The Use of Multi-sensor Capacitance Probes as a Tool for Drip Irrigation Management in Humid Regions.

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Abstract.

Irrigation management in humid regions is more complex than in arid regions, and this is particularly so for drip irrigation under plastic mulch. Good measurements of soil water content can help. Multi-sensor capacitance probes (MCPs) measure soil water content simultaneously at discrete depths, and a new generation can also respond to salinity and therefore may be useful in nitrogen management. Replicated field studies on drip irrigated watermelon have been conducted in Delaware in which MCPs were used to monitor water content under different relative irrigation amounts. The objectives are to develop improved irrigation guidelines and to evaluate the potential for nitrogen management. Results indicate that MCPs may be an important tool, but there are many practical details to be considered, such as their placement and interpretation of the wealth of data they generate.

Introduction

Drip has become the preferred method of irrigation for some crops, (particularly high value vegetable crops) in the humid Eastern USA. For example, in Delaware most watermelon production now uses drip tape under plastic mulch. While this method is potentially very efficient in terms of water use, it is also complex in terms of soil water distribution and dynamics, particularly when rainfall during the season is significant.

The reasons for the complexity when compared to sprinkler irrigation include:

- Irrigation water is applied to only part of the field, and is applied as a line of equally spaced point sources rather than relatively uniformly to the entire field.
- The areal extent of the canopy is often not the same as the areal extent of the roots.
- Rain falling directly on the plastic mulch cannot infiltrate, but runs off to the edge. Rainwater is therefore concentrated at the edge, where it can infiltrate the soil but must then move laterally to contribute to soil water content under the mulch.
- Rain can enter the soil under the mulch through the planting holes (perhaps also channeled by stem flow) and through cuts and tears that may develop in the mulch, but this direct contribution to soil water content is difficult to quantify.
- Both the lateral and vertical root distribution relative to the drip tape may be affected by irrigation management itself.
- In sandy soils, downward movement of water below the drip tape may be significantly higher than lateral movement, making it difficult to adequately replenish the wetted soil volume without causing deep percolation.
- The evaporative component of evapotranspiration (ET) is suppressed by the plastic mulch.
- Nutrients are commonly applied through the drip tape (fertigation), and so will have the same distribution and dynamics as the irrigation water.

In terms of management, growers typically will tend to over-irrigate as insurance against under irrigation. This tendency may be exacerbated in mulched drip irrigation because the water is "out of sight" and because soil water content under the mulch cannot be readily assessed.

We have been conducting research in Delaware since 2004 using Multisensor Capacitance Probes (MCPs) to measure soil water content and dynamics under mulched drip irrigated watermelon. Watermelon may be particularly difficult to manage under humid conditions because of the wide row spacing typically used (therefore the fraction of the field under mulch is relatively low) and because the crop appears to have an agressive root system. Figure 1 shows a typical layout and probe locations.

