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Soil Water and Shallow Groundwater Relations in an Agricultural Hillslope

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SOIL PHYSICS

Shallow water tables can contribute water for plant use; therefore, plant available water includes not only the water stored in the root zone, but also the water moving up from below the root zone. The purpose of this study was to quantify the amount of water moving upward to the root zone. Automated water content reflectometers were used to monitor soil water content across a landscape in Central Iowa, which had varying shallow water tables. Either manual or automated water table depths were measured. Tipping bucket raingage and eddy covariance evapotranspiration (ET) methods were used to measure rain and evapotranspiration as part of the water balance. Upward water movement ranges were determined from water balance and uncertainties for each component (rain, ET, change in soil water content). In 2006 out of 53 dry days (days that did not have any rain), 37, 43, and 46 d showed net upward flux for shoulder, backslope, and toeslope positions, shown by an uncertainty range that did not overlap zero. In 2007, 37 out of 62 dry days showed net upward flux for the toeslope position. The mean significant net upward flux for dry days was 2.6, 3.2, and 3.1 mm d^{-1} for the shoulder, backslope, and toeslope positions in 2006, and 2.5 mm d^{-1} for the toeslope position in 2007. Mean ET on nonrain days was 4.0 and 4.1 mm d^{-1} in 2006 and 2007. Automated equipment used to develop a water balance approach provided a quantitative approach to estimate net upward soil water flux in agricultural fields.

Abbreviations: ET, evapotranspiration; CSI, Campbell Scientific Instruments.

Logsdon et al. (1999) showed that field variability in water table depth and soil water content is not consistent over time for closed depression topography with strategic tile placement. Presence of a functioning tile (installed ~1.2 m depth) results in a small range of water table depths ~0.9 to 1.2 m until dropping below the tile depth when tile drainage ceases (James and Fenton, 1993). Shoulder and backslope positions are often too far from the tile to be influenced in the short term (days), but drain into the tile in the long term (weeks). "In profile, backslopes are bounded by a convex shoulder above and a concave footslope below" (Soil Science Society of America, 2008). A wet spring may result in a more uniform water table distribution among the landscape positions, except for deeper water table depths near the tiles. Then the water table redistribution during the summer and fall, according to the pressure head gradient, results in deeper water table depths upslope than for toeslope and depressional positions. The total water table-depth-range will be greater over the season in drier years for summit, shoulder, and backslope positions than for toeslope and depressional areas (Logsdon et al., 1999). Khan and Fenton (1994) observed 10-yr water table-depth-ranges from 1.0 to 3.2 m for well drained, 0.4 to 2.8 m for somewhat poorly drained, and 0.2 to 1.2 m for poorly and very poorly drained fields that were tile-drained.

Shallow water tables contribute to upward capillary movement into the root zone to replenish soil water lost from root uptake (Van Bavel et al., 1968; Allmaras et al., 1975; Van Bavel and Ahmed, 1976; Stuff and Dale, 1978; Chen and Hu, 2004; Loheide, 2008), unless the water table is so shallow that root activity is restricted (Nielsen et al., 1959; Williamson and Kriz, 1970; Carter et al., 1988). This contributes to a smaller range of soil water content over the growing season for toeslope positions (Logsdon et al., 1999), even though overall water uptake may be greater for toeslope positions than for upslope positions. Gentle topography (slopes < 5%) contributes to lateral loss in the upper part of the water table. Lateral additions continuously replenish the water table in toeslope and depressional areas as water is removed by tiles or upward water movement.

Actual amounts of upward water movement (from below the root zone into the root zone) have been difficult to quantify when soil water content and water table depths are only measured periodically. Automated soil water data could be useful in determining soil water flow patterns, such as upward water movement and lateral flow (Morgan and Stolt, 2004; Nachabe et al., 2004, 2005). Even with enhanced monitoring of subsurface conditions, some factors can lead to errors in analysis. Interfering factors include trapped air in the water table that responds to diurnal temperature fluctuations and temperature effects on soil water content determination by automated probes that function at low frequencies (Logsdon, 2005; Logsdon and Hornbuckle, 2006).

Another approach for quantifying upward flow would be to include evapotranspiration and rainfall measurements for a complete water balance (Healy and Cook, 2002; McCoy et al., 2006). The purpose of this study was to use a water balance approach to determine

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water flux in a field with closed depressions and to compare the differences among three positions across a landscape transect. The difference in this study and previous studies is that evapotranspiration was separately measured in this study, but only indirectly calculated for previous studies (Loheide et al., 2005; Schilling and Kiniry, 2007).

