Sprinkler Irrigation and Soil Moisture Uniformity

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Abstract
Uniformity of soil moisture under sprinkler irrigation is important for plant quality; however, sprinkler systems are typically gauged by the uniformity of application above the crop canopy. The objectives of this study were to measure and analyze both application uniformity with catch cans and soil moisture uniformity to quantify the relationship. Under testing on bare soil and turfgrass, soil moisture uniformity was always higher than catch can uniformity when quantified by the low quarter distribution uniformity. During the testing of this project, the low quarter distribution uniformity of soil moisture in the upper 10 cm of soil approximated the low half distribution uniformity from catch can data.

Introduction

The uniformity of sprinkler irrigation is a central design goal (Keller and Bliesner, 2000). Uniformity of water application is sought to minimize variability of crop yield, or plant quality in the case of turfgrass and landscapes. The catch can test is a commonly used measurement tool to assess the uniformity of sprinkler systems. Standards have been developed for center pivot and linear move irrigation machines (ASAE, 2001) and testing protocols have been developed for turfgrass and landscape irrigation (IA, 2005). Once the data are collected by catch cans, a number of different calculations can be performed. A common measurement of variability in water application on turfgrass and landscapes include the low quarter distribution uniformity (DU_{lq}),

$$DU_{lq} = \frac{\overline{V}_{lq}}{\overline{V}_{tot}} \qquad [1]$$

where: $\overline{V}_{lq}$ = average of the lowest one-fourth of catch-can measurements, mL
$\overline{V}_{tot}$ = average depth of application over all catch can measurements, mL

To distinguish between a measure of uniformity and efficiency, DU_{lq} should be expressed as a decimal as suggested by Burt et al. (1997). The lower half distribution uniformity can be calculated from DU_{lq} as follows (IA, 2005),

$$DU_{lh} = 0.386 + (0.614 * DU_{lq}) \qquad [2]$$

The Christiansen Uniformity Coefficient is (Christiansen, 1941; ASAE, 2001) is commonly used in agricultural sprinkler uniformity assessment and is expressed as,

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$$CU = 100 * \left[1 - \frac{\sum_{i=1}^{n} \left| V_i - \overline{V} \right|}{\sum_{i=1}^{n} V_i} \right] \qquad [3]$$

where: V_i = individual catch can measurement, mL

$\overline{V}$ = average volume of application over all catch can measurements, mL

In addition, the coefficient of variation (CV) in application volume can be computed as the standard deviation of all catch can measurements divided by the average catch can volume for a test. Both DU_{lq} and CU have been related to the CV analytically (Warrick, 1983) and verified experimentally on center pivot and linear move irrigation machines (Heermann et al., 1992; Dukes, 2006).

Analysis of catch can data ignores the process of water redistribution on the soil surface in the case of bare soil, as water moves through the crop canopy, and horizontally as the water infiltrates. There is some indication in the literature that variability in catch can data does not adequately represent soil moisture variability. Mateos et al. (1997) found that the CV of infiltrated water was one-third of the applied water as measured by catch cans under sprinkler irrigation. Sprinkler uniformity below the canopy of winter wheat was improved compared to the uniformity of application as measured above the canopy (Li and Rao, 2000). This finding indicates that the canopy can redistribute water to achieve improved uniformity before redistribution within the root zone is considered. Stern and Bresler (1983) found that the CV of catch can data was two to three times higher than soil water CV in the top 40 cm one day after sprinkler irrigation on sand and sandy loam soils. Since there was no runoff, the authors speculated that the high soil water uniformity was due to redistribution within the soil profile. Li and Kawano (1996) evaluated sprinkler uniformity and soil water uniformity on a bare volcanic soil (0.74 g/cm^3 bulk density, saturated water content of 0.64 m^3/m^3) and a bare sandy loam (1.2 g/cm^3 bulk density, saturated water content of 0.40 m^3/m^3). Soil water CU after irrigation approximated initial soil water CU after several hours. Hart (1972) modeled the redistribution of soil water and showed that soil water uniformity was consistently higher than application uniformity due to influence of initial soil water content, average application rate, and total water applied. Mecham (2001) showed that TDR measurements in the top 12 cm of soil after irrigation of turfgrass resulted in 26%-35% higher DU_{lq} results (DU_{lq} increase of 0.18-0.20) compared to catch can testing. The author attributed this difference to horizontal water distribution as it moved through the turfgrass and thatch layer into the soil. Wallach (1990) described the distribution of infiltrating water over an irrigated area as a sinusoidal function and presented the solution for two dimensional steady state flow equations where variability of water application was damped as water infiltrated.

