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

Tiejun Wang *, David A. Wedin, Trenton E. Franz, Jeremy Hiller

School of Natural Resources, University of Nebraska-Lincoln, Hardin Hall, 3310 Holdrege Street, Lincoln, NE 68583, USA

A R T I C L E   I N F O

Article history:
Received 8 October 2014
Received in revised form 11 December 2014
Accepted 13 December 2014
Available online 20 December 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Juan V. Giraldez, Associate Editor

Keywords:
Soil moisture
Temporal stability
Plant phenology
Climate variability
Native grassland
Nebraska Sand Hills

S U M M A R Y

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.

© 2014 Elsevier B.V. All rights reserved.

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.,...
in regions with fragile ecosystems (Zhang and Shao, 2013), such as the Nebraska Sand Hills (NSH). The 58,000 km

2.1. Study area

The study area 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 a mean annual temperature of 8.1 °C and the mean annual precipitation of 576 mm (1960–2000 means for Rose, Nebraska, from High Plains Regional Climate Center, http://www.hprcc.unl.edu/). About 90% of the landscape at the BBR was made up of 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 sub-surface horizon. At interdunal locations, A horizons and AC horizons extended to an average depth of 22.8 cm and 39.1 cm, respectively. Intermundial soils were classified either as the Valentine series or where A horizons exceeded 25 cm as the Dundy 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 ridgetops 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 diskking. 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
treated as de-vegetated plots. Note that the vegetation in the Pulse plots was killed in 2008, while vegetation was alive in 2006, 2007 and 2009. Thus, for the convenience of comparison, the Pulse plots were classified as vegetation plots.

Given the same initial conditions for the GDEX plots and similar soil texture and topography across different plots (Hellerich, 2006; Wang et al., 2008, 2009b), the GDEX site provided an ideal system for studying the impact of vegetation on TS SM. All the plots were equipped with 6 plastic access tubes for measuring soil moisture. Half of the tubes were 2 m deep, while the other half were 3 m deep. At each plot, four access tubes were installed along a transect (one at a dunetop location, two at the side slopes, and one in the interdunal area), while the remaining two were put at the highest and the lowest position of each plot. Volumetric soil moisture measurements were collected using a TRIME-TDR device (IMKO GmbH, Germany), which provides a single measurement averaged across the 20 cm long probe for each reading. Thus, a 30 cm deep reading is an average value for the 20–40 cm depth. From 2006 to 2009, soil moisture was measured every 2–3 weeks during growing seasons and monthly during non-growing seasons, which resulted in a total of 64 measurement periods. Soil moisture measurements were made at up to 12 depths in each access tube: 10, 30, 50, 70, 90, 110, 140, 160, 190, 220, 260, and 280 cm depth. Owing to multiple reasons (e.g., falling objects in access tubes and temporary loss of access to the tubes due to snow drifts), soil moisture data were incomplete for some sampling locations. To make the maximum use of the data, locations with at least 90% of the total sampling occasions from 2006 to 2009 (e.g., >57) were selected in this study (Fig. 2). Based on this criterion, the following analyses are based on a total of 35 locations with 62 measurements on average per each site. Based on grassland rooting depths in NSH (Eggemeyer et al., 2009; Wang et al., 2009b), this study uses soil moisture results at two depths: 30 cm (in the rooting zone) and 110 cm (below the rooting zone) for analyzing the impact of vegetation on TS SM.

2.3. Statistical analysis

The most applied technique for quantifying TS SM is based on the concept of relative difference (RD) of soil moisture introduced by Vachaud et al. (1985):

$$RD_{ij} = \frac{\theta_{ij} - \overline{\theta}_j}{\overline{\theta}_j}$$  (1)

where $\theta_{ij}$ is soil moisture content at location $i$ and time $j$, and $\overline{\theta}_j$ is mean soil moisture content at time $j$ and can be computed as:

$$\overline{\theta}_j = \frac{1}{N} \sum_{i=1}^{N} \theta_{ij}$$  (2)

where $N$ is the number of sampling locations across the study area at time $j$. By its definition, $RD_{ij}$ represents the deviation of soil moisture content at location $i$ from the mean moisture content at time $j$.

