheric Administration [NOAA], 2003). These climatic conditions, coupled with low water holding capacity of Florida's predominately sandy soils, make irrigation indispensable for the high quality landscapes desired by homeowners (Haley et al., 2007; National Research Council, 1996). More than 15% of all new homes in the U.S. were built in Florida between 2005 and 2006 (United States Census Bureau [USCB], 2007); most of them with automatic in-ground irrigation systems (Tampa Bay Water, 2005; Whitcomb, 2005); which has been reported to result in higher water use compared to manual irrigation or manually moved sprinklers (Mayer et al., 1999).

A recent study carried out by Haley et al. (2007) in Central Florida, found that homeowners tended to irrigate by as much as 2-3 times the plant requirements. Over-irrigation can not only negatively affect landscape/turfgrass quality, but tends to have environmentally costly effects because of wasted water and energy, leaching of nutrients or agro-chemicals into groundwater supplies, degradation of surface water supplies by sediment-laden irrigation water runoff, and erosion. In turfgrass, it has also been reported that over-irrigation promotes the establishment and survival of some turfgrass weeds (Busey and Johnston, 2006; Colbaugh and Elmore, 1985; Youngner et al., 1981), increase in severity of some pathogens (Davis and Dernoeden, 1991; Kackley et al., 1990), and increased evapotranspiration (Biran et al., 1981).

Irrigation time clocks, or timers, are an integral part of an automatic irrigation system and, when correctly programmed, are an essential tool to apply water in the necessary quantity and at the right time. Modern irrigation timers provide a large number of features, including the possibility to receive feedback from one or more sensors, allowing accurate control of irrigation water and automation of the irrigation systems (Zazueta et al., 2002; Boman et al., 2002).

Numerous types of soil moisture sensors have been used for decades to measure soil water content, including neutron scattering, resistance blocks, tensiometers, and granular matrix sensors (Gardner, 1986; Seyfried, 1993; Leib et al., 2002; Leib et al., 2003; Or, 2001) including turfgrass and landscape irrigation applications (Augustin and Snyder, 1984; Qualls et al., 2001). Newer methods to measure soil water content ($\boldsymbol{\theta}$), based on the dielectric properties of the soil, are being used in greater numbers, because they are non-destructive, provide almost instantaneous measurements, require little or no maintenance, can provide continuous readings through automation, and their cost has decreased substantially in recent years. An additional advantage of these modern sensors is that accurate measurements may be made near the surface (important for shallow rooted crops such as turf) compared to techniques such as the neutron probe. Some of the techniques based on the dielectric methods have been classified as time domain reflectometry (TDR) and time domain transmissometry (TDT). Most TDR and TDT instruments operate by sending an electromagnetic step pulse signal down steel rods buried in the soil. When the signal reaches the end of the probes (TDT), or is reflected back to the control unit (TDR) the signal is then detected and analyzed. The time taken for the pulse varies with the soil dielectric properties, which are related to the water content of the soil surrounding the probe (Topp, 2003; Blonquist et al., 2005). Muñoz-Carpena (2004) summarizes the working principle, description, advantages, and drawbacks of different field devices for monitoring soil water content, and gives evaluation criteria for the selection of a specific soil moisture sensor (SMS).

Modern commercially available SMS-systems include a controller that interfaces with the irrigation timer. This piece of equipment is a milestone in the development of the SMS industry because it sends a signal to the buried SMS, interprets the signal behavior and converts it to a sensed soil moisture content ($\boldsymbol{\theta}_S$). At the same time, the controller acts as a switch and allows the operator to choose a desired soil moisture content threshold ($\boldsymbol{\theta}_{Th}$), above which scheduled irrigation events will be bypassed. Typically, the adjustable $\boldsymbol{\theta}_{Th}$ can be set between relatively dry to relatively wet soil moisture conditions; depending on the plant material, soil type, installation depth of the SMS, etc. These features, coupled with a simple and user-friendly design, and a substantial reduction in the purchase cost, have allowed the use of the SMS technology for control of residential irrigation systems.

An automatic SMS-based irrigation system is designed to maintain a desired $\boldsymbol{\theta}$-range in the root zone that is optimal or adequate for plant growth and/or quality, by eliminating unnecessary irrigation cycles. This type of system adapts the amount of water applied according to plant requirements and actual weather conditions (Dukes, 2005; Pathan et al., 2003). Modern commercially available SMSs work under the bypass configuration, which skips or allows an entire scheduled irrigation cycle based on $\boldsymbol{\theta}_S$ relative to $\boldsymbol{\theta}_{Th}$ at the beginning of that event (Muñoz-Carpena and Dukes, 2005).

In order to achieve these goals in sandy soils, where the storage of water is minimal, coupled with shallow turfgrass root depth, the continuous and accurate monitoring of the soil moisture status becomes of great consequence. Automatic control of irrigation, based on SMSs, has been successfully reported in coarse textured soils, achieving water savings without diminishing yields of vegetable crops (Nogueira et al., 2002; Dukes and Scholberg, 2005; Dukes et al., 2003; Muñoz-Carpena et al., 2003; Shock et al., 2002; Zotarelli et al., 2008) nor quality of turfgrass (Pathan et al., 2003). Automatic irrigation systems with a rain sensor feedback have been also recommended to save water in Florida (Cardenas-Lailhacar and Dukes, 2008).

