USE OF MULTISENSOR CAPACITANCE PROBES AS IRRIGATION MANAGEMENT TOOL IN HUMID AREAS: CASE STUDIES AND EXPERIMENTS FROM THE MID-ATLANTIC REGION

I. R. McCann, J. L. Starr

ABSTRACT. Multisensor capacitance probes (MCPs) were used to provide valuable and detailed information on soil water dynamics under irrigated farm management in Delaware. Near-continuous real-time soil water content and dynamics were measured at five soil depths within the rootzone of: 1) farmer-managed drip and sprinkler irrigation of several crops in 2002 and 2003; and 2) researcher-managed drip-irrigated watermelons (L. Citrullus lanatus) under irrigation rates of 50%, 100%, and 150% (low, medium, and high) relative to ET₀ in 2004 and 2005. The objectives were to assess how these probes might be used to improve irrigation management and to examine the dynamics of soil water under humid conditions and typical grower management. The farmer-managed irrigations generally had a primary active rooting depth of 35 cm, but irrigation water was commonly observed to percolate to 100-cm depth. The high irrigation rate in the researcher-managed trials (more typical of farmer management) resulted in 29% of the irrigations causing water percolation to 70 cm, which was about six times the rate under medium irrigation. The yield of watermelon was not significantly affected by the wide range in irrigation amount, indicating that growers could reduce irrigation in humid conditions without impacting yield or quality. The use of MCPs would enable accurate monitoring of soil water trends and, in combination with weather forecasts, provide confidence that reducing typical irrigation amounts should not result in crop water stress or decreased yield.

Keywords. Irrigation, Soil water content, Capacitance, Sensor, Drip, Sprinkler.

Irrigation management in humid areas is more complex than in arid areas because of the high variability and the unpredictability of the within-season rainfall. In common with other humid regions in the United States, the total irrigated area in the Mid-Atlantic region has been steadily increasing. In 2002, the irrigated area in the region totaled 258,000 ha (2002 Census of Agriculture), a 42% increase in 10 years (fig. 1). This increase has been driven by the need to irrigate during periods of insufficient rainfall in order to stabilize yields and maintain profitability. However, the combination of high value crops, sandy soils, and intermittent and variable rainfall in this region makes irrigation management a challenging task for producers.

The irrigation systems used in the Mid-Atlantic region are predominantly sprinkler (primarily center pivot) or drip (commonly drip tape under plastic mulch). Although such irrigation systems can be efficient in terms of water delivery to the root zone, they still require good irrigation scheduling to reach their potential for optimizing water and nutrient uptake. In some years rainfall is sufficient to meet or exceed all crop water requirements, and so irrigation is not essentially needed. In other years, however, crop water requirements may be high and rainfall insufficient to make much or even any contribution towards meeting crop water requirements.

Figure 2 shows monthly reference evapotranspiration (ET₀) estimated from daily weather data using the Penman-Monteith method, together with rainfall distributions in Georgetown, Delaware, during the summer months from May to August for the seven years from 1999 to 2005. It can be seen that there is high variability, particularly in rainfall patterns, between individual months in the same year, and between years. In particular, 2002 was a year with high ET₀ and low rainfall and therefore significant irrigation was

Figure 1. Land under irrigation in the Mid-Atlantic states of Delaware, Maryland, North Carolina, South Carolina, and Virginia, from national agricultural census data.
required, while 2003 had low $ET_0$ with a relatively high rainfall and typically no irrigation was required. Long-term monthly rainfall averages from May to August are 93, 89, 101, and 133 mm, respectively, with an annual total of 1117 mm. Average monthly maximum air temperatures from May to August are 23.3°C, 27.8°C, 30.6°C, and 29.4°C, respectively, while the corresponding minimum air temperatures are 11.1°C, 15.6°C, 18.9°C, and 17.8°C, respectively.