With a time series of $RD_{ij}$, the mean relative difference (MRD) of soil moisture at location $i$ is defined as:
where \( m \) is the number of observations at location \( i \) over time. The term \( \text{MRD} \) is used to quantify the relative wetness condition at a location compared to the mean moisture condition within a field over the observation period. Therefore, locations with \( \text{MRD} \) values close to zero can be used as representative locations for monitoring soil moisture.

The standard deviation of \( \text{RD} \) (SDRD) describes the temporal variability of \( \text{RD} \) and is used to measure TS SM:

\[
\text{SDRD}_i = \left[ \frac{1}{m-1} \sum_{j=1}^{m} (\text{RD}_{ij} - \text{MRDi})^2 \right]^{0.5}
\]

Locations of high TS SM are associated with low \( \text{SDRD} \) values. In this study, the metrics of \( \text{MRD} \) and \( \text{SDRD} \) were used as a primary tool to investigate the impact of vegetation on the pattern of TS SM.

The Spearman nonparametric test was also employed to examine the temporal persistence of the spatial pattern of soil moisture (Vachaud et al., 1985; Vanderlinden et al., 2012). Given the rank \( R_{ij} \) of a variable \( S_j \) at location \( i \) and time \( j \), the Spearman correlation coefficient for variable \( S_j \) at different time \( j \) can be calculated as:

\[
r_s = 1 - \frac{6 \sum_{i=1}^{n} (R_{ij} - R_{ij})^2}{n(n^2-1)}
\]

where \( n \) is the total number of observational sites. A higher value of \( r_s \) indicates that the spatial pattern of soil moisture is more persistent through time.

In the following sections, the Spearman test is first used to examine the temporal persistence of the spatial pattern of soil moisture on different sampling dates; the effect of vegetation on TS SM is then investigated based on soil moisture data at multiannual (from 2006 to 2009), interseasonal (growing vs. non-growing seasons), and interannual (2007 vs. 2009) time scales; the TS SM patterns at different treatment plots are finally analyzed. It should be stressed that the existence of missing soil moisture data in computing \( \text{MRD} \) can lead to non-zero mean \( \text{MRD} \) (MRD) values (Vanderlinden et al., 2012). Examinations of the results of this study revealed that the majority of \( \text{MRD} \) values fell below 0.5%. Thus, given the values and ranges of \( \text{MRD} \) presented in the following sections, the missing soil moisture data would not alter the conclusions made in this study.

3. Results and discussions

3.1. Temporal evolution of soil moisture under different vegetation conditions

Soil moisture dynamics are partly controlled by climatic conditions (Western et al., 2002). To examine the climatic controls on soil moisture dynamics, daily data on precipitation (\( P \)) and potential evapotranspiration (\( \text{PET} \)) at the BBR from 2006 to 2009 were retrieved from the High Plains Regional Climate Center (http://www.hprcc.unl.edu/), and then integrated into monthly data (Fig. 3). During the study period, the annual \( P \) in 2006 (528 mm) and 2007 (566 mm) was lower than the long-term mean annual \( P \) (576 mm), while annual \( P \) in 2008 (701 mm) and 2009 (604 mm) were higher. The cumulative \( P \) during growing seasons (from May to October) was also significantly higher in 2008 (617 mm) and 2009 (453 mm) than in 2006 (332 mm) and 2007 (336 mm). Regarding monthly \( \text{PET} \), there was a decreasing trend in summer seasons from 2006 to 2009. Meanwhile, Istanbulluoglu et al. (2012) showed that this decreasing trend in \( \text{PET} \) during summer seasons had a little impact on vegetation growth at the BBR, as \( P \) was the dominant factor controlling vegetation dynamics in this water-limited environment.

