THE EFFECTS OF DUNE STABILIZATION ON THE SPATIOTEMPORAL DISTRIBUTION OF SOIL MOISTURE RESOURCES, NORTHERN GREAT PLAINS, CANADA

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BSc. Geography (Concentration GIS),

University of Lethbridge, 2008

A Thesis
Submitted to the School of Graduate Studies
of the University of Lethbridge
in Partial Fulfilment of the
Requirements for the Degree

MASTER OF SCIENCE

Department of Geography
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

DEDICATION

To my late companion Heidi List

ABSTRACT

In dryland environments, the availability of soil moisture is the primary control on plant species' distributions. In the sandhill regions of the northern Great Plains, vegetation establishment has transformed highly mobile, desert-like dune fields into stabilized landscapes covered by mixed-grassland prairie. This study examines how dune stabilization has modified the spatiotemporal distribution of soil moisture resources. An ergodic (space-for-time) approach was used, comparing soil moisture dynamics on active and vegetation-stabilized dunes in the Bigstick Sand Hills of southwestern Saskatchewan. Results indicate that while dune stabilization has enhanced near-surface soil moisture availability, deeper profile soil moisture recharge is reduced. Through better understanding how vegetation has modified soil moisture dynamics in stabilizing sandhill regions, better management practices may be implemented to maintain water resource availability and ecosystem health.

ACKNOWLEDGEMENTS

This thesis could not have been completed without the help and support of many people. First, thank you Dr. Chris Hugenholtz for supporting my choice of thesis topic and my endeavours to plan, execute, and publish my research. His foresight, patience, and experience have been invaluable assets in helping guide my research direction. I also thank Dr. Hugenholtz for providing me the opportunity to attend the 2010 Prairie Summit in Regina, for helping me network with other interesting geoscientists, and for his support and accommodation when a significant career opportunity fell into my lap near the completion of my thesis work. Few go as far as Dr. Hugenholtz to help their students achieve great things and become successful.

Dr. Matthew Letts took on an increasing role as co-supervisor of this thesis work after Dr. Hugenholtz moved to Calgary to become the Cenovus Chair in Canadian Plains Mitigation and Reclamation Research. Dr. Letts has patiently guided me through the thesis-writing process, helping me identify both when I have articulated ideas clearly and when my ideas as stated required further clarification or abandonment. His openness and availability during times when contacting Dr. Hugenholtz was not "spatially convenient" have made my thesis writing during the last year much more enjoyable.

My research could not have been performed without easy access to a stabilizing sandhill ecosystem. Many thanks go to Ian, Eleanor, John, and Tracy Bowie for allowing me to access their pristine ranch in the Bigstick Sand Hills. Their friendship and logistical support during both the planning and execution stages of the field work portion of my research is greatly appreciated. Also, thank you to the Martin Grazing Co-op for giving permission to work on their land.

Finally, I would like to thank those people who helped me collect the data used in this thesis, including the greater wealth of data that remains to be analysed by others at a later date. These people often got dirtier and suffered more than I did when augering holes, digging pits, and operating the mobile TDR probe under the adverse weather conditions that typified my field season. Without the help of Tayler Hamilton, Kristine Lamble, Owen Brown, and Tom Barchyn, conducting the field portion of this research would not have been possible.

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A1	Active dune study site #1
A2	Active dune study site #2
ASTM	American Society of Testing and Materials
BSH	Bigstick Sand Hills
C_3	C_3 Photosynthetic carbon fixation process
C_4	C_4 Photosynthetic carbon fixation process
Co. Var.	Coefficient of Variation
F	Freidman statistical test
GIS	Geographic Information System
GPS	Global Positioning System
H	Kruskal-Wallis statistical Test
LOI	Loss on Ignition
P:PE	The ratio of precipitation to potential evapotranspiration
$S_{y,x}$	Standard Error of the Estimate
S1	Stabilized dune study site #1
S2	Stabilized dune study site #2
S.M.	Soil Moisture
St. Dev.	Standard Deviation
TDR	Time-domain reflectometry
USDA	United States Department of Agriculture
Vol.	Volumetric
W	Wilcox Rank Sum statistical test

θ_V	Volumetric soil moisture

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Motivation

Active and vegetation-stabilized aeolian sand deposits cover approximately 6% of the global land surface area and are present on every continent, giving these deposits widespread ecological and cultural significance (Pye & Tsoar, 2009). While the landforms (dunes) that usually denote these sand deposits may be readily observed at the surface, in the subsurface large quantities of accessible freshwater are often present. In regions exhibiting bare, active aeolian dune forms, rapid moisture infiltration rates encourage recharge of deep moisture reserves (Berger, 1992; Chen & Chen, 2004; Harvey *et al.,* 2007). However, the moisture infiltration and storage properties of these sediments become modified following the introduction of vegetation during dune stabilization. To date, few studies have focussed on the changing soil moisture dynamics in naturally stabilizing or stabilized dune ecosystems (Berger, 1992; Shay *et al.*, 2000). Most research has occurred in desert regions where active dunes have been artificially stabilized to enhance the anthropogenic utility of the soils (e.g. Duan *et al.*, 2004; Li *et al.*, 2004B; Zhang *et al.*, 2008). Given the widespread and increasing anthropogenic reliance on aeolian groundwater sources, in conjunction with changing climate, a better understanding of the effects of natural dune stabilization on soil moisture and groundwater recharge is warranted to guide land-use management decisions now and in the future.

