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SPATIAL ASSESSMENT OF SOIL MOISTURE-BASED DISTRIBUTION UNIFORMITY FOR RESIDENTIAL IRRIGATION SYSTEMS.

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RESUMEN. *El riego representa una fracción importante del uso doméstico de agua en Florida, por lo que existe un gran interés en mejorar los métodos para evaluar la eficiencia de estos sistemas de riego. En este estudio se evalúa el uso de mediciones de humedad del suelo para determinar la uniformidad de distribución (UD). Se realizaron ensayos de riego con distribuciones no uniformes inducidas, para evaluar distintas medidas de UD basadas en altura de agua e incrementos de la humedad volumétrica del suelo, determinados gravimétricamente y con TDR. Los resultados indican que la capacidad para distinguir estadísticamente distintos grados de no uniformidad es similar para las medidas de DU calculadas con altura de agua y humedad del suelo, aunque se requiere un número de observaciones suficientemente alto y múltiples mediciones por punto para reducir el error de medición en el caso del TDR.*

ABSTRACT. *Irrigation accounts for an important fraction of the total domestic water consumption in Florida. Therefore, an increasing interest exists in improving methods to evaluate the efficiency of these irrigation systems. In this study the use of soil moisture measurements to determine distribution uniformity (DU) was evaluated. Irrigation experiments were run with different induced nonuniform distributions to evaluate different measures of DU, based on irrigation water depth (ID) and volumetric soil moisture measurements, determined using the gravimetric and TDR methods. The spatial correlation structure and the persistence of ID and soil moisture patterns were analyzed. The results indicate that both, DU measures based on irrigation water depth and soil moisture, show a similar capacity to distinguish statistically different levels of nonuniformity, although a sufficiently high number of measurement points is required and multiple measurements at each point are necessary to reduce the TDR measurement error.*

1. INTRODUCTION

Irrigation accounts for 61% of the average house-hold water supply in Central Florida (Haley *et al.*, 2007). Therefore, and within a context of increasing demand for urban water resources, efficiency of residential irrigation systems has become a major issue of concern among researchers and decision makers. Since irrigation efficiency is difficult to measure, distribution uniformity (DU) can be used as a proxy for the non-management aspect of efficiency. However, the standard catch-can DU evaluation procedure is time-consuming and labor-intensive so that there is a need for more efficient DU testing methods.

Here we will evaluate the use of soil moisture measurements for DU determination, building further on an earlier study by Dukes *et al.* (2006). Distribution uniformity has received considerable attention in agricultural applications, where early modeling studies (Stern and Bresler, 1983) suggested that non-uniform irrigation distributions could affect crop yield adversely, although field experiments (Ayars *et al.*, 1990; Mateos *et al.*, 1997) showed that yields were less affected than expected. These studies showed also that spatial variability of the applied irrigation water depth (ID) is transformed and smoothed into a less variable soil moisture pattern as a consequence of water redistribution by the soil and the crop canopy.

Rather than maximizing yield, the aim of residential irrigation is the maintenance of high quality landscapes, which consists mainly in assuring optimal soil moisture conditions for plant growth. Therefore it is postulated that DU measures based on soil moisture measurements might be more useful and represent better the “real” variability of the plant-available soil moisture, than those based on the applied irrigation water depth.

The objective of this work is to evaluate the performance of three measures of distribution uniformity, using catch-can measured ID and gravimetric and TDR measured soil moisture increments, in their capacity to distinguish different levels of non-uniformity for different measurement point configurations. Persistence of the spatial patterns and their correlation structure are analyzed, and the total soil moisture variability is decomposed into ID variability and unmeasured variability.

2. MATERIALS AND METHODS

2.1. Site description, testing procedure and equipment

The test-site was located at the University of Florida campus in Gainesville, FL. The soil is classified as Arredondo fine sand (Carlisle *et al*., 1981) and consists of a well drained A horizon (0-1.2 m) with an average bulk density of 1.53 g cm^{-3} and a saturated hydraulic conductivity of 22.6 cm h^{-1} , overlaid on a moderately permeable B horizon with a loamy sand to sandy clay loam texture, a bulk density of 1.64 g cm^{-3}, and a saturated hydraulic conductivity of 5.9 cm h^{-1}.

