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Space-time dynamics of soil water and process interactions in semi-arid terrain, Colorado, USA

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Abstract: Soil water is a dominant control of plant growth and hydrologic response in dryland (rainfed) agriculture. In agricultural fields, soil water is typically assumed to move vertically with no differential subsurface lateral flow in semi-arid regions. However, soil water dynamics in the profile can vary by landscape position in relation to terrain attributes and space-time soil and plant characteristics. Previous analyses have shown nested (fractal) characteristics of steady infiltration, terrain, and crop grain yield in these landscapes of eastern Colorado, USA. In this study, we measured soil water content across a landscape with varying topography to better understand soil/plant factors controlling the space-time dynamics. Rates of soil-water change at different depths and over multiple time scales were used to illustrate the space-time dynamics related to infiltration events, soil-water redistribution, and evapotranspiration.

Dielectric capacitance sensors were used to measure (infer from frequency domain readings) hourly soil water content over five years (~2003 to 2008) at 18 landscape positions and four depths (30, 60, 90, and 120 or 150 cm) in a field with alternating strips of winter wheat-fallow rotation. Probes were fully buried to allow representative surface conditions and shallow tillage. Thus, after hand-augered installation of the probes and reconsolidation of soils, in-situ measurements represent field conditions at minimally disturbed sites.

At summit and even some side-slope positions, profile soil-water dynamics may be explained primarily by vertical infiltration, evapotranspiration and redistribution processes. At downslope positions, however, complexities of overland flow and subsurface unsaturated lateral flow appear to influence soil water dynamics with depth. Rates of soil-water change at different depths and over multiple time scales were used to illustrate the space-time dynamics related to infiltration events, soil-water redistribution, and evapotranspiration.

Process interactions in space and time further complicated the analyses of soil-water dynamics, as crop water use affected profile soil water during the growing season. Crop water use accounted for most of the inter-strip variability, while soil hydraulic properties and near-surface hydrology affected the variability across landscape positions within each strip. Both short-term hydrology and long-term soil development influenced the observed space-time patterns. The potential for surface flow accumulation may help explain the accumulation of subsurface lateral flow that also might affect the dynamics of soil water content at a given landscape position and depth. The topic of deconvolving surface infiltration from subsurface flow convergence is an ongoing research challenge.

Feedbacks such as down-slope nutrient transport, differential soil development, and plant water uptake variability along the soil catena must be considered to fully explain space-time interactions. We propose application of a soil-terrain hydrology model that simulates variably saturated subsurface lateral flow in tandem with overland flow in semi-arid landscapes. Better understanding of such interactions should aid variable-rate management to enhance both production and sustainability.

Keywords: *Profile soil water, undulating terrain, dryland agriculture, loess soils, process interactions*

1. INTRODUCTION

Water fluxes at the land surface and in the soil are important for various agro-ecological processes, including plant water uptake and chemical transport. Rainfed (dryland) cropping systems depend on the storage of soil water in the root zone to sustain a crop during dry periods in the growing season. Both the storage and flow of water vary in space and time, particularly due to spatial variability in terrain and soil properties and to temporal variability in precipitation.

The dynamics of volumetric soil water content (SWC) have received broad interest in hydrology, soil science, agriculture and ecology. Electronic sensors with automated datalogging can be deployed at multiple spatial locations, which makes it possible to explore detailed SWC in space and time. Many studies have focused on hillslope SWC, including some recent work (e.g., Daly and Porporato, 2005; Kim and Kim, 2007; Lin et al., 2006; Liu and Zhang, 2007; Lyne Ensign et al., 2006; Schmidt et al., 2007; Tromp-van Meerveld and McDonnell, 2006). A few studies (Hoover and Wolman, 2005; Ivanov et al., 2008; Newman et al., 2006; Zhu and Shao, 2008) are particularly relevant to our study, because they highlight water-limited environments. With the exception of the study in Beltsville, Maryland, USA (DeLannoy et al., 2006; Guber et al., 2008), we are not aware of any SWC monitoring systems with our space-time data intensity.