Although there has been much work relating irrigation uniformity to yield analytically (Letey et al., 1984; Stern and Bresler, 1983; Varlev, 1976; Seginer, 1979 to name a few) or with simulation models (Mantovani et al., 1995; Pang et al., 1997), there are fewer studies that have measured the influence of uniformity on crop yield. Application CV as high as 0.48 did not influence yield of cotton compared to uniformly irrigated (CV = 0.20) plots (Mateos et al., 1997). Although the authors speculated that part of the reason for no influence on yield was because cotton is a drought tolerant crop, the CV of applied water was 2-4 times higher than the CV of infiltrated water. The yield of winter wheat did not vary when irrigated with different sprinkler irrigation uniformity treatments with seasonal CU ranging from 72% to 84% Li et al. (2005). The authors speculated that uniformity of sprinkler irrigation may have not impacted results in this project due to redistribution of applied water via canopy interception, redistribution of water in the soil, the extensive root system of wheat, and adequate rainfall over the crop season. However, these results may not apply to shallow rooted crops. In another study on winter wheat, Li and Rao (2003) found that yield was not influenced by sprinkler CU ranging from 62% to 82%. Ayers et al. (1990) found that nonuniformity as low as CU = 60% in a width of six to nine rows was insufficient to negatively impact sugar beet yield on a silty clay loam soil due to water redistribution within the soil. However, they found that nonuniformity at the same level (CU = 60%) across 16 to 24 rows reduced average yield.

Thus, there is a body of evidence that in agricultural systems soil moisture uniformity is generally higher than catch can values after sprinkler irrigation. However, there is only limited literature supporting this finding on turfgrass and bare soil. The Irrigation Association has recommended DU_{lq} as a performance measure of sprinkler systems; however, this measurement index may not adequately represent conditions in the soil.

The objective of this project was to compare the variability of irrigation application over a bare soil and established turfgrass areas with residential sprinklers as measured by water captured in catch cans and soil moisture content in the upper root zone. Our hypothesis was that the soil moisture content after irrigation is more uniform that water captured in catch can testing which may limit negative impacts on landscape quality due to low sprinkler uniformity.

Materials and Methods

Plot testing

Uniformity testing was conducted at the University of Florida Irrigation Research Park, Gainesville, Florida between February and November 2005. Tests were conducted on bare soil that was maintained by a combination of tillage, mowing, and herbicides. The site is mapped as an Arredondo fine sand soil (Thomas et al., 1985) which is well-drained with 7.3% to 10.3% field capacity by volume (all moisture contents in this manuscript reported on a volumetric basis) and 2.2% to 3.3% range wilting point based on laboratory measurements in the top 20 cm. This soil has a sand content in the 90.7% to 93.5% range and silt content in the 2.2% to 5.6% range. Organic matter content is less than 1% (Carlisle et al., 1978; Carlisle et al., 1981; Carlisle et al., 1989). The steady state infiltration rate has been measured on this site as 179 mm/hr (Gregory et al., 2005)

A sprinkler system was established in two identical 4.6 m X 4.6 m plot areas side by side. Quarter circle spray head sprinklers (Prospray model, Hunter Industries, Inc.; 15Q MPR nozzles, Rain Bird, Inc., Glendora, CA) on each corner were used to irrigate the plots.

Catch cans were placed within the sprinkler grids 0.5 m from the edge of the sprinkler coverage area with a can to can spacing of 0.9 m for a total of 25 catch cans in each grid. The catch cans were plastic containers with a 0.16 m diameter and 0.20 m height. This size catch can has been shown to have similar uniformity results compared to larger diameter catch cans under center pivot sprinkler irrigation testing (Dogan et al., 2003). Pressure gauges were installed on the supply line and the looped piping network at the furthest point from the supply to document any pressure losses in the system.

Weather data were collected within 100 m of the site with an automated weather station that measured rainfall, temperature, relative humidity, solar radiation, wind speed, and wind direction.

Before testing, soil cores were collected with an intact core sampler (10 cm length, 5.7 cm diameter, 260 cm^3 core volume) within 15 cm of each catch can and a measurement was taken with a portable Time Domain Reflectometry (TDR) probe (Field Scout 300, Spectrum Technologies, Inc., Plainfield, IL) with 20 cm long rods for an approximate sensing volume of 565 cm^3 estimated by assuming an approximate 3 cm radial sensing zone around the probe rods (Muñoz-Carpena et al., 2005). The TDR measurement was taken on an opposite side of the bucket compared to the intact soil core sample. After the irrigation system was run approximately 30 minutes, another intact core sample was collected in a 90 degree rotation around the catch can and within 15 cm of the catch can. Also, a final TDR measurement was taken across from this intact core sample. Soil water content in the intact cores was determined gravimetrically (Gardner, 1986) and bulk density was used to calculate moisture content by volume in the soil samples (Blake and Hartge, 1986). Tests were only performed when initial soil moisture content was less than or equal to 8-10% (approximate field capacity).