Tests were performed using the catch-can method according to the ASABE standards (ASAE, 2001). Twenty-five catch-cans were placed in a uniformly spaced 0.9 m grid within a 4.6 × 4.6 m distribution area, with spray heads (Prospray, Hunter Industries, Inc; 15QC1 MPR nozzles, Rain Bird, Inc., Glendora, CA) located at the corners (see Fig. 1). The intercepted volume was measured after 30 min of irrigation, which, according to the manufacturer’s specifications, yields irrigation depths of 20, 13, and 11 mm at supply pressures of 414, 138, and 69 kPa, respectively.

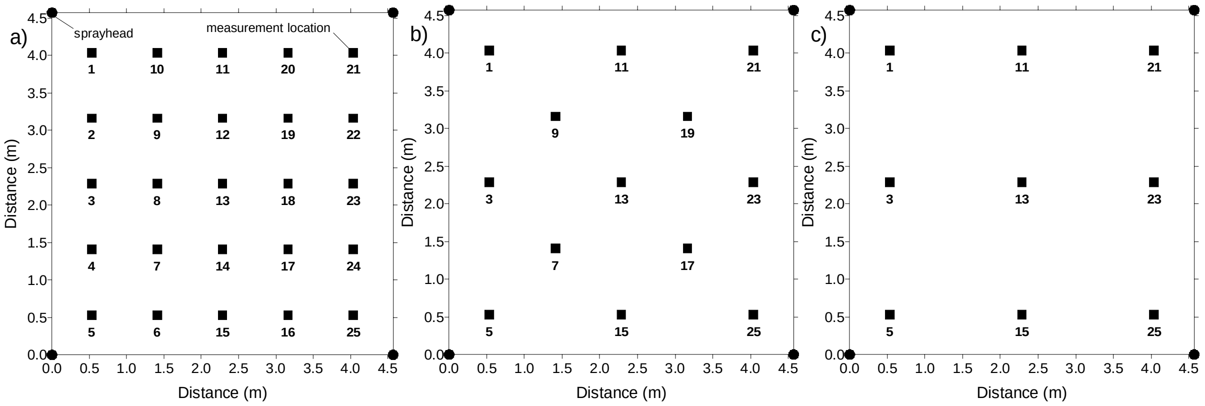

Figure 1. Disposition of the four spray heads and the 25 measurement points at the test-site (a) and alternative measurement configurations with 13 (b) and 9 (c) measurement points.

Catch-can dimensions were within the specifications of the ASABE standard. Before and after executing the tests, TDR readings (FieldScout TDR 300 Soil Moisture Meter, Spectrum Tecnologies, Inc., IL) were made with rods of .20 m, and gravimetric samples (10.4 cm length, 5.7 cm diameter) were collected using a bulk-density core sampler. Samples were weighted and oven-dried at 105ºC during 36 hours. A total of fifteen test runs, applying pressures of 69, 138 and 414 kPa, were executed between February 23 and November 8, 2005.

2.2. Methods for calculating distribution uniformity

Two common methods for calculating uniformity from catch-can measured irrigation depths are the lower quarter distribution uniformity, DU_{lq}, (Merriam and Keller, 1978) and Christiansen's coefficient of uniformity, CU, (Christiansen, 1942). The DU_{lq} is calculated as the ratio of the mean of the lower quarter of the distribution and the mean irrigation depth:

$$DU_{lq} = 4\sum_{i=1}^{n_{lq}} x_i \Big/ \sum_{i=1}^{n} x_i = m_{lq}/m\,, \tag{1}$$

where the irrigation depths, x_i, are ranked in ascending order, n_{lq} is the rank of the lower quartile, and n is the number of observations. The CU is calculated as one minus the average of the absolute deviation from the mean depth divided by the mean depth (ASABE, 2000):

$$CU = 1 - \left(\sum_{i=1}^{n} \left| x_i - m \right| \Big/ \sum_{i=1}^{n} x_i \right), \tag{2}$$

where m is the mean irrigation depth. A third measure for DU used in this study is the complement of the coefficient of variation (Wilcox and Swailes, 1947), 1-CV. All three equations were used with ID and gravimetric and TDR measured soil moisture increments, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$ respectively.