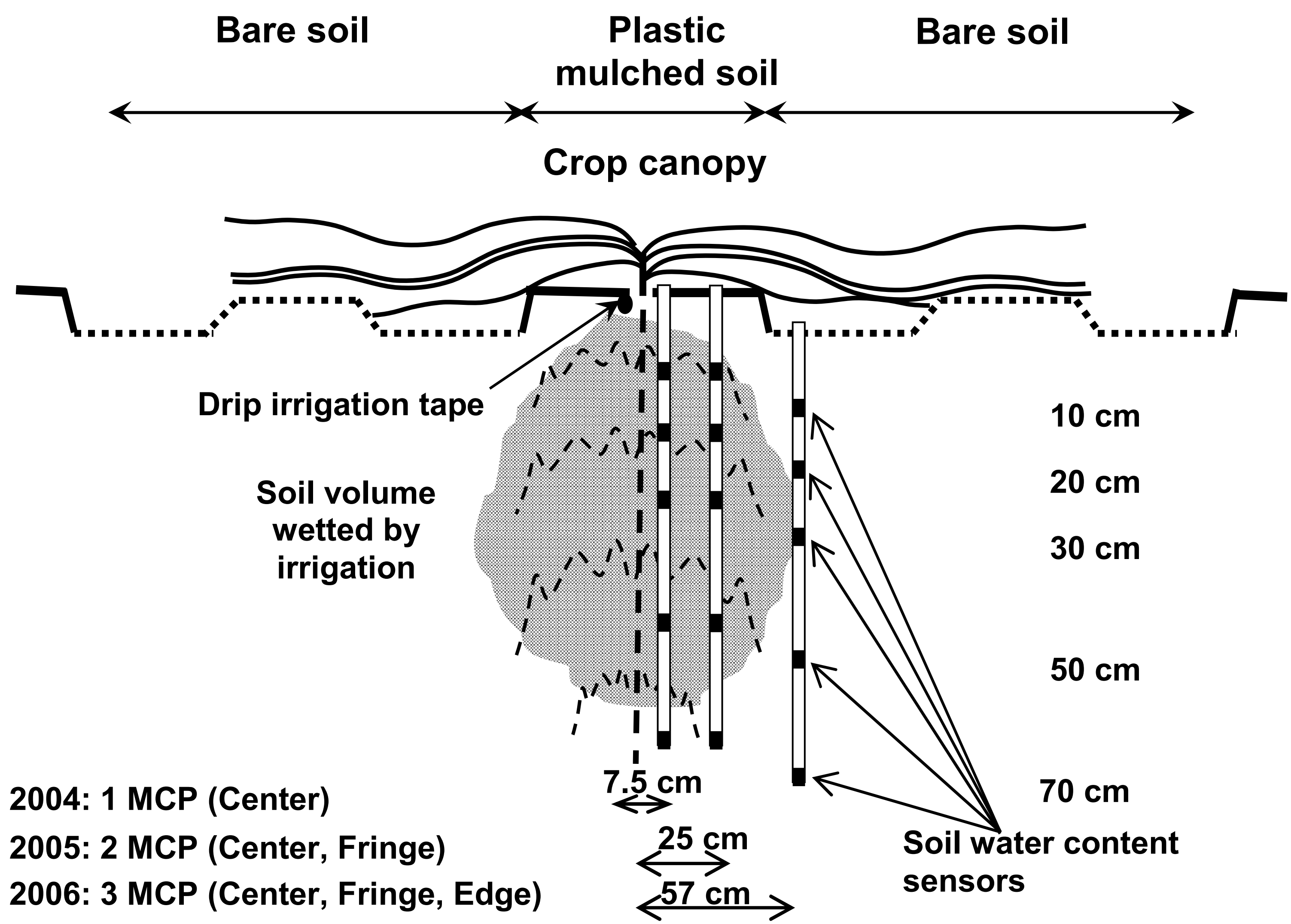

Figure 1. Plastic mulched drip irrigation of watermelon and layout of MCPs in 2004, 2005 and 2006. The center position and fringe position are in the mulched area, while the edge position is in the bare soil outside the mulch.

There are a number of soil water sensors available, each with advantages and disadvantages. Sensors that provide an electrical signal have the advantage of easy measurement, logging and data processing. Such sensors include those that measure the dielectric constant of the soil, which depends primarily on volumetric soil water content and electrical conductivity. Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) are the technologies currently being used. MCPs use a number of capacitance sensors (FDR) mounted on a probe that is inserted into the soil and remains in place for the duration of the period during which measurements are required. MCPs therefore measure volumetric soil water content at discrete depths based on the dielectric constant of the soil surrounding them. The MCPs we used were EnviroSCAN®[1] or TriSCAN® (Sentek Pty. Ltd., 77 Magill Rd, Stepney, South Australia 5069), in which up to 16 sensors can be placed on a single probe, with depth intervals set by the user in 10-cm increments. The probes are installed in access tubes that are inserted into the soil so as to make good contact with it. EnviroSCAN probes operate at a single frequency range chosen such that water content rather than electrical conductivity is the primary determinant of the dielectric constant. TriSCAN probes have similar sensors, but are dual frequency in that, in addition to the frequency used in EnviroSCAN probes, they also operate in a frequency range in which electrical conductivity (expressed as "Volumetric Ion Content" (VIC)) can be measured (Buss et al, 2004). In non-saline environments and sandy soils VIC can be related to soluble nutrient content. The zone of major influence of the sensors represents a cylinder of soil approximately 10 cm along the axis of the probe with a 10 cm ring around its 5-cm diameter PVC access tube (Paltineanu and Starr, 1997). Starr and Paltineanu, 1998; Paltineanu and Starr, 2000; Fares and Alva, 2000; and Starr and Timlin, 2004 have investigated Enviroscan MCPs.

Evett et al (2002) have compared measurements made using TDR and FDR instruments, including MCPs, with those made using a neutron probe, and conclude that the neutron probe has superior accuracy. However, while the neutron probe has the advantage of sampling a relatively large soil volume with perhaps greater accuracy than many other methods, it cannot be logged and, because it requires licensing, is unsuitable for direct use by growers. The accuracy of capacitance probes can be improved with on-site calibration, but it is not likely that many growers would do this before using them.

Methods

We conducted replicated studies in 2004, 2005 and 2006 on mulched drip-irrigated seedless watermelon (cv. Millionaire) at the University of Delaware Research and Education Center in Georgetown (38˚ 38' N 75˚ 27' W). The soil texture at this site is sand to loamy sand over sandy loam or sandy clay loam. Plant and row spacing were 0.91m (3ft) and 2.44m (8ft) respectively, following standard production practice in the region. A row of seeded watermelons (as pollenizers) were planted for every 2 rows of seedless watermelons. In all years seedlings were transplanted during the third week of May. The plots, which were 9.14m (30ft) long, were irrigated using drip tape (T-Tape, T-

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[1] Trade names are used in this publication to provide specific information. Mention of a trade name does not constitute a guarantee or warranty of the product or equipment by the USDA or an endorsement over other similar products.

Systems) at one of three different rates, roughly corresponding to 50%, 100%, and 150 % of estimated ET (ratios of 1:2:3). These rates, (low, medium, and high) 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 one and three hours respectively. While the run time for the 100% treatment varied during the season, the 50% and 150% ratios were always maintained. Anecdotal observations suggest that typical grower irrigation may be at least as much as the 150% treatment. The width of the raised bed covered by plastic mulch was approximately 76 cm (30 inches), and the spacing between the drip tape emitters was 30 cm (12 inches). Nitrogen was applied preplant at the rate of 56 Kg/mulched ha (50 lb/ mulched ac) and in two fertigations of 56 Kg/mulched ha (50 lb/mulched ac) area during the season. In each year ET_0 was estimated using the FAO-56 Penman-Monteith method (Allen et al, 1998) from data collected by a nearby automated weather station.