In the southern Canadian Prairie region, large tracts of sand dunes have become vegetated over the last 200 years, representing a major transformation of these ecosystems (Wolfe *et al.*, 2001; Wolfe & Hugenholtz, 2009; Hugenholtz *et al.*, 2010). Following cold and

dry conditions during the Little Ice Age (ca. 1550-1850 AD) prairie dunefields (commonly referred to as sandhills) converted from desert-like conditions to the relatively verdant landscapes we see today (Wolfe & Hugenholtz, 2009). Beginning around 200 years BP, expanding vegetation cover transformed the dunes from highly mobile, barchan dunes to vegetation-stabilized parabolic dunes, which represents a complete reversal in dune morphology from active, bare dunes with arms pointing downwind to vegetation stabilized dune arms pointing upwind (David *et al.*, 1999). Currently, less than 1% of Canadian Prairie dunefields are mobile and active, and it is expected that this percentage will soon approach zero (Epp & Townley-Smith, 1980; Hugenholtz *et al.*, 2010). Changes in climate in conjunction with the establishment of vegetation have modified a variety of biophysical processes within these landscapes. (Hulett *et al.*, 1966; Shay *et al.*, 2000; Hugenholtz *et al.*, 2010). Elsewhere, it has been shown that dune stabilization reduces soil moisture recharge through increased evapotranspiration and reduced infiltration rates (Barnes & Harrison, 1982; Berger, 1992; Li *et al.*, 2007). However, few studies have investigated how natural dune stabilization influences soil moisture dynamics in climatic and geomorphological settings comparable to those of Canadian Prairie sandhill ecosystems.

This thesis investigates the impact of vegetation expansion, i.e. sand dune stabilization, within a formerly active Canadian Prairie sandhill ecosystem. *The objective of this research is to determine how the establishment of vegetation has modified the spatial and temporal distribution of soil moisture in a formerly active Canadian Prairie sand dune ecosystem*. To accomplish this, an investigation was undertaken to compare soil moisture between bare, active dunes, which represent former landscape conditions, and vegetation-stabilized dunes, which represent the current state of the majority of this ecosystem. Following this introduction, a detailed background that provides an overview on soil moisture dynamics within active and stabilized

dune ecosystems is presented. In Chapter 2, temporal soil moisture dynamics within the vertical soil profiles of active and stabilized dunes are examined. In Chapter 3, the spatiotemporal dynamics of near-surface soil moisture in relation to topography and vegetation cover types are examined. In Chapter 4, the main conclusions of this research are outlined. However, before examining the details of the studies, I will provide the necessary background to place these chapters within the framework of dune soil moisture research.

1.1.1 Literature review

Soil moisture is an important component of the hydrological cycle and is influenced by several controlling factors, including: precipitation, evaporation, transpiration, interception, infiltration, storage, runoff, and discharge (Ward & Robinson, 2000). These controls modify soil moisture dynamics to varying degrees within different ecosystems, necessitating the study of soil moisture dynamics at the scale of individual, unique ecosystems (Knapp *et al.*, 2008). This literature review will begin by discussing a simplified model of soil moisture controls for active dunes, where effects of vegetation are absent or minimized. Following this, I will review how vegetation modifies soil moisture dynamics within stabilizing dune ecosystems. Finally, I will outline my research hypothesis and thesis outline.

1.2.1 Dune soil moisture dynamics in the absence of vegetation

From first principles the hydrological cycle comprises inputs, outputs, and storage of water. Soil moisture is a component of the latter. Precipitation is the primary moisture input for most dune ecosystems (Qiu *et al.*, 2001). In dryland dune regions, convective precipitation often dominates the precipitation regime, especially during the summer months (HilleRisLambers *et al.*, 2001; Kim & Wang, 2007). The high intensity, short duration, and spatial variability of convective precipitation may enhance the spatiotemporal heterogeneity of soil moisture across the landscape (Douville, 2004; Sridhar *et al.*, 2008; Sridhar & Wedin, 2009). If the intensity of incoming precipitation exceeds the infiltration rate of the soil, runoff and perched water tables may occur (Berger, 1992; Gosselin *et al.*, 1999). However, if a precipitation event fails to deposit sufficient moisture, soil moisture recharge deeper within the soil profile will not occur (Salve & Allen-Diaz, 2001; Schneider *et al.*, 2008).

Condensation may act as an important input for soil moisture in some active dune environments. While Bagnold (1941) suggested that bare sand may not readily experience condensation near the soil surface due to poor heat conduction, others suggest that condensation is an important source of moisture in desert dune environments (Danin, 1991; Pan & Wang, 2009). Cooling of the soil surface after the mid-day temperature peak helps recharge desiccated near-surface soil layers through condensation of atmospheric moisture (Dincer *et al.*, 1974). Water vapour sourced within moist soil layers below the surface may also condense near the surface as the ground cools, enhancing the redistribution of soil moisture within the near surface (Yamanaka & Yonetani, 1999).

Precipitation falling on active sand dunes is usually absorbed quickly because the coarse texture and porosity of the deposit is conducive to rapid infiltration. Infiltration rates

in excess of 100 cm day^{-1} can occur (Chen & Chen, 2004; Wang *et al.*, 2008). In contrast, infiltration rates in finer sediments (clays, silts) can be several orders of magnitude slower than those found in dune sands (Kramer, 1944; Yair, 1990; Kozak & Ahuja, 2005). While relatively uncommon in regions with sandy soils, infiltration rates can decrease due to compaction (Yair,1990; Tao *et al.*, 2001; Dunkerly, 2002), salinity (Mamedov *et al.*, 2001) and sediment pore-clogging with finer sediment particles (Wakindiki & Ben-Hur, 2002).

Soil texture also determines the moisture storage capacity of a soil by controlling the amount of pore space between sediment particles. Fine-textured soils generally store more soil moisture per soil volume than coarse soils (Bouma, 1977; Barnes & Harrison, 1982; Sridhar *et al.*, 2008). While coarse soils have larger pore spaces between sediment particles, the total volume of these large pore spaces is less than that of the many smaller pore spaces found in fine-textured soils (Bouma, 1977; Sridhar *et al.*, 2008).

The capillary rise of soil moisture above a saturated soil zone is controlled by the matric suction of pore spaces within that soil (Wind, 1961). Matric suction is determined by the size of pore spaces within a soil; with smaller pore spaces exerting greater matric suction potential when the soil is dry (White, 1987). Because of this, the potential for capillary rise is greatest in fine soils (such as clays), and lowest in coarse, sandy soils (Kramer, 1944; Loope *et al.*, 1995). Limited capillary rise in sandy soils protects moisture reserves within the soil profile from depletion by limiting moisture transfer to near-surface soil layers that are more susceptible to evaporative losses (Stephens & Knowlton, 1986).