2.3. Persistence of spatial patterns

The persistence of the spatial patterns of ID, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$ for the five test-runs at each supply pressure was evaluated using the method proposed by Vachaud et al. (1985). For each test-run, j, the observations, $x(u_{ij})$, with location u_i and i=1,…,25, were scaled by subtracting and dividing by the spatial mean, m_j, to obtain the relative difference, $\delta\left(u_{ij}\right)$:

$$\delta\left(u_{ij}\right) = \left(x\left(u_{ij}\right) - m_j \right) \Big/ m_j\ . \tag{3}$$

The mean (MRD) and standard error of $\delta\left(u_{ij}\right)$ were calculated for each point, using data from the 5 test-runs at each supply pressure and mapped.

2.3. Geostatistical analysis and sources of variability

Since there were too few observations available for each test-run to infer individual variograms, an approach similar to the one proposed by Sterk and Stein (1997) was adopted to calculate stratified variograms. Assuming persistence of the spatial patterns, the same spatial correlation structures can be considered for the five test-runs at each supply pressure, for ID, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$. First, data from each test-run were standardized according to:

$$s\left(u_{ij}\right) = \left(x\left(u_{ij}\right) - m_j \right) \Big/ \sigma_j\ , \tag{4}$$

where σ_j is the standard deviation of test-run j. Pooled sample auto-variograms were computed for each supply pressure from the merged standardized dataset using the traditional equation (Goovaerts, 1997), pairing indistinctively data from the same and different test-runs. In order to control for the effect of combining data from different test-runs, also the stratified sample auto-variogram was computed from the standardized data using the following expression:

$$\gamma_{\alpha\alpha}^{s}(h) = \frac{1}{2N_s(h)} \sum_{j=1}^{5} \sum_{i=1}^{n_j(h)} \left[s(u_{ij}) - s(u_{ij}+h) \right]^2\ , \tag{5}$$

where $N_s\left(h\right)=\sum_{j=1}^{5} n_j(h)$ is the total number of data pairs separated by a distance *h*, and $n_j\left(h\right)$ is the number of data pairs belonging to the *j*th test-run, separated by a distance *h.* Using Eq. (5) only data values from the same test-run are paired and possible inhomogeneities of the merged standardized dataset do not affect the results. To analyze the joint spatial variation between the variables also pooled sample cross-variograms (Goovaerts, 1997) were calculated from the merged standardized datasets.

Stern and Bresler (1983) determined how much of the variability in $\Delta\theta$ (i.e., $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$) can be explained by the nonuniformity in ID, considering both as random variables and assuming a linear relationship, $\Delta\theta = a\ ID + b$, for which $\sigma^2_{\Delta\theta} = a^2\sigma^2_{ID} + \sigma^2_b$, and where *a* is a deterministic constant and *b* represents all other unmeasured crop and soil factors. *b* can be considered to represent also measurement errors and procedural effects arising from short-range variability in ID and $\Delta\theta$. Introducing the correlation coefficient between $\Delta\theta$ and ID, $r_{\Delta\theta\times ID}$, this equation can be rewritten as $\sigma^2_b = \sigma^2_{\Delta\theta}\left(1-r^2_{\Delta\theta\times ID}\right)$, showing that the variability of the unmeasured factors represents $\left(1-r^2_{\Delta\theta\times ID}\right)$ of the variance of $\Delta\theta$, and $a=\sigma_{\Delta\theta}\ r_{\Delta\theta\times ID}/\sigma_{ID}$.