In each year of the study MCPs with sensors at 10, 20, 30, 50 and 70 cm depth were carefully installed to minimize air gaps, using a manufacturer supplied auger system and access tubes with cutting rings. Prior to installation each sensor on each probe was "normalized" by making measurements in distilled water and air using the manufacturer's default calibration. After installing the access tube silicone sealant was applied around it to prevent direct water infiltration between the tube and the plastic mulch. The MCPs were connected by cables to the logger, and logged at 10 minute intervals. However the number and location of MCPs differed each year (as shown in figure 1), as follows:

2004.

Four replications of the three irrigation rates were used (12 plots total). In each plot an EnviroSCAN probe was installed near the center of the raised bed (termed the "center" position) 15 cm (6 in) from an individual plant and 7.5 cm (3 in) from the driptape. The probes were not located relative to the emitters. There was thus 1 MCP per plot, 12 MCPs total with a combined total of 60 sensors.

2005

As in 2004, four replications of the three irrigation rates were used. In each plot an EnviroSCAN probe was installed at the center position but located relative to the emitters (midway between adjacent emitters at the closest available location to a plant). An additional probe was installed midway towards one edge of the raised bed (approximately 27 cm (10.5 in) from the drip tape, 19 cm (7.5 in) from the plant, and termed the "fringe" location) in order to assess lateral water movement from the drip line toward the edge of the raised beds. There were thus 2 MCPs per plot, 24 MCPs total, with a combined total of 120 sensors.

In addition, TriSCAN (dual frequency) probes were installed in the center and fringe positions in two replications of two treatments in an adjacent complementary study established to evaluate response to nitrogen. Irrigation and preplant nitrogen application was the same as the 100% irrigation treatment. One of the treatments received four fertigations of 28 Kg N/mulched ha (25 lb N/mulched acre) during the season while the other treatment received two fertigations of 56 Kg N/mulched ha (50 lb N/mulched acre). A total of 8 TriSCAN probes (40 sensors) were therefore used in addition to the 24 Enviroscan probes.

2006.

Probes were installed in the same two positions as in 2005 (center and fringe), with an additional probe installed in each plot outside the plastic mulch approximately 57 cm (22.5 inches from the plant, 64 cm (25.5 inches) from the drip tape), in what is termed the "edge" position. These probes was therefore in bare soil in the area where runoff from the mulch collects after rainfall. Probes were installed in 3 replications of the three irrigation treatments. There were thus 3 MCPs per plot for a total of 27 MCPs with a combined total of 135 sensors. The probes were located relative to the emitters as in 2005, but the seedlings were also planted relative to the emitters (adjacent).

In addition, two more irrigation treatments were instrumented in one replication. The treatments were no irrigation (0%) except for the two fertigations, and very high irrigation (250%). EnviroSCAN probes were installed in the center position in the 0% treatment, and in the center and fringe positions in the 250% treatment. The center position probe in the very high irrigation treatment had an additional sensor installed at 100cm to monitor infiltration to and water uptake from this depth. There were thus three additional MCPs with 16 sensors.

Eight TriSCAN probes (40 sensors) were also installed, as in 2005, to measure response to the same two fertigation treatments.

The amount of data generated in such experiments is considerable. For example in 2006 there were a total of 30 EnviroSCAN probes (151 sensors) measuring soil water content every 10 minutes to provide almost 22000 measurements per day. In addition the 8 TriScan probes (40 sensors) were logged every 30 minutes and provided almost 2000 additional measurements of soil water content per day along with the same number of measurements of VIC.

In drip irrigation, actual crop water use cannot be estimated by applying the same crop coefficient to ET_0 as with other methods of irrigation. Even with a full canopy, drip irrigated crops often have lower crop water use. Clark et al (1996) reported that irrigation of $0.3ET_0$ was sufficient for drip irrigated watermelon. We used ET_0 as a guideline for the 100% irrigation treatment, but assumed that the crop would use water only from the area under the mulch, which is about 30% of the total field area. Thus, irrigation was applied to replenish water only from this mulched area, and so was similar to the requirements reported by Clark et al.

