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Real-time soil water dynamics over large areas using multisensor capacitance probes and monitoring system

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Abstract

Better methods are needed to accurately measure and record soil water content in real-time and at specified depths on a field scale. Recent developments of such a system using multisensor capacitance probes offers great potential for rigorous investigation of soil water dynamics over large areas. The purpose of this report is to show some of the kinds of information that can be obtained using this system to study the real-time soil water content dynamics at short time intervals (10 min), typically at four depth positions, under long-term, field-scale conditions, with our probes located as far as 125 m form the data logger. The systems have been used in the field for three years of continuous study (at 10 min increments), to study changes in soil water content, at four soil depths (commonly at 10, 20, 30, and 50 cm) as part of a research project to quantify temporal and spatial variation in soil properties under plow-tillage (PT) and no-tillage (NT) maize (*Zea mays, L.*). The multisensor capacitance probes and monitoring system have proven to be highly sensitive and robust for field scale soil water research. Viewing the soil water dynamics in real-time provides opportunity for precise control over the timing and amount of water that needs to be applied for optimal crop production yet avoiding excess deep percolation losses of water and agrochemicals to groundwater.

Keywords: Capacitance probes; TDR; Soil water content; Soil water monitoring

1. Introduction

Greater understanding of the spatial and temporal dynamics of water under different soil conditions and cultural practices is required for the best use of available water resources while minimizing environmental pollution. Also, there is a continuous need for better methods to perform accurate, real-time, nearly continuous, soil water measurements at specific soil depth intervals and minimal soil disturbance, and covering large areas. New developments in precision agriculture, remote sensing, surface and subsurface preferential water flow patterns, simulation models for soil–water–plant–atmosphere interrelationships over large areas and permanent watch of leakage from the waste material depositing sites, will depend upon accurate 'ground truth' data provided by independent real-time soil water content monitoring systems covering micro to large scale hydrobasins. A survey of soil water measurement methods in current use showed gravimetric analysis as the most common method, followed by neutron thermalization and, far behind, by time domain reflectometry (TDR) and gamma attenuation (Green and Topp, 1992).

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More than 60 years of international work has been conducted on the correlation between the apparent dielectric constant of the soil–air–water–chemicals mixture (K_a) and the volumetric soil water content (θ_v) at different electromagnetic field frequencies. In the last 20 years two methods, TDR and capacitance, have proven to be accurate and useful for real-time monitoring studies (Paltineanu and Starr, 1997). Abundant experimental data show that the TDR technique is useful in studies of real-time soil water content dynamics, with average resolution commonly ranging from 0.02–0.005 $cm^3\ cm^{-3}$ water (Topp et al., 1980, 1982a, b; Topp and Davis, 1985; van Wesenbeeck and Kachanoski, 1988; Zegelin et al., 1989, 1992; Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Herkelrath et al., 1991). However, TDR systems are typically limited to small plots of land due to the requirements for short cable length (<25 m) between TDR rods and data loggers (Heimovaara, 1993). Another limitation of the TDR is the difficulty of monitoring discrete soil depths without having to install rods horizontally from a soil pit. These limitations have been overcome with new multisensor capacitance probe and soil water monitoring system with probes that can be located 500 m from a central data logger. Detailed description of the system, along with comparisons to other measuring devices was given by Paltineanu and Starr (1997). We also tested the sensors in the laboratory on a carefully compacted silt loam soil and obtained a highly significant (r^2=0.992 for n=15, and RMSE=0.009 $cm^3\ cm^{-3}$ water), nonlinear (θ_v=0.490 $SF^{2.1674}$) relationship between the soil volumetric water content (θ_v, $cm^3\ cm^{-3}$) and the scaled frequency ($SF=(F_a-F_s)(F_a-F_w)^{-1}$]. The SF represents the ratio of individual sensor's frequency (inside a PVC pipe, 5 cm O.D.) in soil (F_s), in non-saline water (F_w), and in air (F_a). 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 PVC access pipe (Paltineanu and Starr, 1997). Thus, the water content at each sensor may be expressed as either a volumetric percent or as a depth of water (mm/10 cm). Sensors are placed in the probes at user selected depths (10 cm increments) and reading intervals (1 and 9999 min). These multisensor capacitance probes and monitoring systems have been extensively used as an irrigation management tool in Australia since 1991 (Buss, 1993). We have been using the system as a research tool in several field experiments since 1995. The purpose of this report is to show some of the kinds of information that can be obtained using this system to study the real-time soil water content dynamics at short time intervals (10 min), typically at four depth positions (i.e., 10, 20, 30, and 50 cm depths), year around and multiyear, at field-scale conditions (0.5 ha), with our probes located as far as 125 m from the data logger.