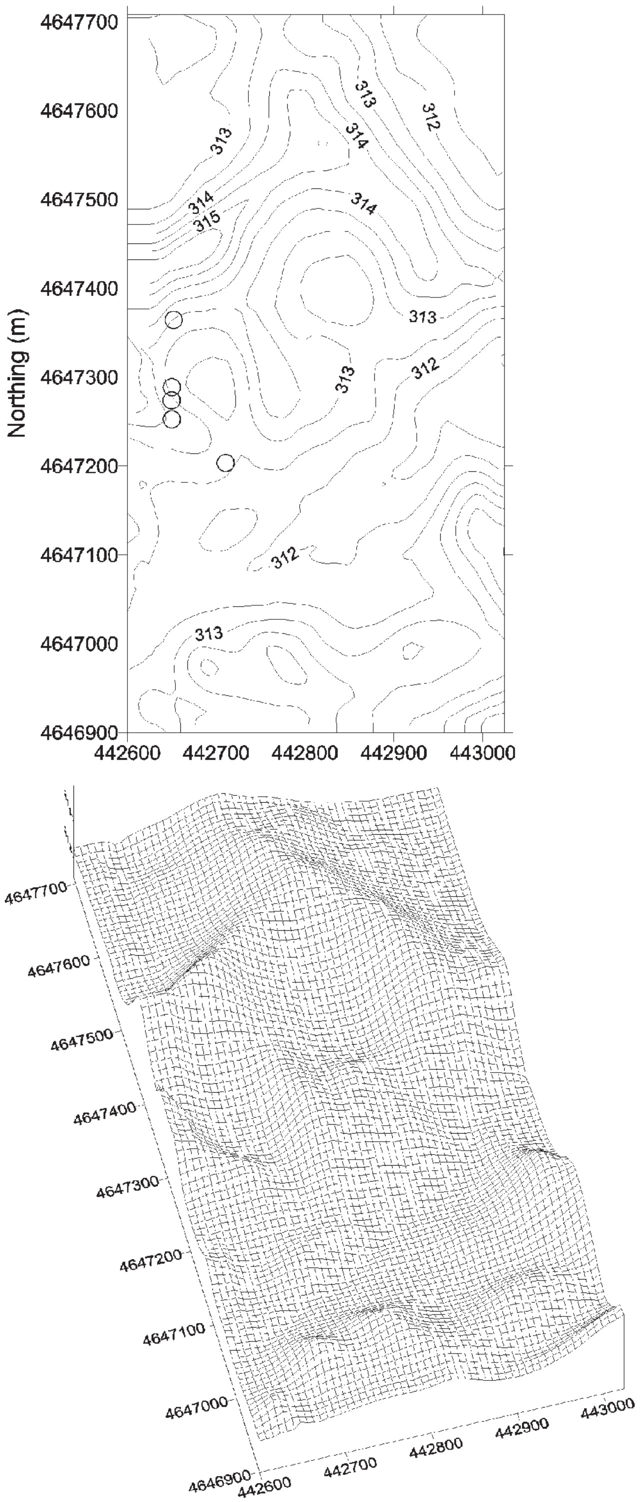

Fig. 1. Field site for 2006 and 2007 data sets. The northernmost point was the site for 2007 (toeslope), and the next points were toeslope, backslope, and shoulder positions in 2006. The southernmost point is the eddy covariance tower and rain gauge. Mean sea elevation is in meters. The contour data is shown below as a wire-mesh diagram to better display the gentle hills and valleys.

MATERIALS AND METHODS

Field Details

Measurements were made in a central Iowa field, planted to soybean [*Glycine max* (L.) Merr.] 11 May 2006, and to corn (*Zea mays* L.) 11 May 2007. No other crops were grown in these Des Moines lobe soils, which are characterized by closed depressions that are often tile-drained (Khan and Fenton, 1994; Logsdon et al., 1999). In the Des Moines lobe the tile drains are not uniform but are arranged to drain the closed depressions. This study in 2006 began to address issues of landscape position, but there were not enough soil moisture probes to instrument the whole root zone at all three sites. The study was enhanced in 2007 and concentrated on using more probes at one site to instrument more of the root zone, but then only one site could be studied.

In 2006, at three positions on a hillslope (shoulder, backslope, toeslope), we installed wells and neutron access tubes (Fig. 1, 2). The shoulder and backslope positions were Clarion soils (fine-loamy, mixed, superactive, mesic Typic Hapludolls), and the toeslope position was a Webster soil (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2008). In 2007 we also instrumented a different toeslope position (Webster soil) (Fig. 1, 2).

In 2006, elevations above mean sea level for the shoulder, backslope, and toeslope positions were 313.4, 313.1, and 312.8 m (Fig. 1, 2). The slopes for the three positions were 3.08, 3.28, and 0.83%; the mollic epipedon depths were 0.45, 0.37, and 0.81 m deep, and depths to carbonates were 0.70, 0.79, and 1.16 m. In 2007, the toeslope position had a mean sea elevation of 313.5 m, the depth of the mollic epipedon was 0.79 m, and the depth to carbonates was 1.8 m. A sand layer was evident ~1 to 1.4 m within the sediments (not shown) above the glacial till (>1.8 m). The slope was 3.06% (Fig. 1, 2). The toeslope position used in the 2007 study was at a higher elevation than the toeslope for 2006 because the hill was longer (Fig. 2). Hand-drawn tile maps from the early 1900s showed a tile extending diagonally from northwest to southeast past the toeslope position from 2007, then straight west between the toeslope positions from 2007 and 2006 (Fig. 2). The angled portion was approximately 100 m east of the 2007 position, but did not extend as an angled area to the east of the 2006 sites. These approximate tile positions were not field-verified.