The capacity of the different distribution uniformity measures and measurement point configurations to distinguish different nonuniformities will be evaluated in terms of the least significant difference, LSD, and the ratio between the LSD and the range of DU values.

3. RESULTS AND DISCUSSION

3.1. Test-run results

Manufacturer reported and mean observed irrigation depths (ID) were statistically the same (α=.05) at the different supply pressures. Observed individual test-run ID ranged from 6.7 to 23.0 mm, with a decreasing CV for increasing supply pressures (Table 1). Similarly, gravimetric and TDR measured soil moisture increments, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$, respectively, showed a decreasing CV with increasing supply pressure.

Table 1. Mean and CV (between parenthesis) of irrigation depth, ID, and gravimetric and TDR measured initial and final soil moisture contents, θ_i and θ_f, respectively, and soil moisture increments, $\Delta\theta$, for the different test-runs.

	Test-run number	gravimetric			TDR			ID
		θ_i	θ_f	$\Delta\theta$	θ_i	θ_f	$\Delta\theta$	
		cm^3 cm^{-3} (%)						mm
69 kPa	1	.111 (13)	.152 (28)	.052 (70)	.076 (14)	.093 (19)	.020 (74)	6.7 (53)
	2	.056 (26)	.129 (25)	.077 (46)	.046 (32)	.070 (27)	.027 (78)	8.5 (46)
	3	.055 (15)	.154 (23)	.099 (38)	.061 (15)	.080 (18)	.022 (64)	13.4 (39)
	4	.110 (14)	.195 (24)	.089 (38)	.079 (15)	.130 (26)	.054 (57)	10.9 (49)
	5	.050 (13)	.143 (25)	.090 (42)	.057 (26)	.094 (17)	.036 (47)	11.6 (53)
	Mean	.078 (16)	.155 (25)	.081 (47)	.064 (20)	.093 (22)	.032 (64)	10.2 (48)
138 kPa	1	.119 (10)	.186 (11)	.068 (27)	.102 (14)	.144 (16)	.042 (52)	11.9 (28)
	2	.060 (13)	.160 (17)	.100 (27)	.036 (18)	.064 (21)	.030 (45)	12.2 (32)
	3	.122 (9)	.191 (11)	.069 (33)	.108 (7)	.160 (17)	.053 (56)	13.6 (36)
	4	.068 (16)	.166 (14)	.098 (30)	.048 (27)	.095 (22)	.048 (50)	13.6 (32)
	5	.064 (11)	.165 (23)	.104 (39)	.038 (21)	.069 (27)	.034 (56)	15.2 (37)
	Mean	.087 (12)	.174 (15)	.088 (31)	.066 (18)	.106 (21)	.041 (52)	13.3 (33)
414 kPa	1	.064 (23)	.189 (19)	.125 (26)	.054 (26)	.113 (31)	.066 (50)	19.0 (20)
	2	.084 (10)	.219 (12)	.134 (21)	.076 (17)	.159 (18)	.083 (36)	19.6 (22)
	3	.062 (23)	.201 (13)	.139 (22)	.054 (31)	.106 (15)	.052 (33)	19.3 (32)
	4	.092 (10)	.202 (14)	.110 (27)	.088 (12)	.170 (18)	.081 (41)	23.0 (29)
	5	.060 (21)	.197 (17)	.138 (23)	.058 (22)	.187 (25)	.132 (36)	21.3 (31)
	Mean	.072 (17)	.201 (15)	.129 (24)	.066 (22)	.147 (21)	.083 (39)	20.4 (27)

