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Revealing the relative influence of soil and topographic properties on soil water content distribution at the watershed scale in two sites

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SUMMARY

Soil and topographic properties are two important factors controlling soil water content (SWC) distribution in a horizontal dimension. The objective of this study was to use structural equation modeling (SEM) to reveal the relative influence of soil and topographic properties on SWC distribution at the watershed scale. Experiments were conducted in two representative sites: St. Denis National Wildlife Area (SDNWA) in the Canadian prairie landscape with a humid continental climate, and LaoYeManQu (LYMQ) watershed on the Chinese Loess Plateau with a cold semi-arid environment. Soil water contents were measured along a 576 m long transect at the SDNWA and over an area of 20 ha at the LYMQ. The influences of soil and topographic properties on SWC were determined at various soil layers and under various antecedent soil water conditions. Results showed that soil and topographic properties jointly controlled SWC distribution at the SDNWA, but soil properties contributed more to SWC variability than topographic properties. At the LYMQ, only soil properties dominated SWC distribution. The influences of soil and topographic properties at the SDNWA were stronger under wetter conditions, whereas the influence of soil properties at the LYMQ presented slight differences between different antecedent soil water conditions. The influence of soil properties decreased and then increased with depth from 0–20 cm to 120–140 cm at the SDNWA, whereas the influence of topographic properties at the SDNWA and the influence of soil properties at the LYMQ decreased with depth. This study implied that SWC was a local and nonlocal control in the humid continental climate, whereas only a local control operated in the cold semi-arid environment.

1. Introduction

Soil water content (SWC) controls water and energy fluxes at the boundary between soil and atmosphere (Famiglietti et al., 1998). It varies spatio-temporally under the influence of a series of hydrological processes such as infiltration and evapotranspiration (Western et al., 2004). Controlling factors of SWC distribution in a horizontal dimension is crucial for understanding soil water dynamics.

The influence of soil and topographic properties on SWC has been widely recognized in different hydrological environments (Gómez-Plaza et al., 2001; Grayson et al., 1997; Perry and Niemann, 2007; Western et al., 1999). Some major soil properties controlling SWC distribution include soil texture (Crave and Gascuel-Odoux, 1997), porosity (Niemann and Edgell, 1993), organic carbon content (Biswas and Si, 2011a), bulk density (Jacobs et al., 2004), soil thickness (Zhu and Lin, 2011), and hydrophobicity (Tarchitzky et al., 2007). Topographic properties controlling SWC distribution mainly include elevation (Crave and Gascuel-Odoux, 1997), slope (Moore et al., 1988; Essig et al., 2009), slope aspect (Famiglietti et al., 1998), curvature (Moore et al., 1988), specific contributing area (Brocca et al., 2007), and wetness index (Beven and Kirkby, 1979).

The influences of soil and topographic properties on SWC depend on antecedent soil water conditions. Burt and Butcher (1985) observed that SWC and wetness indices were more correlated during wetter conditions. On the Rattlesnake Hill, Texas, Famiglietti et al. (1998) revealed that soil properties such as soil porosity and hydraulic conductivity dominated surface SWC distribution under wet conditions, while topographic properties (i.e., relative elevation and slope aspect) and soil properties (i.e., clay content) controlled SWC distribution under dry conditions. Florinsky et al. (2002) observed seasonally varying relationships between SWC and topographic characteristics in the Canadian prairie, although those correlations were observed to be weak in a particular low relief site. At the Little Washita site in central Oklahoma, USA, Yoo and Kim (2004) reported that the roles of topographic factors decreased with time and the roles of soil and land-use-related factors increased with time after the cessation of rainfall. In the Tarrawarra catchment in Australia, Perry and

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Niemann (2007) observed that SWC patterns were dominated by soil properties in both wet and dry conditions and by topographic properties in moderately wet conditions. On a hill-slope of the Chinese Loess Plateau, Hu et al. (2008) observed that the influences of aspect, elevation, organic matter content, clay content, and bulk density increased with increasing SWC. In the Shale Hills Catchment in central Pennsylvania, USA, Takagi and Lin (2012) observed that decrease of SWC that occurred mainly through evapotranspiration had a significant influence on near-surface SWC patterns under dry conditions, while topography controlled SWC patterns under wet conditions.

The relative roles of soil and topographic properties in controlling SWC distribution are related to the dominant hydrological processes taking place at different antecedent soil water conditions. Soil water content patterns have been recognized to switch between two preferred states. The dry state is controlled by local controls which represent the dominant influence of soil properties and only local terrain (areas of high convergence) on SWC, usually resulting in vertical movement of soil water. The wet state is controlled by nonlocal controls which represent the dominant influence of catchment terrain on SWC, governing lateral water distribution through both surface and subsurface paths (Grayson et al., 1997; Western et al., 1999). Although the relative importance of soil and topographic properties at different antecedent soil water conditions were determined in different areas, the influencing factors observed tend to be subjective because they were usually limited to those measured. Thus, some other influencing factors may be masked as we are confined to our current knowledge on soil water processes and measurement methods. This may bring some uncertainty to our understanding of the relative influence of soil and topographic properties on SWC distribution. In addition, soil and topographic properties were observed to jointly control SWC distribution in a given antecedent soil water condition (Famiglietti et al., 1998). Therefore, it is difficult to distinguish the relative roles of soil and topographic properties on SWC distribution (Cantón et al., 2004).