The goal of this research was to find out if modern SMS systems could reduce irrigation water application while maintaining acceptable turf quality compared to time-based irrigation schedules used by homeowners in Florida. The objectives of this research were to: 1) analyze the performance of SMS systems relative to actual soil moisture content, and 2) quantify irrigation water use and assess turf quality differences between a) a time-based scheduling system with and without a RS, b) a time-based scheduling compared to a SMS-based irrigation system, and c) different commercial irrigation SMS systems.

Materials and Methods

The experiment was carried out at the Agricultural and Biological Engineering Department facilities, University of Florida, Gainesville, Florida. Turfgrass plots (3.7 m x 3.7 m) were established on a field covered with common bermudagrass [*Cynodon dactylon* (L.) Pers] and were sprinkler irrigated by four quarter-circle pop-up spray heads (Hunter 12A, Hunter Industries, Inc., San Marcos, CA). Turfgrass management was carried out according to recommendations by the University of Florida (Trenholm et al., 2003). The soil is an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (Carlisle et al., 1981; Thomas et al., 1985; United States Department of Agriculture [USDA], 2003). The field site and experimental setup was described in detail by Cardenas-Lailhacar (2006).

Soil Moisture Sensor Systems

Four SMS systems were evaluated: Acclima Digital TDT RS500 (Acclima, Inc., Meridian, ID), Watermark 200SS probe with a WEM controller (Irrometer Company, Inc., Riverside, CA), Rain Bird MS-100 (Rain Bird, Inc., Glendora, CA), and Water Watcher DPS-100 (Water Watcher, Inc., Logan, UT). These systems were codified as AC, IM, RB, and WW, respectively. The probes were buried in the soil were the majority of the roots were present, at a depth of 7-10 cm.

The controllers were connected in series with common residential irrigation timers; model ESP-6 (Rain Bird International, Inc., Glendora, CA). As recommended by manufacturers of the controllers with relative set points (RB and WW), $\boldsymbol{\theta}_{Th}$ were set 24 hours after a significant rainfall event filled the soil profile with water (i.e. to ensure field capacity). The $\boldsymbol{\theta}_{Th}$ were adjusted by means of a knob between "moist" and "dry" on the RBs (on a 1 to 8 scale), and on the WWs (on a -3 to +3 scale). On the RB controllers, $\boldsymbol{\theta}_{Th}$ was found by turning the dial until an LED (indicator of irrigation need) turned ON and OFF, and was ultimately set at position #2.5. On the WWs, the knob was set in the midway position and then the calibration button was pushed, which allowed its auto-calibration and set point. The IM controllers were set at #1, which corresponds to 10 kPa of soil water tension according to the manufacturer (approximately, field capacity). Finally, the AC controllers were set at a soil volumetric water content of 7%, which is field capacity for this soil (Thomas et al., 1985; Cardenas-Lailhacar, 2006).

Soil Moisture Content

The actual $\boldsymbol{\theta}$ of each plot was monitored with a capacitance probe (20 cm ECH_20, Decagon Devices, Inc., Pullman, WA), which were buried diagonally, between 7 and 10 cm from the surface, and between 10 and 30 cm from the SMS system probes. The ECH_20 probes were connected to HOBO micro-loggers (Onset Computer Corp., Bourne, MA) and readings were recorded every 15 minutes. Before the beginning of the experiment, calibration of the ECH_2O probes was performed at the research site using the thermogravimetric (or gravimetric) soil sampling method described by Gardner (1986). Four probes were installed in the field and connected to a HOBO micro-logger. Undisturbed soil samples were collected from the field (using a core sampler of 137.4 cm^3) at less than 20 cm from the probes, and at the probe burial depth. Samples were taken at a $\boldsymbol{\theta}$ between 5% and 14% by volume (all water contents expressed as volume of water per volume of sample). The $\boldsymbol{\theta}$ of each sample was then compared to the ECH_2O probe readings recorded with the HOBO micro-loggers at the same date and time when the samples were taken.

Field Treatments

Three time-based and four SMS-based treatments (brands AC, RB, IM, and WW) were established (Table 1). All these treatments were tested at an irrigation frequency of two days per week; which represents the most common irrigation restriction imposed in Florida and current watering restriction in the study area (Florida Department of Environmental Protection [FDEP], 2007; St. John's River Water Management District, 2007). Two time-based treatments were connected to a rain sensor: with-rain-sensor (WRS) and deficit-with-rain-sensor (DWRS). The rain sensor (Mini-click II, Hunter Industries, Inc., San Marcos, CA) was set at a 6 mm rainfall threshold. A without-rain-sensor treatment (WORS) was also included, in order to simulate homeowner irrigation systems with an absent or non-functional rain sensor, which has been reported as high as 75% in Florida (Whitcomb, 2005). Finally, a non-irrigated treatment (NI) was implemented as a control for turfgrass quality.

All treatments were scheduled to apply the same amount of water per week, except for treatments DWRS (60% of this amount), and NI (non-irrigated). Therefore, differences in water application among treatments were the result of sensors bypassing scheduled irrigation cycles. The weekly irrigation amount was adjusted on a monthly basis to completely replace historical ET, according to guidelines recommended by Dukes and Haman (2002). The system to record the data of the irrigation applied to each plot is described in Cardenas-Lailhacar et al. (2008). Turfgrass quality was visually assessed and rated using a scale of 1 to 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 homeowner. For turfgrass quality assessment, all experimental treatments were replicated four times with respect to turfgrass quality, in a completely randomized design.