The main aim of this study is to explore space-time dynamics in SWC measured at discrete depths over a range of landscape positions in a wheat field in Colorado, USA. Divergence of the flux of soil water is related to the dynamic change in storage, which is used to infer soil water processes along hillslopes, including lateral subsurface flow. The relevant processes and their interactions in space and time are discussed in light of the data analysis.

2. MATERIALS AND METHODS

The space-time dynamics of SWC were measured at four depths along two transects within an undulating agricultural field. SWC values were determined using in-situ frequency-domain dielectric sensors, and terrain attributes were computed from gridded elevations.

2.1. Site Description

The farm field used in this study is part of a producer-owned and operated farm located in eastern Colorado (40.61^o N, 104.84^o W). The average annual potential evaporation is approximately 1200 mm, while the average annual precipitation is approximately 350 mm. The terrain in northeastern Colorado is generally undulating, with aeolian deposits of silt- and sand-sized material mantling sedimentary rock (primarily sandstone) and fluvial deposits. The unconsolidated sediment and soils in our study fields are relatively thick (at least 3 m) with no surface expressions of groundwater or perched water in the root zone. Thin, calcareous horizons have been sampled at depths of 15 to 50 cm, but soil development is not very pronounced otherwise. The elevation ranges from approximately 1559 to 1588 m, with slopes exceeding 13% (m m^{-1} x 100%).

The 109-ha field (Fig. 1) is managed in strips approximately 120 m wide of winter wheat and fallow that alternate annually based on a wheat–fallow rotation. SWC probes are located to span a broad range of landscape positions, terrain attributes and soil types. Green et al. (2009) described the spatial variability of measured infiltration rates in this field and their fractal geometry.

2.2. Measurement of Soil Water Content

SWC data were derived from frequency-based dielectric measurements using Sentek EnviroSCAN®[1] capacitance sensors (Kelleners et al., 2004; Schwank et al., 2006; Schwank and Green, 2007). Probes were inserted into hand-augered plastic access tubes, sealed and buried. Wires to off-field data loggers were also buried in trenches and back-filled, such that there was no affect on farming and shallow soil tillage operations above the probes. Cable lengths do not affect measurements, because analogue resonant frequency measurements are converted to digital signals on the probe within each access tube. Each probe contains four ring capacitors centered at depths of 30, 60, 90, and 120 or 150 cm, where the vertical interval of measurement is approximately 10 cm each, and the signal penetrates an annulus of soil extending less than 10 cm. For more information on the measurement volume, see previous studies (Evett et al., 2006; Paltineanu and Starr, 1997; Schwank et al., 2006).

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[1] Brand names are used for readers to reference more detailed specifications about the instruments used. USDA-ARS and the authors do not have any vested interest in any of the cited commercial products.

