Dry-Out Periods of Rain Sensors vs. Soil Dry-Out: Water Saving Potential and Recommendations

B. Cardenas and M.D. Dukes*

Rain sensors (RSs) are devices that may help to irrigate residential landscapes more efficiently. When a predetermined amount of rain occurs, an RS interrupts the programmed irrigation cycle. When rainfall stops, RSs allow irrigation after a dry-out period. However, no actual RS dry-out times have been compared with soil dry-out times. The objectives of this study were (i) to determine the seasonal dry-out periods of two RSs; (ii) to estimate the dry-out periods of three soil textures (sand, loam, and clay loam) through a soil water balance model using numerical flow equations; (iii) to compare the dry-out period of these soil textures to the dry-out period of two RSs; and (iv) to propose recommendations for increased or decreased RS dry-out period, if any. Existing RS dry-out data from previous studies performed in Central Florida were assembled along with hourly weather data to estimate hourly turfgrass evapotranspiration (ETc). Precipitation data were used with ETc to simulate soil dry-out, using the WAVE 3.0 model. Modeled soil dry-out times were compared against actual RS dry-out data. The average RS dry-out time was not different between the RS brands tested, which was around 19 h. The dry-out time of the sand-textured soil was different from the loam and clay loam, which were similar to one another. The dry-out times of the soils modeled were always above 52, 75, and 89 h for sand, clay loam, and loam, respectively. Therefore, these results show that the RSs tested do not follow the dry-out characteristics of any of the soil textures modeled. An electronic mechanism that could delay the RSs resuming to the allowing irrigation mode is recommended to the industry.

Abbreviations: ETc, turfgrass evapotranspiration; ETo, reference evapotranspiration; Kc, crop coefficient; RS, rain sensor.

The primary use of residential outdoor water is irrigation, which is commonly used to ensure acceptable landscape quality (Haley et al., 2007; DeOreo et al., 2016; USEPA, 2018). Studies, however, have reported that over-irrigation occurs in many areas in the United States (Haley et al., 2007; DeOreo et al., 2016). One of the reasons for this undesired outcome is that some automatic irrigation systems do not receive feedback of the agroclimatic conditions at the targeted area (Davis and Dukes, 2015a, 2015b). A typical example of this situation is to see irrigation systems running during—or shortly after—a substantial rainfall event.

The irrigation industry has produced different solutions to address this issue. As a result, an increasing number of municipalities throughout the country have mandates and/or cost-saving programs for the use of different devices that would help to irrigate landscapes more efficiently.

One of the different irrigation sensing approaches are rain sensors (RSs). When these devices are attached to an automatic irrigation system, they can interrupt the signal of the irrigation controller (or timer) when there has been a predetermined amount of rain, eliminating unnecessary irrigation.

The most common RS models use hygroscopic disks that absorb water and expand proportionally to rainfall amount (Dukes and Haman, 2013). When the disks expand to a certain level, they activate a switch—integrated in the RS—that interrupts the automatic irrigation system circuit, preventing irrigation.
The circuit will remain interrupted as long as the disks remain expanded. When the rain stops, the disks begin to dry out and contract, and eventually the switch closes and allows irrigation (Hunter Industries, 2017). The time that it takes the RS to reset for normal sprinkler operation after the rain has stopped is determined by weather conditions—temperature, wind, sunlight, relative humidity, etc.—which will determine how fast the hygroscopic disks dry out.

The University of Florida Agricultural and Biological Engineering Department has conducted multiple research projects during the past decade examining different RSs. These studies were typically conducted to test RS accuracy relative to rainfall amounts (Cardenas-Lailhacar and Dukes, 2008; Meeks et al., 2012b), consistency of operation over time (Meeks et al., 2012a), or to compare RS performance with that of smart irrigation controllers (Davis et al., 2009; McCready et al., 2009; Cardenas-Lailhacar et al., 2008, 2010; Cardenas and Dukes, 2016a, 2016b). As a result, a database of the dry-out characteristics of several expanding-disk RS models was available for analysis.