Data Collection

Data were obtained from 20 July through 14 December of 2004 and from 25 March through 31 August of 2005. Turfgrass quality ratings were carried out by the same person in July, October and December of 2004, and in April, May and July of 2005. Weather data were collected every fifteen minutes by an automated weather station (Campbell Scientific, Logan, UT), located beside the experimental site. Statistical data analyses were performed using the general linear model (GLM) procedure of the Statistical Analysis System software (SAS, 2000). 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

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

Both 2004 and 2005 were rainy years (Figures 1 and 2), with high frequency rainfall and a large amount of cumulative precipitation, which is not uncommon in this region. During the experiment, the average frequency of rainfall events, as percent of rainy days, was similar to historical records (Unied States Department of Commerce [USDC], 2007) for the same periods (31% vs. 34% during 2004, and 38% vs. 37% in 2005). The cumulative rainfall during 2004, however, was 73% higher than a normal year (944 mm vs. 546 mm). This difference was mainly caused by a tropical storm and two hurricanes that hit the research area during late-August and September; accounting for 530 mm, or 56% of total rainfall. Most of the rain fell during August and September (793 mm), and the least rain fell in October and November (116 mm). During 2005, it rained 732 mm, which was very close to a normal year (711 mm), and with frequencies very close to historic rainfall in all months except in April (above) and June (below).

SMS Performance

To analyze the performance of the SMSs, it was important to detect when actual irrigation cycles occurred and how were they related to $\boldsymbol{\theta}$. To determine actual $\boldsymbol{\theta}$, ECH_2O probes were installed in every plot. These sensors were previously calibrated (Figure 3) and a site-specific calibration curve was developed ($y = 0.6991x - 0.0174$). The degree of linear association ($R^2=0.70$) was considered adequate, and was used to determine $\boldsymbol{\theta}$ on the different plots.

Figure 4 shows the $\boldsymbol{\theta}$ and daily rainfall in 2004 for the treatment that received no irrigation (NI), so every single increment in $\boldsymbol{\theta}$ was due to a rainfall event. Differences between the dry and wet periods were reflected in $\boldsymbol{\theta}$ as well. It can be seen that most of the time wet conditions prevailed; except for a dry period between 21 October to 24 November, when the two small rain events occurred (1.5 and 2.5 mm, respectively).

Figures 5 and 6 show the $\boldsymbol{\theta}$, during 2004, in plots that contained the SMSs treatments. These figures are shown as examples of when the SMS-based treatments allowed or bypassed scheduled irrigation events and what the level of $\boldsymbol{\theta}$ was at that time. It can be seen that, in general, the SMS-based treatments followed the dryer and wetter periods, controlling the number of irrigation cycles on the different treatments. More scheduled irrigation cycles were allowed during the dryer periods of late July-early August and late October-mid November. However, most of the controllers were not found to be precision instruments, which was evidenced when sometimes the different SMS systems bypassed irrigation cycles and sometimes they did not, even when reading the same or a lower $\boldsymbol{\theta}$. Moreover, according to the range of $\boldsymbol{\theta}$ over which the different SMS brands allowed irrigation AC and RB had a narrowest range (3.9 and 2.5 percentile points, respectively) suggesting that they were more accurate and consistent to measure θ than IM and WW (that had a range of 5.5 and 4.5 percentile points, respectively). Finally, the IM controllers were set at position #1, which corresponds to a tension of 10 kPa (i.e. field capacity) according to the manufacturer. However, according to the example of Figure 6, it looks that these sensors were reading a dryer soil condition, allowing irrigation cycles when actually not necessary.

Irrigation Events

As complimentary information to Figures 5 and 6, the proportion of the scheduled irrigation cycles that were allowed by the different treatments, during the main research months of 2004, is shown in Table 2. The time-based treatment without rain sensor (WORS) was programmed to run independently of the weather and/or soils moisture conditions, so every (100%) irrigation cycle was allowed. Regarding the SMS-based treatments, on average, a lesser amount of irrigation events were allowed in August and September (25% and 13%, respectively) compared to October and November (39% and 42%, respectively). These tendencies were concordant with the dryer/rainier periods (Figures 1, and 4 through 6). Moreover, the average of the SMS-based treatments allowed 30% of the scheduled irrigation cycles to run. The IM allowed 67% of them during this period, whereas sensors from brands AC, RB, and WW, allowed just 26%, 14%, and 14% of the irrigation cycles, respectively. These results show that all SMS treatments worked under these conditions, but with variable results.

Irrigation Application

Table 3 shows the results of the irrigation depth applied during the whole experiment by the different treatments, statistical comparisons between them, and the percent of water savings that they achieved compared to the time-based treatments.

Time-based treatments

Table 3; Comparison A, shows that the three time-based treatments (WORS, WRS, and DWRS) were significantly different (P<0.0001) from each other during this study. Treatment WRS (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, 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.

The well-managed or water conservative homeowner profile, imitated by treatment DWRS (with a rain sensor, and 60% of WRS), applied 63% of the water applied by WRS, close to the target of 60%. The total depth was 623 mm, or an equivalent of 61 mm/month. Haley et al. (2007) found within this homeowner profile (also programmed to replace 60% of historical ET) an irrigation water use of 105 mm/month.