Three pressure levels were used in uniformity testing to induce varying levels of non-uniformity of water application. These type of sprinklers tend to have better uniformity with a minimum pressure of 207 kPa (Baum et al., 2005), thus one pressure level above this level was tested (414 kPa) while two pressure levels below 207 kPa were tested (138 and 69 kPa). A 30 minute irrigation cycle resulted in average application depths of 18, 12, and 10 mm at these respective pressures. After sample collection, the sample holes were filled with surrounding soil and tamped to approximate the original bulk density. Only on one occasion were tests performed within four days and on other occasions, weeks or months passed before testing could occur usually due to frequent rainfall that kept soil moisture content above field capacity for extended periods. In any case, sample collection around the catch cans was rotated to obtain a relatively undisturbed sample each time. Each test at a particular pressure level was replicated five times. Catch can volumes were measured with a 1000 mL graduated cylinder.

Since DU_{lq} is recommended by the IA (2005) as a sprinkler irrigation system performance measure, this quantity was calculated according to Equation 1 for catch can and soil moisture data. Data were analyzed with an analysis of variance using the general linear models procedure in SAS (SAS, 2001) with pressure, replicate, and test site as main effects on pre-irrigation and post-irrigation DU_{lq} and soil moisture content of both TDR and gravimetrically determined soil moisture content. Other main effects included catch can DU_{lq} and volume caught. In addition, DU_{lq} of the soil moisture content and catch can means by measurement method were compared using analysis of variance and checked for interaction with pressure.

Residential and Plot Testing on Turfgrass

As part of a project to measure and reduce residential irrigation water use through proper irrigation design and scheduling, intensive catch can measurements were performed on 21 residential homes throughout Marion, Lake and Orange counties in Florida (Haley et al., 2006). Uniformity testing is detailed by Baum et al. (2005); however, in general the tests were conducted in a similar manner as the plot testing described previously except that TDR readings were collected prior to testing on 9 of 21 tests and TDR readings after irrigation were collected on all tests. In addition, all tests were conducted on turfgrass with adequate system pressure during testing. Gravimetric samples were not collected.

Uniformity tests were conducted under controlled conditions on a turfgrass plot at the University of Florida Agricultural and Biological Engineering Turfgrass Test Area to determine the effect of equipment type on uniformity (Baum et al., 2005). Testing consisted of catch can collection of irrigation depth and TDR readings at each catch can after irrigation. Gravimetric samples were not collected. A detailed statistical analysis of the catch can test data is described by Baum et al. (2005). A t-test was used to determine if DU_{lq} determined by TDR measurements was the same as catch can DU_{lq}.

Results and Discussion

Plot Testing

Table 1 shows a summary of the calculated DU_{lq} and the average values of soil moisture content from both TDR and gravimetric measurements. A range of significantly different ($p = 0.0014$) DU_{lq} values were obtained as measured by the catch can method due to adjustment of the system supply pressure. The low test pressure of 69 kPa resulted in a DU_{lq} of 0.39 while increasing the pressure to 138 kPa resulted in a DU_{lq} of 0.55. The 138 kPa pressure level is within the minimum suggested operating pressure of 101 kPa by the manufacturer (Hunter Industries, 2006); however, increasing the pressure to 414 kPa resulted in the highest measured DU_{lq} of 0.63. The DU_{lq} results across increasing pressure levels would be rated as less than “Poor”, “Good”, and “Good”, respectively by the IA (2005) irrigation system quality rating guidelines. As can be seen in Figure 1, although catch can DU_{lq} clearly decreased due to lower irrigation system pressure, the soil moisture DU_{lq} measured gravimetrically was reduced weakly and the TDR measured soil moisture DU_{lq} was not obviously affected by the reduced uniformity in water application. Similar results have been reported by Mateos et al. (1997) and Stern and Bresler (1983) for agricultural sites and by Mecham (2001) on turfgrass.

The soil moisture uniformity prior to irrigation was similar to that after irrigation (Fig. 1), although actual moisture content in the soil increased (Fig. 2). This observation points to a dampening effect on nonuniformity as infiltration occurs that was postulated by Wallach (1990). In addition, soil moisture uniformity before irrigation as measured by the TDR and gravimetrically was not significantly different ($p = 0.734$ and $p = 0.463$, respectively) across pressure levels (Table 1). In fact, soil moisture content as measured by both TDR and gravimetric methods prior to irrigation were well related ($R^2 = 0.76$), indicating relatively steady state moisture conditions in the top 10-20 cm (Fig. 3). This result is not surprising since the test area was relatively homogeneous in the top 10-20 cm of soil due to tillage prior to set up of the test site.