2. Materials and methods

This field study was conducted on a Mattapex silt loam (fine-silty, mixed, mesic Aquic Hapludults) soil at the Beltsville Agricultural Research Center, Beltsville, MD. The Ap horizon had about 35% sand, 56% silt, 9% clay, and 0.8% organic-C. This research was part of a broader field study in which the field site, under continuous maize production, was incrementally changed from moldboard plow tillage (PT) to no tillage (NT) over a four-year period (Starr and Paltineanu, 1998). The experimental site had 26 paired-plots (4.6 by 25 m) separated by a central alley, placed on a quasi uniform 4% slope, with the plots laid out on the contour (Fig. 1). Each 4.6 m wide plot was sepa-

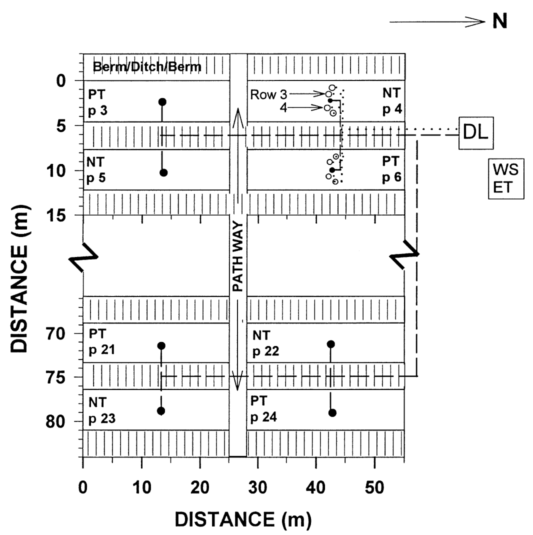

Fig. 1. Schematic layout of plow till (PT) and no till (NT) plots, with position of multisensor capacitance probes (●, ○), cables (- - -, . . .), data logging station (DL), weather station (WS), and ET gauge (ET).

rated by a 3.0 m wide berm and drainage ditch to prevent surface runoff from one plot to the next. Prior to initiating tillage treatments in 1994, all plots were plowed with a moldboard plow to a depth of 20–25 cm, disked, and planted to maize for two consecutive years. In 1995, the plots were in their fourth year of maize, and one-fourth of the plots in their second year of NT. Both tillage treatments were planted with a 6-row no-till planter in 76.2 cm rows at a plant population of about 59000 plants ha^{-1}, with wheel-compaction between rows 2 and 3 and between rows 4 and 5.

A Campbell Scientific[1] weather station and an evapotranspiration simulator (ET gage® Model A, Loveland, CO) placed about 25 m to the north of plot 6 (Fig. 1). Sprinkler irrigation water was only applied as necessary to assure continued growth of maize (Fig. 2), and did not represent a scheduling plan by either ET considerations or capacitance probe data. The amounts of irrigation water applied were measured by a tipping bucket rain gage located between the pair of PT–NT plot 4 and 6, and by collection jars placed on wooden boards in the ditch areas adjacent to the capacitance probe locations.

