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ASSESSMENT OF ROOTZONE WATER REDISTRIBUTION IN CORN FOLLOWING IRRIGATION

M.R.C. CORDEIRO[1], S. SATCHITHANANTHAM[1], R. SRI RANJAN[1]

[1] M.R.C. CORDEIRO, Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6,umcorde8@cc.umanitoba.ca.
[1] S. SATCHITHANANTHAM, umsatchi@cc.umanitoba.ca.
[1] R. SRI RANJAN, ranjan@cc.umanitoba.ca.

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ABSTRACT An understanding of the water redistribution pattern within the corn rootzone will help design better irrigation and drainage systems. The objective of this research was to use time-domain reflectometry (TDR) miniprobes to measure water content within the rootzone of corn at different locations within the rootzone as a function of time. Forty-five TDR miniprobes were installed, in three vertical planes, for measuring volumetric water content and salinity within the rootzone of a corn field located in Winkler, Manitoba. The probes were inserted at 0.1, 0.2, 0.4, 0.6, and 0.8 m depths from the ground surface and at 0.12, 0.24, and 0.36 m radial distances from the base of the corn plant. The soil was thoroughly wetted by applying 50 mm of water within the experimental site. The volumetric water content was measured before and at periodic intervals after the irrigation event. The evening following the irrigation event showed an increase in water content within the entire soil profile. The water content started to decline as the days progressed. However, during the mornings, the soil within the root zone seemed to show an increase in water content when compared to the previous afternoon. An examination of the water content distribution within the root zone indicated an upward migration of water from soil layers located below 0.8 m.

Keywords: Soil water redistribution, Water content measurement, Time-domain reflectometry, Corn.

INTRODUCTION Water redistribution pattern within the plant rootzone is an important factor used in the design of efficient irrigation and drainage systems. However, the investigation of water redistribution within the rootzone profile is complex because it involves processes that depend on the soil type and plant characteristics (Garrigues et al., 2006). Soil moisture content, root morphology, and plant physiological status strongly control water uptake at the rootzone scale. An understanding of these processes is difficult due to limited ability to non-destructively assess the water uptake from within the root zone (Ehleringer and Dawson, 1992). While excavation studies provide a one-point-in-time snapshot of the soil profile, they provide little insight into resource uptake rates or patterns of resource utilization as a function of time.

In order to overcome the limitations of excavation methods which are destructive, minimally-invasive techniques that do not affect the soil properties may be used to continually monitor the soil moisture status in the rootzone. The time-domain reflectometry (TDR) technique can be successfully adapted for this purpose, since most TDR systems are designed for long-term installation and continual monitoring at shallow depths (Schwartz et al., 2008). Different types of TDR probes are commonly used to measure soil water content because of its ability to acquire data quickly, and its relative safety when compared to nuclear methods. Soil water measurements using TDR are derived by converting the measured bulk dielectric constant of a material, such as moist soil, into volumetric water content. A description of the TDR technique is given by Dalton (1992), while the details about the use of the method to determine field soil-water content are provided by Zegelin et al. (1992).

An important consideration of TDR systems is the type (i.e. number of rods) and size (i.e. rod spacing and length) of the probe. According to Malicki et al. (1992), dimension defines the suitability of the probe to particular applications. For example, probes longer than 150 mm may not be suitable for some laboratory applications when the soil column diameter is small or when working with unconsolidated soil samples (Sri Ranjan and Domytrak, 1997). In field applications, the length of the probe has also an influence on the readings, since the soil water content measured is averaged over the entire probe length. The smaller the probe length, the larger the noise in the data necessitating the use of special smoothing algorithms to accurately predict the water content of the soil. For studies on soil water redistribution patterns, probe length is critical. In such cases, miniprobes having a length of 50 mm with outer rods spaced at 10 mm enabled the water content to be measured in a small volume of soil (Sri Ranjan and Domytrak, 1997). This allowed for the readings to be taken within the soil profile as point measurements at different depths and distances from the base of the plant. The smaller probe length also allowed easier insertion into the soil with minimal disturbance in the root zone (Kahimba et al, 2008). Kahimba et al (2008) used miniprobes to obtain volumetric water content data at 0.1, 0.2, 0.4, 0.6, 0.8 m depths from the ground surface. Similarly, an array of miniprobes can be used to acquire a number of point-readings at different depths and different radial distances from the base of the plant, rather than having a single reading averaged over the entire profile.