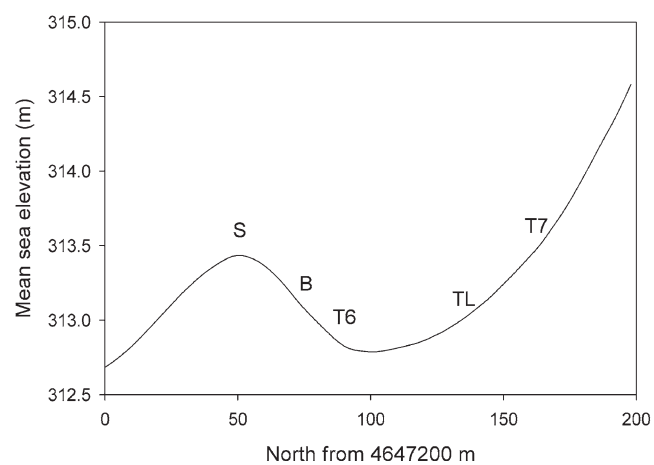

Fig. 2. Transect only Easting 4642650 m showing the 2006 positions of shoulder (S), backslope (B), and toeslope (T6), and the 2007 toeslope position (T7). Also shown is an approximate location of the tile line (TL). The elevation differences are enhanced compared with the lateral distance.

Monitoring Equipment

Tractor-driven hydraulic equipment was used to install neutron probe access tubes and wells. The wells were made of 50-mm inner diam. PVC pipe with screw fittings. In 2006 the screened bottom sections were 0.75 m long, and in 2007 they were 1.5 m long. The neutron probe access tubes were 50-mm diam. steel tubing. Both neutron access tubes and the top sections of wells were sealed with bentonite to prevent water flow down the external side of the tube. The neutron probe access tubes and wells were installed 7 June 2006 and 8 June 2007.

As we prepared the hole for the neutron access tube, the excavated soil was saved in 50-mm diam. plastic liners for two 1.2-m sections down to >2 m, when possible. The soil samples were used for morphologic characterization (2006 and 2007) as well as particle-size analysis by the hydrometer method (2007 only, Gee and Bauder, 1986), and as a check on soil water neutron probe calibration (see Appendix) and bulk density (2006 and 2007).

The neutron probe (Troxler, Triangle Park, NC) was read every 0.2 m, beginning at 0.3 m below the soil surface. The calibration procedure is given in the Appendix. A volumetric sampler (Pikul and Allmaras, 1986) was used to collect surface samples 0 to 0.3 m for surface soil water content at the same time the neutron probe measurements were taken. The samples were subdivided into 0 to 0.1, 0.1 to 0.2, and 0.2 to 0.3 m. The wells were also manually read with a water level recorder at the same time that the neutron probe readings were taken, every 1 to 4 wk. Automated water-level recordings were included in 2007 using a non-venting transducer (miniTROLL from In-Situ, Inc., Ft. Collins, CO), and readings were corrected for barometric pressure (Rasmussen and Crawford, 1997).

Automated Water Balance

In 2006 we installed copper-constantan soil thermocouples (for temperature) and CS616 soil water content reflectometers (Campbell Scientific, Inc.[CSI], Logan, UT) at four depths: 0.3, 0.5, 0.7, and 0.9 m. The CS616s were installed at an angle centered at the desired depth. The exact angle was not determined because of the difficulty installing after planting. In 2007 we installed soil thermocouples and CS616 probes at the 0.05- and 0.15-m depths in both row and interrow positions. The probes were angled at deeper depths (extended beyond row or interrow): 0.3, 0.5, 0.7, 0.9, and 1.1 m. The exact angle was not measured, but the purpose of the angling was to have minimal effect on water movement through the soil, and more uniform soil water along the probe than would be true for vertical installation. Horizontal installation was not possible after planting to avoid disturbing the crops, since a much smaller access pit was needed for angled installation than would be needed for horizontal installation. The CS616 and thermocouples were installed on 29 June 2006 and 22 June 2007, and were read once per hour. The calibration information is given in the Appendix and the concept is described in Logsdon (2009).

Rainfall was measured with a tipping bucket rain gauge (CSI, Logan, UT). Evapotranspiration (latent heat flux) was measured by eddy covariance described by Hatfield et al. (2007). Eddy covariance equipment consisting of a LI-7500 (open-path water vapor- carbon dioxide sensor, Li Cor Bioscience, Lincoln, NE) coupled with a CSAT sonic anemometer (CSI, Logan, UT) was used to measure latent heat as described by Hatfield et al. (2007). Latent heat flux values were converted to millimeters ET using a conversion factor of 0.000381 mm (per W m^{-2}) per 15 min interval (expressed as 15 min totals). Other meteorological data were collected, of interest to this study was barometric pressure. Because the rainfall data had a few missing data points, data were combined with rainfall data from an adjacent field (west of field in Fig. 1) to produce a complete record.

The eddy covariance data were screened as discussed by Hatfield et al. (2007), which often resulted in missing data that were outside allowable ranges. Gap filling of missing ET data was done using an iterative interpolation technique described in Hernandez-Ramirez et al. (2009) and summarized in the Appendix.