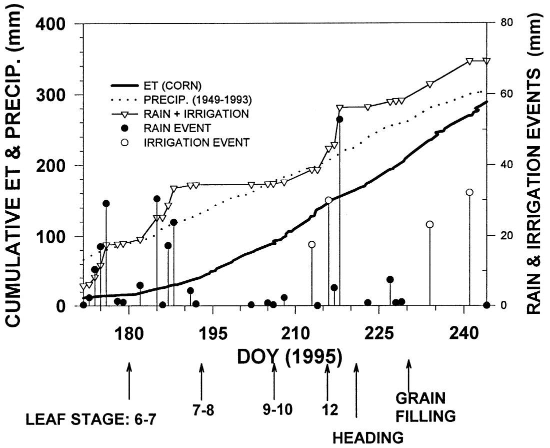

Fig. 2. Individual and cumulative distributions of precipitation (weather station) and irrigations (recorded between plots 4 and 6), 50-y average cumulative precipitation, and ET adjusted for corn growth stage.

[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 of equipment by the USDA nor an endorsement over other similar products.

2.1. Multisensor capacitance probes and soil water monitoring system

Two EnviroSCAN® (Sentek PTY, Ltd., Kent Town, South Australia) soil water monitoring systems with a total of 16 multisensor capacitance probes (with four sensor depths at each probe) were installed at this field site on June 21, 1995. The first set of eight probes were placed in four pairs of the PT–NT plots at the non-traffic interrow position (between rows 3 and 4), with initial results reported by Starr and Paltineanu (1998). A second set of eight probes were placed in plots 4 and 6. Four probes were placed at different in-row and interrow positions, resulting in a total of ten probes installed in the two intensive study plots. Each of our EnviroSCAN® systems had three main parts: (1) eight semi-permanently installed probes with four capacitance sensors each, centered at depths of 10, 20, 30, and 50 cm depths; (2) a data logging station with two 5-wire cables (<500 m) connected to probes; and (3) an internal power supply charged by a solar panel (or by external battery power during extended periods of little to no direct sunlight as occurs in the winter months). After completing probe installation and hook-up to the data logging station, the system was set to record soil water readings at each of the 32 sensors on a 10 min interval. The capacitance data may be downloaded to a portable computer, and viewed directly in the field, either by depth or cumulatively with depth at each probe, with software provided by the EnviroSCAN®. The data may also be dumped to an ASCII computer file for additional detailed numerical and graphical analysis. Software provided by R. Soppe (USDA, ARS, Water Management Research Lab., Fresno, CA) was used to convert the ASCII data to column/row format. An additional program was written to reduce the size of the data files to intervals of 20 min to up to 2 h, whenever the change from one 10 min interval to the next gave volumetric water contents of less than 0.05% at any of the sensors.

3. Results and discussion

Two real-time soil water dynamics monitoring systems (16 probes with four capacitance sensors each), were installed on June 21, 1995 in the PT–NT experiments (Fig. 1), and have been working the year around. The exceptions have been for a few days in the spring of 1996 and 1997 when the probes were removed for plowing, disking, and planting maize. The largest distance from the probes to the data logger was about 125 m. The systems have been robust with few maintenance problems during the 30 months of functioning in a large experimental site (~0.5 ha).

3.1. Sensor response to cable length

The effect of varying cable length was checked by inserting four different cable lengths (25, 100, 400, and 500 m) between a multilevel capacitance sensor probe, with two sensors, placed in the field and connected to the data logger. An average difference in frequency between the readings with the four cable lengths at each sensor was 1 in 12786 (<0.008%), giving a coefficient of variation, associated with the SF for the four distances of 0.0186 and 0.0183%. This CV was about the same as the CV associated with the SF at constant cable length (~3 m) observed when calibrating the sensors in the laboratory (Paltineanu and Starr, 1997). These data confirm the manufacturer's statement that the capacitance sensor readings are not affected by cable lengths up to 500 m, which can cover field areas up to 80 ha.

3.2. Real-time soil water dynamics across a growing season

Characteristic soil water dynamics measured with the multisensor capacitance probes, across the growing season, are illustrated for one PT–NT pair of multisensor capacitance probes (maize row N^0 3 in plots 4 and 6, Fig. 1) are shown in Fig. 3. These data represent the cumulative water content in the 5–55 cm soil depth interval (summation of the four sensor depths, plus interpolated values at the 40 cm depth). Each rapid rise in soil water content corresponded to a rainfall or irrigation event (Fig. 2). The small changes in water content was not 'noisy data', but reflects diurnal changes in soil water content – largely due to ET demand, as shown later. Differences in soil water content have been maintained in favor of NT treatment throughout the growing season. The general pattern of greater water content under NT vs. PT is consistent with these two tillage treatments, with the tillage effects largely due to different bulk density distributions and to different surface soil conditions that affect infiltration and runoff (Starr and Paltineanu, 1998).