For each sampling day, soil moisture contents from the same treatment plots were averaged at the depths of 30 and 110 cm. The results are plotted in Fig. 4 along with aboveground live biomass measured at upland locations averaged by treatment to show the onset and end of growing seasons. At the 30 cm depth, soil moisture was generally lower during growing seasons in the vegetated plots than in the de-vegetated plots, particularly in drier years of 2006 and 2007 (Fig. 4a). It indicates the role of root water uptake in depleting near surface soil moisture for transpiration during growing seasons. Moreover, the differences in soil moisture contents between the vegetated and de-vegetated plots were smaller in the growing seasons of 2008 and 2009. This is because higher \( P \) during the growing seasons of 2008 and 2009 only resulted in
slightly increased soil moisture in the de-vegetated plots, probably as a result of low holding capacities of sandy soils at the BBR; whereas, soil moisture in the vegetated plots were considerably increased due to the elevated $P$. In contrast, the differences in soil moisture contents among different treatment plots were substantially reduced at the 30 cm depth during the non-growing season due to diminished root water uptake. Note that in the growing season of 2008, vegetation at the Pulse plots was killed by herbicide in May, which led to higher soil moisture contents in the Pulse plots than in the Grazed and Control plots. The standard deviation of soil moisture on each sampling date was averaged at 2.30% (from 1.08% to 3.72%) for the Grazed plots, 2.38% (from 0.66% to 5.84%) for the Control plots, 2.54% (from 1.41% to 4.55%) for the Pulse plots, 1.50% (from 0.78% to 3.45%) for the Press plots, and 1.60% (from 0.70% to 3.74%) for the Aggressive plots. Clearly, the spatial variability in soil moisture within the root zone was higher in the vegetated plots, indicating that vegetation tended to increase the spatial variability in soil moisture at the study site, which is consistent with the results of Gomez-Plaza et al. (2000). By comparison, the mean standard deviation of soil moisture based on the data from all the plots varied between 1.91% and 22.50% with an average of 7.47%. For the same treatment, mean soil moisture contents from different plots (i.e., two repetitions for each treatment) also varied. Fig. 5 shows the absolute difference in mean soil moisture contents between the repetitions with the same treatment (denoted as $|\Delta \theta|$). Regardless of treatment and time of the year, $|\Delta \theta|$ was generally less than 4% at the 30 cm depth (Fig. 5a). During growing seasons, $|\Delta \theta|$ was considerably lower than the difference in mean soil moisture contents among different treatments (i.e., vegetated vs. de-vegetated plots), particularly in the drier years; whereas, the differences in mean soil moisture contents within the same treatment and among different treatments were similar during non-growing seasons.

Temporal evolution of soil moisture exhibited different patterns at the 110 cm depth (Fig. 4b). During the growing seasons of 2006 and 2007, soil moisture contents at the 110 cm depth were still lower in the vegetated plots, probably due to less recharge from upper soil layers instead of direct root water uptake. This is evidenced in the lag time of soil moisture depletion between the 30 and 110 cm depth in the vegetated plots during the growing seasons of 2006 and 2007 (Fig. 4b). Moreover, soil moisture contents in the vegetated plots became higher at the 110 cm depth in 2008 and 2009, indicating that vegetation had a negligible impact on soil moisture levels at deeper depths (e.g., below root zone) except through controlling recharge. Lastly, Fig. 5b shows that $|\Delta \theta|$ at the 110 cm depth was similar to the difference in mean soil moisture contents among different treatments throughout the study period. Combined with the root density distribution data at the BBR (Wang et al., 2009b), Fig. 4 thus demonstrates that the temporal evolution of soil moisture within the root zone (e.g., 30 cm) was significantly affected by plant phenology at seasonal scales.

### 3.2. Overall patterns of TS SM

#### 3.2.1. Spearman's rank correlation coefficient

The temporal persistence of the spatial pattern of soil moisture is commonly observed in field studies with only few exceptions (e.g., Jia and Shao, 2013). The non-parametric Spearman correlation test is routinely used to examine the temporal persistence of the spatial pattern of soil moisture (Vachaud et al., 1985; Vanderlinden et al., 2012). Since this study was comprised of a total of 64 field campaigns, for the purpose of brevity, only two sampling dates were selected from each calendar year (one from spring and the other one from summer) for calculating the Spearman rank correlation coefficient $r_{s}$. The coefficient $r_{s}$ was calculated between the selected field campaigns and the results are summarized in Table 2. Similar to previously reported values (e.g., Brocca et al., 2009; Zhao and Shao, 2013), the majority of $r_{s}$ was significant at the $p$ level <0.01 at both depths, indicating the temporal persistence of the spatial pattern of soil moisture at the BBR. However, no further information could be derived from the Spearman correlation test to detect the impact of vegetation on TS SM (e.g., between growing and non-growing seasons).