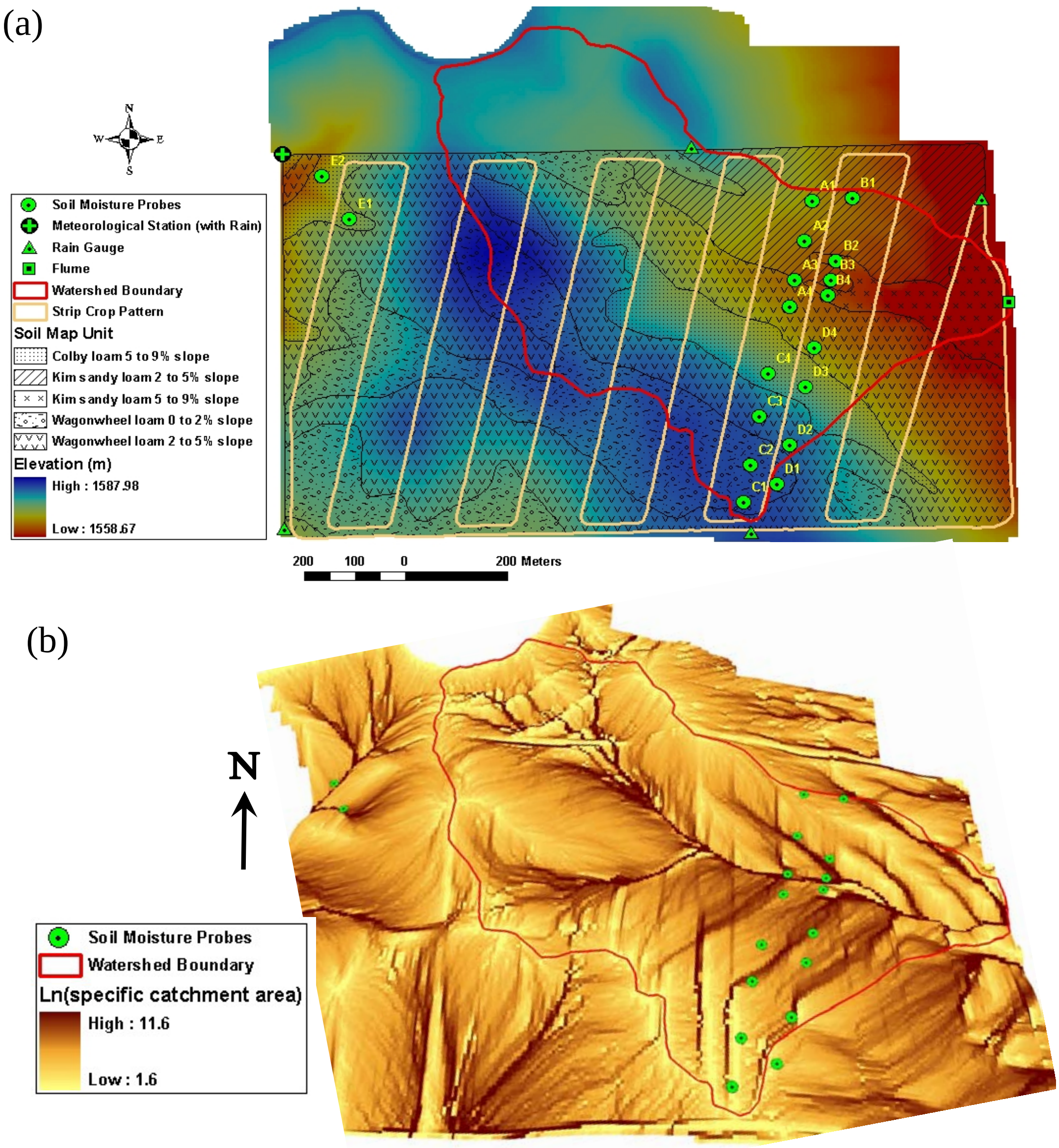

Figure 1. Field site maps showing: (a) plan view of instrument locations with elevation (color map), soil units (patterns), and a catchment boundary (red line) delineated for the runoff flume on the eastern edge; and (b) three-dimensional view of the field and catchment area with *ln*(specific catchment area) overlaid on topography to show potential surface flow paths using the D∝ method.

2.3. Data Analyses

Temporal dynamics in SWC were evaluated for each sensor (slope position and depth), particularly by exploring changes in storage and the rate of these changes over different temporal scales (weekly to annual). The data could also support hourly to daily analyses not reported here. Changes in the temporal dynamics with depth were then used to explore differences between landscape positions and to infer the potential for lateral subsurface flow. Finally, spatial terrain attributes were used as surrogates for hydrologic and pedo-geomorphic controls on SWC in space and time.

Conservation of mass dictates that the rate of change in SWC within some control volume equals the divergence of water flux denoted by the darcy flux tensor ***q***:

$$\int_V \frac{\partial \theta}{\partial t} dV = \oiint_S \nabla \cdot \boldsymbol{q}\, dS \qquad [1]$$

where θ is volumetric SWC in the measurement volume *V*, *S* is the surface encompassing *V*, *t* is time, $\nabla\bullet$ is the divergence operator, and $\oint$ denotes integration over a surface. Spatial integration yields a volume of water per unit time. Integrating [1] over a time period ΔT yields the change in SWC (calculated from measured data) that equals the cumulative change in volume over ΔT.