While drip irrigation can be more efficient than sprinkler irrigation, drip irrigation management for plastic mulched crops is more complex because: i) the water source is essentially a line of point sources rather than being relatively spatially uniform; ii) evaporation is suppressed under the plastic mulch; iii) rainwater is excluded by the plastic mulch (except through the planting holes and any other holes and tears that develop) and consequently runs off the raised bed; iv) variable amounts of this runoff water may infiltrate at the edge of the bed and become available for plant growth; and v) the canopy can have a different areal extent than the root zone. These complexities and the fact that the water is essentially “unseen” make drip irrigation more difficult for growers to manage. Regardless of the irrigation method, without good quantitative information on soil water content and guidelines on irrigation scheduling, there is a tendency for irrigators to apply excess water in order to minimize the risk of under-irrigation. Any excess water that drains below the root zone around the sensors, requiring that care be taken during installation to minimize this potential source of error. The water that is measured increases the influence of air gaps around its PVC access pipe. The relatively small volume of soil that is measured increases the influence of air gaps around the sensors, requiring that care be taken during installation to minimize this potential source of error. The water content measured by each sensor may be expressed as either a volumetric percentage or a depth of water in 10 cm of soil and the scaled frequency, as given in equation 1:

$$\theta_v = 0.490 \text{SF}^{2.1674}$$

($r^2 = 0.992$ for $n = 15$; RMSE = 0.009 cm$^3$ cm$^{-3}$ ) (1)

where $\theta_v$ is volumetric soil water content (cm$^3$ cm$^{-3}$); and SF is the scaled frequency, defined as:

$$\text{SF} = (F_a - F_v)/(F_a - F_w)$$

(2)

where $F_a$, $F_v$, and $F_w$ are the capacitance sensor frequencies in air, soil and non-saline water, respectively.

This calibration result was shown to be qualitatively similar over a wide range of soil textures. Each sensor’s zone of primary influence represents a soil cylinder approximately 10 cm along the axis of the probe, with a 10-cm diameter ring around its PVC access pipe. The relatively small volume of soil that is measured increases the influence of air gaps around the sensors, requiring that care be taken during installation to minimize this potential source of error. The water content measured by each sensor may be expressed as either a volumetric percentage or a depth of water in 10 cm of soil (mm/10 cm). Although these probes and soil water management system are widely used as an irrigation management tool, published research on such use is quite limited.

The objectives of this research were:

- to assess the use of MCPs as a tool to improve irrigation management,
- to identify potential irrigation management improvements and guidelines by monitoring soil water content and dynamics under 1) grower-managed sprinkler and drip irrigations, and 2) researcher-managed drip irrigations.

The hypothesis being tested is that the soil water content and dynamics obtained with MCPs provide valuable information to both the grower and research communities in managing irrigation in humid areas.
EXPERIMENTAL PROCEDURES

Soil water content within the rootzone was monitored in 2002 and 2003 on-farm at sites with grower management, and in 2004 and 2005 under controlled research conditions at an experiment station using a randomized complete block design. In all cases, MCPs were used to make near-continuous real-time soil water measurements.


Several irrigated fields were made available by farmers for these studies in 2002 and 2003. These fields were instrumented with MCPs to monitor water dynamics in the soil profile in response to farmer-managed irrigation practices. Soil textures observed during probe installation at these field sites were dominated by sand, as is typical of the irrigated lands in the region. Over this two-year period, three fields were irrigated by center pivot, including two fields of corn (L. Zea mays) and a double-cropped field of sweet corn followed by soybeans (L. Glycine max); and five fields were drip-irrigated, including four fields of watermelon (L. Citrullus lanatus) and one field of green pepper (L. Piper nigrum). The drip-irrigated fields were grown on raised beds under plastic mulch (Lamont, 2005). Four MCPs were randomly placed in each field.

In the center-pivot fields the MCPs were installed after corn emergence and placed in the crop row between two corn plants. In the drip-irrigated watermelon fields the MCPs were placed in the crop row approximately 15 cm from a melon plant and 5 cm from the drip tape. The green pepper field was grown in double-rows with the drip tape placed in the center of the bed. The MCPs were positioned between two pepper plants and offset approximately 5 cm from the planting row toward the drip tape.