Results and Discussion

Figure 2 shows daily and cumulative ET0 (a), daily and cumulative rainfall (b), irrigations (c) and the total measured soil water content in the top 70 cm in the center position for the 2006 plot that included the very high (250%) and no irrigation (0%) treatments in addition to the 50%, 100% and 150% treatments. Each measurement depth represents the range from 5 cm above to 5 cm below. For example the 20 cm measurement depth represents soil water content from 15 to 25 cm. The total water content was obtained by summing the water contents at the measurement depths and interpolating at the depths for which there was no direct measurement, ie between 30 and 50 cm, and between 50 and 70 cm. There was a large rainfall event early in the season that resulted in ponded water at the edge of the mulch, the effect of which can be clearly seen in the measured soil water content. The soil water content at the beginning of the measurement period (17 June) varies considerably, from about 100mm to 160mm. This difference may be real and due to spatial variability in soil type or water content, or it may be due to lack of calibration. Regardless of the reasons for the differences, the trends over time can be seen. The 0% treatment results in the lowest water content by the end of the season, and shows none of the responses to irrigation seen in the higher irrigation rates. However, rain did replenish soil water content. The rapid response to the large rain early in the season indicates that water likely entered through the planting hole, whereas the later rainfall event in the middle of the measurement period caused a more gradual rise, indicating lateral movement into the bed from outside. In the 150% and 250% irrigation treatments water content did not increase over time, indicating that the soil may have been at its maximum in both cases. It was thus not possible to distinguish between these two rates of over-irrigation with a probe at the center position. Water content in the 100% treatment declined during the first 3 weeks of July, indicating that irrigation was not sufficient to maintain it at a high enough level. Water content in the 50% treatment declined at about the same rate as the 100% treatment. There was also a spike in the 50% plot following a rainfall event that is not apparent in the 0% and 100% treatment. This spike indicating rapid infiltration of rainfall through the mulch either through the planting hole or in a possible leak around the access tube seal. The effect of slower lateral movement of water following the rainfall event is readily seen in the 0% treatment.

The replications of the 100% irrigation treatment showed that soil water content was being maintained in the 100% irrigation treatment. Unexpected leaks around a probe, unpredictable entry of rainfall through the planting hole, spatial variability of soil water content or plant water uptake, and differences between probes due to calibration, location and root density all suggest that it would not be wise to depend on measurements from a single probe to manage irrigation over an entire field.

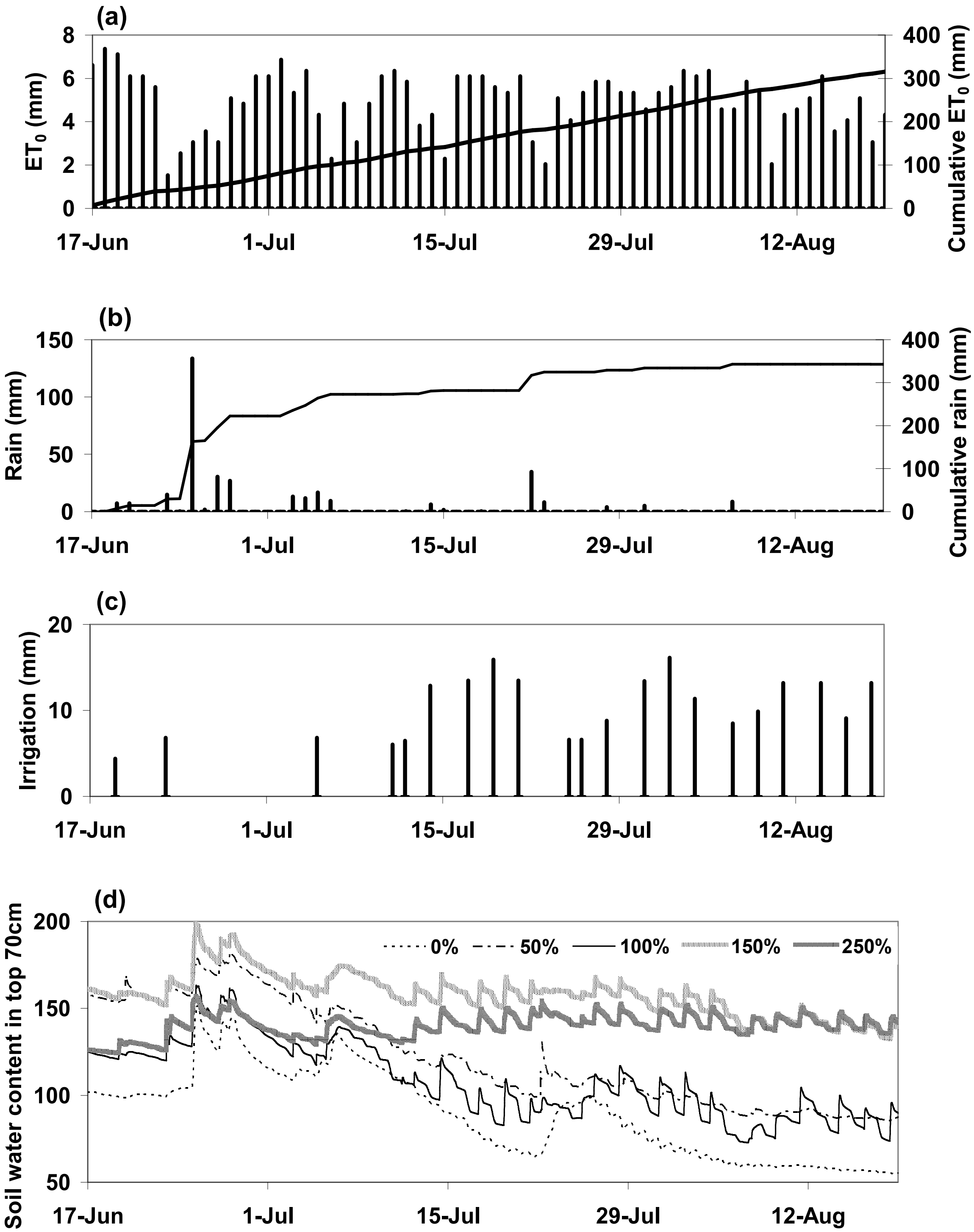

Figure 2. Daily and cumulative reference evapotranspiration (ET_0) (a), daily and cumulative rainfall (b), daily irrigation in the 100% treatment, and total soil water content in top 70 cm for the 0%, 50%, 100%, 150% and 250% irrigation treatments in one replication during the 2006 growing season.