$$\Delta\theta(\Delta T) = \int_{\Delta T}\left(\int_{V=1}\frac{\partial\theta}{\partial t}dV\right)dt = \int_{\Delta T}\left(\oint_S \nabla\bullet\boldsymbol{q}\, dS\right)dt \qquad [2]$$

By setting V = 1 (unit volume), we see that the measured change in SWC equals the flux divergence integrated over the surface of V and over an arbitrary time period ΔT. Here, we explore changes in SWC at each probe location and sensor depth. For each sensor, the left hand side of eq. [2] (i.e., $\Delta\theta$) was computed each week for ΔT = 1, 7, 14, 21, …, 364 days. The weekly interval in *t* and ΔT was selected for pragmatic reasons given the size of the dataset and resulting matrices. Average rates of change $\Delta\theta/\Delta T$ for different values of ΔT also were computed. Here, we explore some characteristic time periods for wetting and drying cycles that display the strongest dynamics.

If horizontal gradients in soil-water flux are small relative to vertical gradients, only the vertical flux divergence is considered. For example, sharp wetting front causes a large divergence as the front passes into the upper surface of V followed by a small divergence after the front goes below the lower surface. A more diffused wetting front can have the same change in θ after the front passes completely through the measured depth interval (approximately 10 cm in this case), but the dynamics will differ within that period.

3. SPECIFIC HYPOTHESES

Although horizontal gradients in θ and $\boldsymbol{q}$ (see eq. [1]) may be small relative to vertical gradients, we hypothesize that subsurface lateral flow, though rarely if ever saturated, affects profile SWC dynamics in two main ways: 1) subsurface flow accumulation causes the soil profile to be wetter on average in downslope and topographically convergent positions; and 2) deeper soils can wet up directly from focused lateral flow, rather then wetting from above only. An implication of Hypothesis 1 is that wetter soils respond more dynamically than drier soils to the same surface influx due to increased hydraulic conductivity and decreased available storage. Testing of both hypotheses is somewhat confounded by differential soil development going along a soil catena, where side-slopes tend to have coarser soil textures, and low slope positions tend to have relatively high fractions of fine materials that can hold more water at a given matric potential.

4. RESULTS AND DISCUSSION

Page limits prevent a full presentation of the data in this paper, so we opted to show example illustrations of the data along with a concise interpretation of the analyses and general behaviors.

4.1. Soil Water Dynamics (Example)

Field measurements started during relatively dry conditions, especially in the deeper soil profile (e.g., Fig. 2 shows water contents at four depths for probe A1). Snow and rain in Mar-Apr 2003 wet the shallow horizons only, whereas rain in Apr 2005 wet the full profile during fallow. Drying was observed during the crop phase at all depths.

SWC dynamics with depth are illustrated for probe A1 (Fig. 3) in terms of the change in SWC (Eq. 2) and rate of change at each time and for all values of ΔT. Thus a range of values is plotted for each time. Based on Eqs. 1 and 2, maximum and minimum values of $\Delta\theta$ reflect the corresponding extremes in flux divergence at each depth.

The maximum $\Delta\theta(\Delta T)$ for each depth represents the intra-annual variation, and the cumulative infiltration affects the changes at all depths. Likewise, $\Delta\theta < 0$ indicates drying of a soil layer. The wetting and drying with depth are clearly seen during 2003 in Figs. 2 and 3. Amplitude decreases with depth. Figures 2a,b are really two-dimensional representations of the dependent variable, $\Delta\theta$ or $\Delta\theta/\Delta T$, versus time (x axis) and ΔT in the third dimension. Although this makes the figures difficult to interpret, it allows a more quantitative assessment of the min/max change or rate of change at each time (looking forward in time by ΔT).

Figure 2b shows many short periods of SWC dynamics at 30 cm that may not penetrate even to 60 cm. Strong dynamics at depth (120 cm) for this example occurred only once (2005) in the data record.