The increase in soil moisture content from irrigation ranged from 0.02 m^3/m^3 to 0.14 m^3/m^3 in the top 10 to 20 cm of soil. This increase was strongly related to an increase in volume of water applied for irrigation (Fig. 2). On average, the TDR measured soil moisture content increased 0.08, 0.04, and 0.03 m^3/m^3 for pressures of 414, 138, and 69 kPa, respectively. Similarly, the soil water content determined by gravimetric measurement increased 0.13, 0.08, and 0.07 m^3/m^3 for the same respective pressures (Table 1; Fig. 2). The larger change in gravimetric moisture content compared to TDR measured moisture content was likely due to the fact that gravimetric measurements were taken from the top 10 cm while the TDR measurements were taken in the top 20 cm of soil. However, the slope of the linear regression in soil moisture change relative to irrigation volume indicates that the change in soil moisture was similar for both gravimetric and TDR measurement techniques (Fig. 2). Thus, although both methods were sensitive to changes in soil moisture content as a result of varying irrigation levels, the upper 10 cm of soil produced larger magnitude changes (Fig. 2) for measurements that were collected immediately after irrigation. Gravimetric measurements showed consistently lower soil moisture values before and after irrigation events (Fig. 3).

Though the TDR measurements showed soil moisture response to varying levels of irrigation, soil moisture content uniformity was not significantly ($p = 0.538$) changed across varying application uniformity due to pressure changes (Table 1; Fig. 1). Gravimetric soil moisture DU_{lq} of 0.69 was significantly ($p = 0.0005$) lower at 69 kPa compared to the other two pressures (DU_{lq} = 0.83 at 414 kPa and 138 kPa). Gravimetric DU_{lq} was likely affected to a greater degree compared to TDR DU_{lq} due to the shallower sample depth. Authors of previous studies speculated that canopy interception acts to redistribute water (Mateos et al., 1997; Stern and Bresler, 1983; Mecham, 2001). However, in our work on bare soil there was no canopy interference. Thus, any redistribution was purely lateral movement prior to infiltration and or horizontal redistribution within the soil.

When DU_{lq} of soil moisture and catch cans was compared, it was found that there was an interaction between pressure and measurement type (i.e. catch can, gravimetric, or TDR). Thus, means of testing method were compared within each pressure category (Table 2). The uniformity as determined from catch can data was consistently lower than post-irrigation soil moisture measurements. Uniformity tended to remain the same when comparing soil moisture content before and after irrigation; however, gravimetric uniformity at 69 kPa was significantly reduced after irrigation (Table 2).

Although catch can DU_{lq} is recommended as an irrigation system performance indicator, catch can DU_{lh} is recommended for scheduling. When used for scheduling, DU_{lq} has been found to unrealistically overestimate irrigation requirements (IA, 2005). DU_{lh} was calculated from DU_{lq} data according to Equation 2. Since the conversion from DU_{lq} to DU_{lh} is a linear relationship (Eq. 2), the variability explained by linear regression was not improved. However, the catch can data better represented the soil moisture uniformity for bare soil testing (Fig. 5) and tests performed on turfgrass (Fig. 6).

Residential Testing

Similar to the bare soil plot experiment, the uniformity of TDR measurements was always significantly higher than catch can measurements (Table 3). In particular, the soil moisture was very uniform regardless of decreasing uniformity due to irrigation equipment (i.e. from rotary sprinkler to spray heads) despite the fact that Baum et al. (2005) found rotary sprinklers to have significantly ($p = 0.043$) higher average DU_{lq} of 0.49 compared to 0.41 for a spray heads across a variety of brands. Redistribution on residential sites and on turfgrass plots can be attributed to canopy interception as well as surface and subsurface lateral redistribution. When catch can DU_{lq} varied between 0.30 to 0.80, soil moisture DU_{lq} varied from 0.50 to 0.80 (Fig. 5). Overall, the average IA (2005) quality rating of residential homes tested was lower than "Poor", whereas the average quality rating across all rotor and spray head testing was "Very Good" and "Poor", respectively. In contrast, the respective soil moisture uniformity rating was "Good", Very Good", and "Excellent". Thus, redistribution of applied water can increase the effective uniformity to acceptable levels.

During the residential irrigation experiment, monitoring of water use was conducted for 30 months. A reduction in turf quality was not apparent due to uniformity problems. This likely occurred due to plentiful rainfall (Haley et al., 2006). Thus, in humid region problems associated with nonuniform irrigation are also buffered by input of rainfall.

Conclusions

Although catch can measurements have been used for many years to quantify sprinkler irrigation application uniformity, it is clear that this method neglects the important process of water redistribution through the plant canopy, on the soil surface, and beneath the soil surface. The complex process of redistribution acts to effectively compensate for non-uniform application of water down to 10 cm when catch can DU_{lq} is not lower than approximately 0.45-0.50. Despite testing on a highly permeable sandy soil, soil moisture testing in the top 10 cm is more sensitive to sprinkler application variability compared to 20 cm; however, testing should be performed at the depth where water extraction will occur by crop roots. Soil moisture variability is less sensitive as depth increases and variation in application depths are dampened. Finally, soil moisture distribution uniformity approximates DU_{lh} calculated from catch can measurements.

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Table 1. Summary of catch can, time domain reflectometry (TDR) probe soil moisture content, and gravimetric (Grav.) soil moisture content uniformity.