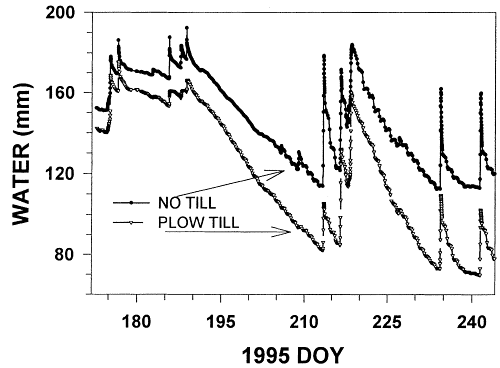

Fig. 3. Cumulative water content (5–55 cm) in maize-row 3 of plots 4 and 6.

3.3. Field determination of the in situ apparent water holding capacity (aWHC)

As shown in Fig. 3, several rainfall events between DOY 175 and 192, before high ET demand, caused only temporary rises in the soil water content as the macro pores filled and drained. The repeating pattern of nearly constant maximal water contents following these early-season rainfall events, when the maize plants were very small (6–7 leaves, Fig. 2) indicates an in situ aWHC at each probe. Thus the aWHC for the NT profile (5–55 cm) was about 172 mm, and about 160 mm under PT. The aWHC for each sensor depth interval can also be determined from the water content data at each sensor depth (Fig. 4). For example, the aWHC at the 10 cm sensor of NT (covering a sensing depth interval of 5–15 cm) was about 27 mm under NT (Fig. 4(a)). The aWHC is very important for establishing irrigation and drainage strategies and for minimizing leaching of agrochemicals to deeper soil layers.

3.4. Establishing 'breaking points' between periods of high and low rates of water loss

After the early season rainfall events, no additional important rain fell for 24 days (DOY 189-213), when maize plants were growing rapidly from 7 to 11 leaves, resulting in rapid drying of the soil profile under both

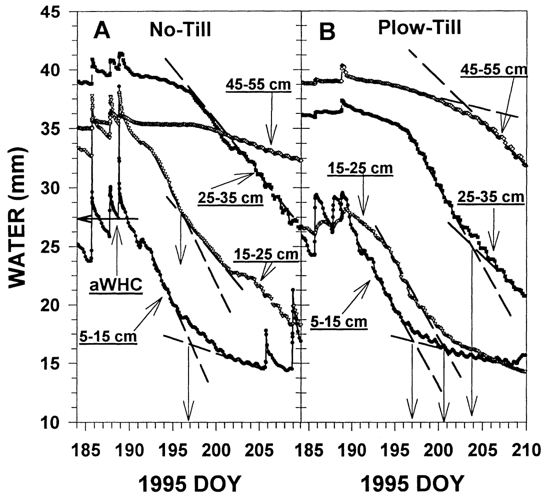

Fig. 4. Water content distribution at four sensor depths in maize-row 3 (plots 4 and 6), and showing the apparent water holding capacity and breaking points.

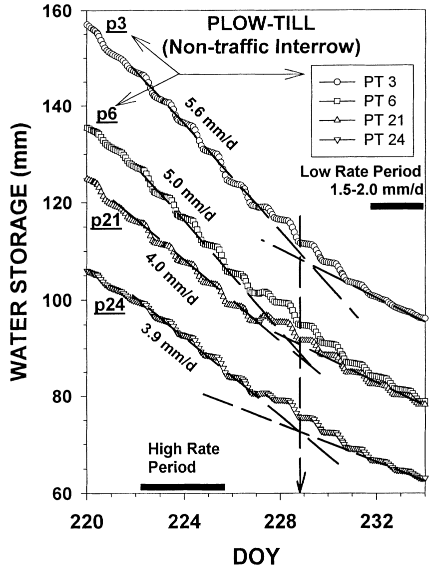

Fig. 5. Soil water dynamics (cumulative for 5–55 cm) during a period of high Et and full canopy for four PT plots. The vertical arrows approximate the breaking points between high and low rates of water loss, and the dashed lines represent the mean rates of water losses.