The distribution of the four MCPs in each field varied with the crop and field size, with distances from 70 to 300 m between the data logger and the last (fourth) probe. Five soil water capacitance sensors were positioned on each of the four probes at depths of 10, 20, 40, 70, and 100 cm in 2002; and at depths of 10, 20, 30, 50, and 100 cm in 2003. The 2003 sensor arrangement enabled a better assessment of the active rooting depth for these soils. We used the manufacturer’s default calibration equation because our laboratory calibrations (unpublished data for sandy soils) were highly correlated ($R^2 = 0.99$) with the default equation.


Replicated studies on drip-irrigated seedless watermelon, grown under plastic mulch, were conducted at the University of Delaware Research and Education Center near Georgetown, Delaware (38.38 N, 75.32 W; www.rec.udel.edu). Four replications of three irrigation treatments were established, consisting of three relative irrigation rates with ratios of 1:2:3, corresponding to low, medium, and high irrigation amounts, respectively. The medium irrigation rate was designed to approximately meet ET demand. Thus the three rates roughly correspond to 50%, 100%, and 150% of estimated ET. Anecdotal observations suggest that typical grower irrigation may be at least as much as the 150% treatment. The three rates were imposed by varying the run time of the drip tape so that, for example, if it was determined that an irrigation of two hours duration was needed to meet ET (the 100% treatment), the 50% and 150% treatments received water for 1 and 3 h, respectively. While the run time for the 100% treatment varied during the season, the 50% and 150% ratios were always maintained except occasionally for early season irrigations to ensure good establishment. Watermelon seedlings were transplanted the third week of May in both years with plant spacing within rows being 0.91 m (3 ft) and spacing between rows being 2.44 m (8 ft), corresponding to typical production practices. Nitrogen was applied preplant at the rate of 56 kg/mulched ha (50 lb/mulched acre) and in two fertigations of 56 kg/mulched ha (50 lb/mulched acre) area during the season. The raised beds, covered by plastic mulch, were 9.1 m (30 ft) long and approximately 0.76 m (30 in.) wide. The spacing between the drip tape emitters was 0.30 m (12 in.). Data from a nearby weather station were used to estimate daily ET$_0$. Textural analysis of the soil removed during probe installation in 2004 showed that the top 0.30 m was a loamy sand (average 80% sand, 5% clay), while below 0.30 m it was a sandy loam (average 73% sand, 16% clay). This soil, being dominated by sand, is typical of the soils in the area.

In 2004, one MCP was installed in each of the four treatment replications near the center of the raised bed, approximately 0.15 m from an individual plant. This probe position at the center of the watermelon bed was designed to enhance measurement of deep percolation losses and water uptake by plants. In 2005 an additional MCP was installed approximately 0.19 m away towards one edge of the raised bed (fig. 4), in order to assess lateral water movement from the drip line toward the edge of the raised beds. The different shapes of the two wetting envelopes (or wetting “onions”) simply illustrates that this wetting envelope varies with several factors, such as soil properties, initial soil water content, and irrigation rate.

The seasonal volume of water applied to the plots under the low, medium, and high irrigation rates was 823, 1492, and 2232 L, respectively. In drip irrigation these volumes of water cannot be converted into an equivalent depth of application unless an assumption is made about the area over which the volume is applied. The length of the plots was 9.1 m, and making the rather simplistic assumption that the wetted width is equal to the width of the mulch and is also uniform with depth, the corresponding equivalent depths of irrigation would be 118, 215, and 321 mm, respectively. The actual ratio of water applied in the low and high rates relative to the medium rate was 55% and 150%, respectively. In 2005 the corresponding volumes of water applied under the low, medium, and high irrigation rates were 736, 1375, and 2053 L, respectively, with equivalent irrigation depths of 106, 197, and 294 mm. The actual ratio of the low and high rates compared to the medium rate was 54% and 149%, respectively.