			Distribution Uniformity (DU_{lq})						Volumetric Soil Moisture Content			
Date	Pressure (kPa)	Rep[a]	TDR Pre-Irr	Grav. Pre-Irr	TDR Post-Irr	Grav. Post-Irr	Catch Can	Catch Can Depth (mm)	TDR Pre-Irr (m^3/m^3)	Grav. Pre-Irr (m^3/m^3)	TDR Post-Irr (m^3/m^3)	Grav. Post-Irr (m^3/m^3)
23-Feb	414	1	0.74	0.80	0.64	0.83	0.72	17	0.054	0.064	0.113	0.189
5-Apr	414	2	0.79	0.87	0.80	0.86	0.70	18	0.076	0.084	0.159	0.216
5-Apr	414	3	0.89	0.88	0.77	0.82	0.61	21	0.088	0.092	0.170	0.200
10-Jun	414	4	0.71	0.79	0.68	0.80	0.58	19	0.059	0.062	0.191	0.197
8-Nov	414	5	0.72	0.83	0.83	0.85	0.56	17	0.054	0.062	0.106	0.201
9-Apr	138	1	0.84	0.89	0.81	0.88	0.64	11	0.102	0.119	0.144	0.184
9-Apr	138	2	0.91	0.91	0.81	0.85	0.53	12	0.108	0.122	0.160	0.190
13-Jun	138	3	0.71	0.79	0.79	0.84	0.56	12	0.048	0.069	0.095	0.165
27-Sep	138	4	0.84	0.82	0.77	0.78	0.54	11	0.036	0.060	0.064	0.160
27-Sep	138	5	0.77	0.88	0.78	0.78	0.49	14	0.039	0.064	0.071	0.165
13-Jun	69	1	0.84	0.85	0.77	0.69	0.37	6	0.076	0.111	0.093	0.152
3-Aug	69	2	0.83	0.82	0.71	0.66	0.33	10	0.079	0.110	0.130	0.192
3-Aug	69	3	0.69	0.71	0.67	0.70	0.39	12	0.046	0.056	0.070	0.126
18-Oct	69	4	0.74	0.84	0.81	0.71	0.37	10	0.059	0.056	0.095	0.143
18-Oct	69	5	0.82	0.83	0.82	0.69	0.49	12	0.061	0.055	0.080	0.152
Avg[b]	414		0.77a	0.83a	0.74a	0.83a	0.63a	18a	0.07a	0.07a	0.15a	0.20b
	138		0.81a	0.86a	0.79a	0.83a	0.55b	12b	0.07a	0.09a	0.11b	0.17b
	69		0.78a	0.81a	0.75a	0.69b	0.39c	10c	0.06a	0.08a	0.09b	0.15c

[a]Test replication within a pressure group.
[b]Numbers in columns followed by different letters are statistically different at the 95% confidence level by Duncan's Multiple Range Test.

Table 2. Mean distribution uniformity (DU_{lq}) of soil moisture determined from time domain reflectometry (TDR) probes, gravimetrically, and catch can measurement from bare soil plot testing at each pressure level.

	DU_{lq} by Measurement Method				
Pressure (kPa)	TDR Pre	Grav Pre	TDR Post	Grav Post	Catch Can
414	0.77AB[a]	0.83A	0.74B	0.83A	0.63C
138	0.81AB	0.86A	0.79B	0.83AB	0.55C
69	0.78A	0.81A	0.76A	0.69B	0.39C

[a]Numbers in rows followed by different letters are statistically different at the 95% confidence level by Duncan's Multiple Range Test.

Table 3. Distribution uniformity (DU_{lq}) of soil moisture determined from time domain reflectometry (TDR) probes and catch can measurement from residential testing and on plot testing on turfgrass.

	DU_{lq} by Measurement Method			
	TDR Pre-Irr	TDR Post-Irr	Catch can	Prob*
Residential	0.61	0.68	0.44	<0.0001
Rotor		0.77	0.72	0.0037
Spray		0.80	0.47	<0.0001

*Probability value from a paired t-test where $p < 0.05$ indicates a significant difference between post-irrigation TDR soil moisture DU_{lq} and catch can DU_{lq}.