The treatment simulating an irrigation system with an absent or non-functional rain sensor (WORS) accounted for 1514 mm, or 148 mm/month. Thus, this treatment applied 52% more water than the treatment with a functional rain sensor (WRS), whereas WRS saved 34% of the water applied by 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 (Figures 1 and 2). 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 (2007) 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 vs. SMS-based treatments

Table 3 (Comparison B) shows that there was a significant (P<0.0001) difference between the averages of time-based and SMS-based treatments; with 1044 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. In addition, 68% of the water applied by WORS was saved, on average, by the SMS-based treatments.

Water savings

Table 3 shows the water savings (%) of each treatment compared to the time-based treatments DWRS, WRS, and WORS. As expected, WORS applied more water than all the other treatments. On the other hand, IM allowed more water to be applied compared to the other brands and to the other time-based treatments. 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 DWRS treatment, brands AC, RB and WW showed water savings of 44%, 70% and 57%, respectively. On the other hand, IM applied 77% more irrigation than DWRS.

Treatment IM was the only SMS-based treatment that applied more water than the time-based WRS (11%), and far from the water savings achieved by the other SMS-based treatments: AC recorded irrigation water savings of 65%, RB 81%, and WW 73%. It is important to remark that these water savings were on top of those already achieved by WRS. Therefore, these results show that, in general, SMSs can also act as rain shut-off devices, although with a superior performance in terms of water savings. When the irrigation treatments were compared to more than 75% of the surveyed homeowners in Florida (Whitcomb, 2005), this is with a non-functional or absent rain sensor (WORS), the difference in water savings increased: 77%, 88% and 82% for AC, RB, and WW, respectively. Even IM (which applied 11% more water than WRS) showed water savings (27%) with respect to WORS, indicating that this sensor was operative but did not bypass as many scheduled irrigation cycles as other SMS-based treatments.

This experiment was carried out as a closed control loop irrigation system, where the decision whether to initiate an irrigation cycle was regulated by a SMS. These results clearly demonstrate that the use of SMSs (along with traditional timers in residential irrigation systems, scheduled to run two day a week) 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 historical irrigation requirements. However, a recent study suggests that, during wet or frequent rainfall weather conditions, to schedule high frequency irrigation cycles (i.e. everyday) appears to be a better strategy regarding water conservation in turfgrass irrigation, than to schedule them for one or two days a week (Cardenas-Lailhacar et al., 2008).

Turfgrass Quality

Differences in turfgrass quality, including non-irrigated plots, were not detected among treatments, and always exceeded the minimum acceptable rating of 5. This could be 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 (Figures 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.

Conclusions

High frequency rainfall events, which were close to a normal year, occurred during the time frame of the experiment. Rainfall was 73% higher than a normal year in 2004, and normal in 2005. Most of the SMS-based treatments automatically canceled the majority of the irrigation cycles during the rainy periods, and responded to dry periods by allowing irrigations to occur.

The three time-based treatments (WORS, WRS, and DWRS) were significantly different from each other during the study period. The treatment with a functional rain sensor (WRS), set at 6 mm, applied significantly less water (34%) than the without-rain-sensor (WORS) treatment, showing the importance of a well-maintained rain shut-off device in all automated irrigation systems in Florida. On the other hand, treatment DWRS, applied close to the desired 60% of the water applied by 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.

It was concluded that irrigation was not necessary to maintain an acceptable turf quality during the experimental period, which was evidenced by acceptable quality in non-irrigated plots, due to the propitious environmental conditions that favored the growth and development of the bermudagrass.

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 IM treatment was the only SMS-based treatment that applied more water than WRS (11%), whereas the other brands (AC, RB, and WW) resulted in irrigation water savings compared to WRS (65%, 81%, and 73%, respectively). These results showed that most SMSs can also act as rain sensors, but with superior performance in terms of water savings. When these last brands were compared to WORS, the differences in water savings increased to 77%, 88%, and 82%, for AC, RB, and WW, respectively. Even IM showed 27% in water savings compared to WORS over the 308-day study period.

It should be noted that specific performance of the individual sensors largely depends on the threshold setting, the sensor burial depth, and individual probe installation. Even when sensor burial depths and installation were as similar as practically possible in this experiment, the sensor thresholds might have varied slightly, hence affecting the results to some extent. In spite of this, and even when not yet precision instruments, soil moisture sensor systems appear to be a promising technology that could lead to a complete automation of residential irrigation systems, to attain important water savings, and to achieve sound environmental and economic benefits to the state if implemented. Testing this technology under real household conditions is recommended to validate these results.

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Table 1. Irrigation treatment codes and descriptions.

Treatment Codes	Soil Moisture Sensor Brand or Treatment Description
Time-based	
WORS	Without rain sensor
WRS	With rain sensor
DWRS	Deficit with rain sensor, 60% of WRS
SMS-based [a]	
AC	Acclima
RB	Rain Bird
IM	Irrometer
WW	Water Watcher
NI	No irrigation

[a]SMS = Soil moisture sensor

Table 2. Scheduled irrigation cycles allowed by treatment (2004).