In theory, the dry-out periods of the RSs follow or simulate the soil dry-out. These RS dry-out periods, however, have never been contrasted with the dry-out periods of different soils, which would provide a better idea of their performance as a device to save water while maintaining good turf quality.

The objectives of this study were (i) to determine the seasonal dry-out periods of two RSs; (ii) to estimate the dry-out periods of three soil textures (sand, loam, and clay loam) through a soil water balance model using numerical flow equations; (iii) to compare the dry-out period of these soils textures to the dry-out period of the two tested RSs; and (iv) to propose recommendations for increased or decreased RS dry-out period, if any.

Materials and Methods

Site Description and Measurements

From 1 Jan. through 31 Dec. 2007, several RS brands and models were tested at University of Florida Agricultural and Biological Engineering Department research facilities in Gainesville, FL (Fig. 1). Among these RSs, two wireless models were selected for this study, the Toro TWRS (The Toro Company) and the Hunter RainClik (Hunter Industries).

The Toro TWRS (Toro) had four rainfall threshold activation set points, ranging from 3 to 19 mm. Following recommendations from Cardenas-Lailhacar and Dukes (2008) for Florida weather conditions, the Toro was set at a 6-mm threshold set point. The Hunter RainClik (Hunter) did not have a rainfall set point. Instead, it had a built-in “Quick Response” technology designed to shut off the timer when it starts to rain. Although the Toro had an electronic built-in water delay feature to postpone irrigation from 1 to 5 d, this feature was not evaluated to measure the default hygroscopic disk’s dry-out time.

Four replications of each RS were exposed to the elements (Fig. 1) and connected by means of AM16/32 multiplexers to CR 10X model dataloggers (Campbell Scientific). Each time one of these RSs changed status (from allowing irrigation to bypass mode, or vice versa), a timestamp was recorded by the datalogger to the nearest second.

An onsite automated weather station (Campbell Scientific), also provided with a CR 10X datalogger, recorded every 0.25 mm of rainfall by means of a tipping bucket (Fig. 1). The weather station and RS dataloggers were synchronized within 1 s. Two rain events just greater than 6 mm were recorded by the tipping bucket; however, none of the RSs switched to bypass mode and, therefore, the events were not taken into account. Additional weather data such as temperature, relative humidity, wind speed, and solar radiation were recorded at 1-min intervals and averaged every 15 min. Seasonal averages of weather conditions and total amount of rainfall for 2007, along with historical data, are given in Table 1.

The weather data were used as inputs to calculate hourly reference evapotranspiration (ET$_0$) using the REF-ET software developed by Allen (2016). Other inputs to this software included anemometer height, temperature and relative humidity sensor height, weather station elevation and latitude, and (required for hourly data) the weather station longitude. The Environmental Water Resource Institute (2005) Standardized Reference Evapotranspiration Equation was chosen.

The results of the ET$_0$ calculations were multiplied by unitless monthly crop coefficients ($K_c$) to estimate the local turfgrass evapotranspiration (ET). The turfgrass $K_c$ coefficients were taken from Jia et al. (2009) for values reported near a Citra, FL, location that is 31 km away from the Gainesville site. These $K_c$ values ranged between 0.35 (in January–February) and 0.90 (in May).

Model Setup and Simulation Runs

Three soil texture types were chosen for evaluation: sand, loam, and clay loam (Table 2). Deep sands are the most common topsoil in Florida, often limited underneath by clayey soil (Milavarapu et al., 2017). The time that it takes the RS to reset for normal sprinkler operation after the rain has stopped is determined by weather conditions—temperature, wind, sunlight, relative humidity, etc.—which will determine how fast the hygroscopic disks dry out.