The CV of gravimetric and TDR measured θ_f (after irrigation) did not follow this behaviour, indicating that the direct use of this measure for evaluating distribution uniformity seems less suited. Overall mean $\Delta\theta_{TDR}$ were on average 40, 47, and 64% smaller than $\Delta\theta_{grav}$ for the 69, 138, and 414 kPa supply pressures, respectively, which could be attributed at least in part to different measurement depths and non-uniform wetting of the sampled soil depth. This is probably also the reason why the TDR measured soil moisture increments yielded the highest overall CVs, while those for irrigation depth and $\Delta\theta_{grav}$ were almost identical. It points towards the importance of generating non-uniform distributions with the same volume of applied water(by adjusting the irrigation time) and using similar exploration depths for the gravimetric and TDR measurements. The ratio of the CVs of $\Delta\theta$ (infiltrated water) and ID were higher than expected. Stern and Bresler (1983) found ratios of .42 and .29 for a loamy sand and a sandy clay loam soil, respectively. Mateos et al. (1997) obtained ratios ranging from 0.23 to 0.45 in a loam soil. The infiltrated water is redistributed in the superficial soil horizon as a function of the initial moisture content and the soil hydraulic properties at each point. This process transforms the ID spatial pattern into a spatially less variable $\Delta\theta$ pattern. Since water flow in sandy soils is predominantly vertical, higher CV ratios can be expected in this case.

3.2. Persistence of patterns

The spatial patterns observed for ID, $\Delta\theta_{grav}$, and $\Delta\theta_{TDR}$ during the different test-runs became more persistent as the supply pressure (and the applied water depth and its uniformity) increased, as can be seen from the corresponding standard deviation maps shown in figure 2. Similarity between the patterns of ID, $\Delta\theta_{grav}$, and $\Delta\theta_{TDR}$ was lost as the supply pressure decreased. Persistence of ID patterns was highest, intermediate for $\Delta\theta_{grav}$, and lowest for $\Delta\theta_{TDR}$. The observed pattern corresponds as expected with the combined circular pattern of the four spray heads, resulting in values lower than the plot average at the four corners, nearby the spray heads, and in the center of the plot, especially at the smallest supply pressure. This may offer opportunities for reducing the number of measurement points. The observed persistence in figure 2 indicates that the same spatial correlation structure can be assumed for the different test-runs at a single supply pressure.

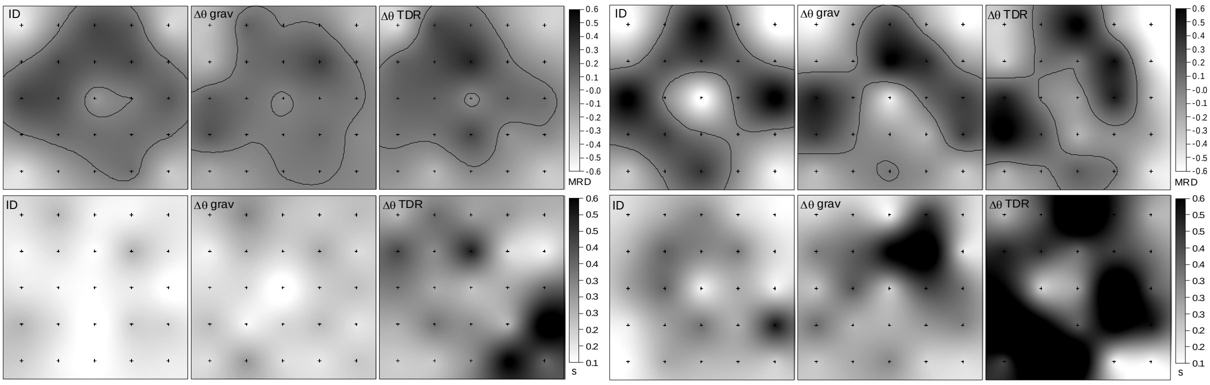

Figure 2. Mean relative difference (MRD) and corresponding standard deviation (s) maps for irrigation depth, ID, and gravimetric and TDR measured soil moisture increments, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$, respectively, for test-runs at 414 (left) and 69 kPa (right). Contour MRD = 0.