The objective of this research was to assess the water redistribution pattern within the rootzone of corn after a 50-mm irrigation event. An array of TDR miniprobes was used to acquire soil moisture and electrical conductivity readings in the soil profile. The results of volumetric water content measurements at five different depths and three distances from the plant as a function of elapsed time following an irrigation event are presented, and the changes in redistribution pattern with time is discussed.

MATERIAL AND METHODS The study was carried out in Winkler, Manitoba, Canada, between August 31 and September 4, 2009, at coordinates 49°07.094' N and 97°57.548'W. The field was cropped with corn, and the row spacing was 0.76 m (30 inches). The sunrise and sunset times on August 31 were 6:43 am and 8:15 pm, respectively. On September 4, the sunrise was five minutes later and the sunset was ten minutes earlier. During this period, the minimum temperature was 10.9°C on August 31 and the maximum temperature was 26.5 °C on September 3; the average temperature was 18.7°C (Environment Canada, 2009). The soil in the area belongs to the Reinland Series, which is an imperfectly drained Gleyed Rego Black soil having coarse loamy texture (Podolsky, 1991). The dry bulk density of the soil was determined by taking 100-cm^3 samples at five different depths (0.1, 0.2, 0.4, 0.6, and 0.8 m), and the porosity was calculated by:

$$\phi = 1 - \left(\frac{\rho_b}{\rho_p} \right), \quad (1)$$

where ϕ is the soil porosity, ρ_b is the dry bulk density (g cm^{-3}), and ρ_p is the particle density (assumed to be 2.65 g cm^{-3}). The bulk density varied from 1.44 to 1.58 g cm^{-3}, and the porosity varied from 0.40 to 0.46.

Field data collection Forty-five, 0.05-m long TDR miniprobes were custom made and individually calibrated in our laboratory. They were installed at five different depths (0.1, 0.2, 0.4, 0.6, and 0.8 m from the ground surface) and three different distances from the plant (0.12, 0.24, and 0.36 m from the base of the plant), totalling 15 probes in each of the three replicates (Figure 1). The probes were installed following the procedure described by Kahimba and Sri Ranjan (2007). An area of about 5 m x 4 m enclosing the three replicates was delimited and the soil was thoroughly wetted by applying 50 mm of water. Soil moisture and electrical conductivity readings were acquired using a Metallic Cable Tester 1502B (Tektronix, Inc., Beaverton, OR, USA), which was connected to the 15 probes in each replicate by means of a 16-channel Vazec multiplexer (Vadose Zone Equipment Company, Amarillo, TX, USA). WinTDR 6.1 software (Department of Plants, Soils and biometeorology, Utah State University, Logan, UT, USA) running in a laptop PC was used as the interface to control the TDR system and acquire the data.

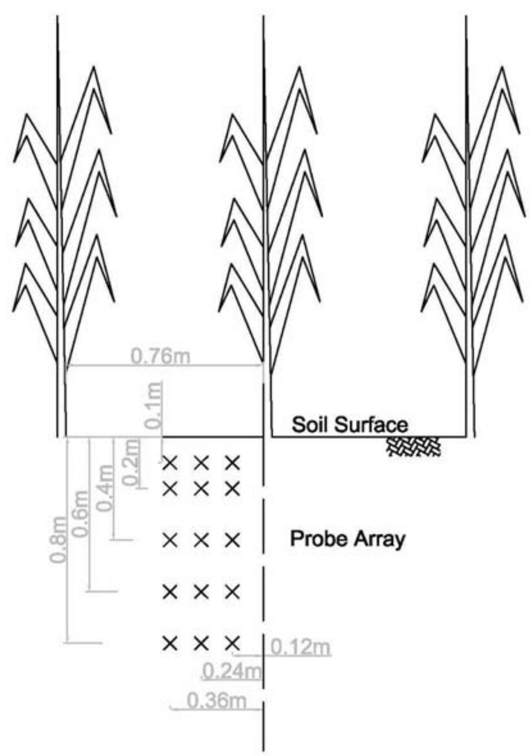

Figure 1. Scheme of the probe array installation, indicating the depths and distances from the plant in meters.

Data analysis Triplicate readings were acquired for each probe before the irrigation event and at three times a day (i.e. morning, between 10:30 and 11:30 am; afternoon, between 14:30 and 15:30 pm; and evening, between 18:30 and 19:30 pm) during the subsequent four days. The average of these readings was used as the input value in the data analysis. The volumetric water content data as a function of depth and distance from the base of the plant was plotted at successive times as 2D contour plots using SigmaPlot 2000 (Systat Software Inc., San Jose, CA, USA). These snapshots of soil water distribution at different times showed a pattern of redistribution. The soil water content was also statistically compared between different periods of the day for the same position using matched-pairs procedure in JMP 8.0 software (SAS Institute Inc., Cary, NC, USA).