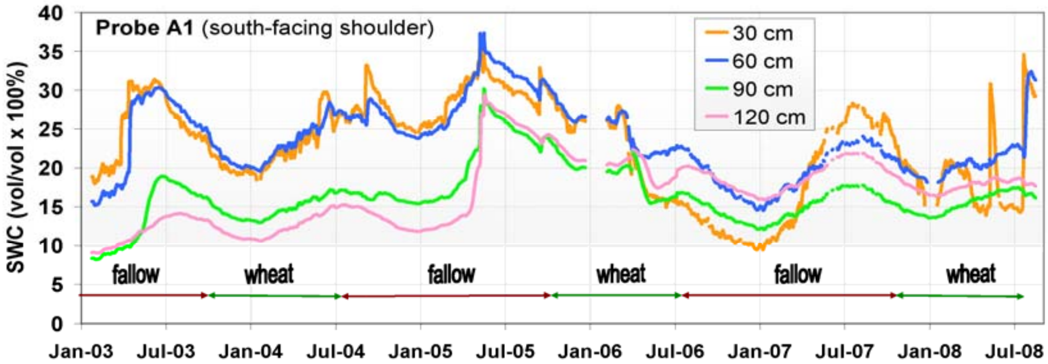

Figure 2. Time series of daily SWC values for probe A1 (see Fig. 1) at four sensor depths. Cropping and fallow periods are indicated for the winter wheat-fallow rotation.

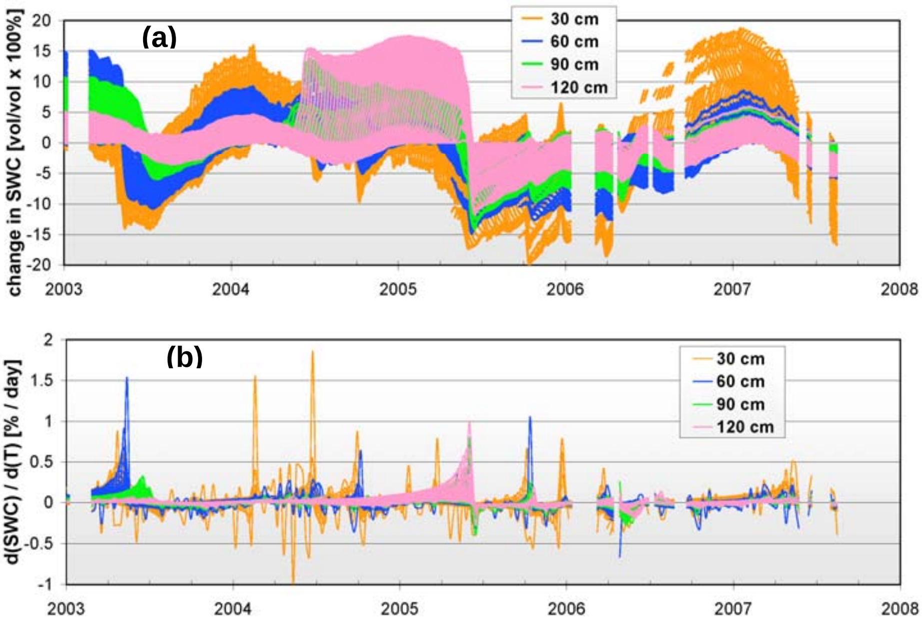

Figure 3. Changes (a) and rates of change (b) in SWC measured at four sensor depths in probe A1 (Fig. 1). Each time includes changes (a) and rates (b) computed for all time lags of ΔT = 1, 7, 14, …, 364 d. Gaps exist due to missing data. Due to the forward difference method, values are plotted only through Sept. 2007.

4.2. Space-Time Patterns

Using the information illustrated in Fig. 2, we computed the timing of max/min flux divergence with depth. The time lag is a vertical response time. In 2003 at A1, for example, time lags in the maximum rate of change in SWC from 30 to 60 and 60 to 90 cm were 21 and 28 days, respectively (noting our analysis used 7 d increments). The response at 120 cm is highly dampened and small in 2003. In 2005, the dynamics penetrate more rapidly to 120 cm.