Figure 3 shows an example of VIC (a) and soil water content (b) as measured at each depth in the center position of one plot that received 2 fertigations of 56 Kg N/mulched ha (50lb N/mulched ac). Early in the season soil water content was relatively high, and this apparently resulted in some leaching of pre-plant N to the lower depths. In particular during the last week of June there was a large drop in VIC at 30cm and a smaller more gradual increase at 50 and 70 cm. Before the 1st fertigation VIC levels at 10, 20 and 30 cm had dropped to relatively low and stable values, while at 50 cm it was steadily declining. The 1st fertigation caused VIC to progressively increase at 10, 20 and 30 cm, with the peaks occurring in sequence. After about 10 days VIC at these depths had declined to about the same as before the fertigation. At 50 cm, VIC briefly leveled out before continuing its steady decline. The 2nd fertigation caused a similar response at 10, 20 and 30 cm, but of a larger magnitude. It also caused VIC at 50 cm to level out and slightly increase rather than continuing to decline, indicating some movement of nitrogen to this depth. The duration of the response was about the same as to the 1st fertigation. VIC at 10, 20 and 30 cm then declined to the same relatively low level as before. By the end of the season VIC at 50 cm was also approaching the same level, and at 70 cm continued

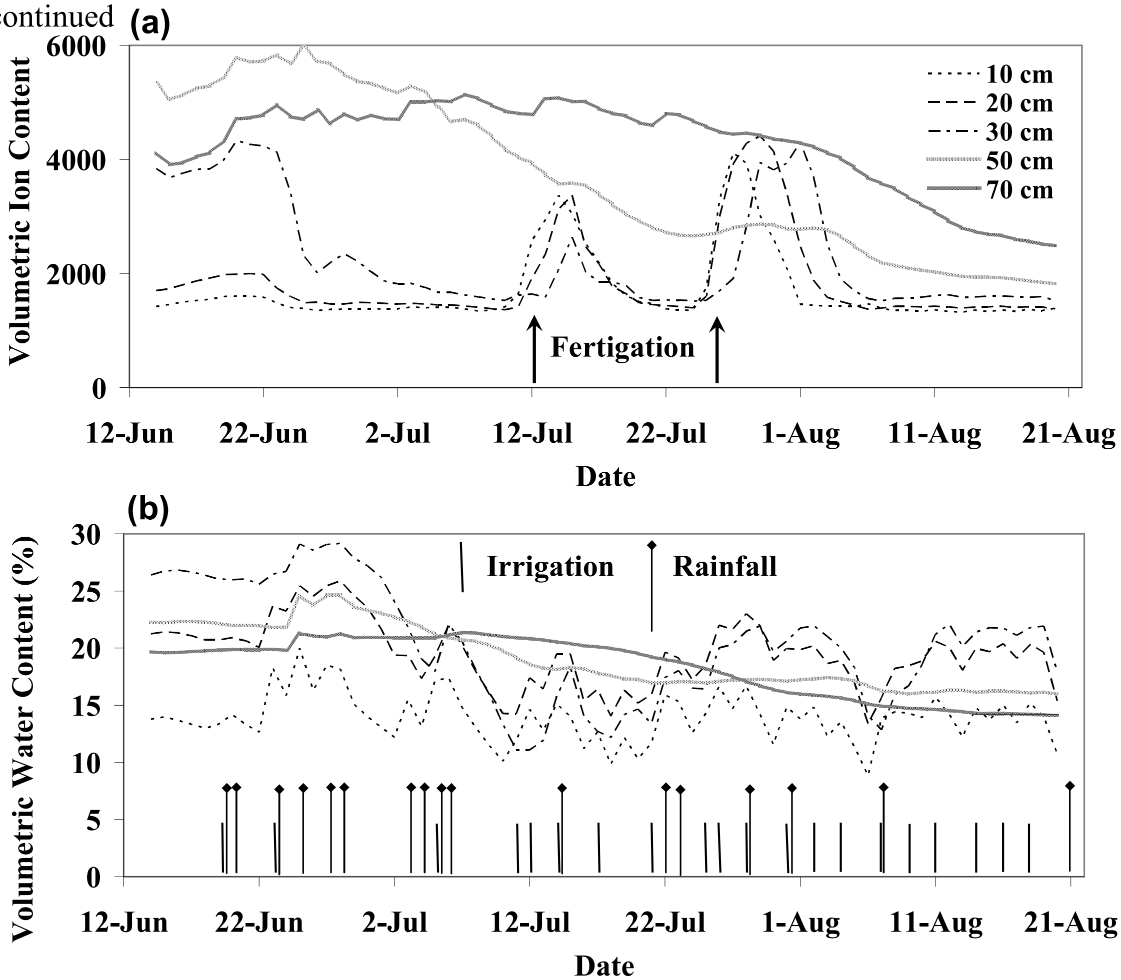

Figure 3. Volumetric Ion Content (a) and simultaneous volumetric soil water content (b) at 10, 20, 30, 50 and 70cm, measured in the center position of one plot that received two fertigations of 56 Kg N/Ha each. The timing (but not magnitude) of irrigation and rainfall events are also shown in (b)

to decline. Trends in soil water content from the beginning of July onwards showed neither consistent increases nor decreases, indicating that the 100% irrigation treatment approximately replaced crop water use from the center of the bed.