Treatment	Allowed per Month (%)				Total Allowed
	Aug	Sep	Oct	Nov	(%)
WORS	100	100	100	100	100
AC	22	13	22	33	26
RB	33	0	0	22	14
IM	33	38	100	100	67
WW	11	0	33	11	14
SMS-based (Avg.) [a]	25	13	39	42	30

[a]SMS = Soil moisture sensor; Avg.= Average

Table 3. Total cumulative irrigation depth applied to treatments, statistical comparisons, and percent water savings compared to time-based treatments DWRS, WRS, and WORS. Data based on Cardenas-Lailhacar et al. (2008)

Treatment	Cumulative depth (mm)	Comparisons[a]		Water savings (%) vs.		
		A	B	2-DWRS	2-WRS	2-WORS
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			
SMS-Based						
2-AC	348			44	65	77
2-RB	188			70	81	88
2-IM	1105			-77	-11	27
2-WW	270			57	73	82
SMS-Avg[c]	**478**		b	23	52	68

[a] A = Between time-based treatments
B = Time-based treatments vs. SMS-based treatments

[b] Different letters within a column indicate statistical difference at P<0.0001 (Duncan's Multiple Range Test)

[c] SMS =Soil moisture sensor; Avg = Average

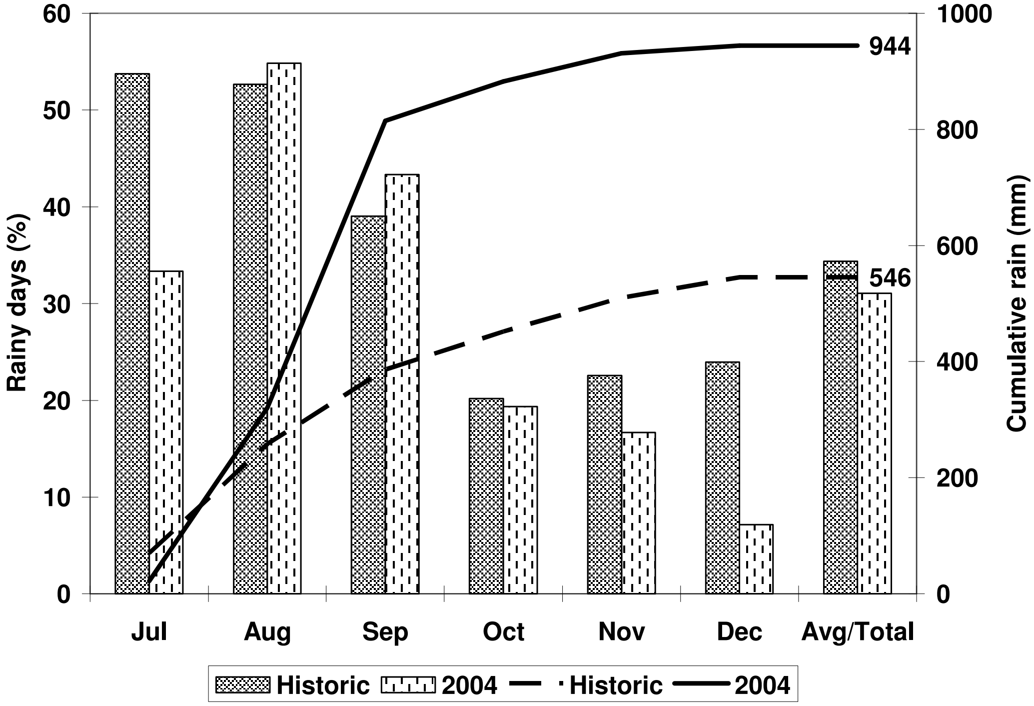

Figure 1. Percent of rainy days per month and cumulative rainfall in 2004 (21 July through 14 December 2004). Historic data based on USDC (2007).

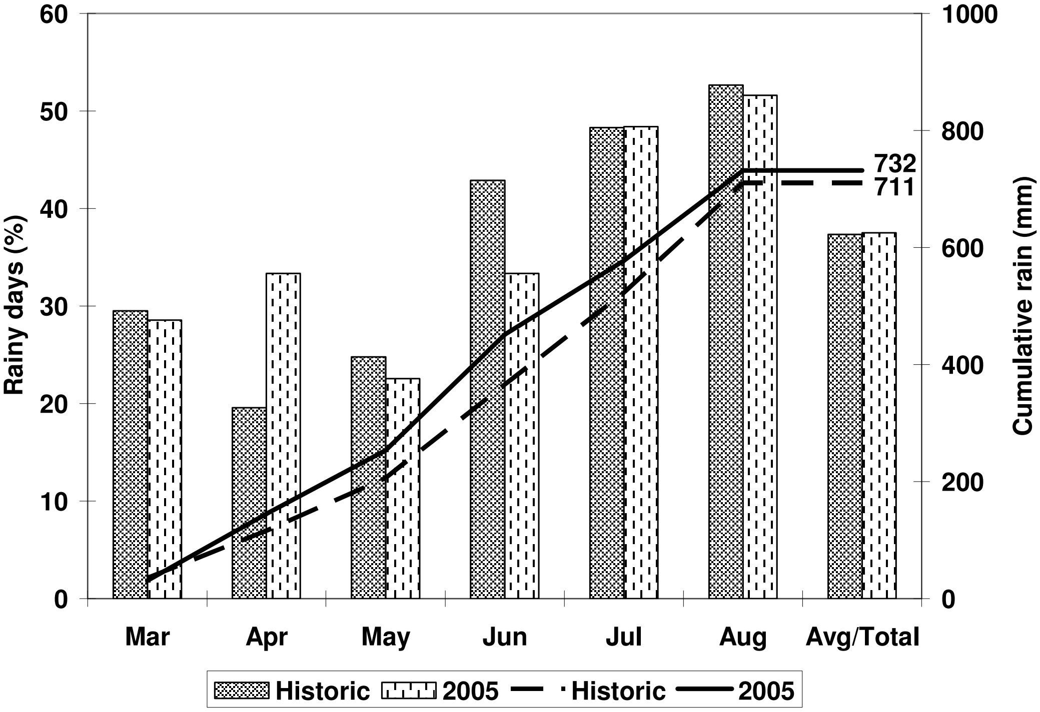

Figure 2. Percent of rainy days per month and cumulative rainfall in 2005 (25 March through 31 August 2005). Historic data based on USDC (2007).