tillages (Fig. 3). All extended drying cycles that occurred in the presence of high ET demand resulted in an initial multidaily high rate of water loss followed by a distinctly slower multidaily rates of water loss. ‘Breaking points’ were observed at the intersection of the slopes of the two quasi steady rate of water loss, both by separate (Fig. 4) and cumulative soil depths (Fig. 5). Thus the breaking point for NT at the 5–15 cm and 15–25 cm depths occurred at DOY 197 a transition period of about four days between the high- and low-loss rates is evident at the 5–15 cm depth under NT (Fig. 4(a)). The small rainfall events from DOY 203–205 resulted in a temporary cessation of water removal at the 15–25 cm depth under NT. A small delay in the rate of water loss also occurred at the 25–35 cm depth of NT, but the overall rate of water loss remained nearly constant across the entire drying period. A slow but steady rate of water loss developed at the 45–55 cm depth interval soon after the breaking point occurred in the top two layers, indicating some root activity at this deepest depth. A similar pattern was observed for PT but the breaking points occurred sequentially in time (DOY 197, 201, and 204) at the top three sensor depths. Also, unlike that observed for NT, a breaking point was evident at the 25–35 cm depth of PT, which means that the maize roots were searching for water at that depth. ‘Breaking points’ become important in predicting irrigation applications. For example, if our first priority in this research was to maximize crop yields then we would have applied our first irrigation about two weeks earlier than we did. We have observed that the critical soil water content that results in these breaking points remain quite constant. Thus viewing the data in real-time allows the user to anticipate when the breaking points will occur and to provide irrigation at the right time. The amount of water to apply can then be easily determined as the difference between the aWHC and the breaking point for each probe location.

3.5. *Real-time dynamics of cumulative soil water contents at four plot replicates*

Real-time changes in cumulative soil water content (5–55 cm) at four plot replicates under PT during a drying cycle of the four non-traffic interrow positions across the entire experimental site (Fig. 1) are shown in Fig. 5. The highly variable initial water contents across the four replicates at DOY 220 are partially due to different amounts of sprinkler irrigation that were applied four days earlier, i.e., plots 3, 6, 21, and 24 received 36, 30, 0 and 0 mm or water, respectively.

The breaking points here, under full maize canopy, occurred approximately at the same time across the experimental site – even with the large variation in initial water contents in the four plots. The variation in these high rates of water loss (from 5.6–3.9 mm/d) for the four plots were directly related to the initial water contents, thus the different plots arrived at a critical low-water content at about the same time. As a result, the final slow-rates of water loss were about the same for the four PT positions, even though the total soil water content varied greatly across the experimental site. Clearly, local soil properties and associated rooting patterns affect the ability of the maize plants to extract water. Inspection of the diurnal variation in water loss indicates both internal drainage and ET losses of water. Night-time losses in soil water content are the clearest indication of internal drainage losses, and were most evident here in the wettest plots at the start of the drying cycle (plots 3 and 6 from DOY 220 to 222). As internal drainage decreased (night-time losses approached zero), the daytime losses are clearly due to ET demand alone (maize at ear formation stage) resulting in the diurnal changes in soil water content becoming increasingly 'stair step' like in appearance.