RESULTS The soil water variation as a function of time is shown in Figure 2, while the soil water distribution in the soil profile for the morning, afternoon, and evening periods is shown in Figure 3 as snapshots for each time. The average water content in root zone before wetting was 0.22, but the depths close to the surface had water content of about 0.20. At 0.8 m depth and at 0.36 m distance from the base of the plant the water content was found to be as high as 0.30 (Figure 3a). After wetting, the average soil moisture within the root zone increased to 0.3. The highest water content in the profile was observed in the morning of Day 2 with values as high as 0.35 at depths ranging from 0.1 to 0.5 m. However, these values decreased during the day reaching an average of 0.25 by the evening (Figures 3c through 3e). The water content started to decline as the days progressed. During Day 3 morning, the profile was drier at the surface, uniform between 0.2 and 0.6 m, and wetter at 0.8 m. The situation remained stable during the early part of Day 3 and by the evening, some radial replenishment was observed between the depths of 0.2 and 0.5 m and at a distance of 0.36 m from the base of the plant. From this point on, the pattern was drier in the afternoon, showing some replenishment in the evening that persisted until the following morning. This pattern is depicted by the last portion of Figure 3, from hour 60 to hour 86. The afternoons are characterized by the low peaks, while mornings are characterized by the high peaks before afternoons. The moisture in this case seemed to be coming from the wetter part of the profile at 0.8 m, in which θ_v remained stable between 0.30 – 0.35 (Figures 3j through 3m).

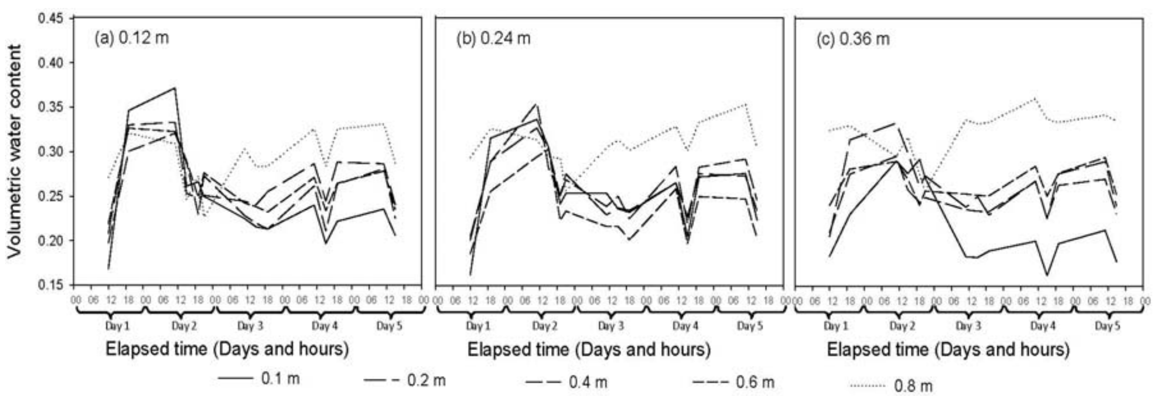

Figure 2. Water content (%) variation with time during the experiment. Letters (a) through (c) represent distance from the plant (m), while lines represent probes at different depths (m).