#### 3.2.2. Effect of soil depth on TS SM

The GDEX offered an opportunity to study the impact of vegetation on TS SM in water-limited environments. Given similar soil texture and topography across different treatment plots (Hellerich, 2006; Wang et al., 2008, 2009b), soil moisture data from the de-vegetated plots were used as a baseline for detecting the impact of vegetation on TS SM at the BBR based on the metrics of MRD and SDRD. To this end, soil moisture data from all the sampling locations with a total of 64 sampling dates were combined together to calculate MRD and SDRD. The ranked MRD and associated SDRD are plotted in Fig. 6 for the depths of 30 and 110 cm. In general, Fig. 6 confirms the existence of TS SM at both depths. More importantly, Fig. 6a shows the impact of vegetation on the ranking of MRD at the 30 cm depth. With the presence of root water uptake at the 30 cm depth, locations in the vegetated plots had consistently lower MRD ranks than those in the de-vegetated plots with only few exceptions (Fig. 6a). The sites with positive MRD values from the vegetated plots (e.g., Location 25, 26, and 9 shown in Fig. 6a) were generally located at the dunetop positions, where vegetation was less dense. Moreover, within the vegetated or de-vegetated plots, there appeared to be no clear patterns of MRD, indicating that other factors (e.g., grazing and dead plant residues) had negligible impacts on MRD. Finally, no clear pattern of MRD can be observed at the 110 cm depth due to diminished root water uptake (Fig. 6b), which is consistent with the results presented in Fig. 4. Soil moisture at the BBR also tended to be less temporally stable at the 30 cm depth (mean SDRD of 26.4%) than at the 110 cm depth (mean SDRD of 17.2%). It is in line with previous findings that soil moisture was more temporally stable at deeper soil depths (e.g., Martinez-Fernandez and Ceballos, 2003; Guber et al., 2008; Jia et al., 2013).

The effects of treatment (five levels), depth (two levels), and topographical location (two levels; e.g., upland vs. lowland) on
MRD, and the effects of their interactions on MRD were examined by a three-way analysis of variance (ANOVA) model. By treating depth as a categorical variable, the model made no assumption about the shape of the relationship between MRD and depth. The three-way ANOVA model was highly significant ($p < 0.0001$, $r^2 = 0.55$). Among the three variables, treatment was the most important factor controlling MRD ($F = 6.1287$, $p = 0.0002$), which was followed by topographical location ($F = 2.8768$, $p = 0.0934$) and depth ($F = 0.1453$, $p = 0.7040$). The treatment by depth interaction was also significant ($F = 6.1936$, $p = 0.0002$), while the impacts of other interactions on MRD were insignificant. In addition, Table 3 shows the Pearson correlation coefficients of MRD and SDRD with other soil and topographical factors measured at each monitoring location, including soil carbon content (averaged at 0.55% by weight and ranging from 0.05% to 2.21%), elevation (averaged at 766.7 m and ranging from 761.4 to 773.6 m), and slope (averaged at 8.1% and ranging from 1.3 to 19.1%). No measurements of bulk density and soil texture were taken at the monitoring locations, but the well-sorted eolian sand deposits at the study area showed little spatial variations in those two parameters (Hellerich, 2006; Wang et al., 2008, 2009b). Except for the negative correlation between elevation and SDRD, the Pearson correlation coefficients showed no dependence of MRD and SDRD on those soil and topographical factors.

Overall, the results of the statistical analysis suggest that vegetation may outweigh other factors in controlling the pattern of TS...
SM (e.g., ranking of MRD), particularly in regions with considerable spatial heterogeneities in vegetation covers. This conclusion is different from the findings of Zhao et al. (2010), who showed that vegetation was less important than soil properties in determining TS SM in a semi-arid grassland, likely due to the homogeneous sandy soils at our study site. Owing to the contrasting vegetation conditions among different treatment plots, the results in Fig. 6 might not be viable for identifying representative locations. Nevertheless, Fig. 6 shows that in regions with heterogeneous vegetation covers, it is critical to consider the spatial distribution pattern of vegetation for identifying representative locations within the root zone. Lastly, Fig. 6 implies that representative locations may change with depth, as also found by Martinez-Fernandez and Ceballos (2003), because the relative importance of different controlling factors (e.g., root water uptake) on TS SM varies with depth.