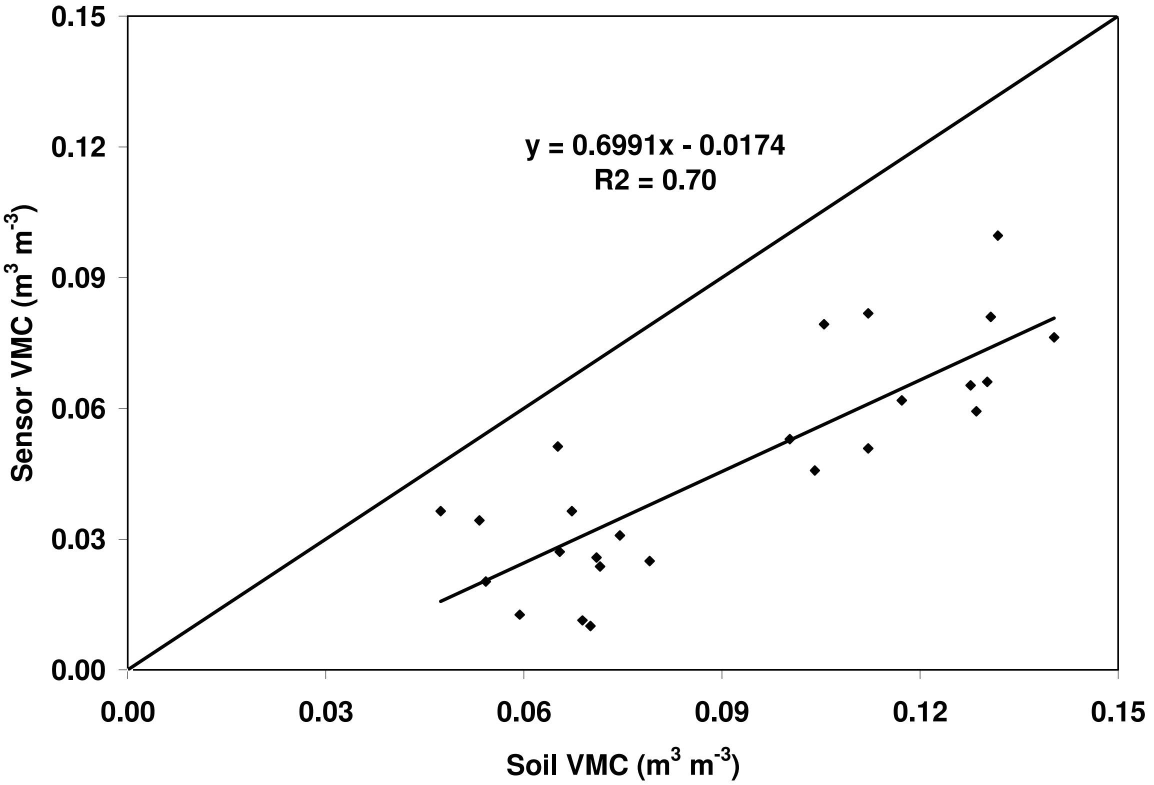

Figure 3. ECH_2O calibration results for an Arredondo fine sand; linear regression (VMC= volumetric moisture content).