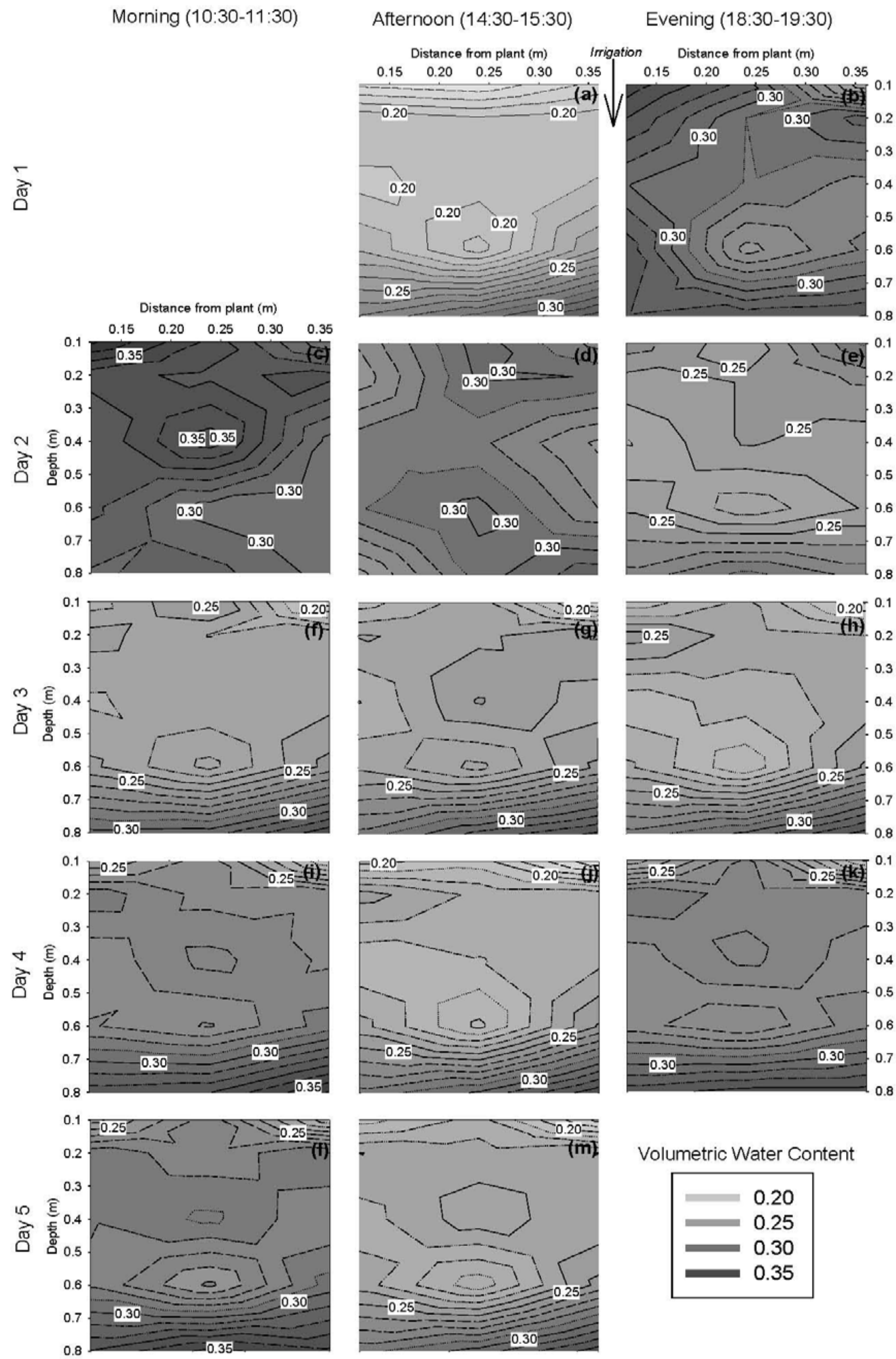

Figure 3. Changes in water distribution in the root zone of corn during the 4 days of monitoring. Letters (a) through (m) indicate different snapshots in time.

Table 1. Comparison of average volumetric soil water content for different times of the day at the same distance from plant and depth.

	0.12 m			0.24 m			0.36 m		
Depth	Morning	Afternoon	Evening	Morning	Afternoon	Evening	Morning	Afternoon	Evening
0.1	0.268 a	0.220 b	0.262 a	0.283 a	0.243 b	0.266 ac	0.222 a	0.199 b	0.228 ab
0.2	0.288 a	0.245 b	0.280 a	0.274 a	0.250 b	0.263 ab	0.283 a	0.254 b	0.271 ab
0.4	0.273 a	0.236 b	0.252 ab	0.293 a	0.250 b	0.262 cb	0.268 a	0.238 b	0.254 ab
0.6	0.279 a	2.249 b	0.268 ab	0.255 a	0.230 b	0.233 ab	0.281 a	0.257 b	0.263 cb
0.8	0.308 a	0.281 a	0.297 a	0.326 a	0.304 a	0.314 a	0.334 a	0.331 a	0.319 a

Letters a to c compare the means row-wise.

Table 2.Comparison of average volumetric soil water content for different distance from plant at the same time of the day and depth.