Water Balance

Soil water changes were compared with ET and rainfall data. For areas with a shallow water table, we propose determining net drainage/upward flow (N) by water balance:

$$\frac{\Delta S}{\Delta t}=P-\mathrm{ET}+N \qquad [1]$$

in which $\frac{\Delta S}{\Delta t}$ is change in soil profile water for the depth of automated measurements (0.3 to 0.9 in 2006, 0 to 1.1 m in 2007) over the cumulated 24 h time (t), P is precipitation, and ET is evapotranspiration. The N would include lateral additions and loss, which would be most pronounced during and after rain events. Note that $\frac{\Delta S}{\Delta t}$ only included the unsaturated zone above the water table when the water table was more shallow than the deepest measurement depth. The reason for this restriction would be due to little if any root growth in the water table, and the control section considered was the root zone. This resulted in a more shallow control section early in the season, since the root system that was still growing and would grow into the water table. Previous unpublished data by the senior author showed corn and soybean roots extending to around 1.3 m in these soils at the end of the season unless the water table was more shallow.

Error Analysis

The seasonal days considered (all automated equipment working) were 30 June to 19 September 2006, and 23 June to 13 August, then 29 August to 30 September 2007. In 2006 there were 53 d without rain, and in 2007 there were 62 measured days without rain. The 2-wk gap in 2007 occurred when the CS616 equipment was not working, and there were rain and thunderstorms nearly every day during the gap period.

The uncertainty range was determined for each water budget component before combining into overall uncertainty. Different conversion factors have been used to convert latent heat to ET, and the smallest conversion factor is 3.7% lower than the factor we used (Feddes and Lenselink, 1994); therefore, a 3.7% uncertainty was subtracted from the lower end of the range to account for different conversion factors. An estimate of missing data (± fraction of points estimated) was also included in the uncertainty range. The rainfall uncertainty was estimated as 0.0018 mm per each 15-min interval with recorded rain (Feddes and Lenselink, 1994). In addition, canopy interception was set to 0.21 mm (subtracted from low end of the rainfall range for each rainfall event) for all rains exceeded 0.59 mm (Feddes and Lenselink, 1994). Rain intercepted by canopy would not enter the soil, which was why this interception amount extended the lower end of the range; however, the intercepted rain could still evaporate. Although the canopy interception would change with plant growth, water content reflectometers were installed ~1 1/2 mo after planting, when the canopy was established.

The maximum uncertainty in ΔS is related to incorrect slope estimation in the calibration equation (see Appendix, b in Eq. [3a] and Logsdon, 2009), because a varied intercept (see Appendix, a in Eq. [3a]) would not alter the change in soil water profile (mm). The maximum ΔS uncertainty was determined from the percentage of change due to the range of possible slopes in the CS616 calibration equations. The uncertainty was for change in soil water content rather than uncertainty in soil water content itself. Because field CS616 calibration data were often scattered, outliers could influence the b value. All possible calibration equations were considered (see Appendix), each with a different subset (or total) of available calibration data. The range

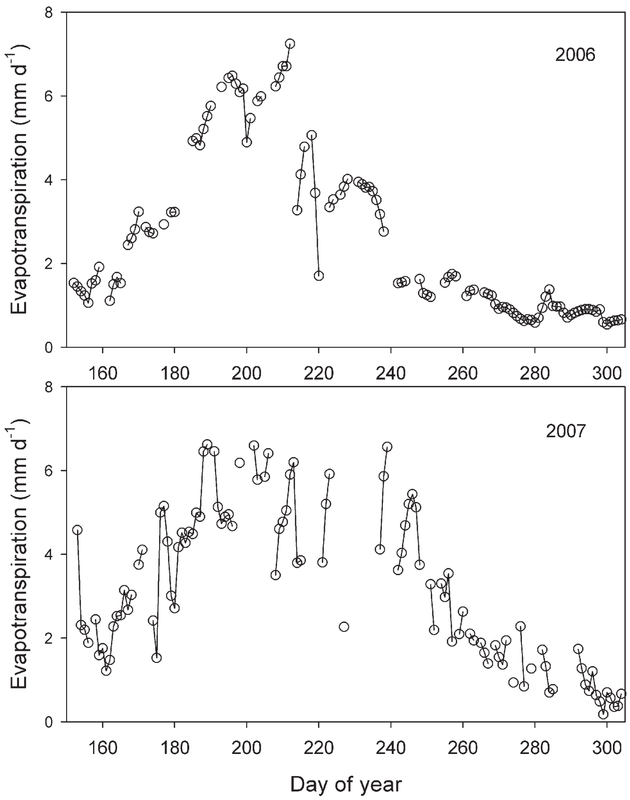

Fig. 3. Seasonal evapotranspiration on dry days for the 2006 and 2007 seasons. The day of year (152–304) axis is from June 1 to October 31. Soybean in 2006 and corn in 2007 were both planted May 11. Note that days with rain are excluded.