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Model Setup and Simulation Runs

Three soil texture types were chosen for evaluation: sand, loam, and clay loam (Table 2). Deep sands are the most common topsoil in Florida, often limited underneath by clayey soil (Milavarapu et al., 2017).
Less common are clayey textures found in urban settings as a topsoil, either occurring naturally or brought up by soil movement during housing developments (Hochmuth et al., 2016). The WAVE model (Vanclooster et al., 1994) was used to simulate the dry-out period of the three soil texture types. To achieve this, WAVE computed a soil water balance through numerical flow equations. The van Genuchten equation (van Genuchten, 1980) was used for the moisture retention characteristic curve (with no hysteresis), associated with the hydraulic conductivity model by Brooks and Corey (1964). Values within the recommended probability distributions for soil hydraulic parameters by soil texture (Meyer and Taira, 2001) were used as inputs (Table 2).

The upper boundary of the different soil textures was assumed to be covered by turfgrass, with the same amount, distribution, and length of roots yearlong, to a depth of 30 cm (considered the lower boundary). Peacock and Dudeck (1985) found that St. Augustinegrass [Stenotaphrum secundatum (Walter) Kuntze], the most common turfgrass in Florida, had 91% of the root mass in the upper 30 cm. Below this lower boundary, each soil was assumed to have more of the same unlimited soil texture underneath, allowing the free deep percolation of the water. Hourly rainfall, ET₀, and monthly Kₑ values for warm-season turfgrass were also used as inputs to the WAVE model.

Rainfall measurements from 2007 were used to calculate the dry-out periods of the RSs and soil types. The dry-out period for each RS was defined as the amount of time to the nearest minute from when the rainfall event stopped—and the RS was already in bypass mode—until the RS switched back to allowing irrigation mode.

The chosen volumetric water content values to start each soil dry-out simulation were 6.5, 20.0, and 27.5% for sand, loam, and clay loam, respectively. These values are deemed representative of a management allowable depletion level, at which no turf water stress is assumed (Allen et al., 1998; Ratliff et al., 1983; Jensen and Allen, 2016).

With the infiltrated rainwater, the volumetric water content of the different soils increased. Once the rain stopped, the soils began to lose water by evapotranspiration and/or drainage. The amount of time to the nearest minute that it took for each soil texture, from when the rain stopped until they reached again their management allowable depletion point, was considered as their specific dry-out period.

### Potential Irrigation Bypass and Water Savings

The irrigation cycles that could be potentially bypassed, and the subsequent irrigation water potentially saved, were also estimated (note that the concept “potential” is used here, since the RSs were not connected to an actual irrigation system, but to a datalogger).

The St. Johns River Water Management District has established irrigation restrictions to protect the limited water resources and prevent excessive irrigation, including in the area where this experiment was performed. These restrictions vary depending on the property type, address number, and time of the year (Table 3) and apply to private wells and pumps, ground or surface water, and water from public or private utilities (Gainesville Regional Utilities, 2017). Therefore, on each occasion that an RS was on bypass mode, it was contrasted with the watering restrictions stated in Table 3. If during an allowed watering window an RS was in bypass mode, the irrigation system would have not turned on, hence saving the water of that entire irrigation cycle.

### Statistical Analyses

The results for the year of data were divided in averages per season (winter, spring, summer, and fall) for an easier visualization and comparison of the outcomes. The four seasons included data from the following months: December, January and February for winter; March, April, and May for spring; June, July, and August for summer; and September, October, and November for fall.

Statistical data analyses were performed using the general linear model (GLM) procedure (Proc GLM) of the SAS software (SAS Institute, 2017).
Analysis of variance was used to determine treatment differences for a completely randomized design. Duncan’s multiple range test was used to identify mean differences between treatment dry-out times, RS bypass period, seasons, and number of irrigation events. Probability values <0.05 were considered significant.

Results

Rain Sensor Dry-Out Time

The average dry-out times between the Toro and Hunter RSs were not statistically different, in any season (Fig. 2). However, a statistical difference was observed between the average winter and spring dry-out time. During the winter, both RS brands took an average of 21 h to dry out compared with 14 h during the spring. These results are due to the lower atmospheric evaporative capacity during the winter, compared with the high spring temperatures and lower relative humidity than the rest of the year (Table 1).

