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Effect of vegetation on the temporal stability of soil moisture in grass-stabilized semi-arid sand dunes

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SUMMARY

Soil moisture is a critical state variable affecting a variety of land surface and subsurface processes. Despite the complex interactions between soil moisture and its controlling factors, the phenomenon of temporal stability of soil moisture (*TS SM*) has been widely observed under natural conditions. In this study, the control of vegetation on *TS SM* is investigated by artificially manipulating surface vegetation (e.g., vegetated and de-vegetated plots) in a native grassland-stabilized sand dune area with similar soil texture and topography. Soil moisture data were collected at the depths of 30 cm (within the root zone) and 110 cm (below the root zone) over a period of four years. Using soil moisture data from the de-vegetated plots as a baseline, *TS SM* within the root zone is shown to be mainly affected by vegetation phenology at the study site. Therefore, the control of vegetation on *TS SM* varies on both seasonal and annual time scales. The change in the interseasonal patterns of *TS SM* is tightly related to plant phenology and the control of vegetation on the ranking of mean relative difference (*MRD*) of soil moisture significantly weakens during non-growing seasons due to diminished root water uptake. It suggests that the timing of sampling schemes (e.g., growing season vs. non-growing season) may alter *TS SM* patterns. On annual time scales, *TS SM* is affected by climatic conditions, as the control of vegetation on *TS SM* becomes stronger under drier conditions. In particular, vegetation tends to create larger contrasts in soil moisture levels between vegetated and de-vegetated plots in drier years. The soil moisture data also provide evidence that vegetation tends to reduce *TS SM* and increase spatial variability in soil moisture at the study site. The standard deviation of relative difference (*SDRD*) of soil moisture at the 30 cm depth (within the root zone) is considerably larger in the vegetated plots than those in the de-vegetated plots. As such, the effectiveness of using representative locations for monitoring mean soil moisture conditions in the vegetated plots deteriorates.

1. Introduction

Soil moisture is a key driver linking land surface and subsurface processes over a range of spatiotemporal scales (Western et al., 2002; Robinson et al., 2008; Vereecken et al., 2008; Seneviratne et al., 2010). The nonlinear feedback mechanisms between soil moisture and its controlling factors (e.g., precipitation, vegetation, and soil) lead to complex spatial and temporal patterns of soil moisture, presenting a grand challenge for interpreting and utilizing soil moisture data collected across different spatiotemporal scales (Western et al., 2002; Jacobs et al., 2004; Vanderlinden et al., 2012). To resolve this issue, significant strides have been made to understand various controls on the spatiotemporal patterns of soil moisture. One such attempt to examine the temporal pattern of soil moisture was based on the concept of temporal stability of soil moisture (*TS SM*; note that other terms such as rank stability or order stability have been also proposed and used in the literature (e.g., Chen, 2006; Teuling et al., 2006)) first proposed by Vachaud et al. (1985). By analyzing soil moisture data measured in three field plots, Vachaud et al. (1985) found a temporal persistence in the spatial pattern of soil moisture storage. In particular, Vachaud et al. (1985) showed that soil moisture at certain locations was close to the mean moisture condition within a field, while other locations exhibited consistently drier or wetter conditions than the mean. Therefore, Vachaud et al. (1985) suggested that information based on *TS SM* could be used to select representative locations for monitoring soil moisture.

Since the seminal work of Vachaud et al. (1985), numerous studies have used *TS SM* for various research and application purposes, such as identifying representative locations (Grayson and Western, 1998), optimizing monitoring schemes (Brocca et al.,

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2010), filling missing soil moisture data (Pachepsky et al., 2005), scaling soil moisture contents (Jacobs et al., 2004), validating remotely sensed soil moisture data (Cosh et al., 2004), delineating water management zones (Starr, 2005), and inferring soil hydraulic properties (Wang, 2014). A number of factors have been shown to affect *TS SM* at different spatiotemporal scales, including soil properties and depth, topography, vegetation, and moisture state (c.f., Vanderlinden et al., 2012). However, contradictory findings about the controls on *TS SM* were also reported in previous field studies, mostly owing to the fact that soil moisture interacts with those controls in a highly nonlinear manner (Western et al., 2002). Other reasons may include differences in the spatial and temporal scales studied, inconsistencies in sampling schemes and techniques, and contrasts in local conditions (Kachanoski and de Jong, 1988; Gomez-Plaza et al., 2000; Brocca et al., 2009; Vanderlinden et al., 2012). Therefore, despite previous efforts, studies are still needed to elucidate the roles of different factors in controlling *TS SM*, particularly regarding the role of vegetation.

Several recent studies have attempted to relate *TS SM* to vegetation (Gomez-Plaza et al., 2000; Zhao et al., 2010; Biswas and Si, 2011). Gomez-Plaza et al. (2000) found that the spatial pattern of soil moisture became less stable when the impact of vegetation was included. Zhao et al. (2010) showed that vegetation was less important than soil properties in determining *TS SM* in a semi-arid grassland. Biswas and Si (2011) revealed that changes in interseasonal patterns of *TS SM* in a hummocky area were tightly related to the presence of vegetation and its spatial pattern. The control of vegetation on soil moisture and *TS SM* is particularly important in regions with fragile ecosystems (Zhang and Shao, 2013), such as in the Nebraska Sand Hills (NSH). The 58,000 km^2 NSH is the largest native grassland-stabilized sand dune area in the Western Hemisphere, and possesses unique ecological and hydrological importance in the region (Loope and Swinehart, 2000; Wang et al., 2009a, 2015); however, severe drought-induced devegetation caused dune mobilization several times in the past ten thousand years in the NSH (Miao et al., 2007).