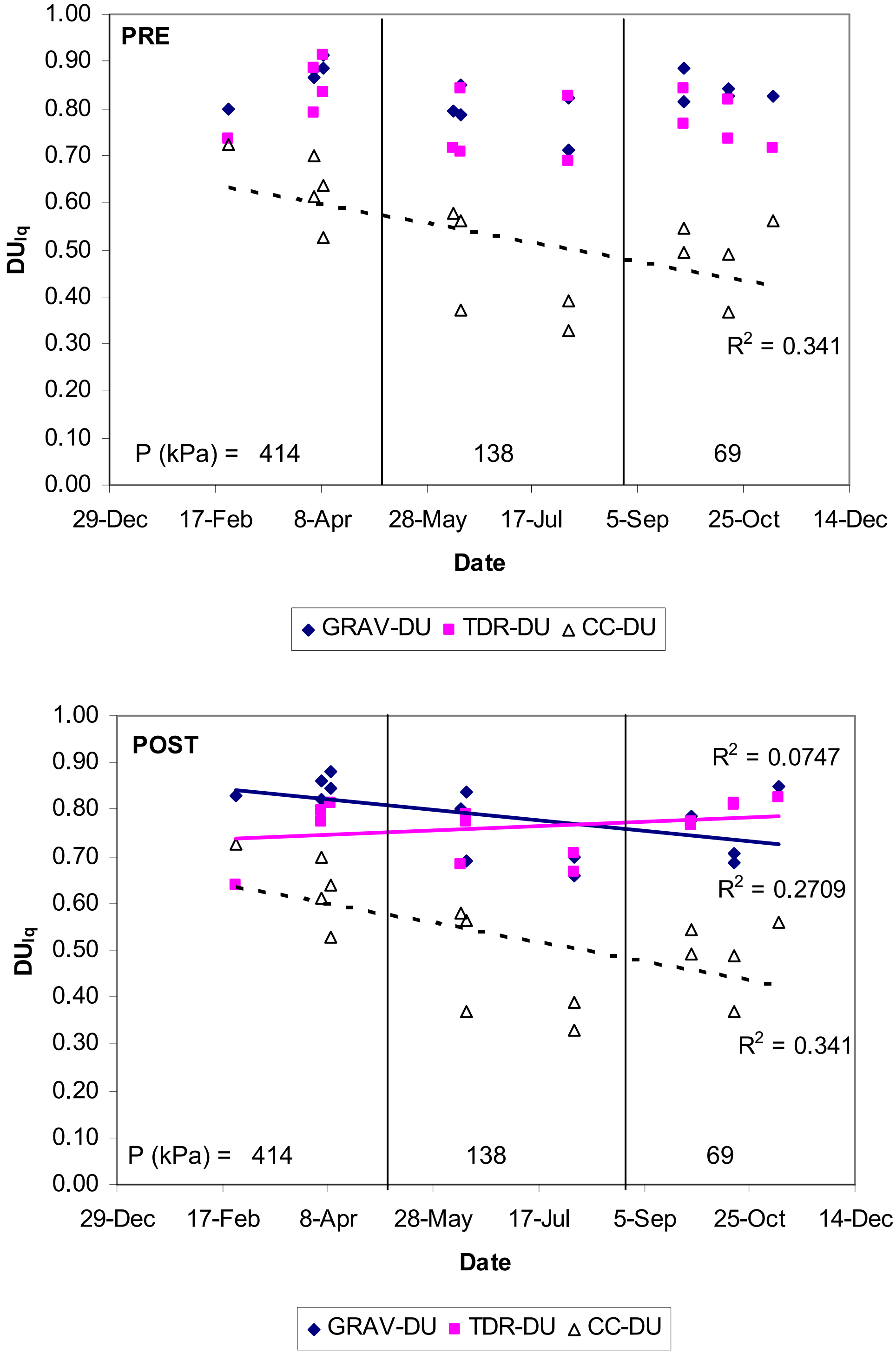

Figure 1. Gravimetric (GRAV-DU), TDR (TDR-DU) soil moisture DU_{lq} and catch can (CC-DU) DU_{lq} pre-irrigation and post-irrigation as a function of irrigation system pressure.