Spatially, the responses vary by landscape position. To help illustrate the differences by landscape position, the two strongest wetting events are shown in more detail for A1 and B3 for comparison (Fig. 4). At a toe-slope position (B3) in the same soil unit, for example, the infiltration front moved much more rapidly to all depths. In 2003, B3 responded at 90 cm (Fig. 4c) before A1 had responded at 30 cm, and the SWC of A1 at 90 cm did not peak until late June (Fig. 2). Meanwhile, B3 was responding to subsequent smaller events at 30, 60 and 90 cm, and the wetting front arrived at 150 cm (deep) in early May. In 2005 (Fig. 4b,d), all sensors down to 90 cm responded rapidly, but the initial conditions near the surface of B3 were drier due to the wheat crop. Nevertheless, the large available storage at B3 was filled rapidly, indicating larger flux divergences for B3 than for A1.

Using the rates of change in SWC (illustrated only for A1 in Fig. 3b) at B3, rates of change at 150 cm exceed 1% SWC d^{-1} in 2003 and 8% SWC d^{-1} in 2005. The first wetting front in 2003 had a time lag of 14 d from 60 to 90 cm. The second event in 2003 was concurrent with the one reported above for A1, but the response was almost instantaneous to 90 cm, and the time lag from 90 to 150 cm was 14 d. The dynamics at B3 require additional water supply at the surface (rainfall plus runon), but supply from subsurface lateral flow was not implicated at the weekly time scale. Because deeper SWC was higher at B3 than A1 (Fig. 4), subsurface flow may be responsible for keeping the deeper soil horizons recharged. This phenomenon needs to be explored further, including other methods, but the current analyses can help identify locations for further work.