RESULTS

FARMER-MANAGED Drip and Center-Pivot Irrigated Crops (2002-2003)

Water Percolation

A graphic illustration of the MCP data is shown in figure 5. In this example, soil water dynamics data from one MCP in pivot-irrigated field corn illustrated that the farmer-
managed irrigations commonly sent water pulses to 100-cm soil depth (fig. 5). In this visual sample result, the MCP data are displayed as a stacked graph in figure 5a and with a common y-axis in figure 5b. The stacked graph has each sensor depth shown separately and in sequence of their positions in the soil profile. The beginning values of soil water content at each depth are shown on the y-axis of the stacked graph (fig. 5a). The scale of the graphs at individual depths is different, but the graph is easier to interpret for irrigation management than the common axis graphs shown in figure 5b because the individual graphs are kept separate. Eight pivot irrigations were applied during this 12-day example. Soil-water peaks are clearly visible at shallow depths, as is the subsequent reduction in soil water content caused by drainage and ET. Four of the eight irrigation events resulted in water percolation to the 100-cm depth (indicated by arrows in fig. 5a), showing that the farmer was applying too much water, i.e., water percolation below daily water uptake depths (discussed below). Note that this deep percolation occurred only when there were irrigation events on two consecutive days. Total deep percolations to at least 100 cm, across all crops and irrigation events over two years are shown in table 1.

Drip irrigations had nearly 43% more irrigation events that percolated to 100-cm as compared to pivot-irrigation (30% vs. 21%). This higher deep percolation rate under drip irrigation was due in part to the point source of water input and the placement of the MCPs within about 6 cm of the drip tape, in contrast to the more spatially uniform distribution of water under pivot irrigation. This calculation may underestimate the proportionate number of irrigation events with water percolation to 100-cm depth for both irrigation methods because the soil was often already near saturation at that depth in some of the fields. Under such conditions, water that percolates into near-saturated soil may not result in a detectable increase in soil water content (Timlin et al., 2001; Starr and Timlin, 2004). The percolation of water through the soil profile has implications for N management and leaching. If the grower in this example had this information on water movement, it is likely that the irrigation and fertigation management would have been changed because percolation beyond the root zone represents an economic loss in terms of the excess water applied and the loss of N as well as having potential negative impact on the environment. Deep percolation and the loss of N as a result of rainfall is beyond the

<table>
<thead>
<tr>
<th>Irrigation[\textsuperscript{b}]</th>
<th>Irrigation Events[\textsuperscript{c}]</th>
<th>Percolations to 100 cm</th>
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<tbody>
<tr>
<td>Drip</td>
<td>860</td>
<td>262</td>
</tr>
<tr>
<td>Pivot</td>
<td>472</td>
<td>100</td>
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[\textsuperscript{a}] Measured with multisensor capacitance probes.
[\textsuperscript{b}] Drip-irrigated water melons (four fields) and peppers (one field).
Pivot-sprinkler-irrigated field corn (two fields), sweet corn (one field), and soy beans (one field).
[\textsuperscript{c}] Total irrigation events summed across all probes.
plants grew along with their water demand. Later in the season, water percolation to the 50-cm sensors can be seen by the slow rise in soil water content at the two lower irrigation rates, and by the return of the regular increase in soil-water content with each 150% irrigation. Summary results of water percolation to the two deepest sensor depths, 50- and 70-cm, with data from all center-position probes and irrigation treatments in 2004 and 2005 are shown in table 2. Water percolation to 70 cm at the 50% and 100% ET irrigation rates shows the difficulty of eliminating deep percolation under sandy soils and intermittent rainfall conditions. Even so, the percentage of the 150% ET0 irrigations that percolated to 70 cm over both years was four to five times greater than at the 100% and 50% ET0 irrigation rates.

Table 2. Percentage of drip irrigation events on watermelon in which water percolated to 50- and 70-cm soil depths[a], under three irrigation rates.

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<tr>
<td>50</td>
<td>50 cm</td>
<td>14</td>
<td>16</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>70 cm</td>
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<td>35</td>
<td>29</td>
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<td>100</td>
<td>50 cm</td>
<td>39</td>
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<tr>
<td></td>
<td>70 cm</td>
<td>54</td>
<td>89</td>
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<tr>
<td></td>
<td>70 cm</td>
<td>54</td>
<td>89</td>
<td>35</td>
<td>29</td>
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</table>

[a] Measured at probes near the drip tape, i.e., not including fringe probe data in 2005.
[b] As approximate percentage of ET0.
[c] Not including fringe probe data.
Daytime soil water decreases between irrigation events were strongly evident at the top three sensors during the growing season. Gradual water uptake at the two deeper depths is indicated by the slow decline in soil water content in the later part of the growing season for all three irrigation rates. However, water uptake started to increase about 5 July 2004 at the 150% irrigation rate (see circle #3 in the bottom panel, fig. 6c). This increased water uptake at the 70-cm depth may have resulted from less water uptake at the shallower depths due to water logging or oxygen deficiency.