When the whole year is taken into account, the average dry-out times of the different RSs were always <24 h (Fig. 2). Even when the winter and spring seasons were statistically different, there was not much difference between 21 or 14 h of dry-out time from a practical point of view, because the average window for the different RSs to bypass an irrigation cycle would be very limited (<21 h after the rain stops). These seasonal results are far from the advertised “72 h to reset when fully wet, under dry and sunny conditions” (Hunter Industries, 2017).

Soil-Type Dry-Out Times

During the modeling process, the maximum dry-out time allowed to the different soil types was 168 h (7 d). This period was chosen because even in wintertime homeowners are allowed to irrigate at a 1 d wk⁻¹ schedule in Central Florida (Table 3). Notwithstanding this, the average soil dry-out period during winter was 137 h, which was statistically longer than the 72 h during summer (Fig. 3). This may be explained by the lower ETc (Table 1), coupled with the dormancy state or minimum growth of the turfgrass during winter, compared with summer.

The dry-out periods of the three textures modeled were always longer during the winter and shorter during the summer (Fig. 3). The sand ranged from 52 to 92 h, the loam from 89 to 162 h, and the clay loam ranged from 75 to 157 h. On average, the sand had the shortest dry-out period throughout the year (70 h) and was statistically different from loam and clay loam (116 and 104 h, respectively). These statistical differences between the textures were observed in every season (Fig. 3).

Table 3. Watering restrictions by property type, address number, and time of the year, as set by the St. Johns River Water Management District, for the area where the experiment was carried out.

<table>
<thead>
<tr>
<th>Time of year</th>
<th>Residential</th>
<th>Nonresidential, all addresses</th>
</tr>
</thead>
</table>
| Odd-numbered/no address | Even-numbered address | n is the number of observations used. The graph includes standard error bars. Letters given parenthetically after seasons are the first letters of the months in each season (December–November).

Fig. 2. Rain sensor dry-out times (2007). Within each season, bars with double asterisks (**) are not significantly different from each other (P > 0.4), and n is the number of observations used. The graph includes standard error bars. Letters given parenthetically after seasons are the first letters of the months in each season (December--November).

Fig. 3. Soil-type dry-out times (2007). Within each season, bars with different letters are significantly different from each other (P < 0.0001), and n is the number of observations used. The graph includes standard error bars. Letters given parenthetically after seasons are the first letters of the months in each season (December--November).
Even when loam and clay loam were not statistically different in their dry-out time, the clay loam texture showed a tendency, throughout the year, to dry out sooner than the loam (Fig. 3). This is counterintuitive, owed to the higher clay content of the clay loam. However, these outcomes were mainly due to the common high-intensity rainfall events in the region, which resulted in greater runoff and less water infiltration into the clay loam than the loam-textured soil. Therefore, the subsequent smaller amount of water stored in the clay loam dried out sooner than the larger amount of water stored in the loam-textured soil.

For example, between 1800 and 2300 h of 21 October, a total amount of 5.8 mm of rain fell (Fig. 4). Under this low rain intensity (<1 mm h⁻¹), the WAVE model simulated that all precipitation infiltrated in the soils (no runoff). The resultant dry-out period was shorter for sand, medium for loam, and longer for clay loam. Different outcomes, however, resulted from high-intensity rainfall events, which are common in the region. For example, Fig. 5 shows that between 1100 and 1700 h on 3 August, a total of 37.1 mm of rain fell. During this period, three hourly peaks of 14.2, 7.9, and 14.7 mm of rain were recorded. Note that when >6 h have passed between two consecutive rainfalls, they were considered as two different rainfall events, as suggested by Huff (1967).

Under these circumstances, the sand-textured soil infiltrated all the rainfall, the loam infiltrated 39%, and the clay loam only 27%, whereas the non-infiltrated water was considered as runoff according to the WAVE model. As a consequence of the small amount infiltrated by the clay loam, the dry-out period of this soil texture was similar to that of the sand (Fig. 5) and shorter than that of the loam soil, during this rainfall event. Situations like this were often found in the data, which resulted in a tendency of the clay loam soil to dry out slightly faster than the loam texture on average.