3.3. (Geo)statistical relationships between ID, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$

The correlation between ID, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$ varied strongly between test-runs and supply pressures, but was significant (α=.01) for all cases when considering the mean of the five test-runs (see 1-r^2 in Table 2). In general, correlation increased with decreasing supply pressure and associated nonuniformity. The lowest correlations were observed between $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$, ranging from .56 (414 kPa) to .68 (69 kPa), most likely due to differing sampling depths and volumes, larger experimental errors of TDR measurements, and slightly differing sampling locations nearby the catch-cans. $\Delta\theta_{grav}$ was best correlated with ID, with correlation coefficients ranging from .72 (414 kPa) to .85 (69 kPa).

Pooled and stratified sample variograms (not shown) were very similar, indicating that pairing observations of different test-runs did not affect the variogram calculation, with a range of approximately 2 m for all three variables. Table 2 shows that the nugget variance (c_0), a measure of the variability that can not be explained by the geostatistical model (i.e. microscale variability not captured by the sampling design and measurement or procedural errors), was smallest for ID (.27-.37) and represented more than half the total variance of $\Delta\theta_{grav}$ (.55-.74) and $\Delta\theta_{TDR}$ (.53-.83). The procedural errors of the three variables can be considered independent, so that the nugget variance of the sample cross-variograms derived only from unexplained microscale variance. Table 2 shows that the sample cross-variograms had a much smaller nugget, indicating that there existed little correlation between increments at the microscale, so that the large nugget variances of $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$ can be attributed mainly to measurement and procedural errors.

Table 2. (Geo)statistical parameters explaining the relationships and the proportion of the variability of $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$ explained by ID and non-measured factors, including procedural errors (see text for explanation of symbols).

	414 kPa			138 kPa			69 kPa		
	ID	$\Delta\theta_{grav}$	$\Delta\theta_{TDR}$	ID	$\Delta\theta_{grav}$	$\Delta\theta_{TDR}$	ID	$\Delta\theta_{grav}$	$\Delta\theta_{TDR}$
m	20.4	.129	.083	13.3	.088	.041	10.2	.081	.032
σ^2	30.3	9.6×10^{-4}	10.5×10^{-4}	19.3	7.4×10^{-4}	4.5×10^{-4}	24.0	14.5×10^{-4}	4.2×10^{-4}
c_0	.27	.71	.83	.37	.74	.53	.32	.55	.79
	ID×$\Delta\theta_{grav}$	ID×$\Delta\theta_{TDR}$	$\Delta\theta_{grav}$×$\Delta\theta_{TDR}$	ID×$\Delta\theta_{grav}$	ID×$\Delta\theta_{TDR}$	$\Delta\theta_{grav}$×$\Delta\theta_{TDR}$	ID×$\Delta\theta_{grav}$	ID×$\Delta\theta_{TDR}$	$\Delta\theta_{grav}$×$\Delta\theta_{TDR}$
$1-r^2$	.48	.52	.69	.36	.45	.66	.28	.48	.54
a	.0029	.0027	.53	.0039	.0033	.54	.0054	.0022	.32
b	.069	.028	.039	.037	-.003	.019	.026	.011	.022
b/m	.54	.34	.47	.42	-.08	.46	.32	.31	.68
c_0	.17	.10	.15	.21	.12	.17	.11	.27	.04

To determine how much of the variability in $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$ can be explained by the nonuniformity in ID, the parameters of the linear relationship proposed by Stern and Bresler (1983) were calculated and are shown in Table 2. Other non measured sources of variability than ID accounted for 28-48 % and 45-56 % of the variance of $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$, respectively, while other sources of variability than $\Delta\theta_{grav}$ represented 53-69% of the variance of $\Delta\theta_{TDR}$. In general, the proportion of the mean and the variability of $\Delta\theta_{grav}$, explained by ID increased as the pressure decreased and the induced nonuniformity increased. The “backgroud noise” in the $\Delta\theta_{grav}$ measurements, due to soil moisture redistribution and procedural errors, could make it difficult to detect small irrigation nonuniformities (i.e., at 441 kPa), but becomes proportionally less important as the irrigation nonuniformity increases. These results seem to support the use of soil moisture measurements for evaluating DU. However, sensor measurements should be handled with care, since the $\Delta\theta_{TDR}$ measurements accounted for only 33-53% of the mean and 31-47 % of the variance of the $\Delta\theta_{grav}$ measurements, but with an increasing proportion of the variance explained as the nonuniformity increased. This unexplained variability could be reduced by repeating several sensor measurements at each point and by producing nonuniform irrigation distributions with the same volumes of applied water (by adjusting irrigation times), so that variability arising from different soil wetting depths, as compared to the sensor explored soil depth, can be eliminated.