Topography can strongly influence the spatiotemporal distribution of moisture on dunes. Slope position, aspect, and curvature can all influence soil moisture distributions on active dunes (Daultry, 1970; Miller *et al.*, 1983). The gravitational redistribution of soil

moisture to lower slope positions often makes soils near the base of active dunes moister than those near the dune crest (Qiu *et al.*, 2001; de Rosnay *et al.*, 2009). The direction (or aspect) a dune slope faces affects the amount of solar radiation received at the surface, thereby influencing spatial soil moisture patterns by modifying ground temperature, evaporation, and transpiration within a dune landscape (Rummel & Felix-Henningsen, 2004). Slope steepness and curvature also influence moisture distribution on dunes (Daultry, 1970). Steep, convex dune slopes tend to be drier, whereas shallow, concave slopes tend to have higher moisture contents (Daultry, 1970; Maestre *et al.*, 2003).

Dune sediment laminae of different textures also affect the redistribution of moisture within the soil profile (Berndtsson *et al.*, 1996). The laminae range in thickness from sub-centimetre to several decametres and are the result of different depositional mechanisms (e.g., ripple migration, grainfall, grainflow), often leading to significantly different sediment textures within adjacent dune laminae (Bridge & Best, 1988). Soil moisture infiltration within dunes can follow individual laminae instead of penetrating through them, thus enhancing the lateral redistribution of soil moisture (Gardner & McLaren, 1999). The combination of steep slopes and laminae may also significantly reduce moisture penetration into the dune profile and may at times enhance the potential for runoff (Berndtsson *et al.*, 1996).

Soil moisture outputs from active, unvegetated dunes are controlled mostly by water exchange with the atmosphere (evaporation) and groundwater discharge. The coarse texture of dune sands limits evaporation to near-surface (< 30 cm) layers (Gardner & McLaren, 1999). Below this, evaporation is greatly reduced, with some soil water vapour being transported toward the surface along vapour gradients within the soil profile (Yamanaka &

Yonetani, 1999). Dune areas may also act as sources of surface water recharge for lower topographic positions (Winter, 1986; Chen & Chen, 2004). Steady surface stream flow may be maintained by dune moisture discharge in the form of steam baseflow (Gosselin *et al.*, 1999; Chen *et al.*, 2003).

So far I have discussed the hydrological controls on soil moisture in bare, active dune regions. However, some dune regions (such as the one being studied) have undergone vegetation stabilization, modifying some controls on dune soil moisture dynamics and introducing others. These modifications will be discussed in the next section.

1.2.2 The influence of vegetation on dune soil moisture dynamics

Active sand dunes are generally considered harsh environments for vegetation establishment (Mangan *et al.*, 2004). On active dunes, erosion inhibits vegetation establishment through plant burial and root exposure (Chadwick & Dalke, 1965; Pavlik, 1980; Tsoar, 2005). Sand near the dune surface is also easily dried through evaporation, limiting plant germination and growth potential (Gardner & McLaren, 1999; Yamanaka & Yonetani; 1999). Dune sands are also normally nutrient poor, further reducing plant growth potential (Mangan *et al.*, 2004; Rosenthal *et al.*, 2005).

Species that do well during initial dune colonization stages tend to germinate quickly to avoid seedling root exposure or burial, or invade from nearby vegetated areas through the spread of rhizomes (Danin, 1991). Initial vegetation growth dramatically lowers surface wind speeds, reducing sediment transfer and enabling other vegetation types to become established on the stabilizing dune (Baldwin & Maun, 1983; Fearnehough *et al.*, 1998). As the

dune surface approaches stability, the near-surface soil properties of the dune change, thus modifying the storage and infiltration properties of the soil profile. Vegetation alters a number of processes that regulate the spatiotemporal variability of soil moisture, including: infiltration rate, interception, transpiration, macroporosity, and landcover heterogeneity.

As vegetation becomes established on a dune surface, the proportions of fine sediment and organic matter increase in the soil profile (Danin, 1991; Fearnehough *et al.*, 1998). The reduction of surface winds following vegetation establishment can lead to substantial layers of fines being added to the soil profile (Duan *et al.*, 2004). Through succession, the amount of organic material also increases (Hulett *et al.*, 1966; Li *et al.*, 2007). The combination of greater fine sediment and organic matter contents increase the moisture storage capacity of vegetation stabilized dune soils (Baldwin & Maun, 1983; Duan *et al.*, 2004). However, these changes also reduce water infiltration rates and enhance the possibility of runoff in stabilized dune areas (Hennessy *et al.*, 1985; Neave & Abrahams, 2002). Locally, infiltration may be enhanced due to the presence of soil macropores that form as a result of dune stability, vegetative growth, and soil disturbance by animals (Canton *et al.*, 2004; Ensign *et al.*, 2006).

In addition to modifying soil properties, vegetation modifies dune soil moisture dynamics by altering interception and transpiration rates, and by introducing landcover heterogeneity. The interception of incoming precipitation reduces the total amount of precipitation that is incident upon the dune surface (Canton *et al.*, 2004). Precipitation intercepted by vegetation on the dune surface may evaporate before reaching the soil, thereby modifying precipitation inputs into the subsurface (Berndtsson *et al.*, 1996; Schneider *et al.*, 2008). Furthermore, precipitation interception enhances soil moisture heterogeneity

beneath the vegetative canopy (Canton *et al.*, 2004; Ensign *et al.*, 2006). This enhanced heterogeneity is especially prevalent beneath shrub and tree cover types, where canopy cover has the greatest potential to redistribute moisture before it reaches the dune surface (Schneider *et al.*, 2008).