**Rain Sensors vs. Soil-Type Dry-Out Times**

The average dry-out times of the different soil types were always significantly longer than the RS dry-out times (Fig. 6). In summer, the three soils modeled resulted in the shortest dry-out time during the year (with ~52, 75, and 89 h for sand, clay loam, and loam, respectively), but the dry-out times for Toro and Hunter
RSs were even shorter (~19 h for both brands). During winter, the statistical differences remained between the soils and the RSs, but the difference in hours was even greater: the dry-out time of the RSs was ~21 h, whereas the sand, loam, and clay loam averaged 92, 157, and 163 h, respectively.

These results show that the RSs tested do not follow the dry-out characteristics of any of the soil textures modeled, in any season, and need to be adjusted to the agroclimatic conditions of the region, such that they remain to be considered an adequate option for water conservation. According to Whitcomb (2005), only 25% of the homes with an automatic irrigation system were equipped with an RS in Florida, and the author added that anecdotal evidence suggests RSs are often improperly installed. Similarly, Cardenas and Dukes (2016b) reported that only 4 out of the 92 houses visited for their study had an RS previously installed, and of those, only one was functional. If the dry-out times were closer to the advertised 72 h to reset, RSs would probably have a better market acceptance than they currently do.

**Rain Sensor Bypass Mode Period**

As with the RS dry-out times (Fig. 2), the bypass mode periods between the different RS brands were not significantly different in any season (Fig. 7). The average bypass mode period was very similar for both brands, with ~27 h for Toro and 29 h for Hunter. This similarity could be due to the hygroscopic disk material, which appeared to be similar for both models. The slightly longer bypass mode period of Hunter was due to the second set of hygroscopic disks of this model (RainClik’s Quick Response), which were designed, according to the manufacturer, to “stop irrigation the instant rain starts to fall” (Hunter Industries, 2017), whereas the Toro RSs would need (in theory) at least 6 mm of rainfall (threshold set point).

These results are similar to those reported for the Hunter RS when Cardenas-Lailhacar and Dukes (2008) tested them during 2005 and found that 80% of the times this model dried out in <24 h after the sensors changed to the bypass mode. It is important to note that the dry-out times of the different RSs were previously tested with their vent rings completely open and completely closed, but no statistical difference was observed between these two conditions (Meeks et al., 2012a).

**Potential Irrigation Bypass and Water Savings**

The irrigation events potentially bypassed were calculated, considering that these RSs would have been installed in a residential setting (Table 4). The chances of bypass irrigation were computed for both RSs, and for homes with odd- and even-numbered addresses.

As established in Fig. 7, there were no differences in the bypass mode period between the tested RS brands. This same behavior resulted, between and within the RS brands, in the number of irrigation events potentially bypassed on odd- or even-numbered addresses, which were not statistically different (Table 4). Toro RSs would have bypassed 19 and 23 irrigation events for odd- and even-numbered addresses, respectively, and Hunter would have bypassed 18 and 23 irrigation events, also respectively. Likewise, the number of irrigation events potentially bypassed, independently of the RS brand, was not statistically different between the even and odd addresses, with 19 and 23 irrigation events on average, respectively (Table 4). Proportionally speaking, the odd- and even-numbered homes would have saved 22 and 27%, respectively, of the irrigation water programmed to be applied that year.

These results concur with several studies performed in Florida with hygroscopic expanding-disk RSs under controlled plot experiments. The addition of an RS set at a 6-mm threshold to a time-based schedule reduced irrigation by 21% during 14 mo of mainly dry weather conditions (Davis et al., 2009). A study in Central Florida compared irrigation application between a timer only and a timer plus an RS set at 6 mm, among other treatments. The water savings for the RS were 17%, under mostly dry weather conditions,
These results can also be the reason of the low acceptance of these devices by homeowners in Florida, as reported by Whitcomb (2005) compared with the timer alone (McCready et al., 2009). Other studies testing RSs in Central Florida resulted in up to 34% water savings under normal rainfall frequency (Cardenas-Lailhacar et al., 2008), and 13 to 24% under dry weather conditions (Cardenas-Lailhacar et al., 2010), without adversely affecting turfgrass quality.