3.4. Distribution uniformity

As expected, the DU increased with increasing supply pressure (Fig. 3). The highest uniformity was observed for $\Delta\theta_{grav}$, followed by ID, as consequence of the moisture redistribution in the soil. Due to the large variability in the TDR measurements $\Delta\theta_{TDR}$ uniformity was lower than the ID uniformity. The DU_{lq} measure provided the lowest values and the CU the highest. Variability between the 5 test-runs increased as the supply pressure decreased. Note that DU measures based on statistical dispersion, such as CU or 1-CV, provide nearly identical values for ID and $\Delta\theta_{grav}$. Despite the noisy nature of the $\Delta\theta_{TDR}$ data, it can be seen in figure 3 that they provide proportionally larger differences between the 138 and 414 kPa nonuniformities as compared to ID or $\Delta\theta_{grav}$, for al three DU measures. These results seem to support the use of DU measures based on soil moisture measurements.

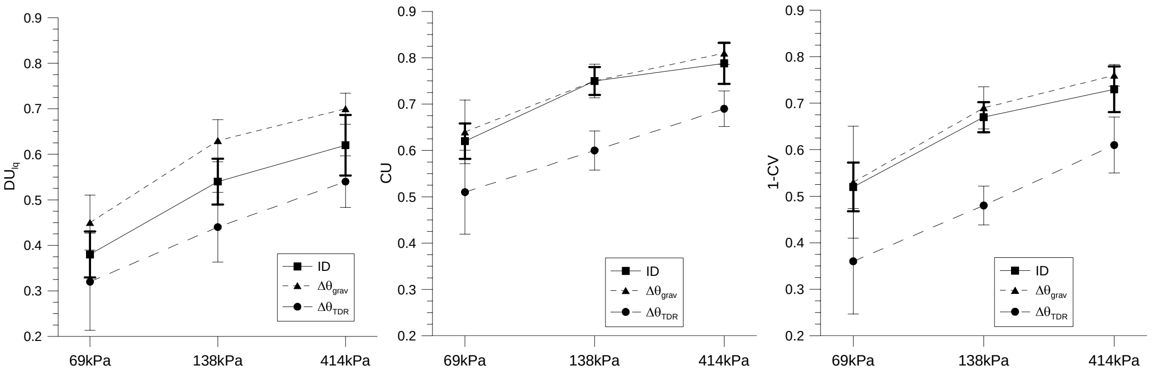

Figure 3. Mean distribution uniformity at different supply pressures as expressed by the lower quarter distribution uniformity, DU_{lq}, the Christiansen´s uniformity coefficient, CU, and the complement of the coefficient of variation, 1-CV, calculated from irrigation depth, ID, and gravimetric and TDR measured soil moisture increments, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$, respectively, for 25 point grid. Error bars represent the 90% CI.

3.5. Capacity to distinguish nonuniformities

Uniformity measures based on catch-can ID had on average the lowest LSD and LSD/range, with CU and 1-CV performing best in general. Reducing the number of measurement points form 25 to 9 caused only a modest increment of the LSD, which was annulated when compared to the range of DU values. All three measures, calculated from grids of 25, 13 and 9 points, produced significant (α=.05) differences between uniformity values for the 414 and 69 kPa, as well as for the 138 and 69 kPa test-runs. The 414 and 138 kPa test-run uniformity measures showed only significant differences for the 9-point DU_{lq} and 1-CV. As a result, the ID-based DU evaluation procedure can be simplified using 9 in turn of 25 catch-cans, without any loss of performance, at least for the conditions of this experiment.