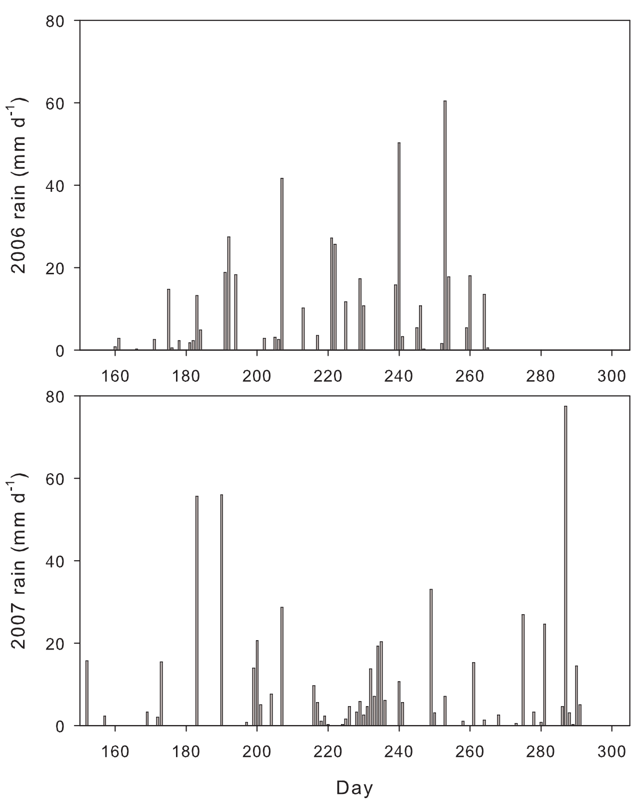

Fig. 4. Seasonal rainfall in 2006 and 2007 from June 1 to October 31 (day of year 152 to 304). Note that rainfall was not recorded after early October 2006 because equipment had been removed for harvest.

(high-low b values, see Appendix Eq. [3a, b]) was determined from all possible calibration equations for that site and depth. Then the effect of the half range on ΔS was determined for each site and depth. This was averaged for the soil profile based on contribution of each depth increment to the water storage in the profile using the trapezoid rule for integrating across depths. The mean ΔS errors bars were ±8.5, 7, 6, and 10.5% for 2006 shoulder, backslope, and toeslope positions, and 2007 toeslope position. If the calculated net (N) range was higher than zero on dry days, this was considered a significant indication of net upward water movement, whereas a range containing zero would be inconclusive concerning net upward movement on that dry day. A range lower than zero would indicate net drainage.

RESULTS AND DISCUSSION

Net Water Flux

Seasonal ET trends showed a rise until around day of year (DOY) 200, followed by a tailing decline (Fig. 3). Although peak daily ET values were similar for corn and soybean ET remained at high values longer for corn in 2007 than for soybean in 2006. The ET seasonal trends reflected plant water uptake changes as the crops grew, matured, and senesced. In these 2 yr, soil water was neither excessive nor deficient at these sites.

Seasonal P from 1 June to 30 September was 469 mm in 2006 and 415 mm in 2007. Rain was more evenly distributed in 2006 than in 2007 (Fig. 4). There were 2 wk without rain in 2007 from mid June to early July. Late July to mid August 2007 there were small rain events nearly every day, and the CS616 water content data during this time were missing. Data collected in late August to early September showed water table recharge in 2006, but late season recharge did not occur in 2007 until there was rain in October (Fig. 4, 5).

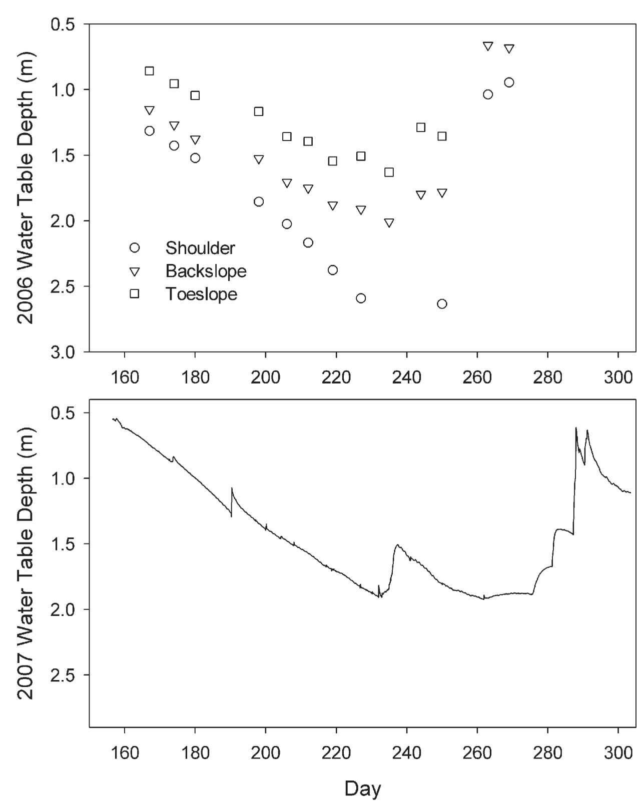

Fig. 5. Seasonal water table depths for 2006 shoulder, backslope, and toeslope positions, and for toeslope position in 2007. The date of the *x* axis is from June 9 to October 7 (152–304).

In 2006 out of 53 dry days, 37, 43, and 46 d showed net upward flux for shoulder, backslope, and toeslope positions (Fig. 6), indicated by a positive uncertainty range that did not overlap zero. The shallower water table depths (Fig. 5) for the toeslope and backslope positions enabled more days with net upward flow than for the shoulder position. The water table was more shallow in the toeslope and backslope landscape positions due to lateral redistribution in the saturated zone; therefore, lateral redistribution indirectly affected net upward flux. Net negative ranges not overlapping zero occurred on 7, 3, and 3 d for shoulder, backslope, and toeslope positions in 2006. Net negative trends suggested either vertical or lateral drainage away from the site.