These controlled experiments resulted in similar outcomes from RSs tested under residential settings. In a study conducted in Pinellas County, Florida, from July 2006 to December 2008, homes equipped with an RS applied between 14 and 24% less irrigation than homes without an RS (Haley and Dukes, 2007). A similar study performed from February 2011 to September 2013 in homes in the same region resulted in 12 to 21% water savings. None of these results, however, were statistically significant from homes without an RS.

Conclusions

Considering the results obtained in this research, it is clear that the RSs tested do not reflect the natural dry-out time of the different textures modeled and thus have limited usefulness under the Central Florida agroclimatic conditions. The sandy soils—the most common soil type in Florida—do not dry out or require irrigation as often as the RSs allow, not even during the summer. This may be the reason why different studies testing RSs resulted in lower water savings than other similar devices (i.e., soil moisture sensors and/or ET-controllers; Cardenas-Lailhacar et al., 2008, 2010; Davis et al., 2009; McCready et al., 2009; Cardenas and Dukes, 2016a, 2016b). These results can also be the reason of the low acceptance of these devices by homeowners in Florida, as reported by Whitcomb (2005) and by Cardenas and Dukes (2016b).

As demonstrated in a previous study in the region (Meeks et al., 2012a), a mechanical device to increase the dry-out period of these devices does not seem to be the correct approach to simulate the natural dry-out times of the soil textures studied. Instead, the use of an electronic mechanism that could delay the return of the RS to the allowing irrigation mode seems to be a better option.

After these results, a minimum 48-h delay in summer to a maximum 92-h delay in winter for rain events of 6 mm or more seems a good recommendation under the climatic conditions of Florida. Therefore, if the end user could select from a number of hours (or days) for delaying the RSs to resume to the allowing irrigation mode, the RS could come closer to the natural dry-out time of the local soil. Even though this feature was included in the Toro model tested, it was not evaluated in this study.

If an electronic mechanism was included to allow these suggested delays, the current design and mechanism of the different RS models, and its hygroscopic discs for sensing rainfall, would not need to be changed. Previous research has proven that different brands and models sensing the amount of rainfall by means of hygroscopic discs are accurate up to 2 yr after installation. Therefore, the addition of a delay function to the receiver of the wireless models, or to an interface between the RS and the timer, could greatly improve the functionality and the water saving potential of these devices. Research should be performed to establish if this proposed approach is correct.

Table 4. Potential number of irrigation events, events that could have occurred, and events that could have been bypassed by the tested rain sensors, depending on residential address and rain sensor brand.

<table>
<thead>
<tr>
<th>Event</th>
<th>Odd-numbered addresses</th>
<th>Even-numbered addresses</th>
<th>Odd-numbered addresses</th>
<th>Even-numbered addresses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toro</td>
<td>Hunter</td>
<td>Toro</td>
<td>Hunter</td>
</tr>
<tr>
<td>Total possible</td>
<td>86</td>
<td>86</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>Occurred</td>
<td>67†</td>
<td>68†</td>
<td>63†</td>
<td>63†</td>
</tr>
<tr>
<td>Bypassed</td>
<td>19†</td>
<td>18†</td>
<td>23†</td>
<td>23†</td>
</tr>
</tbody>
</table>

† Not significantly different between odd- or even-numbered addresses within each rain sensor brand.

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Considering the results obtained in this research, it is clear that the RSs tested do not reflect the natural dry-out time of the different textures modeled and thus have limited usefulness under the Central Florida agroclimatic conditions. The sandy soils—the most common soil type in Florida—do not dry out or require irrigation as often as the RSs allow, not even during the summer. This may be the reason why different studies testing RSs resulted in lower water savings than other similar devices (i.e., soil moisture sensors and/or ET-controllers; Cardenas-Lailhacar et al., 2008, 2010; Davis et al., 2009; McCready et al., 2009; Cardenas and Dukes, 2016a, 2016b). These results can also be the reason of the low acceptance of these devices by homeowners in Florida, as reported by Whitcomb (2005) and by Cardenas and Dukes (2016b).

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