One of the primary mechanisms through which moisture is removed from the soil profile in vegetated environments is transpiration. The effects of transpiration on soil moisture reserves vary with different landcover types. Grasses tend to have relatively shallow root systems compared to shrubs or trees, limiting soil moisture depletion to the near-surface (Barnes & Harrison, 1982; Sridhar *et al.*, 2006). Root systems for shrubs and trees often penetrate deeper into the subsurface, enabling those species to draw on and deplete deeper soil moisture reserves (Tolstead, 1941; Wilcox & Thurow, 2005). However, grasses usually have finer root systems that are capable of drawing on limited near-surface moisture supplies, giving them a competitive edge for survival under drought conditions (James *et al.*, 2003). This competitive edge can lead to a reduction in shrub cover on dunes during prolonged periods of drought (Duan *et al.*, 2004; Li *et al.*, 2004A).

From the synthesis of literature it seems clear that dune soil moisture dynamics are modified by vegetation stabilization. Because the stabilization process alters pedogenic properties, as well as soil moisture inputs (interception) and outputs (transpiration), it is likely that the presence of vegetation on sand dunes enhances soil moisture heterogeneity within these landscapes. In the next section, I will review the results of other studies that have investigated the effects of dune stabilization on the spatiotemporal distribution of soil moisture, thus establishing the foundation for my research hypothesis.

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1.2.3 Previous soil moisture research in stabilizing dune environments

Soil moisture research in dryland ecosystems has become a popular research topic in recent decades. While many studies have emphasized the effects of desertification (e.g. Schlesinger *et al.*, 1990, Reynolds *et al.*, 2007), relatively few studies have investigated changes in soil moisture dynamics in stabilizing dune environments (e.g. Duan *et al.*, 2004; Zhang *et al.*, 2008), and even fewer of these have been conducted in naturally (as opposed to anthropogenically) stabilized dune ecosystems (e.g. Berger, 1992; Shay *et al.*, 2000). This section summarizes the key results of studies conducted in stabilizing dune ecosystems, providing context for my research hypothesis as well as defining how my research provides a unique contribution to soil moisture research in aeolian environments.

One of the most significant effects of dune stabilization by vegetation is the depletion of deep profile (> 50 cm) soil moisture and a reduction of groundwater recharge (Gupta, 1979; Berger, 1992; Duan *et al.*, 2004; Li *et al.*, 2004A). These changes are the result of vegetation-induced modifications of surface soil properties (i.e., sediment texture and organic matter), as well as increased withdrawals of soil moisture reserves through transpiration (Bowers, 1982; Fearnehough *et al.*, 1998; Li *et al.*, 2004B; Ensign *et al.*, 2006). However, several studies have also found that changes in near-surface soil properties can enhance soil moisture availability in upper soil layers (e.g. Shay *et al.*, 2000; Duan *et al.*, 2004). Thus, it appears that soil moisture profiles within active dunes undergo a reversal during dune stabilization, from a desiccated surface layer with moisture available at depth under active dune conditions, to a moist surface layer with drier sediment at depth under vegetation-stabilized conditions.

Of those stabilizing dune regions studied, few have been more exhaustively studied than the Tengger Desert in China. In this region, active dunes along the Baotou-Lanzhou railway were artificially stabilized using straw mats and xerophytic vegetation to reduce aeolian sediment transport, thus stabilizing the dune surface (Fearnehough *et al.*, 1998; Duan *et al.*, 2004). In the 55 years since artificial stabilization was initiated, dune soil moisture dynamics have substantially changed. Stabilization has reduced mean soil particle size and increased organic matter content (Duan *et al.*, 2004; Li *et al.*, 2004B). While these changes enhanced biodiversity on the dunes and facilitated the colonization of annual, non-xerophytic vegetative species (Li *et al.*, 2007), they also altered the soil moisture regime. As stabilization progressed, deeper soil layers within the dunes became desiccated because (i) finer sediment and organic material near the surface reduced infiltration rates, which reduced moisture recharge at depth, and (ii) the presence of dune vegetation increased evapotranspiration, which removed soil moisture (Fearnehough *et al.*, 1998; Li *et al.*, 2004A). It has been suggested that because of a lack of deep profile soil moisture recharge, deep-rooted xerophytic species are becoming extirpated from the study region in favour of opportunistic, shallow-rooting species that take advantage of light, intermittent precipitation events (Fearnehough *et al.*, 1998; Li *et al.*, 2004B). These results suggest a significant shift in soil moisture conditions within dunes in this region, from higher moisture at depth under active dune conditions, to higher near-surface moisture and reduced moisture at depth under stabilized conditions.

Other studies similar to those mentioned above have obtained similar results. When compared to bare, active sand dunes, soil moisture recharge below the near-surface layers of stabilized dunes is reduced (Danin, 1991; Berger, 1992; Neave & Abrahams, 2002). However, most of these studies have been carried out in regions that experience significantly

less precipitation than the southern Canadian Prairie region examined in this study. In other dune ecosystems on the North American Great Plains, studies have shown that soil moisture dynamics may be different from those observed in drier desert regions.

The most studied stabilized dune ecosystem in the North American Great Plains is the Nebraska Sandhills. The Nebraska Sandhills ecosystem encompasses 50,000 km^2 (¼ of Nebraska), and was active approximately 900 years BP (Mason *et al.*, 2004). Because open sand is now restricted to small blowouts (wind erosion hollows) in this region, soil moisture research has focussed mostly on the stabilized dunes. In spite of this limitation, soil moisture recharge in the stabilized dunes of the Nebraska Sandhills contrasts with that observed in stabilized desert dunes. Deep profile soil moisture and groundwater recharge are commonly observed in the Nebraska Sandhills region (Winter, 1986; Gosselin *et al.*, 1999; Sridhar & Wedin, 2009). The greater precipitation in the Nebraska Sandhills (400-700 mm $year^{-1}$) compared to most desert dune regions could be a factor that enables moisture to percolate past fine surface sediments and the root systems of transpiring vegetation, allowing soil moisture and groundwater recharge to occur (Chen *et al.*, 2003; Sridhar & Wedin, 2009). Another difference is that the transpiration output of dune vegetation in the Nebraska Sandhills is seasonal; thus, outside the growing season surface water is capable of infiltrating and recharging deep soil moisture and groundwater (Winter, 1986; Gosselin *et al.*, 1999).