	Morning			Afternoon			Evening		
Depth	0.12 m	0.24 m	0.36 m	0.12 m	0.24 m	0.36 m	0.12 m	0.24 m	0.36 m
0.1	0.268 m	0.283 m	0.222 m	0.220m	0.243 m	0.199 m	0.262 m	0.266 m	0.228m
0.2	0.288 m	0.274 m	0.283 m	0.245m	0.250 m	0.254 m	0.280 m	0.263 m	0.271m
0.4	0.273 m	0.293 m	0.268 m	0.236m	0.250 m	0.238 m	0.252 m	0.262 m	0.254m
0.6	0.279 m	0.255 m	0.281 m	2.249m	0.230 m	0.257 m	0.268 m	0.233 n	0.263mn
0.8	0.308 m	0.326 m	0.334 nm	0.281m	0.304 m	0.331 nm	0.297 m	0.314 m	0.319m

Letters m and n compare the means row-wise.

Table 2.Comparison of average volumetric soil water content for different depths at the same time of the day and depth distance from plant.

	0.12 m			0.24 m			0.36 m		
Depth	Morning	Afternoon	Evening	Morning	Afternoon	Evening	Morning	Afternoon	Evening
0.1	0.268 r	0.220 r	0.262 r	0.283r	0.243 r	0.266 r	0.222 r	0.199 r	0.228 r
0.2	0.288 r	0.245 sw	0.280 rs	0.274rs	0.250 r	0.263 r	0.283 st	0.254 st	0.271 r
0.4	0.273 rs	0.236 rs	0.252 rtv	0.293rtv	0.250 r	0.262 r	0.268 rt	0.238 rtw	0.254 r
0.6	0.279 rs	2.249 tw	0.268 rsv	0.255rs	0.230 r	0.233 r	0.281 st	0.257 stx	0.263 r
0.8	0.308 rt	0.281 v	0.297 rsw	0.326rtv	0.304 s	0.314 s	0.334 sv	0.331 svy	0.319 s

Letters r to y compare the means column-wise.

The water depletion pattern during the afternoon was partially confirmed by the statistical analysis comparing the soil moisture status in the soil profile at the same depths and spacing from the plant temporally. As seen in Table 1, the difference in water content between morning and afternoon was statistically significant at depths below 0.3 m and at 0.12 m radial distance from the plant. This region is expected to show a larger variation in water content since it is closer to the wetter layer in the profile (i.e. 0.8 m) and closer to the dense part of the roots, which makes this area subjected to a higher plant water uptake. Table 2 shows that there is a statistically significant difference in water content between radial distances only at deeper layers, indicating little radial movement of water towards the plant at shallower layers. Table 3 shows the expected difference between depths, indicating vertical movement of water.

The electrical conductivity (EC) within the soil profile did not show much variation after the wetting event (data not shown). Before wetting, the average electrical conductivity of the soil was 0.36 dS/m, but it increased to 0.43 dS/m in the evening immediately following the irrigation event and to 0.51 dS/m during the following morning on Day 2. On Day 2, the EC had decreased to 0.41 dS/m and remained stable thereafter. This level of electrical conductivity indicates very weak salinity.

DISCUSSION During the irrigation event, the infiltration rate was observed to be low, leading to some ponding of the water on the soil surface. The delay observed between the wetting event and the uniform, high water content of the profile in Day 2 was probably due to the slow infiltration. This may also have influenced the establishment of the distinctive pattern observed from the end of Day 3, where the profile is dryer in the afternoon and wetter in the evening and next morning. Figure 3 indicates that the soil moisture variation in the major part of the profile was 0.05 or less, while the soil moisture at 0.8 m depth was stable at about 0.32, which is approximately closer to the field capacity of the soil. The replenishment observed in the profile seems to be coming from the deep layers, as indicated by the statistical analysis (Table 3). Figure 3 seems to depict lateral movement of water from radial distances away from the plant (probably the mid-row spacing which is less subject to plant uptake), but this possibility was not confirmed by the statistical analysis (Table 2).

The vertical water pathway may take place through the root system when the ET ceases, in a process called hydraulic lift (Caldwell and Richards, 1989). In this process, water moves from relatively moist to drier soil layers using plant root systems as a conduit. Water released from roots during periods when ET ceases (usually at night) into the upper soil layers is then absorbed the next day and transpired. While hydraulic lift has been shown in a relatively small number of species in arid and semi-arid regions, the process is believed not to be restricted to these species and regions (Caldwell et al., 1998). In fact, the sequence of snapshots in Figure 3 seems to support this claim for corn, but more detailed investigations would be necessary to confirm this possibility.