Figure 7 shows the cumulative soil water content at the top three sensors, i.e., from 5- to 35-cm soil-water sensing depths, during the 2005 growing season at the center and fringe positions. The data are averaged across the four MCPs, (one MCP in each of the four replicates), in each of the three irrigation treatments. The soil water content generally followed the irrigation rate, with the 50% treatment having the lowest water content and the 150% treatment the highest at both center and fringe positions. Before the first irrigation on 24 June 2005, the three irrigation treatments all showed similar declining soil water contents in response to crop growth and ET demand. After 24 July 2005 changes in the soil-water content at the center positions responded rapidly to each irrigation. In contrast, direct changes in soil water content at the fringe position were most apparent at the 150% irrigation treatment, probably due to greater lateral water movement into the fringe area at this high irrigation rate.

The relative position of the center and fringe soil water storage curves crossed in early July (at the vertical arrows) as lateral water flow was insufficient to replenish losses due to plant uptake, especially at the two lower irrigation rates. However, as the plants approached senescence in late July, water uptake declined and the soil water content at the fringe and center positions became approximately equal.

**WATER UPTAKE**

Closer examination of data over a short period of time can reveal information on water uptake and the rooting pattern of the crop. As an example of daily water uptake, data for 23 and 24 July 2005 are shown in figure 8. During these two days ET0 was relatively high (5.6 mm on each day), there was no irrigation or rainfall, and the canopy was fully developed. Data in figure 8 shows the cumulative change in soil water content relative to the value measured at 06:00 on 23 July, for two consecutive days, for depth increments of 10 to 30 cm, 30 to 50 cm, and 50 to 70 cm, and for all three (50%, 100%, and 150%) irrigation treatments. The values displayed are averaged across the four replications of each irrigation treatment for both the center and fringe MCPs. In the center of the bed the greatest decline in water content in the 10- to 30-cm depth increment occurred in the 100% irrigation treatment, while the smallest decline occurred in the 150% treatment. The decline in the 50% treatment on 23 July matched that of the 100% treatment, but on the following day the decline in the 50% treatment was less, suggesting that there may have been some water stress on that day. At the edge of the bed, however, the 50% treatment had a substantially lower decline in soil water content compared to the other two treatments, perhaps a result of decreasing root activity away from the drip tape. With the exception of the 10- to 30-cm depth increment in the center of the bed, the 150% irrigation treatment had the largest daytime decline in soil water content over the two days. This suggests that the 150% treatment had greater root activity away from the drip tape and with depth, perhaps due to the generally high water content and corresponding lower oxygen availability near the drip tape. Water in the 150% treatment is extracted during the daytime even at 70 cm, although there also appears to be some soil water drainage losses during the night. Neither the 50% nor the 100% irrigation treatments showed much water extraction at 70 cm.

This figure also shows the result of internal drainage from upper to lower layers by the night-time rise in soil-water content at the deepest depths of the high irrigation rate (figs. 8e and 8f).

**MEASUREMENT VARIABILITY**

Variability in measurements between replications of the same irrigation treatment is primarily due to actual temporal and spatial differences in soil water content. Scaled frequency differences between individual sensors and the corresponding \(\theta_i\) (eq. 1, 2) have been shown to be very small (0.9%, Paltineanu and Starr, 1997). Visually, all the sensors responded to irrigation treatments with rapid increases in soil water content, followed by slower decreases due to drainage or water uptake. However, it is easier to compare absolute measurements when soil water content is not changing rapidly. Soil water content is least dynamic early in the morning before any irrigation that day and after redistribution during the nighttime. As an example of variability between replications, measured soil water content at 6 AM from 5 to 35 cm (the top three sensors) is shown in table 3 for the month of July 2005, the primary irrigation period. In table 3 the
Figure 8. Average change in soil water content from 5 to 35 cm in the center (a) and fringe (b); from 35 to 55 cm in the center (c) and fringe (d); and from 55 to 75 cm in the center (e) and fringe (f), for the 50%, 100% and 150% irrigation treatments for a two-day period between 23 and 24 July 2005 during which there were no irrigations or rainfall. The shaded areas represent the overnight period between 6:00 PM and 6:00 AM. The error bars indicate the standard deviation of the four replications at the end of the period for the 100% rate.