3.2.3. Interseasonal variations in TS SM

The control of vegetation on soil moisture dynamics at the BBR naturally leads to the question as to whether plant phenology would have any effect on interseasonal patterns of TS SM, which has been rarely investigated in previous studies with few exceptions (e.g., Biswas and Si, 2011). For this purpose, soil moisture data from 2006 to 2009 were regrouped into growing (from May to October with a total of 37 sampling dates) and non-growing (from November to April with a total of 27 sampling dates) seasons at the 30 cm depth. The resulting MRD and SDRD are shown in Fig. 7. Compared to the overall pattern of MRD shown in Fig. 6a, the dependence of MRD on vegetation became even stronger during growing seasons (Fig. 7a). More interestingly, with the absence of active vegetation during non-growing seasons, the effect of vegetation on the ranking of MRD substantially weakened, resulting in

### Table 3

<table>
<thead>
<tr>
<th>Observational period</th>
<th>Depth (cm)</th>
<th>Variable</th>
<th>Soil carbon</th>
<th>Elevation</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006–2009</td>
<td>30</td>
<td>MRD</td>
<td>–0.049</td>
<td>0.002</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SDRD</td>
<td>0.017</td>
<td>–0.496***</td>
<td>–0.068</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>MRD</td>
<td>–0.180</td>
<td>–0.207</td>
<td>–0.034</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SDRD</td>
<td>–0.073</td>
<td>–0.320**</td>
<td>–0.188</td>
</tr>
<tr>
<td>Growing season (2006–2009)</td>
<td>30</td>
<td>MRD</td>
<td>–0.274</td>
<td>0.035</td>
<td>–0.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SDRD</td>
<td>0.025</td>
<td>–0.429***</td>
<td>–0.022</td>
</tr>
<tr>
<td>Non-growing season (2006–2009)</td>
<td>30</td>
<td>MRD</td>
<td>–0.362**</td>
<td>–0.079</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SDRD</td>
<td>–0.181</td>
<td>–0.265</td>
<td>–0.106</td>
</tr>
<tr>
<td>Calendar year 2007</td>
<td>30</td>
<td>MRD</td>
<td>–0.238</td>
<td>–0.025</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SDRD</td>
<td>–0.044</td>
<td>–0.477***</td>
<td>0.071</td>
</tr>
<tr>
<td>Calendar year 2009</td>
<td>30</td>
<td>MRD</td>
<td>0.120</td>
<td>–0.118</td>
<td>–0.080</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SDRD</td>
<td>0.352*</td>
<td>–0.245</td>
<td>–0.090</td>
</tr>
</tbody>
</table>

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

![Fig. 7](image-url)
a smaller range of MRD values (Fig. 7b). In particular, over half of the sampling locations from the de-vegetated plots showed negative MRD values. Meanwhile, SDRD during growing seasons (averaged at 25.6%) was also higher than values during non-growing seasons (averaged at 21.3%). Two reasons might lead to the higher SDRD during the growing seasons: (1) the larger number of sampling dates in the growing seasons and (2) the tendency of vegetation to reduce TS SM as shown in the following section. The change in the interseasonal MRD patterns shown in Fig. 7 can be attributed to the high conductivities and low holding capacities of sandy soils at the BBR, which led to quick recovery of soil moisture during non-growing seasons in the vegetated plots to the soil moisture levels observed in the de-vegetated plots (Fig. 4a). Biswas and Si (2011) also observed that the changes in interseasonal patterns of TS SM in a hummocky area were tightly related to the presence of vegetation and its spatial pattern. Fig. 7 highlights that due to seasonal changes in plant phenology, the timing and/or frequency of sampling schemes may alter MRD patterns and thus affect the selection of representative monitoring sites. Although a considerable portion of existing studies focused only on TS SM during growing seasons, it appears that a full year of observations is necessary to have a complete effect of plant phenology on TS SM.