Alternatively, the upward water movement could be driven by capillary rise, as a result of the hydraulic gradient created from water uptake by plants. In this process, water is drawn from deeper layers, driven by the hydraulic gradient created in the soil profile due to high evapotranspiration (ET) from the upper layers (Smedema et al. 2004). Higher water uptake corresponds to higher ET periods, which is mainly determined by radiation, air temperature, humidity and wind speed (Allen et al. 1998). The results indicated that drier soil profile occurred in the afternoon, when radiation is more direct and temperatures are higher, thus favouring larger ET and, consequently, higher soil water uptake by plants. In the evening, the water content at depths between 0.2 and 0.6 m were drier compared to the deeper layers within the rootzone profile, which resulted in a hydraulic gradient driving the water upwards. The capillary rise from the water table may represent the source of soil moisture coming from below. The texture of the soil also favours the presence of thicker capillary fringe, which is at saturation and slightly negative pressure. The capillary fringe will further decrease the distance between the water source and the drier layers, thus facilitating the upward movement of the water.

CONCLUSION Studying the redistribution of moisture in the soil profile is an important aspect when designing irrigation and drainage systems. However, it requires a monitoring system that acquires data quickly and at regular intervals. This work made use of TDR miniprobes to monitor water redistribution within the rootzone of corn after a wetting event in a farm in Winkler, MB, Canada. The analysis of contour plots and statistical procedures indicated that after an initial increase in water content, the water status of the soil profile tends to follow a pattern in which the soil is drier in the afternoon due to high water demand by plants but its water content is replenished in the evening when the evapotranspiration decreases. The data also suggests that hydraulic lift may play a role in the replenishment as an alternative pathway for the soil moisture movement. The electrical conductivity during the monitoring period remained stable after the wetting event.

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REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1988. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and drainage paper 56. Rome: Food and Agriculture Organization of the United Nations.

Caldwell, M. M., and J. H. Richards. 1989. Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia 79: 1-5.

Caldwell, M. M., T. E. Dawson, and J. H. Richards. 1998. Hydraulic lift: consequences of water efflux from the roots of plants. Oecologia 113: 151-161.

Dalton, F. N. 1992. Development of time-domain reflectometry for measuring soil water content and bulk soil electrical conductivity. In Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. G. C. Topp, and R. E. Green. 143-168. Madison, WI: SSSA.

Ehleringer, J. R., and T. E. Dawson. 1992. Water uptake by plants: perspectives from stable isotope composition. Plant, Cell Environ. 15: 1073-1082.

Environment Canada. 2009. National Climate Data and Information Archive. Available at: http://www.climate.weatheroffice.ec.gc.ca/radar/index_e.html. Accessed 5 December 2009.

Garrigues, E., C. Doussan, and A. Pieret. 2006. Water uptake by plant roots: I – Formation and propagation of a water extraction front in mature root systems as evidenced by 2D light transmission imaging. Plant and Soil 283: 83-98.

Kahimba, F.C., R. Sri Ranjan, J. Froese, M. Entz, and R. Nason. 2008. Cover crop effects

on infiltration, soil temperature, and soil moisture distribution in the Canadian Prairies. Applied Engineering in Agriculture 24(3): 321-333
Kahimba F. C., and R. Sri Ranjan. 2007. Soil temperature correction of field TDR readings obtained under near freezing conditions. Can. Biosystems Eng. 49: 1.19-1.26.
Malicki, M. A., R. Piagge, M. Renger, and R. T. Waiczak. 1992. Application of time-domain reflectometry (TDR) soil moisture miniprobe for the determination of unsaturated soil water characteristics from undisturbed soil cores. Irrigation Sci. 13: 65-72.
Podolsky, G. 1991. Soils of the Rural Municipality of Rhineland. Report No. D76. Winnipeg, Canada: Canada-Manitoba Soil Survey.
Schwartz, B. F., M. E. Schreiber, P. S. Pooler, and J. D. Rimstidt. 2008. Calibrating access-tube time domain reflectometry soil water measurements in deep heterogeneous soils. Soil Sci. Soc. Am. J. 72: 917-930.
Smedema, L. K., W. F. Vlotman, and D. W. Rycroft. 2004. Modern Land Drainage: Planning, Design, and Management of Agricultural Drainage Systems. Leiden, The Netherlands: A.A. Balkema Publishers.
Sri Ranjan, R., and C. J. Domytrack. 1997. Effective volume measured by TDR miniprobes. Trans. ASAE 40(4): 1059-1066.
Zegelin, S. J., I. White, and G. F. Russel. 1992. A critique of the time domain reflectometry technique for determining field soil water content. In Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. G. C. Topp, and R. E. Green. 187-208. Madison, WI: SSSA.