It is unclear whether the understanding of soil moisture in the Nebraska Sandhills can be transferred directly to infer its dynamics in Canadian Prairie sandhill ecosystems. The vegetation is fundamentally different between these regions, especially in terms of the higher proportion of warm-season (C_4) grasses in Nebraska, which have higher water-use efficiency than the cool-season (C_3) grasses in Canada (Thorpe *et al.*, 2001). Furthermore, there is an

increased proportion of shrub and forest in Canadian sandhills, which may affect deeper soil moisture dynamics (Thorpe *et al.*, 2001). There may also be differences in the configuration of groundwater systems beneath sandhills in the two regions that could influence soil moisture distributions (Muhs & Wolfe, 1999).

1.2.4 Canadian sandhill soil moisture research

Soil moisture research within stabilizing Canadian Prairie sandhill regions has been limited to near-surface investigations, thereby preventing the characterization of soil moisture dynamics in the deeper rooting zone and beyond. A detailed study of near-surface (< 30 cm) soil moisture beneath active and stabilized dunes in the Bald Head Hills of Manitoba was conducted by Shay *et al.* (2000). They found that soil moisture availability was enhanced under stabilized conditions in near-surface sediments. Similar results were reported by Ensign *et al.* (2006) for a coastal dune system in Ontario.

Studies investigating soil and vegetation properties of Canadian sandhill regions (Hulett *et al.*, 1966) provide limited context for understanding the potential impact of dune stabilization on soil moisture dynamics. Furthermore, studies investigating the transpiration patterns of vegetation within Canadian sandhill ecosystems are limited, thereby reducing our ability to predict temporal dynamics of soil moisture beneath different landcover types found in these regions. Without this knowledge, it is difficult to predict how soil moisture dynamics have been modified by widespread dune stabilization.

The objective of this study is to determine how the establishment of vegetation in a formerly active Canadian Prairie dune ecosystem has modified the spatiotemporal

distribution of soil moisture. Given the state of current research on soil moisture dynamics in stabilizing dune ecosystems, *my hypothesis for this research is that soil moisture dynamics have been modified by the establishment of vegetation in the study region, with near-surface soil moisture availability being enhanced and deeper soil moisture recharge being reduced*. I will now outline my thesis research objectives, briefly explaining how I aim to determine how soil moisture dynamics have been modified by the establishment of vegetation in the study region.

1.3 Thesis outline

This thesis presents results and discussion about soil moisture dynamics in a stabilized Canadian Prairie sandhill ecosystem. My objective is to determine how soil moisture resources vary between active and stabilized sand dunes. Through this comparative approach I will determine how soil moisture dynamics have changed as vegetation cover expanded, and thereby interpret the significance of these changes in the context of natural processes and anthropogenic demands on near-surface water resources.

First, following the work of Shay *et al.* (2000) and Hubbard *et al.* (2009), I investigated vertical soil moisture dynamics beneath active and stabilized dunes (Chapter 2). Previous soil moisture research in sandhills has mainly focussed on relatively shallow (< 100 cm) soil moisture dynamics. My study measured soil moisture at depths beyond 100 cm, which provided a new perspective on its variability and dynamics within and below the plant rooting zone. The results of Chapter 2 indicate significant differences in vertical soil moisture dynamics beneath active and stabilized dunes, and that these differences become enhanced as depth increases. These results suggest a significant change in soil moisture availability and potentially even groundwater recharge due to dune stabilization.

The second study examined the spatiotemporal dynamics of near-surface (< 6 cm) soil moisture across active and stabilized dunes (Chapter 3). This study follows that of Pan & Wang (2009) and clarifies the role of topography and vegetation cover on soil moisture dynamics in the uppermost soil layer. Results suggest that the establishment of vegetation on dunes has significantly increased the near-surface soil moisture storage capacity, thereby enhancing soil moisture availability for vegetative growth and establishment.

Finally, in Chapter 4 I summarize my findings and make recommendations on potential areas for future research.

Overall, this thesis provides several interesting contributions. Sandhill soil moisture dynamics have been and continue to be modified through the establishment of vegetation in these ecosystems. This thesis adds to the understanding of how soil moisture dynamics change during the transition from bare, active dunes, to vegetation-stabilized dunes. Because this research is unique within the study region, it is anticipated that the results will contribute to future land use and water management strategies within Canadian sandhill ecosystems.

CHAPTER 2: FEEDBACK EFFECTS ON INFILTRATION AND SOIL MOISTURE RESULTING FROM SAND DUNE STABILIZATION, NORTHERN GREAT PLAINS, CANADA

2.1 Chapter abstract

Vegetation cover has increased steadily in Canadian Prairie sandhill ecosystems for the last 200 years, effectively transforming these once desert-like areas into relatively verdant ecosystems comprising mostly stabilized sand dunes. Despite considerable research on the geomorphology of Canadian Prairie sandhills and increasing pressure from energy development, little is known about the effects of dune stabilization on soil water resources. In other environments active sand dunes act as recharge pathways for soil moisture and groundwater. Therefore, the hypothesis for this investigation was that the active (bare) dunes would have higher soil moisture at depth than the stabilized dunes, because the presence of vegetation on the latter reduces the infiltration rate and removes soil moisture through evapotranspiration. We used an ergodic (space-for-time) approach by comparing infiltration and soil moisture on active and stabilized dunes in the Bigstick Sand Hills of southwestern Saskatchewan. We measured soil moisture dynamics throughout the 2010 growing season (April-October) using time-domain reflectometry (TDR) sensors installed at four depths down to 200 cm below the surface at an active and a stabilized dune. We also acquired soil samples from two active and two stabilized dunes ten times throughout the 2010 growing season to measure soil moisture dynamics at 50 cm increments down to 500 cm below the surface. The results of this investigation indicate that while soil moisture levels are elevated at 25 cm depth in the stabilized dunes, below that layer soil moisture recharge is significantly

lower when compared to the active dunes. Intra-site differences were less noticeable with changing depth at the active site than at the stabilized site. Inter-site differences in soil moisture dynamics are attributed to transpiring vegetation as well as changes in soil properties (increased clay, silt, and organic matter) attributed to the establishment of vegetation. Overall, the results of this study suggest that the establishment of vegetation within Canadian Prairie sandhill ecosystems has reduced profile soil moisture recharge and has likely had similar effect on groundwater recharge.