The effects of treatment (five levels) and season (two levels), and the effect of their interaction on MRD were examined by a two-way ANOVA model. The model results showed that treatment had a significant impact on MRD ($F = 8.81, p < 0.0001$), while the effect of season alone was insignificant ($F = 0.079, p = 0.7833$). More importantly, MRD was more controlled by the interaction of treatment and season ($F = 59.9, p < 0.0001$). Meanwhile, the Pearson correlation coefficients showed no consistent impacts of soil carbon, elevation, and slope on MRD and SDRD for both growing and non-growing seasons (Table 3), indicating the dominant control of vegetation (or plant phenology) on the interseasonal change in the TS SM patterns.

To further investigate the reasons for causing the shifts in the ranking of MRD from growing to non-growing seasons, changes in MRD values between those two seasons were calculated for each sampling location (denoted as $\eta = \text{MRD}_{\text{Growing}} - \text{MRD}_{\text{Non-growing}}$). The results showed a positive correlation between $\eta$ and elevation in the vegetated plots (Fig. 8). As expected, soil moisture in the de-vegetated plots was relatively higher during growing seasons (indicated by positive $\eta$ values) due to the absence of root water uptake; however, no correlation was found between $\eta$ and elevation. By comparison, positive relationships emerged between $\eta$ and elevation from the vegetated plots. With decreasing elevation, $\eta$ was more negative and soil moisture became relatively drier dur-
ing growing seasons. It is likely due to the fact that lower elevations (e.g., swales) were generally associated with denser vegetation covers at the BBR, which led to greater interseasonal changes in soil moisture at lower elevations. Thus, Fig. 8 suggests that in the vegetated sand dunes at the NSH, interseasonal changes in TS SM was stronger at locations with denser vegetation, where soil moisture exhibited less temporal stability on seasonal scales.

3.2.4. Interannual variations in TS SM

To illustrate the impact of vegetation on TS SM on annual time scales, MRD and SDRD at the 30 cm depth were calculated for the calendar year 2007 and 2009 with similar numbers of sampling dates in the growing (11 for 2007 and 9 for 2009) and non-growing (5 for 2007 and 6 for 2009) seasons. In addition, the MRD and SDRD calculated for the growing season of 2007 and 2009 showed similar results and thus are not analyzed here. The obtained MRD and SDRD are plotted in Fig. 9. Although the effect of vegetation on the ranking of MRD still existed, this effect obviously differed for those two years, which was most likely caused by the variations in P. In the drier year of 2007 (P = 566 mm), the impact of vegetation was more pronounced with most of the MRD values from the de-vegetated plots greater than 30%; whereas, the contrasts in the
**3.3. TS SM at different treatment plots**

To further examine the impact of vegetation on TS SM, MRD and SDRD were calculated for different treatment plots using soil moisture data from 2006 to 2009. The results for the depths of 30 and 110 cm are shown in Fig. 10. The statistical summary of MRD and SDRD is given in Table 4. The obtained MRD ranges for different treatment plots were in general agreement with previously reported values (Gomez-Plaza et al., 2000; Brocca et al., 2009; Gao and Shao, 2012). However, in spite of similar soil texture and topography across all the plots, the MRD ranges from the vegetated plots were noticeably larger at the 30 cm depth than those from the de-vegetated plots (Table 4), suggesting that vegetation tended to increase the spatial variability in soil moisture at the stronger under dry conditions, which would affect the TS SM pattern on annual time scales.

A two-way ANOVA model was also constructed to examine the effects of treatment (five levels) and P (two levels representing 2007 and 2009), and the effect of their interaction on MRD. Although treatment still had the highest impact on MRD \((F = 41.0, p = 0.0001)\), the effect of P on MRD was also significant \((F = 6.88, p = 0.0237)\). The treatment by P interaction was significant as well \((F = 21.1, p < 0.0001)\). Given that the Pearson test did not show any consistent impacts of soil carbon, elevation, and slope on MRD and SDRD during both years (Table 3), the statistical results also corroborate that the interannual variations in TS SM was affected by annual P levels.