An important consideration if producers are to use MCPs (or any form of soil water measurement) is spatial variability of soil water content within a field. This variability is likely greater under drip irrigation because of the relatively limited volume of soil that is wetted. There are large differences in soil water content over a relatively small distance. Confounding the issue of actual variability in soil water content is the issue of differences in response between individual sensors, and differences in the relatively small volume of soil sampled by capacitance sensors. Figure 4 shows, as an example, the differences in measured values (averaged over one hour) integrated over the top 30 cm of soil for the 4 replications of one irrigation treatment (100%) during a two week period in 2005. While ideally measurements in all four replications would be similar, it can be seen that the measured absolute values are actually different. These differences may be real or may be due to the calibration of the sensors. However all four replications do respond to irrigations, and subsequent drainage and drying. Also visible is the "stair-stepping" that occurs when the crop extracts water during the daytime but not at night. Regardless of the source of the absolute differences, the trends can be very useful in irrigation management. In this example, there also does not appear to be a longer term trend of increasing or decreasing soil water content, indicating that irrigation approximately replenished crop water use.

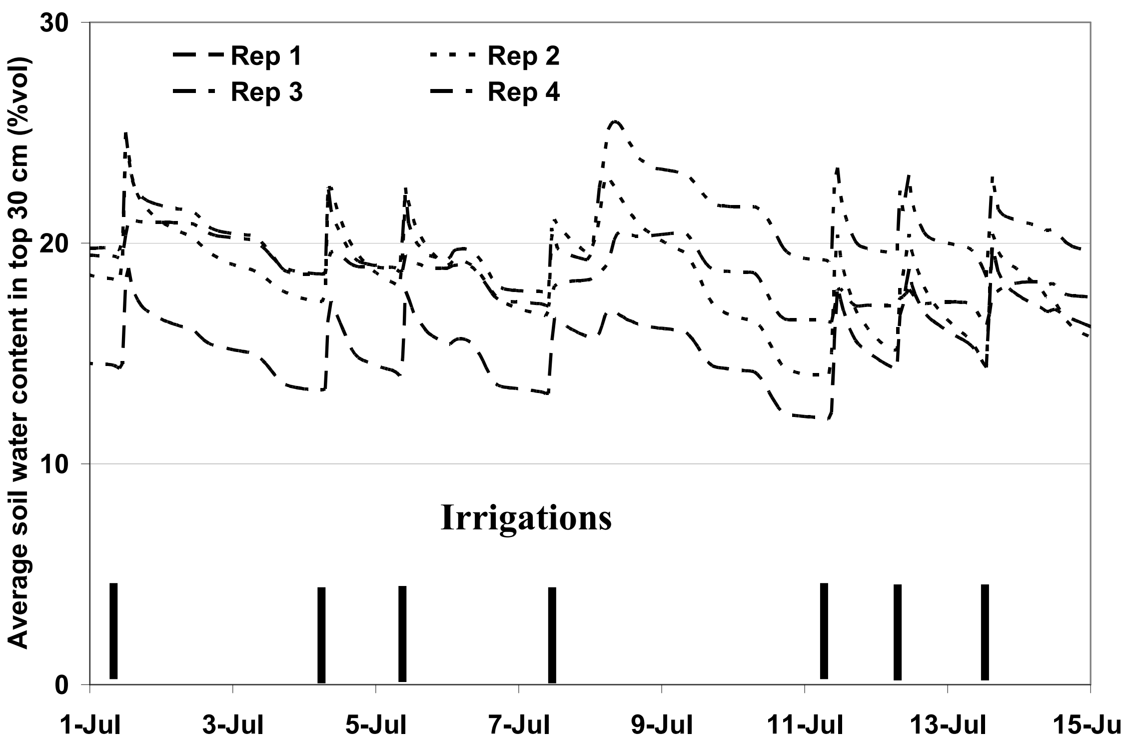

Figure 4. Soil water content in top 30 cm averaged from measurements at 10, 20 and 30 cm during a two week period in 2005, for the 4 replications of the 100% irrigation treatment.

Trends can be more easily seen if differences rather than absolute values are plotted. Figure 5 shows an example of the change in soil water content in one replication in 2006 relative to measured values on 1 July.