2.2 Introduction

Throughout the Canadian prairies, there are vast areas, known as sandhills, which consist of large tracts of sand dunes now mostly stabilized by vegetation. Before approximately 200 years ago, these unique ecosystems were characterized by mobile desert-like barchanoid dunes that exist only in landscapes devoid of vegetation (Wolfe and Hugenholtz, 2009). A transformation ensued over the last 200 years, with the mobile barchanoid dunes evolving into parabolic dunes under the influence of expanding vegetation and a warmer, less arid climate regime. The relatively verdant sandhill ecosystems that now exist provide habitat for a number of endangered species (e.g. *Dipodomys ordii*, *Falco peregrinus*, *Speotyto cunicularia*) and support a wide array of land uses, including several that rely on shallow groundwater resources such as ranching and natural gas extraction. In more arid settings active sand dunes can be important pathways for groundwater recharge (Berger, 1992). Thus, in light of the historical landscape transformation from active (bare) to stabilized (vegetated) dunes, as well as escalating anthropogenic water use since settlement in the late 1800s, it is increasingly important to understand the effect of sand dune stabilization

on the soil moisture and groundwater resources in sandhill ecosystems, especially in support of future land use decisions. To date, the effects of the landscape transformation on water resources in prairie sandhills are largely unknown.

Previous research has demonstrated that the establishment of vegetation cover on formerly active sand dunes has the potential to modify soil hydrology. In the absence of vegetation, sandy soils allow rapid infiltration and storage of meteoric precipitation (Berger, 1992; Wilcox & Thurow, 2006); however, these processes change once vegetation begins to colonize a stabilizing sand dune. At a basic level, vegetation extracts soil moisture for transpiration, thereby depleting soil moisture resources (Schneider & Childers, 1941). By intercepting precipitation and creating soil macropores along root channels it also modifies the amount and spatial distribution of meteoric water reaching the soil surface and infiltrating the subsurface (Aston, 1978; Allison *et al.*, 1985; Orradottir *et al.*, 2008). The addition of organic matter to soil through the death and decomposition of vegetation can also increase the amount of moisture that a soil can hold (Hulett *et al.* 1966; Maestre *et al.* 2003). The gradual addition of organic matter to dune sands through soil genesis decreases the infiltration rate of moisture on stabilized dunes (Barnes & Harrison, 1982). Other studies have found that vegetation growth puts an added demand on near-surface soil moisture, depleting soil moisture resources on vegetated sandhills before the end of the growing season (Barnes & Harrison, 1982; Shay *et al.*, 2000; Sridhar & Wedin, 2009). During drought years, a lack of soil moisture may limit plant transpiration (Chen & Chen, 2004). Prolonged drought may also lead to heterogeneous vegetation growth patterns, further enhancing soil moisture heterogeneity in dryland ecosystems (van de Koppel *et al.*, 2002).

In order to gain insight into soil moisture dynamics in a stabilizing sandhill ecosystem we used an ergodic (space-for-time) approach by comparing the soil moisture regime of active and vegetation-stabilized dunes through the 2010 growing season. In this way we use the active dunes to represent the former mobile landscape (> 200 years ago) and the vegetated dunes to represent the outcome of the historical trend of dune stabilization. This work intends to provide new insight into profile soil moisture dynamics beneath the end-members of the dune activity continuum, from fully active to fully stabilized. Furthermore, soil moisture studies conducted in other sandhill ecosystems have been limited to the top 100 cm of the soil profile, preventing the characterization of soil moisture in the deeper rooting zone and beyond toward the groundwater table. Based on a literature review, the hypothesis for this investigation is that infiltration and soil moisture are higher beneath active dunes due to the absence of vegetation and organic matter in the soil, which remove near-surface soil moisture through evapotranspiration and reduce infiltration on the stabilized dune, respectively. However, due to anomalously high precipitation during the 2010 growing season, we anticipated that the difference would be dampened somewhat by the sheer volume of precipitation that fell over the study area.

2.3 Study area

The study area is the Bigstick Sand Hills (hereafter BSH; 50°10' N, 109°12' E), which represent a southerly extension of the Great Sand Hills of Saskatchewan (Figure 2.1). The nearest long-term meteorological station is located approximately 40 km southwest of the