**Table 4**

Summary of MRD and SDRD for different treatment plots (units are in %). Soil moisture data from 2006 to 2009 were used to calculate MRD and SDRD.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Range of MRD (30 cm)</th>
<th>Range of SDRD (30 cm)</th>
<th>Mean SDRD (30 cm)</th>
<th>Range of MRD (110 cm)</th>
<th>Range of SDRD (110 cm)</th>
<th>Mean SDRD (110 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazed</td>
<td>37.9 to 48.6</td>
<td>22.5–49.7</td>
<td>30.2</td>
<td>15.9 to 21.4</td>
<td>9.4–33.0</td>
<td>16.3</td>
</tr>
<tr>
<td>Control</td>
<td>26.3 to 42.7</td>
<td>16.4–68.2</td>
<td>28.6</td>
<td>33.1 to 135.2</td>
<td>7.9–48.0</td>
<td>17.2</td>
</tr>
<tr>
<td>Pulse</td>
<td>44.6 to 49.4</td>
<td>14.7–35.5</td>
<td>23.2</td>
<td>31.4 to 42.5</td>
<td>10.6–51.7</td>
<td>19.6</td>
</tr>
<tr>
<td>Press</td>
<td>17.8 to 12.5</td>
<td>10.4–21.6</td>
<td>14.7</td>
<td>16.2 to 36.9</td>
<td>7.6–21.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Aggressive</td>
<td>12.4 to 27.6</td>
<td>8.1–19.6</td>
<td>13.7</td>
<td>14.0 to 18.6</td>
<td>8.3–15.4</td>
<td>10.2</td>
</tr>
</tbody>
</table>

**Table 5**

Pearson correlation coefficients of MRD and SDRD with soil and topographic factors at different treatment plots. Soil moisture data from 2006 to 2009 were used to calculate MRD and SDRD.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>Variable</th>
<th>Soil carbon</th>
<th>Elevation</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazed</td>
<td>30</td>
<td>MRD</td>
<td>−0.368</td>
<td>0.744</td>
<td>−0.121</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>SDRD</td>
<td>−0.192</td>
<td>0.392</td>
<td>−0.603</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>MRD</td>
<td>0.065</td>
<td>−0.229</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>SDRD</td>
<td>0.082</td>
<td>−0.150</td>
<td>−0.191</td>
</tr>
<tr>
<td>Control</td>
<td>30</td>
<td>MRD</td>
<td>0.099</td>
<td>−0.398</td>
<td>−0.074</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>MRD</td>
<td>0.298</td>
<td>−0.473</td>
<td>−0.247</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>SDRD</td>
<td>0.017</td>
<td>−0.435</td>
<td>−0.368</td>
</tr>
<tr>
<td>Pulse</td>
<td>30</td>
<td>MRD</td>
<td>−0.085</td>
<td>0.624</td>
<td>0.220</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>MRD</td>
<td>0.236</td>
<td>−0.029</td>
<td>−0.138</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>SDRD</td>
<td>−0.130</td>
<td>−0.343</td>
<td>0.125</td>
</tr>
<tr>
<td>Press</td>
<td>30</td>
<td>MRD</td>
<td>0.107</td>
<td>−0.189</td>
<td>−0.205</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>MRD</td>
<td>−0.407</td>
<td>−0.223</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>SDRD</td>
<td>−0.045</td>
<td>−0.307</td>
<td>0.158</td>
</tr>
<tr>
<td>Aggressive</td>
<td>30</td>
<td>MRD</td>
<td>−0.184</td>
<td>−0.308</td>
<td>0.690</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>MRD</td>
<td>−0.220</td>
<td>−0.008</td>
<td>0.653</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>SDRD</td>
<td>0.590</td>
<td>−0.319</td>
<td>−0.003</td>
</tr>
</tbody>
</table>

\*p < 0.05.
Fig. 11. Comparisons of mean soil moisture with soil moisture from a representative location identified by the MRD value closest to zero for each treatment. Representative locations at each treatment are indicated in parentheses.
NSH. Furthermore, Fig. 10 provides direct evidence that TS SM was reduced with the presence of vegetation. At the 30 cm depth, SDRD in the vegetated plots was consistently larger than those in the de-vegetated plots; whereas, with diminished root water uptake at the 110 cm depth, SDRD in the vegetated plots were significantly reduced. Given that soil moisture at the 30 cm depth was more affected by root water uptake, Fig. 10 thus supports the conclusion that vegetation along with other surface processes (e.g., soil evaporation) is likely to decrease TS SM in surface soil layers (Vanderlinden et al., 2012). Pearson correlation coefficients of MRD and SDRD with soil carbon, elevation, and slope were also calculated for different treatment plots (Table 5). Unlike the results of Zhao et al. (2010) and Zhang and Shao (2013), no clear dependence of TS SM on soil properties and topography was found, probably because of the small spatial variations in soil properties and the smaller number of sampling locations within each treatment.