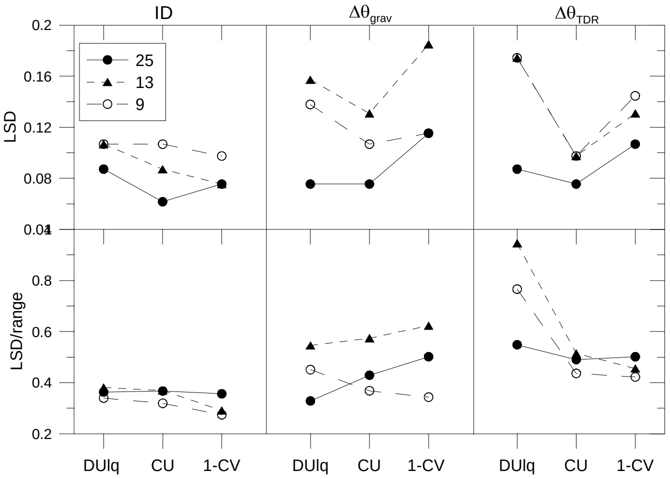

Figure 4. Least significant difference, LSD, and the ratio between LSD and the range of the uniformity values, for irrigation depth, ID, and gravimetric and TDR measured soil moisture increments, $\Delta\theta_{grav}$ and $\Delta\theta_{TDR}$, respectively, for grids of 25, 13 and 9 points (see Fig. 1).

This holds also for the $\Delta\theta_{grav}$-based uniformity measures, although they showed larger LSD and LSD/range values, especially for the 13-point measurement configuration, indicating that the results are not only affected by the number of measurement points, but also by their position within the test area.

The DU measures based on $\Delta\theta_{TDR}$ showed the highest LSD and LSD/range values, especially for DU_{lq} determined from the 13- and 9-point measurement configurations, as a result of instability in the DU_{lq} calculations due to its sensitivity to outliers and to the small number of values available to calculate the lower quarter mean. However, differences between the 414 and 69 kPa and 414 and 138 kPa test-runs were still significant for all three measurement configurations, except for the 9-point DU_{lq}. None of the $\Delta\theta_{TDR}$–based measures were significantly different for the 138 and 69 kPa test-runs. In this case, reducing the number of measurements becomes risky, especially when using DU_{lq}, due to its sensitivity to outliers ($\Delta\theta_{TDR} = 0$ in this case). The different results for the $\Delta\theta_{TDR}$–based measures are mainly caused by the large proportion of non ID-related variability in the data, due to a combination of higher measurement errors of the used TDR probe and a higher proportion of non-wetted soil in the total explored soil depth by this sensor, as compared to the gravimetric measurements. It is expected that increasing the number of measurements at each point and adjusting the applied water depth to the depth of exploration by the sensor could improve the performance of this DU evaluation method.

5. CONCLUSIONS

The results of this experiment indicate that reducing the number of measurement points from 25 to 9 did not affect the performance of the ID-based DU measures. A 60% reduction of the number of catch-cans is expected to reduce proportionally the required labor and time to execute the test-runs. The performance of the gravimetric soil moisture-based uniformity measures was similar to those based on ID at the different measurement configurations. Also in this case a significant reduction of the number of measurement points can be envisioned, which is expected to reduce the associated field and laboratory effort drastically. DU measures, based on TDR measured soil moisture, only achieved the performance of those for ID and $\Delta\theta_{grav}$ when comparing the most extreme induced nonhomogeneities (38 vs. 414 kPa). When reducing the number of measurement points, special care should be taken with outliers and the use of DU_{lq} should be avoided. The performance of sensed soil moisture-based DU evaluation methods can be improved by repeating several measurements at each point. For future experimental work it is recommended to generate the different nonuniform distributions for equal volumes of applied water by adjusting the irrigation time. In this way the opportunity for soil wetting and wetted depth become independent of (non)uniformity, so that the effect of uneven wetting of the sensor-explored depth interval disappears.

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