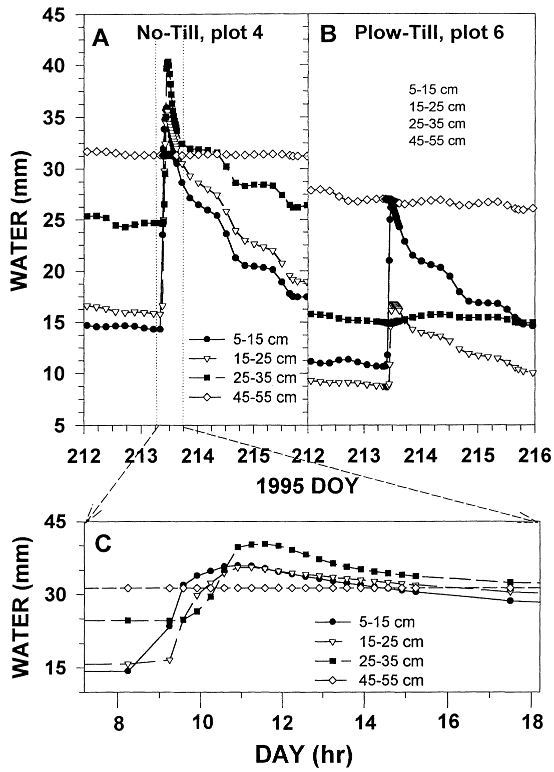

Fig. 6. Water content distribution at four sensor depths in maize-row 3 (plots 4 and 6).

3.6. Small spatial-scale effects of cultural practices on water infiltration

Placement of the multisensor capacitance probes at the row and interrow positions in plots 4 and 6 provided special insight into small-scale effects of cultural practices on the fate of water. One of our observations was the fate of small rainfall events. For example, in Fig. 3, the 2.3 mm rainfall on DOY 208 was not detected under PT, but resulted in an 8.6 mm increase in water content at this in-row position under NT. The stemflow water penetration under NT was mostly within the top sensor region (Fig. 4), but there was also an associated decrease in the rate of water loss at the next sensor depth. The funneling effect by the maize plants, and the greater macroporosity of the in-row position of NT are clearly evident from this data (Paltineanu et al., 1995). As shown in Fig. 3, by the end of the first major drying cycle the soil profile (5–55 cm) was quite dry when 17.5 mm of sprinkler irrigation water was applied on DOY 213. More of this water was detected under NT than PT, with 56.8 mm increase under NT and 23.3 mm increase under PT. In addition to the obvious stemflow effects for both tillages, some of the difference in water infiltration was likely due to some of that water being absorbed by the dryer PT 0–5 cm surface soil (visual observation).

The depth and magnitude of water infiltration with the first irrigation event in detailed is Fig. 6, where the data are plotted by sensor depth across expanded time scales. The irrigation water penetrated to the third sensor depth under NT (Fig. 6(a)), reaching a maximum water content of 35–40 mm for each 10 cm depth interval (i.e., 35%–40% $cm^3\ cm^{-3}$). After the initial rapid drainage of macropores, the water drainage occurred during the first night followed by a combined drainage and plant-water uptake during the first day after irrigation. Very little additional drainage was evident the second night followed by a lower rate of loss the next day, probably due to ET alone. A similar general pattern occurred under PT (Fig. 6(b)), only with less water penetration. The delayed slower rise in water content at the 25–35 cm depth from under

PT DOY 213.5–214 shows internal drainage from above. Further detail of the water penetration under NT is given in Fig. 6(c). Note first the changing time increment of the data plotted, from 1 h down to 20 min intervals and then up to 2 h intervals. This is due to the data compression program, not to varying intervals of the sensor readings. Secondly, note the sequence and speed of water penetration from the first sensor depth to the third depth, with the peak in water contents moving from one sensor depth to the next in about 1 h. This rate of movement suggests substantial filling of meso- and macropores, and their associated higher hydraulic conductivities than might be expected from the soil matrix of silt-loam soil.

4. Conclusions

The multisensor capacitance probes and monitoring system was found to be highly sensitive and robust for field scale soil water research. Real-time soil water dynamics by depths, at both small- and large-areas, can provide crucial information for understanding the impact of cultural and cropping practices on the fate of water in soils. Accurate 'ground truth' data is needed for new developments in precision agriculture, remote sensing, soil–water–plant–atmosphere interrelationship models, and for improved water management under irrigated agriculture. The method provides, among others, the capability for field determination of (1) the 'apparent water holding capacity', (2) the 'breaking points' between periods of high and low rates of water loss, (3) the small spatial-scale effects of cultural practices on water infiltration, (4) real-time viewing of soil water dynamics over large areas, and (5) irrigation scheduling strategies. Such capabilities are needed for a better and understanding of the fate of water and agrochemicals in soils and the effects of soil and crop management practices on the environment.

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