One use of TS SM is to identify representative locations for monitoring soil moisture (Vachaud et al., 1985; Vanderlinden et al., 2012). Several criteria for selecting representative locations have been proposed, including MRD closest to zero (Vachaud et al., 1985), smallest SDRD with an constant offset (Starks et al., 2006), and smallest root mean square error (i.e., $\sqrt{MRD^2 + SDRD^2}$; Jacobs et al., 2004). For a demonstration purpose, the location with the MRD value closest to zero for each treatment was chosen as the representative location, and the relationships between mean soil moisture and soil moisture from the representative locations are shown in Fig. 11. The representative locations were mainly located at side slopes followed by dunetop positions, which is consistent with the findings of Grayson and Western (1998). However, within each treatment, no representative locations remained at the same site for both 30 and 110 cm depths, as the relative importance of different controls (e.g., root water uptake) on TS SM may vary with depth. In general, there were high correlations between mean soil moisture and soil moisture from the representative locations, attesting the feasibility of using representative locations for monitoring mean soil moisture conditions at the study site. In particular, at the 30 cm depth, the correlations between mean soil moisture and soil moisture from the representative locations deteriorated at the Grazed and Control plots. It can be explained by the low TS SM (i.e., high SDRD) at those vegetated plots. Therefore, the effectiveness of using representative locations for monitoring mean soil moisture conditions might be affected with the presence of vegetation and should be explicitly considered for designing experiments elsewhere. In addition, the use of other selection criteria yielded similar results (e.g., similar $R^2$ between mean soil moisture and soil moisture from representative locations), although the representative locations might vary among different selection criteria. The high $R^2$ for multiple representative locations identified by different selection criteria can be largely attributed to the small spatial variations in soil properties at the study site, which led to similar behaviors of soil moisture dynamics at different monitoring sites as indicated by the small standard deviations of soil moisture within each treatment.

4. Conclusions

In this study, the control of vegetation on the temporal stability of soil moisture (TS SM) was investigated at an experimental site in a native grassland, where surface vegetation was artificially controlled to different disturbance conditions. Using soil moisture data from de-vegetated plots as a baseline, the TS SM pattern was shown to be mainly affected by vegetation through root water uptake. As such, representative locations within a field may change with depth, depending on the relative importance of the controlling factors (e.g., root water uptake) with depth. More importantly, the effect of vegetation on TS SM was largely controlled by plant phenology, and thus varied on both seasonal and annual time scales. On seasonal scales, the TS SM pattern depended on plant phenology (e.g., growing vs. non-growing seasons). The control of vegetation on the ranking of mean relative difference (MRD) of soil moisture significantly weakened in non-growing seasons due to diminished root water uptake, suggesting that the TS SM pattern would depend on the timing of sampling schemes. Meanwhile, the interannual variations in TS SM were affected by climatic conditions, as the control of vegetation on TS SM became stronger under dry conditions, resulting in larger contrasts in soil moisture levels between vegetated and de-vegetated plots. Within each treatment, the soil moisture data showed that vegetation tended to increase both spatial and temporal variability in soil moisture. Due to the effect of vegetation, the effectiveness of using representative locations for monitoring mean soil moisture conditions deteriorated.

Acknowledgments

This research was funded in part by NSF (DEB-0322067, D. Wedin) and USDA McIntire-Stennis (NEB-40-044 and NEB-38-089, D. Wedin), and made possible by the field work of undergraduate interns: A. Beringer, C. Darling, J. Dinneen, N. Dobesh, and J. Thompson. Support for T.E. Franz was provided by the Daugherty Water for Food Institute. We would also like to thank R. Teuling and two anonymous reviewers for their constructive comments, which led to the improvements of this work.

References