Due to the importance of vegetation in stabilizing sand dunes and maintaining the landscape in the NSH, it is critical to evaluate the effect of vegetation on the temporal patterns of soil moisture in the region. By artificially manipulating surface vegetation at an experimental site in the NSH, the main objectives of this study were to examine the impacts of vegetation and plant phenology on *TS SM*, as vegetation dynamics (e.g., seasonal changes in plant phenology) may affect *TS SM* in a more complex manner than those factors that are generally constant (e.g., topography and soil properties). To this end, soil moisture data at the depths of 30 cm (within the root zone) and 110 cm (at the bottom of the root zone) were collected from plots with different vegetation disturbances over a period of four years. Using soil moisture data from de-vegetated plots as a baseline, the control of vegetation on the patterns of *TS SM* was investigated at different temporal scales. The results offer additional insights into understanding the role of vegetation in controlling soil moisture dynamics in water-limited regions.

2. Materials and methods

2.1. Study area

This study was part of the Grassland Destabilization Experiment (GDEX), which aimed to investigate the ecological and geomorphic stability of the dunes in the NSH (Wang et al., 2008). The GDEX site was located at the University of Nebraska's Barta Brothers Ranch (BBR) in the eastern NSH (Fig. 1). The climate at the site was semi-arid with the mean annual temperature of 8.1 °C and the mean annual precipitation of 576 mm (1960–2000 means for Rose,

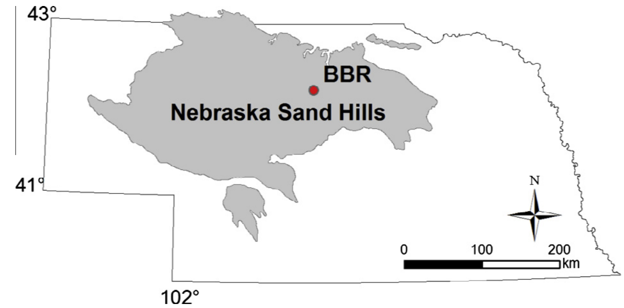

Fig. 1. Location of the University of Nebraska's Barta Brothers Ranch (BBR).

Nebraska, from High Plains Regional Climate Center, http://www.hprcc.unl.edu/). About 90% of the landscape at the BBR was composed by upland dunes and dry interdunal areas with dune heights varying between 5 and 20 m, while the remaining 10% consisted of wet meadows. Vegetation at the site was dominated by native warm-season (C4) grasses with above-ground biomass productivity ranging from 100 to 200 $g\ m^{-2}\ yr^{-1}$ in uplands and 200 to 350 $g\ m^{-2}\ yr^{-1}$ in lowlands (Istanbulluoglu et al., 2012). At the BBR, A (A1/A2) horizons and AC horizons at dune top locations extended to an average depth of 11.8 cm and 27.8 cm, respectively (Wang et al., 2008). Soils were classified in the Valentine series, a mixed, mesic Typic Ustipsamments that lacked any diagnostic subsurface horizon. At interdunal locations, A horizons and AC horizons extended to an average depth of 22.8 cm and 39.1 cm, respectively. Interdunal soils were classified either as the Valentine series or where A horizons exceeded 25 cm as the Dunday series, a sandy, mixed, mesic Entic Haplustolls with a diagnostic mollic epipedon. Soil textural differences at the BBR were very small. Surface soils in the top 10 cm were sandy with the average sand content of 94.4% on ridges and 91.2% in swales. Beneath 10 cm depths, sand contents ranged from 95% to 97% regardless of topographic positions. In 3 m deep soil cores analyzed for root biomass, 60–70% of the total root mass occurred in the top 20 cm and 85–90% occurred in the top 50 cm (Wang et al., 2009b).

2.2. Field measurements

Ten circular plots, each 120 m in diameter, were established for the GDEX at the BBR in May 2004 (Fig. 2). Five treatments (two plots per each treatment) were applied to the circular plots to create a range of experimental disturbance conditions, including Grazed, Control, Pulse, Press, and Aggressive plots. Vegetation was present throughout growing seasons at the Grazed and Control plots. The Grazed plots represented a normal condition in the NSH, while no grazing was allowed in the Control plots. Grazing at the BBR was moderate and well managed, with cattle in pastures for about 6 weeks each summer at a rate of 3.6 hectares per cow. Control plots have been ungrazed since late 2003. The Pulse and Press treatments examined different aspects of ecosystem stability. Pulse plots were killed every third year (e.g., 2005, 2008) and allowed to recover in the intervening years, while Press plots were killed in 2005 and kept dead until the dune surface destabilized and significant erosion began in 2010. Press and Pulse plots were killed with the herbicide glyphosate; dead vegetation and the soil surface were left intact. The Aggressive treatment was designed to accelerate dune destabilization: vegetation was herbicided in May 2004, followed by raking of dead vegetation and light disking. The main characteristics of each treatment are summarized in Table 1. For this analysis, the Grazed, Control, and Pulse plots were treated as vegetated plots, while the Press and Aggressive plots were