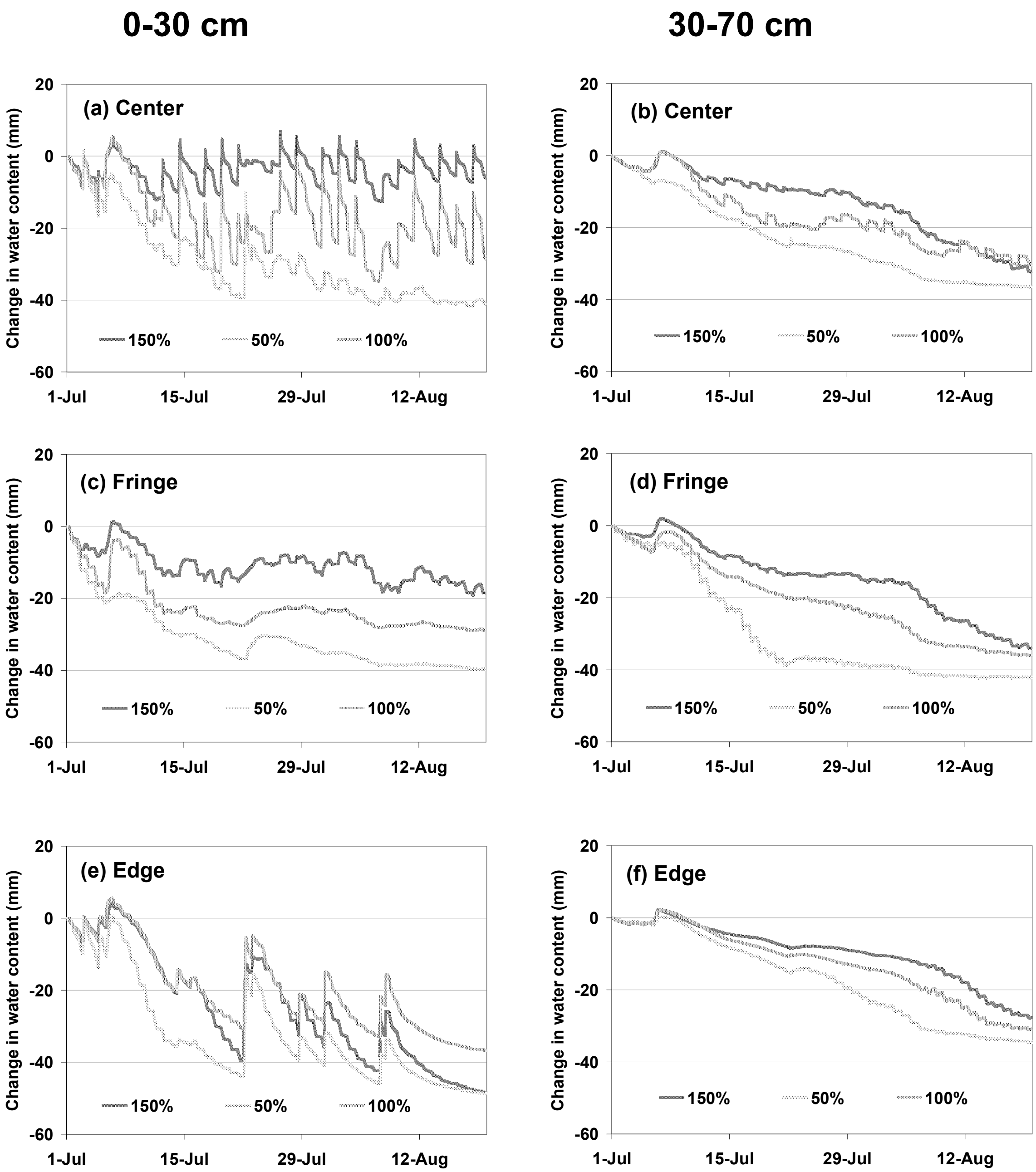

Figure 5. Changes in soil water content from 1st July 2006 in one replication for the 50%, 100% and 150% irrigation treatments from 0-30 cm for the center (a), fringe (c) and edge (e) positions, and from 30-70 cm for the center (b), fringe (d) and edge (f) positions.