Monthly average soil water content under each irrigation rate is the average of the daily measured values (averaged across the four replications of each irrigation treatment). The monthly mean absolute difference is calculated from the daily absolute differences between the measurements in each replication. The coefficient of variation is calculated from the daily standard deviation between replications. Also shown in table 3 is the mean absolute difference in the daily change in water content from the measured water content on 30 June (the day before the month commenced). The average soil water content was lowest under 50% irrigation and highest under 150% irrigation, as expected. The monthly mean absolute difference in θ, between the four replications ranged from 1.35% to 2.01%, while the coefficient of variation ranged from about 11% to 15%. With the small variation in scaled frequency sensor readings these differences are primarily due to spatial variability between replications. A regression of the daily measured soil water content in each replication on the daily average of the four replications for all three irrigation treatments yields an R² value of 0.78 and a standard error in θ, of 2.0%. The monthly mean change in daily soil water content relative to the value on 30 June shows...
that soil water content was declining under 50% irrigation (2.7% lower on average), about the same under 100% irrigation (0.4% lower) and increasing under 150% irrigation (2.5% higher). These trends are as would be expected.

Overall, in both years, soil water content in the 50% treatment was low compared to the 100% and 150% treatments (an example of which is shown in table 3). Figure 9 shows seedless watermelon yield in 2004 and 2005 as a function of irrigation. Surprisingly, yield under the 50% irrigation rate was not significantly lower than under the 100% or 150% rates. The trends in 2004 were for increasing yield with irrigation, but this trend was not repeated in 2005. An analysis of variance (ANOVA) was performed which showed that there was no significant difference between mean yields (p > 0.2) in spite of the large range in irrigation amount. This result was unexpected, and may indicate an efficient use of runoff-water from the plastic mulch during the intermittent rainfall events. Further research needs to be done to substantiate this.

### DISCUSSION

Irrigation scheduling is a challenge in a humid region. There has been much research and development on various important aspects, such as methods to estimate crop water use from weather data that is now often readily available from automated weather station networks. The widespread use of computers and the development of software has made approaches such as the “checkbook” method relatively easy to implement. Despite this, the adoption of scientific irrigation scheduling by growers remains low. All approaches to irrigation scheduling will benefit from measurements of soil water content. The near-continuous and real-time data available from MCPs can yield a wealth of information useful in irrigation management. For on-farm use, it is important to process and display the information in a form that growers can readily and rapidly comprehend, as most of them will be unable to devote much time to detailed examination and data processing. It is, however, easier to interpret the information under sprinkler irrigation than under drip irrigation because infiltration of both rainwater and irrigation is more uniform spatially, as is areal root distribution and crop water use. If measurements show that irrigation water is percolating below the rooting depth, it is relatively easy to reduce irrigation without an adverse effect on yield. Also, trends in soil water content within the root zone can be a guide for irrigation management. For example, if soil water content remains within the range of plant available water but trends downward over a period of a few days, it is likely that irrigation and/or rainfall is not sufficient to meet crop water requirements. Similarly, an upward trend could indicate excessive irrigation. Automatically separating these longer term trends from data that shows large short term changes resulting from irrigation or rainfall events is necessary if this information is to be readily used by growers. These trends would be apparent even if there was an offset error with the sensors, because they require only measurements that are accurate in a relative rather than absolute sense.