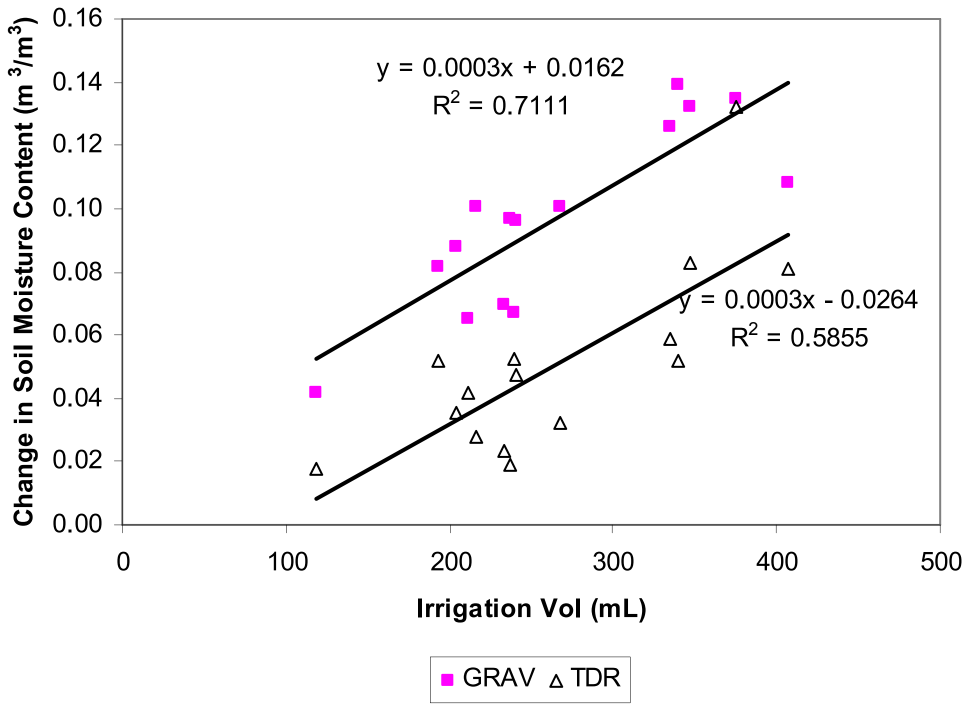

Figure 2. Change in soil moisture content as a function of irrigation volume.

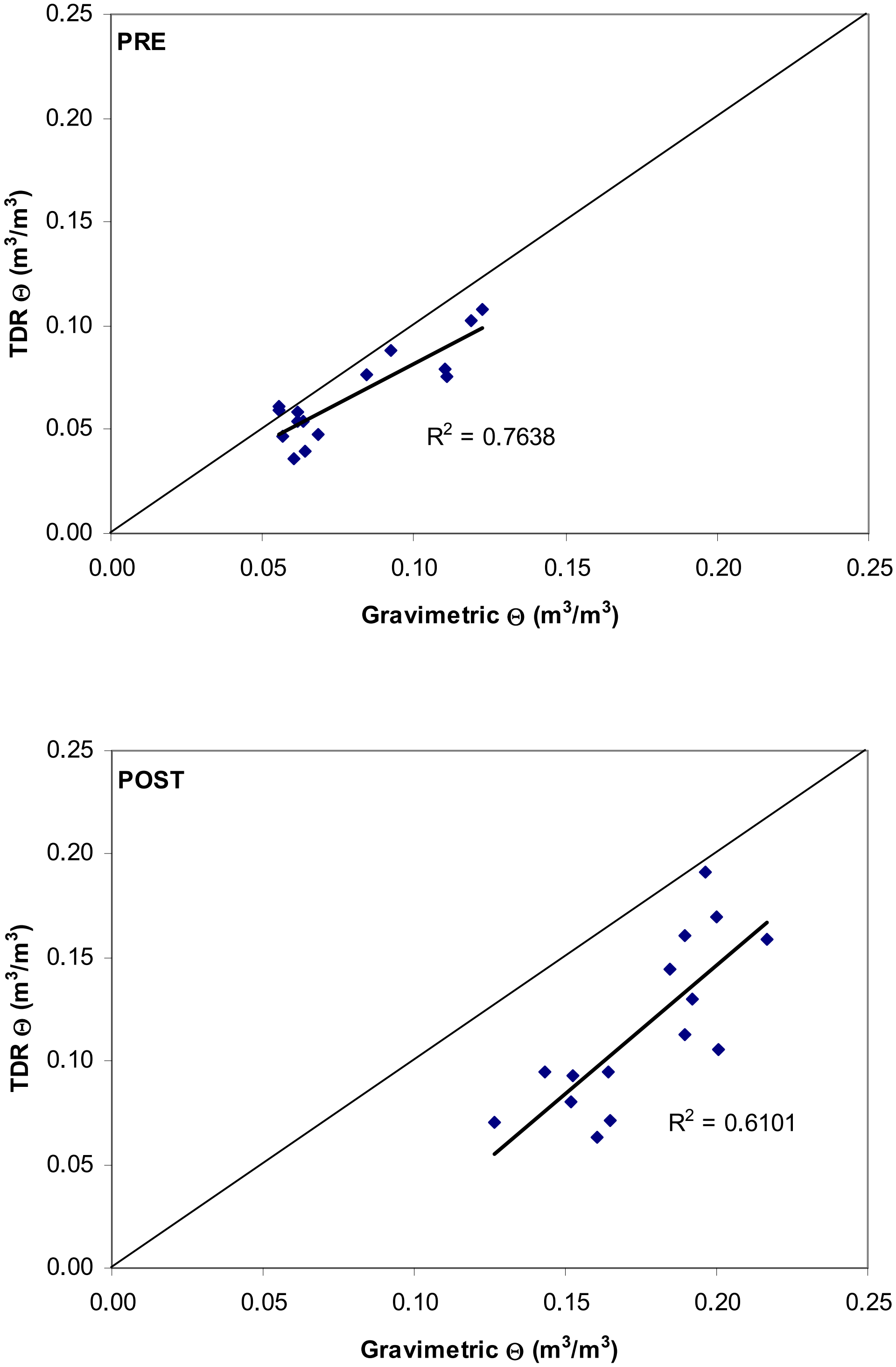

Figure. 3. Soil moisture content (Θ) as measured by time domain reflectometry probe (TDR) in the top 20 cm and gravimetric samples in the top 10 cm before (PRE) and after (POST) irrigation.