In 2007, 37 out of 62 dry days showed net upward flux for the toeslope position, and net negative ranges not overlapping zero occurred 17 d (Fig. 7). The trend for the toeslope position in 2007 was for net drainage after rain events, followed by peak net upward movement 4 to 6 d after the rain. This was especially shown after *P* of 18 mm DOY 172 to 173, 56 mm on DOY 190, 16 mm on DOY 240 to 241, and 36 mm on DOY 249 to 250 (Fig. 7). Results from the data collected in 2007 site might have been close enough to be affected by the tile drain, and the presence of a sand lens in that toeslope position could have facilitated lateral drainage to and away from the site.

The mean net upward flux for dry days was 1.6, 2.5, and 2.6 mm d^{-1} for the shoulder, backslope, and toeslope positions in 2006, and 0.8 mm d^{-1} for the toeslope position in 2007. Considering only those days with net flux ranges above zero, the means were 2.6, 3.2, and 3.1 mm d^{-1} for the shoulder, backlsope, and toeslope positions in 2006, and 2.4 mm d^{-1} for the toeslope position in 2007. Mean ET on dry days was 4.0 and 4.1 mm d^{-1} in 2006 and 2007. Thus, in both years net upward flux might have contributed substantially to plant ET during dry days. In 2006, net upward flux contributed 70% of ET in the shoulder position and 78 to 80% in the backslope and toeslope positions. The overall mean net upward values could not be directly compared between 2006 and 2007 because only part of the root zone was included in the 2006 measurement zone (only 0.3- to 0.9-m depth increment). Some of the ET in 2006 could have been unaccounted for in depths above 0.3 m or below 0.9 m.

The comparison among landscape positions for data collected in 2006 assumed that ET was uniform across the positions. Variability in soil water content, depth of soil profile, and density of vegetative cover could easily violate this assumption of uniform ET. Nonuniform ET could accentuate the landscape position differences, for example, wetter soil at toeslope positions would result in higher ET. If this occurred, then the difference between ET and ΔS would be even larger than the values presented here. On the other hand, if the toeslope position were too wet ET could have been hindered, but wet conditions did not hinder plant growth in either 2006 or 2007 at these sites.

In 2006, out of 29 rain days, there were 20, 22, and 22 d with indicated net drainage (negative, not overlapping zero) for the

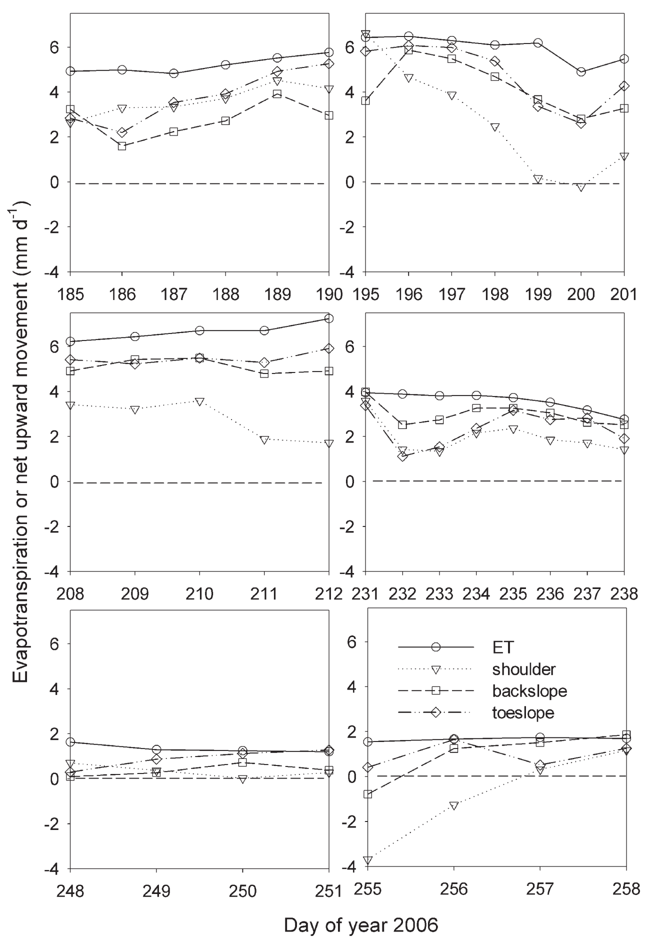

Fig. 6. Selected dry periods showing evapotranspiration and calculated net upward soil water movement for 2006. The different sections are July 4–9, July 14–20, July 27–31, August 19–26, September 5–9, and September 12–15.