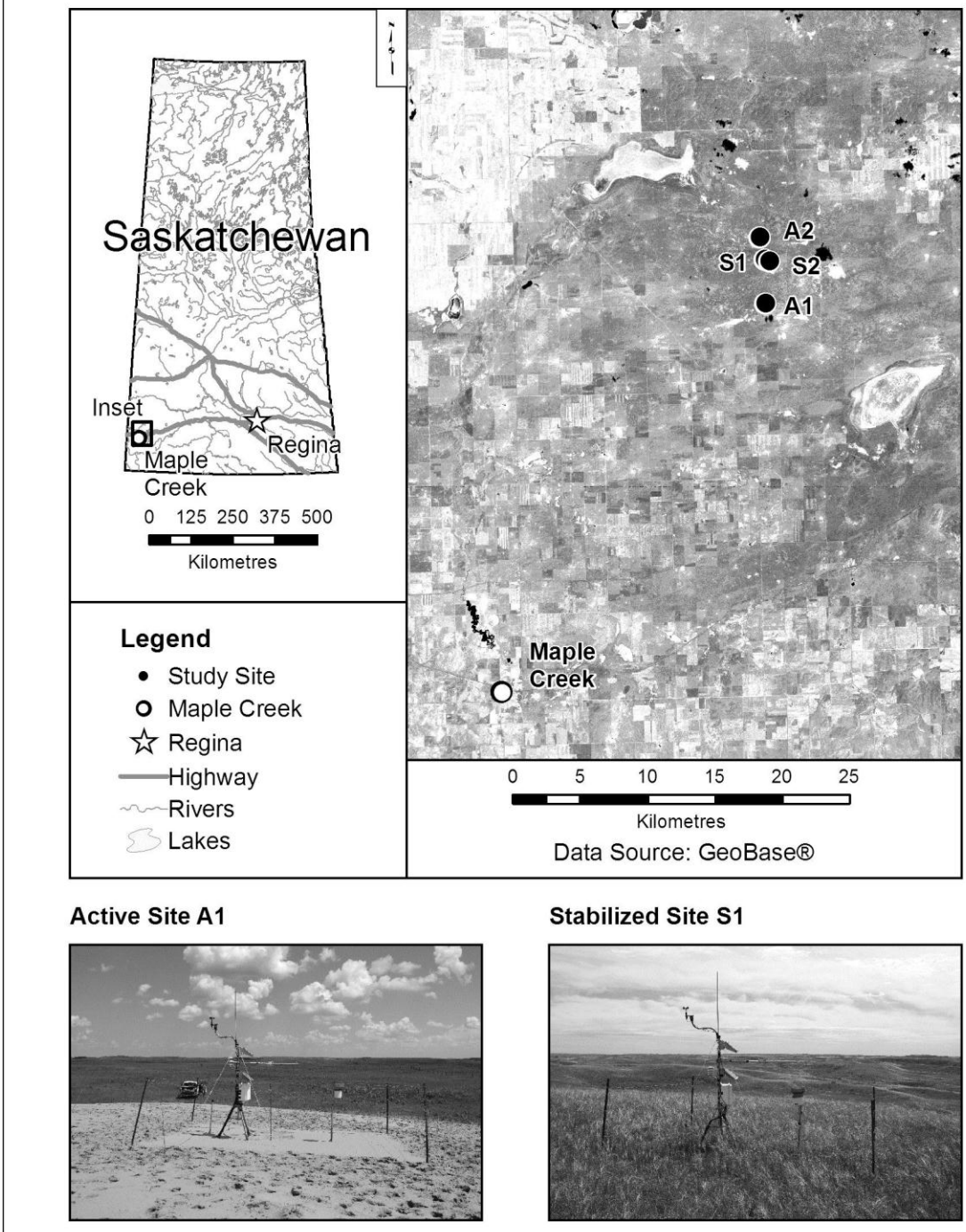


Figure 2.1. Overview map of the study area within the Bigstick Sand Hills of Saskatchewan, Canada, depicting the locations of and conditions present at the active (A1 & A2) and stabilized (S1 & S2) measurement sites. Additional meteorological sensors installed at these sites are part of a parallel investigation that lies outside the scope of this thesis.

research site in the town of Maple Creek. The BSH is characterized by parabolic sand dunes and flat inter-dune areas, both of which are stabilized by vegetation. Less than 1% of dunes are currently active (Wolfe & Hugenholtz, 2009). Geological and geomorphological evidence indicates that the parabolic dunes in the BSH transformed from barchanoid dunes about 200 years BP (Wolfe & Hugenholtz, 2009). Since the transition began, the number of active dunes has substantially decreased (Hugenholtz and Wolfe, 2005; Hugenholtz *et al.*, 2008). Little information is available to understand the implications of this trend on various ecosystem functions and resources.

The climate of the study area is continental, with short, dry summers and long, cold, dry winters. Daily average temperature ranges from -10.4°C in January to 19.3°C in July. Precipitation averages 379.3 mm per year, with 109.6 mm falling as snow. Heavier precipitation in late spring contributes 60% of annual precipitation during the growing season (Environment Canada, 2011). During the winter, chinook winds occasionally raise the air temperature above 0°C, resulting in snowmelt. However, limited potential for infiltration occurs, due to the presence of frozen soil and ice lenses at depth (Hugenholtz *et al.*, 2007).

The 2010 growing season field measurements coincided with above normal precipitation and lower than normal air temperature (Figure 2.2). Total precipitation received in the study area was 482 mm from April to October, which is 76% above the 1971-2000 Maple Creek station mean (Environment Canada, 2011). The combination of a deep snowpack (> 200% average), record precipitation in April and May, high intensity prolonged precipitation events in June, and a cool spring that limited transpiration combined to saturate the soil in areas surrounding the study site and manifested a 1:3700 year flood within the drainage area (Pentland *et al.,* 2011). However, within the sandhills region precipitation was