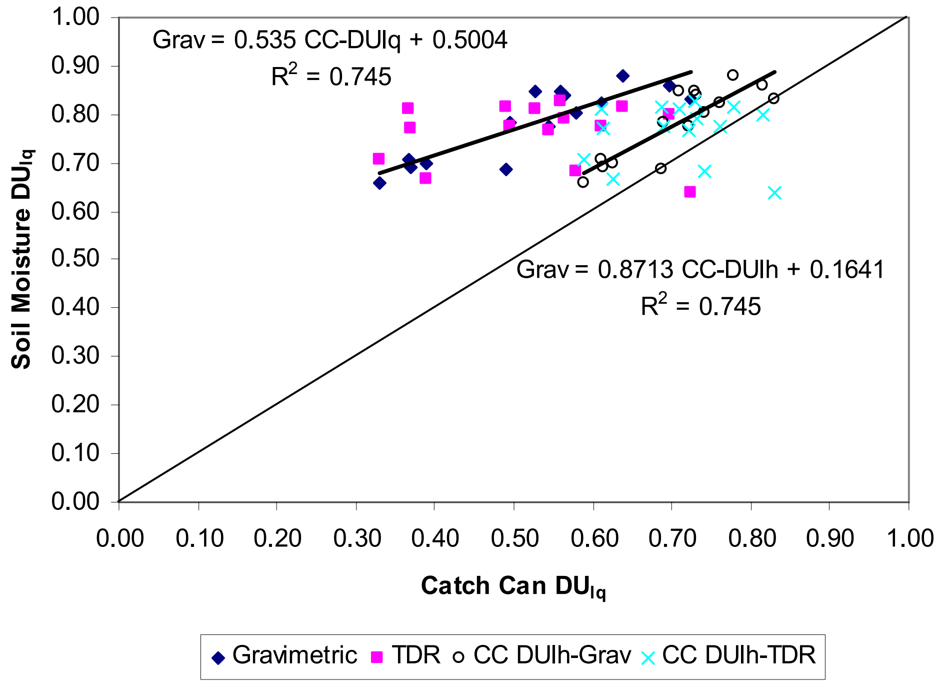

Figure 5. Soil moisture low quarter distribution uniformity as measured by time domain reflectometry probe in the upper 20 cm of soil, gravimetrically in the top 10 cm, and catch can uniformity on bare soil plot studies of spray heads. Note that linear regression is on gravimetric data only.

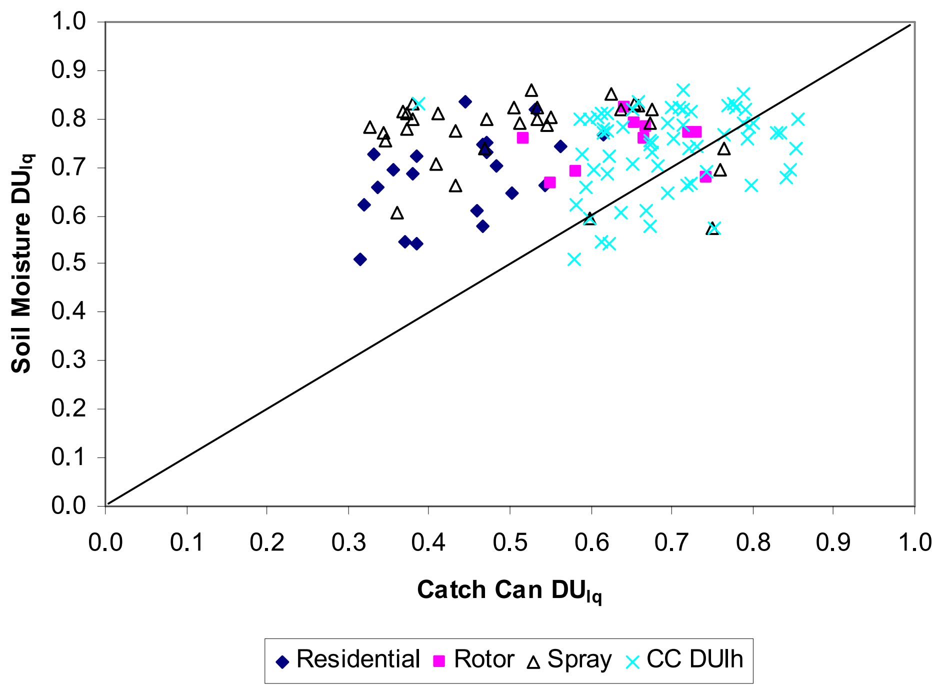

Figure 6. Soil moisture distribution uniformity (DU_{lq}) compared to catch can DU_{lq} for residential, rotary sprinkler, and spray head tests on turfgrass. Note that all soil moisture DU_{lq} data are also plotted against calculated DU_{lh}.