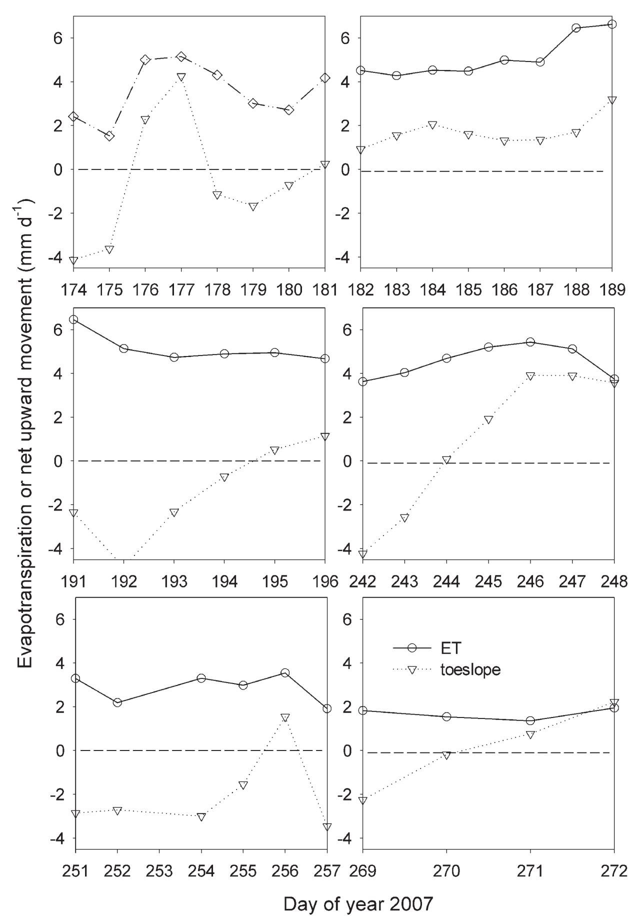

Fig. 7. Selected dry periods showing evapotranspiration and calculated net upward soil water movement for 2007. The different sections are June 23–30, July 1–8, July 10–15, August 30–September 5, September 8–14, and September 20–24.

shoulder, backslope, and toeslope positions. Net additions (positive, not overlapping zero) were 5, 5, and 3 d for the shoulder, backslope and toeslope positions. The 2007 rain days showed net drainage on 22 out of 23 rain days, and no days had net addition. Even given these similarities, the 2007 and 2006 data could not be directly compared because the 0- to 0.3-m depth was only included in 2007; therefore, the wetting front was detected earlier in 2007 than in 2006. Also different crops were grown in 2 yr. As expected, rain usually resulted in net drainage.

The contribution of net upward water movement to soil water and ET has been shown by others. Allmaras et al. (1975) observed upward water movement to contribute 40 to 60% of ET. Van Bavel and Ahmed (1976) attributed around 30% of ET to upward water movement. Stuff and Dale (1978) observed that upward water movement contributed 27% of ET during times of little rain. Using a model Chen and Hu (2004) showed that accounting for upward water movement resulted in 21% higher predicted soil water contents in the root zone, as the water moving up replaced that lost to ET. In our study, net upward flux was shown to be a much larger contribution to ET from corn and soybean (65–80%) in the Des Moines lobe soils.

CONCLUSIONS

Results from our reseach include the following key points: (i) A water balance approach, based on automated monitoring of soil water content, water table depth, evapotranspiration, and rainfall, quantified the sum of net vertical and lateral fluxes at sites in a central Iowa agricultural field. (ii) During dry periods, net upward flux of water into the root zone was indicated from the automated data collected in this study, with net upward flux occurring more frequently for the toeslope and backslope positions (87 and 81%) than for a shoulder position (70%) in 2006. For a toeslope position in 2007 (different site than in 2006) the net upward flux occurred during 60% of the dry days. (iii) Distinguishing between vertical and lateral drainage was not possible with the water balance approach. Since lateral flow resulted in a more shallow water table at toeslope and backslope positions, the result of lateral flow indirectly affected net upward flow, and was also shown by the drainage estimates. The magnitude of lateral flow was not quantified using the study approach. (iv) Net upward water movement could contribute significantly to the evapotranspiration of crops in areas of the field where lateral flow can redistribute soil water within the landscape. Net upward water movement accounted for 65 to 80% of ET during dry days in 2006.

Models of soil water flow should allow for interaction between the shallow water table and the vadose zone. This interaction could be important for increased plant available water (Van Bavel et al., 1968; Allmaras et al., 1975; Van Bavel and Ahmed, 1976; Stuff and Dale, 1978), solute transport back into the root zone (Berkowitz et al., 2004; Logsdon, 2007; Abit et al., 2008), soil water variation at different landscape positions (Logsdon et al., 1999), possible evapotranspiration variation at different landscape positions (Chen and Hu, 2004), and surface and lateral redistribution of soil water and effect on tile drainage (James and Fenton, 1993; Khan and Fenton, 1994; Kohne and Gerke, 2005). Further study is needed to quantify these effects in agricultural landscapes.

APPENDIX

Neutron Probe Calibration

The first step was to determine the volumetric soil water content from the soil sampled when inserting the neutron access tube.

1. Take a 50-mm diam. sample where a neutron tube would be installed.
2. Subdivide it into sections corresponding with midpoint of neutron probe readings.
3. Obtain a wet and oven-dry mass and calculate gravimetric water content.
4. Calculate apparent bulk density from known volume and oven-dried soil mass.
5. Calculate apparent volumetric water content by multiplying bulk density and gravimetric water content.
6. Calculate apparent total porosity from apparent bulk density assuming a particle density of 2.65 Mg m^{-3}.
7. If the apparent water content was greater than the apparent total porosity, then back-calculate both water content and total porosity to make them equal. This discrepancy sometimes occurred because of compression during sampling the wet soil with a hydraulic probe.
8. From total porosity, back-calculate bulk density.