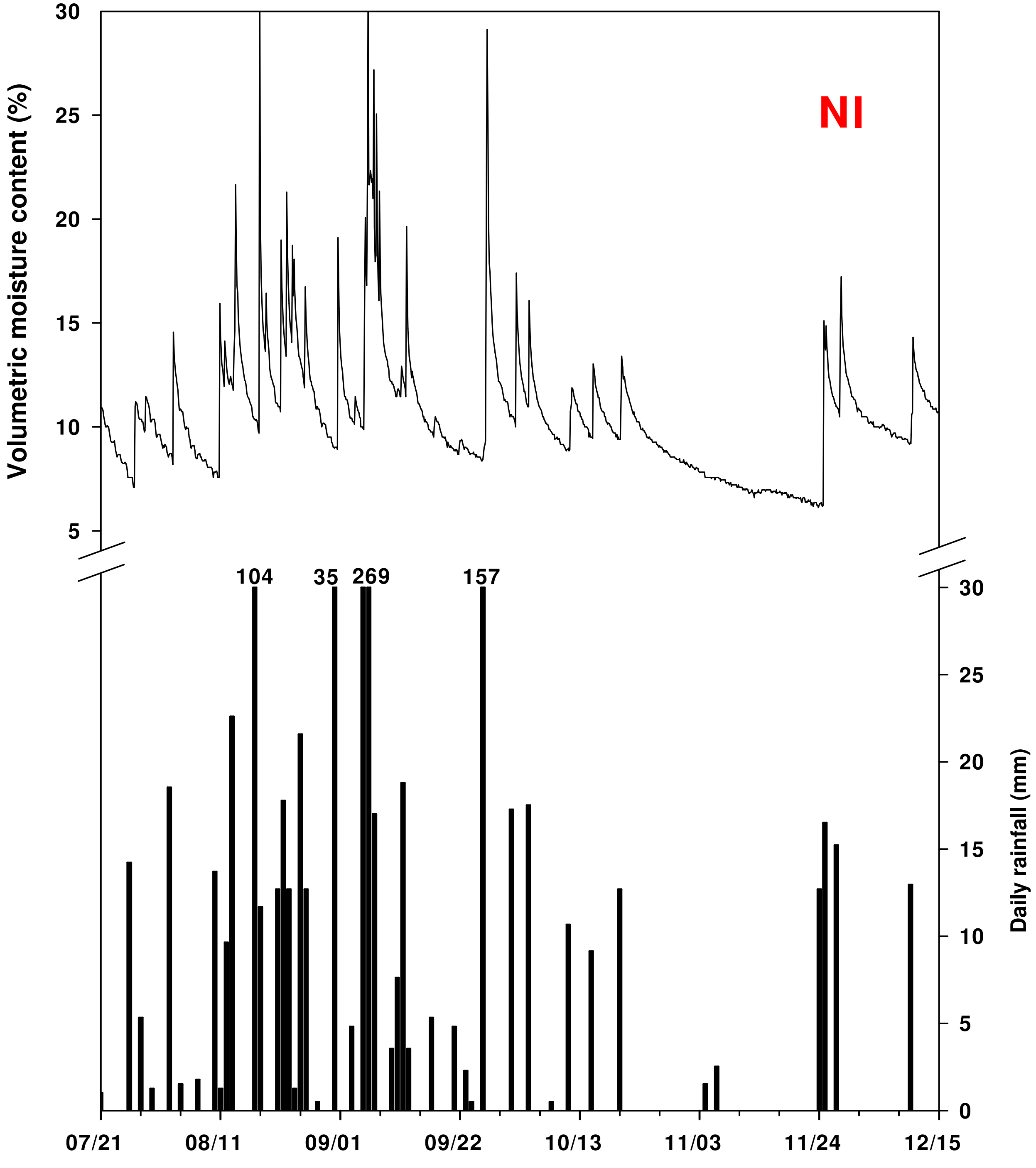

Figure 4. Relationship between soil volumetric moisture content on the non-irrigated treatment and daily rainfall through the experimental period of 2004.