The Prairie Pothole Region of North America contains millions of wetlands that serve important hydrological and ecological functions. The unique hummocky topography and the variable effect of different processes contribute to high spatio-temporal variability in soil water content (Biswas, 2011). Soil properties such as sand content, organic carbon content, depth to $CaCO_3$ layer, A horizon depth and C horizon depth were observed to control SWC distribution (Biswas et al., 2012; Biswas and Si, 2012), whereas topographic properties such as elevation, wetness index, convergence index and flow connectivity were also observed to influence SWC distribution in this area (Biswas and Si, 2011a, 2012; Gala et al., 2012). In the Chinese Loess Plateau, where the soil was claimed to be the most highly erodible soil on earth (Laflen et al., 2000), SWC is crucial for vegetation restoration (Wang et al., 2013; Yang et al., 2012). In this area, both soil and topographic properties have been observed to influence SWC distribution at the watershed scale (Hu et al., 2008, 2010; Huang et al., 2012; Qiu et al., 2010; Yang et al., 2012). Therefore, it is difficult for us to conclude whether soil or topographic properties are more important to regulate SWC distribution at the watershed scale in these two sites.

The relationships between SWC and environmental factors are usually assessed by traditional regression and correlation analysis. While useful for investigating causality between environmental factors and SWC, regression and correlation analysis have the following limitations: (1) They usually assume that the variables are free of measurement error or uncontrolled variation, (2) they seldom satisfy statistical assumptions of the normal theory and often interact multivariately in complex ways (Malaeb et al., 2000), and (3) they can only consider the measured variables (Arhonditsis et al., 2006), which may limit our assessment of complex influences of soil and topographic properties on SWC. If unobserved variables that may control SWC distribution can also be included indirectly, more robust understanding of SWC control may be possible.

Structural equation modeling (SEM) is a multivariate statistical method that allows the assessment of complicated relationships between manifest and latent variables (Arhonditsis et al., 2006). Manifest variables are directly measured variables, whereas latent variables are those not measured directly. Latent variables are estimated in the model from several manifest variables, each of which is predicted to "tap into" the latent variables. This allows the explicit capturing of the unreliability of measurement in the model, thus producing accurate relationships between latent variables (Stephenson et al., 2006). In cases where numerous soil and topographic properties are considered, but none of the observed properties can perfectly reflect the underlying properties of soil and topography, SEM provides a good alternative for determining the relative influences of soil and topographic properties on SWC distribution with limited observed variables.

The objective of this study was to use SEM to reveal the relative influences of soil and topographic properties on SWC distribution at the watershed scale in two representative sites. Specific attention was given to the influences of soil and topographic properties on SWC of various soil layers under various antecedent soil water conditions.

2. Materials and methods

2.1. Study area

Two representative sites were selected in this study. One site was St. Denis National Wildlife Area (SDNWA) in Saskatchewan, Canada (106°50′W, 52°12′N) and another site was LaoYeManQu (LYMQ) watershed in the Chinese Loess Plateau (110°23′E, 38°46′N) (Fig. 1). The two sites differed with climate, topography, soil and vegetation. However, both sites were representative of a greater region, i.e., SDNWA is a typical landscape of the Prairie Pothole Region of North America and LYMQ is representative of Chinese Loess Plateau.

The SDNWA belongs to a humid continental climate (Peel et al., 2007), with a mean air temperature of 2 °C, precipitation of 360 mm, and potential evaporation of 700 mm (Morton, 1983; Atmospheric Environment Service, 1997). It consists of a sequence of gently undulating slopes with various sizes of depressions, knolls and knobs (Pennock et al., 1987), with elevation difference of 2.7 m. The soils at the SDNWA are dominated by Mollisols clay loam textured (Soil Survey Staff, 2010). The SDNWA site is mainly covered by mixed grass, i.e., smooth brome grass (*Bromus inermis*) and alfalfa (*Medicago sativa* L.).

The climate at the LYMQ is cold semi-arid (Peel et al., 2007), with a mean annual air temperature of 8.4 °C, precipitation of 437 mm, and potential evaporation of 1337 mm (Zhao and Shao, 2009). This site is noted for its deep gullies and undulating slopes developed by serious soil erosion (Hu et al., 2013). The serious soil erosion resulted in elevation difference of 74 m. The dominant soils at the LYMQ are Inceptisols sandy loam textured (Soil Survey Staff, 2010). At the LYMQ, the main vegetation species are bunge needlegrass (*Stipa bungeana* Trin.) and korshinsk peashrub (*Caragana korshinskii* Kom.). Other vegetation species include alfalfa (*M. sativa* L.), almond (*Prunus armeniaca* L.) and poplar (*populus*). Eight kinds of land uses were classified according to the dominant vegetation, its coverage, and soil type (Fig. 1).

2.2. Data collection

At the SDNWA, a sampling transect 576 m long was established to represent the typical terrain with undulating slopes (elevation