Assumptions were that minor errors generated by ignoring trapped air (lower apparent bulk density), or a smaller particle density due to high organic matter (higher apparent bulk density) would not affect the outcome of the study because the bulk density was used only indirectly in the final calculations, and only change in water content was considered. Also, only soil depths from 0.3 m (sensing area probably starting at 0.2 m) and deeper were part of the neutron probe readings, and organic matter often diminished at deeper depths. The water contents used in the correction were still much better than they would be if the bulk density had not been corrected for compressed samples.

The next step was the neutron probe calibration from the volumetric water content data.

1. Convert the neutron probe raw counts (per minute) to count ratio (divided by background counts).
2. Collate the particle size, bulk density, depth, and ratio information for the 2007 neutron site as well as 15 sites in an adjacent field.
3. Perform stepwise multiple linear regression for water content as a function of count ratio, bulk density, and fractions of clay, silt, and sand. Only the significant components were left in the calibration equation. The r^2 values for the calibration equations were 0.85, 0.9, and 0.68 for depths of 0.3, 0.5, and 0.7 and lower pooled.
4. Because particle-size information was not available for 2006 data, determine sorbed water contents for 2006 and 2007 samples by equilibration of sieved samples first over distilled water for 2 wk, and then over magnesium nitrate for 2 wk (Logsdon, 2005). Sorbed water incorporates soil properties of texture, mineralogy, and organic matter.
5. Use the water contents from 2006 soil sampling along with sorbed water content and coefficient for ratio (slope) from the calibration equations to determine the calibration equations for 2006.

CS616 Calibration

The CS616 was calibrated based on volumetric soil water contents from the neutron probe data (0.3 m and deeper), and surface soil sampling (0.05 and 0.15 m depths).

1. Convert CS616 period raw data into the square root of apparent permittivity (Kelleners et al., 2005):

$$\varepsilon_a^{1/2} = \frac{(t - 2t_d)c}{4L} \quad [2]$$

where L ~0.26 m (probe length), t_d ~5.4 × 10^{-9} s, c is speed of light (3.0 × 10^8 m s^{-1}), $t = P/S_t$, S_t = 1024, and P is the period instrument output.

2. For the 0.05- and 0.15-m depths, match $\varepsilon_a^{1/2}$ with temperature (T, from thermocouples), and volumetric water contents (θ, from surface volumetric sampling).

$$\theta = a + \varepsilon_a^{1/2}(b - cT) \quad [3a]$$

3. For deeper depths, match $\varepsilon_a^{1/2}$ with θ from neutron probe data. Temperature corrections were not helpful for these deeper depths.

$$\theta = a + b\,\varepsilon_a^{1/2} \quad [3b]$$

4. For each site and depth, determine many possible calibration equations by including or excluding possible outliers, or by restricting the calibration to limited range of water contents or temperatures. Logsdon (2009) showed that the calibration is often different at high and low water contents.
5. For each site and depth, determine the root mean square error (RMSE) for each possible calibration equation.

$$\text{RMSE} = \frac{\sqrt{\sum (m-c)^2}}{\text{num}} \quad [4]$$

where m is measured water content, c is calculated water content, and num is number of data points.

6. For each site and depth, select the calibration equations with the lowest RMSE for wet and dry (if applicable) conditions.

The range of r^2 values for the selected calibration equations ranged from 0.23 to 0.93 for wetter soil water range and from 0.04 to 0.88 for dryer water contents. The lower r^2 values were obtained for dry soils because of the small slope. Nevertheless, the RMSE values for the selected calibration equations ranged from 0.00001 to 0.0081 m^3 m^{-3}.

Eddy Covariance Gap Filling Procedure

The gap-filling procedure for ET was an inverse weighting time average calculation as follows:

$$\text{Gap-filled Flux Density} = \frac{\sum_{i=1}^{n} v/t_i^2}{\sum_{i=1}^{n} 1/t_i^2} \quad [5]$$

where v is a series of neighbored data points (from 1 to n), and t_i is the lag time between the period of missing data to be gap-filled and its n nearest neighbors in time. Our gap-filling algorithm was performed in three sequential steps including gap filling of 15-min missing data, daily mean estimation, and gap filling of missing daily data. Gap-filled 15-min missing data was estimated using Eq. [5] arranged as a one-dimensional moving frame with a maximum of 24 neighbors on the time series and centered in the missing data period of interest. Following a conservative approach, the outcome from gap-filled 15-min data calculation was accepted and incorporated into the dataset only if at least eight neighbor data values were present within the moving frame. Gap-filled datasets (original 15-min data along with valid gap-filled 15-min data for missing periods) were used to calculate daily mean energy flux densities. Nonetheless, for quality control purposes, daily means of energy flux densities (and associated covariates) were rejected if more than 20% of available 15-min data was still missing on a given day after applying our gap-filling technique. Using these screened daily means, gap-filled daily missing data was performed using Eq. [5] in a centered moving frame of at least 4 and maximum 48 neighbor values. Rainy periods were not gap filled because Eddy covariance was not reliable during the time rain was falling.

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