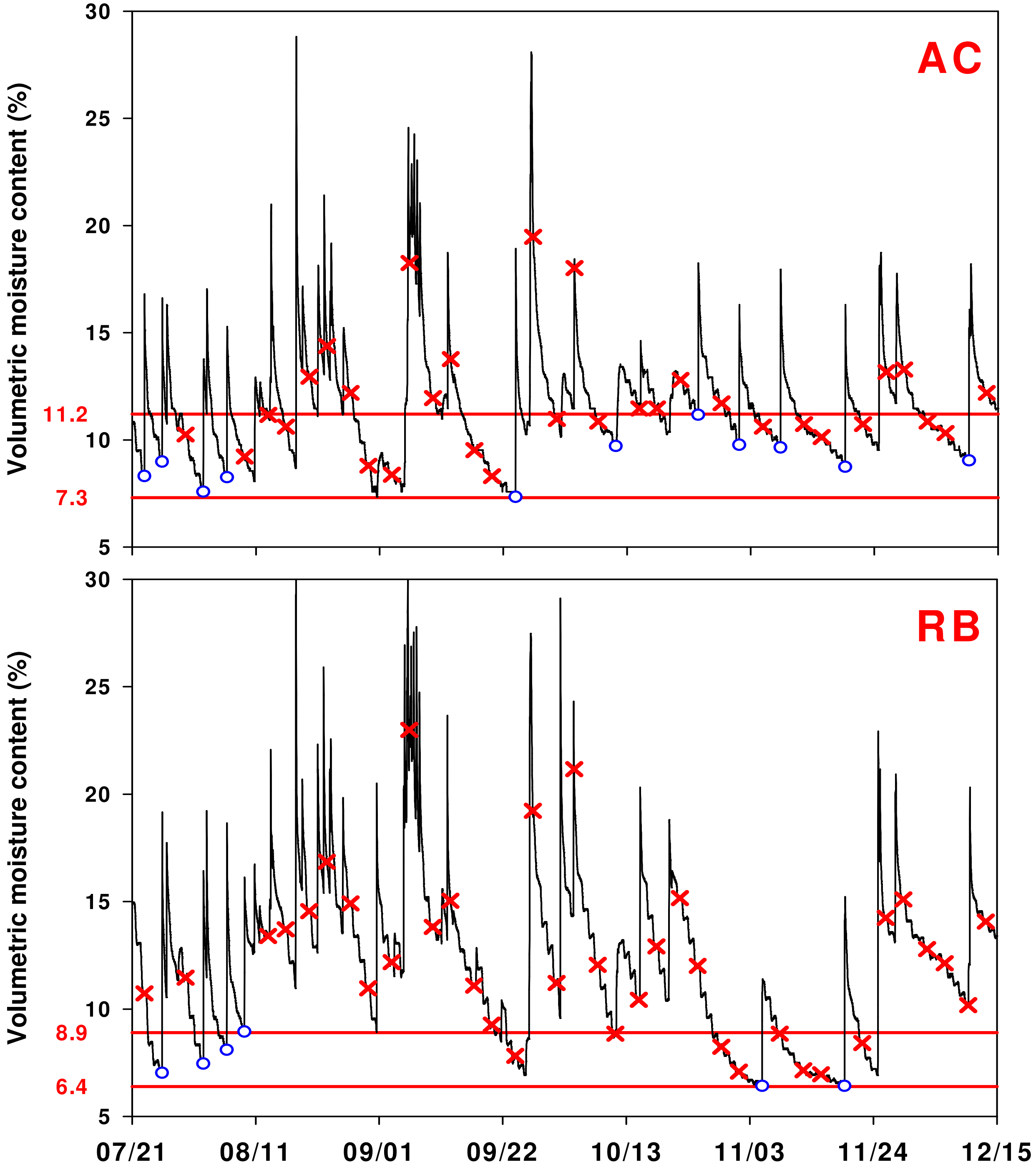

Figure 5. Volumetric moisture content (θ) through the experimental period of 2004, showing results of the scheduled irrigation cycles (SIC), where a red "x" represents a bypassed SIC, a blue circle represents an allowed SIC, and the red lines represent the range of θ when the SIC were allowed; treatments Acclima (AC) and Rain Bird (RB). When an increment in the θ does not have a blue circle on the bottom of the curve, it means that a rainfall event occurred.

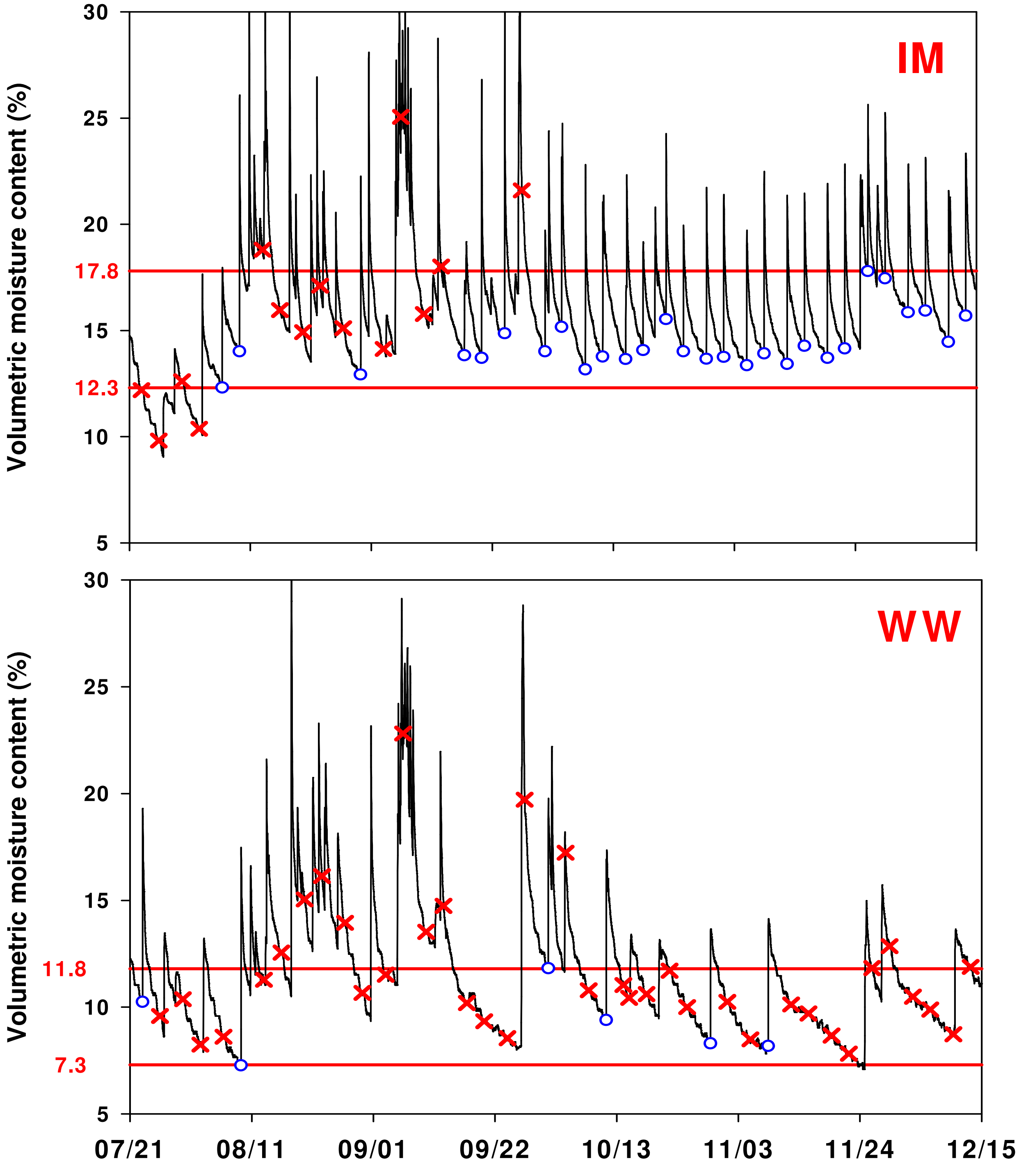

Figure 6. Volumetric moisture content (θ) through the experimental period of 2004, showing results of the scheduled irrigation cycles (SIC), where a red "x" represents a bypassed SIC, a blue circle represents an allowed SIC, and the red lines represent the range of θ when the SIC were allowed; treatments Irrometer (IM) and Water Watcher (WW). When an increment in the θ does not have a blue circle on the bottom of the curve, it means that a rainfall event occurred.