To use MCPs with drip irrigation under plastic mulch is more complex. In a sandy soil it may be difficult to apply sufficient irrigation to meet crop water requirements while preventing irrigation water percolation beyond the rootzone under the drip tape. Although on a field-wide basis the amount of water percolating below the root zone may not be large, it does have implications for nutrient movement as nutrients are usually applied with irrigation. Issues that need additional consideration are the location of the MCPs relative to the drip tape, the emitters, the plant, and the plastic mulch. The difference in the distance from the drip tape between the center and fringe MCPs in 2005 was only 19 cm, but there was considerable difference in the values and dynamics of soil water content at these two locations. Assessing the contribution of rainfall for plastic mulch crops will require additional MCPs placed at the outside edge of the raised beds, and greater understanding of the temporal and spatial root growth pattern and how that is affected by irrigation management. The lack of significant watermelon yield differences is interesting. The irrigation in the three treatments clearly ranged from deficient to excess, as measured by the MCPs. That the low treatment (50%) produced a yield not significantly different from the high treatment (150%) suggests that the crop is compensating for the lack of irrigation. The only water available with which to compensate would be from rainfall, but to use it the water would have to move laterally toward the center of the bed or the roots would have to extend laterally out to the edge of the mulch and beyond. If this is the case, an irrigation strategy could be developed that provided for irrigation amounts more in line with the 50% treatment rather than the 150% treatment as is commonly practiced, and only increased to the 100% rate if there was a sufficiently long period without rainfall. This might also have implications for probe location within the mulched bed. Perhaps the fringe position more accurately reflects the root zone than the center position, and furthermore would not be directly affected by rainfall entering through the planting hole. Further research with additional MCPs will determine whether this strategy and probe location would be better. Regardless of probe loca-

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Table 3. Average soil water content from 5 to 35 cm at 6 AM from 1 to 31 July 2005; mean absolute difference between replications; coefficient of variation; and the monthly average change in soil water content relative to the value at 6 AM on 30 June 2005.

<table>
<thead>
<tr>
<th>Irrigation Rate</th>
<th>Average Measured SWC (vol)</th>
<th>Mean Absolute Difference between Replications (vol)</th>
<th>Coefficient of Variation (%)</th>
<th>Mean SWC Change (vol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>12.6</td>
<td>1.35</td>
<td>14.9</td>
<td>-2.7</td>
</tr>
<tr>
<td>100%</td>
<td>18.3</td>
<td>1.45</td>
<td>10.7</td>
<td>-0.4</td>
</tr>
<tr>
<td>150%</td>
<td>20.5</td>
<td>2.01</td>
<td>13.6</td>
<td>+2.5</td>
</tr>
</tbody>
</table>

Figure 9. Seedless watermelon yield in response to irrigation treatments, averaged across four replicates in both years. Error bars indicate the standard deviation of the yield.
tion, it is important to install the MCPs carefully to eliminate gaps around the access tube and to also avoid cuts or tears in the plastic close to the MCPs as rainwater can enter and cause localized higher soil water contents that are not typical of the field as a whole.

**SUMMARY AND CONCLUSIONS**

These studies were conducted to test the hypothesis that the soil water content and dynamics obtained with multisensor capacitance probes (MCPs) can provide valuable information to both the grower and research communities in managing irrigation in humid areas. To assess the use of MCPs as a tool to improve irrigation management, soil-water dynamics in response to irrigation were monitored in both farmer-managed irrigated fields and researcher-controlled replicated treatments. Monitoring soil water dynamics in farmer’s irrigated fields under intermittent rainfall conditions shows the need to improve irrigation management practices to reduce excess water application and the likely associated movement of nutrients below the rootzone. Irrigation rate studies indicated that rainfall can contribute significantly to the crop water supply, but our work suggests that further work needs to be done to determine its real contribution under plastic mulch crops, and how to include this information in irrigation management.

These studies showed that near-continuous real-time soil water monitoring information can significantly help in managing irrigation by quantifying over-watering, but there are many details that need consideration. Techniques and approaches need to be developed to make it easy and quick for growers to use the information to help with their irrigation decisions. Rather than analyzing graphs, it is likely that many growers would want just a simple recommendation on, for example, how many hours to run their drip system, or what timer setting to use on their center pivot, on any particular day. Economic and cost-benefit analyses are also needed, particularly as the costs of over-irrigation rise due to higher energy costs along with the prices of associated energy intensive inputs such as fertilizer and plastic drip tape. Further research is in progress, under these soil and climate conditions, using this and related technologies with drip-irrigated watermelons and pivot irrigated corn and lima beans (L. Phaseolus lunatus).

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