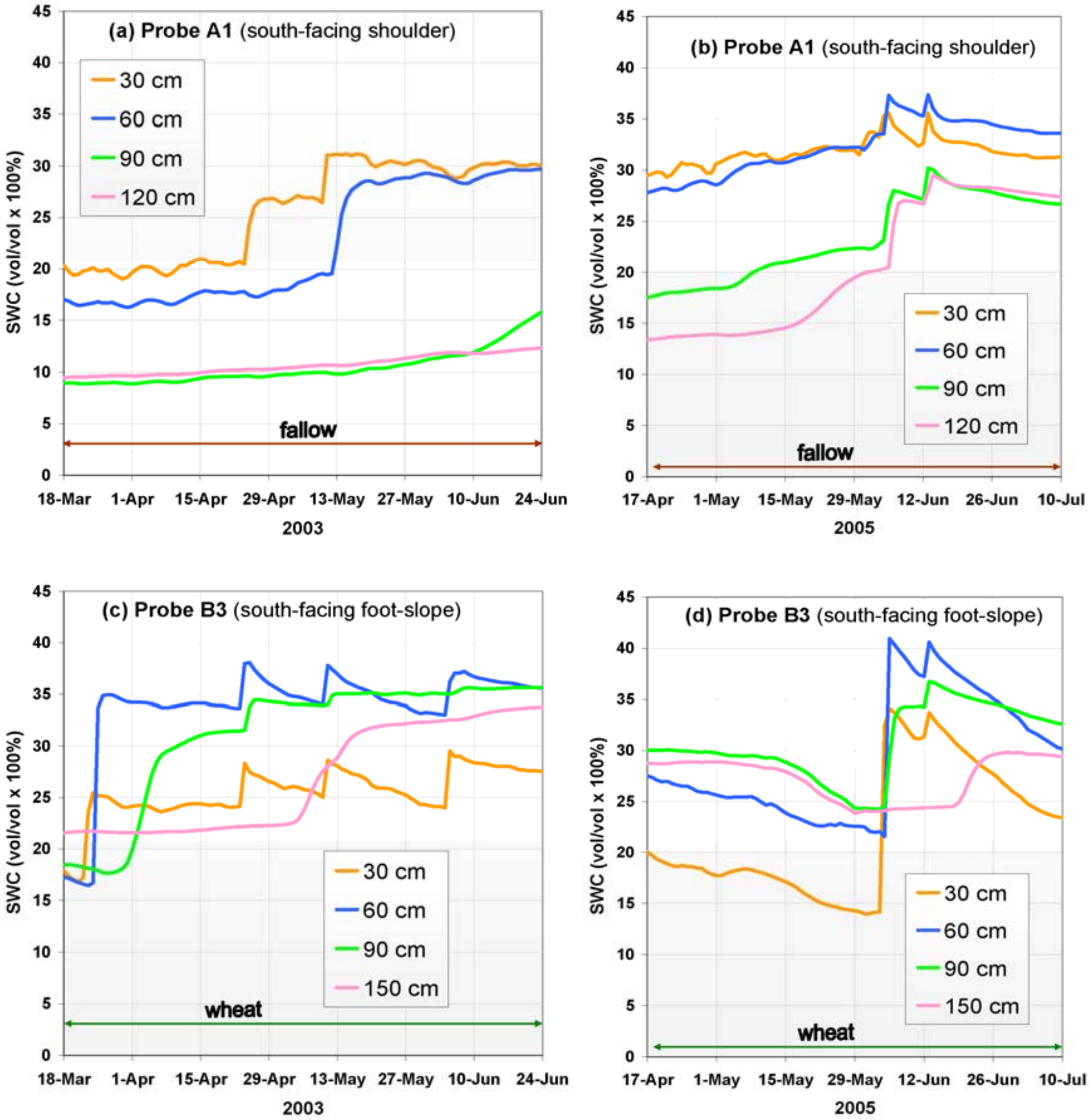

Figure 4. Volumetric soil water content (SWC) versus time for two periods with the most pronounced wetting events – (a, c) Mar-Jun 2003 and (b,d) Apr-Jul 2005 – at probes A1 (a,b) and B3 (c,d). Note that the deepest sensor (pink line) is at 120 cm in A1 and at 150 cm in B3. Also, A1 is fallow when B3 is cropped.

4.3. Terrain Attributes for Spatial Analyses

Ultimately, the types of space-time dynamics in SWC illustrated above can be quantified at every probe and correlated with terrain and soil attributes. Green et al. (2009) found fractal patterns in steady infiltration rates and terrain attributes over the field, but linear correlation of infiltration with individual terrain attributes explained < 6% of the variance. Thus, we do not expect soil properties alone to explain much of the difference in SWC dynamics. However, terrain attributes that are related to potential flow accumulation, may help explain more of the statistical measures of SWC dynamics derived from the data. These relationships will be explored as part of this ongoing study.

4.4. Interpretations of Process Interactions and Feedbacks

SWC is a simple state variable that changes over space and time, but the dynamics thereof can be very complex due to interactions between local soil hydraulics, hillslope hydrological fluxes, soil evaporation and plant water uptake. Surface soil conditions also change in time. We assume that the soil structure and pore network that control water retention and conductivity are static at the sensor depths, but temperature variations including freezing will affect these soil hydraulic properties. Nutrient management, fluxes, and transformations also affect SWC dynamics via plant growth and water use. Soil-water-plant-nutrient interactions are critical in agricultural and ecological systems.

5. SUMMARY, CONCLUSIONS AND FUTURE WORK

Assessment of process interactions and dominant controls in space and time remains a challenging topic in any natural or managed landscape. Here, we used high-resolution temporal SWC data at 18 landscape positions and four depths to explore differences in the temporal dynamics as they relate to water flux. The dynamics of wetting and drying are complex, but slope positions that tend to be wetter clearly respond more rapidly. Further quantitative spatial analyses relating metrics of SWC to terrain attributes looks promising in terms of correlation. However, our hypotheses regarding subsurface flow accumulation require further testing. Much of the SWC dynamics observed to date may be dominated by surface infiltration of rainfall plus run-on of overland flow. Improved understanding of causation requires application of robust process models, which in turn rely upon space-time measurements, such as the SWC data presented here. Future modeling may also help identify causation and dominant controls in such complex systems with space-time process interactions and feedbacks. Such models must include lateral surface and subsurface flow under variably saturated (typically unsaturated) conditions.

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