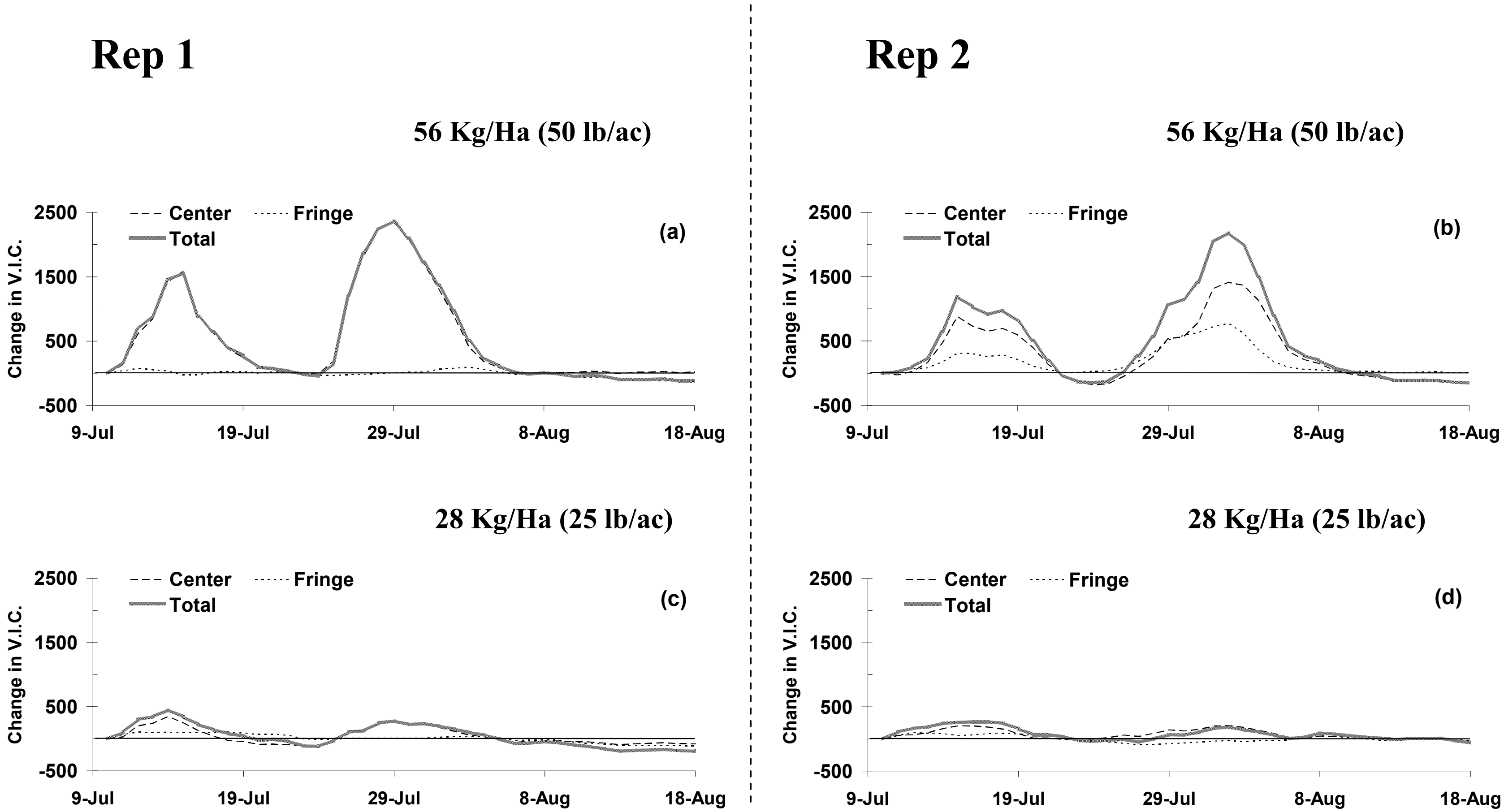

Figure 6. Change in average volumetric ion content in top 30 cm (12 in) compared to the value on 10 July (the day preceding the first fertigation) in the two instrumented replications for fertigations of 56 Kg/Ha (a and c) and 28 Kg/Ha (b and d)

Figure 6 shows the change in VIC relative to the values on the day before the first fertigation, for two replications in which there were two fertigations, either 56 Kg N/mulched Ha (50 lbs/ mulched ac) or 28 Kg N/mulched Ha (25 lb/mulched ac). The TriSCAN probes certainly responded to the fertigations. There was a disproportionately greater response to the higher fertigation rate, and a greater response to the 2nd fertigation at the higher rate. Only in the higher rate in replication 2 was there a significant response at the fringe position. The movement of the nitrogen depends on subsequent irrigation management and crop uptake. The relative VIC response over time can probably provide good information on N trends. For example, an increase at the deepest sensor can indicate leaching.

From a research perspective there is a wealth of information available in analyzing the dynamics of soil water content and VIC. For example, in figure 5 it can be seen that there is root water extraction from the edge position below 30 cm and that infiltrated rainfall does move laterally into the fringe position under the mulch. Root distribution and crop water use can be inferred from the daytime reduction in soil water content at each depth. Changes in VIC over time, combined with soil water trends, can indicate nitrogen movement and uptake.

From a growers perspective, to be useful in aiding irrigation decisions the information should be processed and presented in a way that condenses it and makes it intuitive. Also, from a practical point of view, installation of the MCPs must be easy and the information transmitted wirelessly. However, it is important that the probes be installed properly, with no air gaps. In a humid environment it is also important that rainfall does not concentrate on the plastic mulch around the probe and then infiltrate. A good seal between the probe or access tube and the mulch itself is important, otherwise rainfall will run down the probe and cause high measurements. Some rainfall will however run down through the planting holes, and this is a valid source of water that should be reflected in the measurements. The appropriate number of MCPs to use within a field and where to install them within the row also need consideration. Perhaps three MCPs would represent a reasonable balance between cost and the need to have enough “replication” in a typical field. Positioning MCPs relative to emitters is probably not practical for growers, but installation in the center position relative to plants and the dripline would be appropriate. The additional cost of dual frequency MCPs over single frequency MCPs is not large considering the additional information that is provided.

Conclusion

MCPs, if correctly installed and positioned, can provide valuable information to a grower in humid regions. Unpredictable crop water use and rainfall probably cause growers in such areas to err on the side of over-application more than growers in more predictable arid or semi-arid climates. The trends that can be observed over time with such instrumentation are important and, with some experience, a grower can “calibrate” the sensors for their particular conditions in terms of knowing what range of measured values represents the range of desirable soil water content.

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