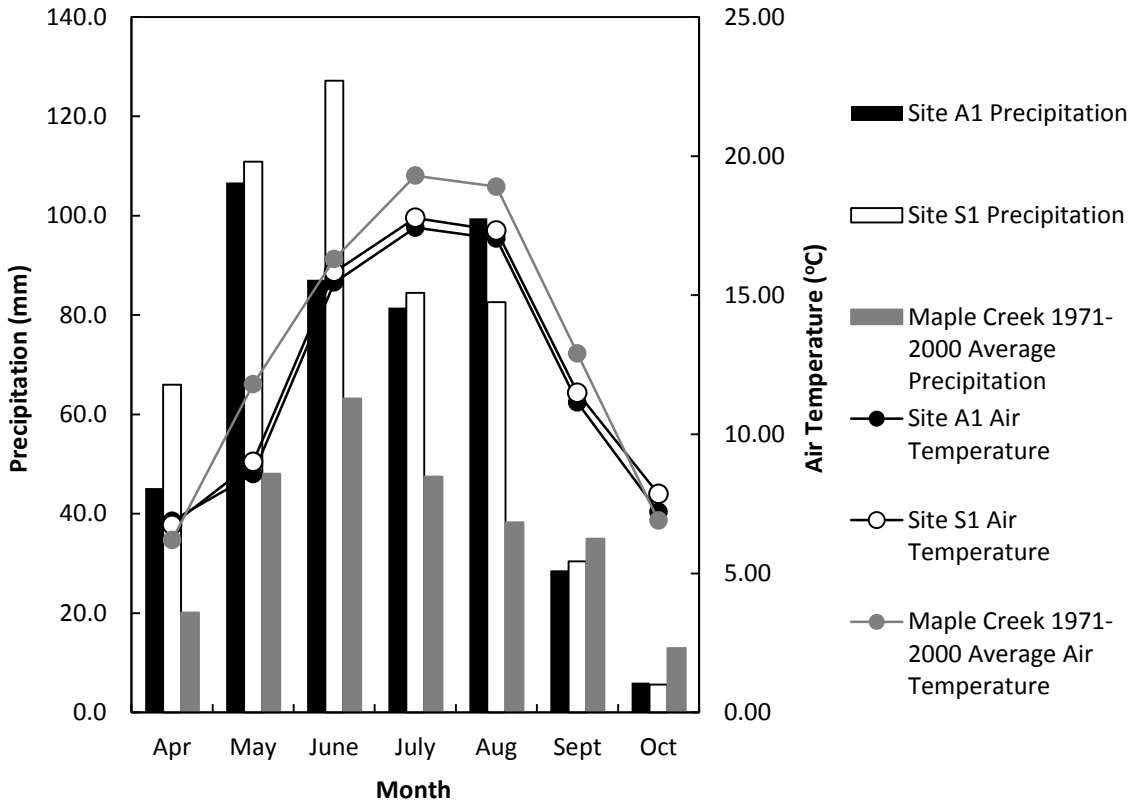


Figure 2.2. Monthly precipitation totals and air temperatures during the study period. The observed precipitation was approximately double that recorded in an average year. Drier weather was observed in the Fall of 2010. Observed air temperature was below mean monthly air temperature for most of the study period.

quickly absorbed into the soil profile. Minimal ponding was observed and was limited to areas of sediment compaction in anthropogenically-modified inter-dune areas (e.g. trails, gas well pads).

In order to examine the effects of dune stabilization on soil moisture we selected four sites, which include two active dunes and two stabilized dunes (Figure 2.1). The latter (S1 & S2) have been stabilized since at least 1946, which is the earliest available aerial photograph showing these sites. Rodent burrows (*Dipodomys ordii* and *Thomomys talpoides*) are commonly found on stabilized dune sites throughout the study area. Conversely, the active

dune sites (A1 & A2) have been devoid of vegetation since 1946. Two sites (one active dune and one stabilized dune) were instrumented with soil moisture probes and rain gauges (A1 & S1). The total distance between these sites is 3.2 km. Figure 2.1 shows the surface conditions at each instrumented site. These sites were also sampled throughout the 2010 growing season (April-October) to obtain vertical profiles of volumetric soil moisture, as were two other nearby sites, comprising one active dune and one stabilized dune (A2 & S2) (Figure 2.1). Soils at all sites are classified as sand based on USDA soil texture classification (Davis & Bennett, 1927). Sand typically comprised 95% of sediment samples by mass. Silts, clays, and organic matter were more prevalent at the vegetated sites but still made up a small proportion of all soil constituents, as discussed in section 2.6.

Vegetation at the two stabilized dunes is representative of other stabilized dunes in the area. Dominant species included scurf pea (*Psoralea lanceolata*), northern wheat grass (*Agropyron dasystachyum*), spear grass (*Stipa comata*), woods' rose (*Rosa Woodsii*), and pasture sage (*Artemesia frigida*). Increased rooting depths are typically observed on dune-head sites due to ease of root penetration and the relative dryness of those sites (Canadell *et al.*, 1996; Wang *et al.*, 2008). The rooting depths of grasses typically penetrate to 100-200 cm depth, whereas shrub roots typically penetrate up to 500 cm in dryland ecosystems (Gibbens & Lenz, 2001). At stabilized dune sites, rooting depths in excess of 200 cm were observed for shrub species as well as grasses.

2.4 Field methodology

At each instrumented site (A1 & S1) we installed four time-domain reflectometry (TDR) probes (ML2x Theta, Delta-T Devices) on 09 April 2010. The principle behind TDR

measurements of soil moisture is based on a relation between the moisture content of the soil and the soils' apparent dielectric constant (Topp *et al.,* 1980). We installed the sensors at four depths below the ground surfaces (25, 50, 100, and 200 cm). These depths were chosen for two reasons. First, we wanted to ascertain the variability of soil moisture across depths within and near the limit of deeply rooted plants present at the stabilized dune site (*Rosa woodsii*), which was expected to range from 100-200 cm based on previous experience in the area (Nimlos *et al*., 1968). Second, for safety reasons it was not possible to install sensors below 200 cm. To install the TDR sensors, we excavated a narrow pit and installed the sensors in the undisturbed walls. During the process, we collected bulk soil samples from the pit walls at the same heights as the TDR sensors so as to enable sensor calibration and to characterize soil texture and organic content. Root density was also estimated using the profile wall method (Böhm & Köpke, 1977; Mickovski & van Beek, 2009). A count of root intersections along four 5 cm by 60 cm areas of the profile wall corresponding to each TDR sensor depth was taken and used as an estimate of root density at depth. This provided insight into the ability of overlying vegetation to draw on soil moisture at the sensor depths and also showed the presence of root channel macropores that would enhance infiltration. We also documented the nature and presence of stratigraphy resulting from aeolian depositional processes.

The TDR probes were hardwired to a datalogger (Campbell Scientific CR1000) that recorded measurements at 1 minute intervals. The area around the instrumented sites was then fenced off to prevent damage from large free-ranging grazers such as cattle. The reason for choosing 1 minute was to gauge the near-surface response of the uppermost TDR sensors to precipitation events. Because the manufacturer's recommended calibration procedure does not perform well in sandy soils (see Schmutz, 2007) we created a soil-specific

calibration curve using raw sensor output (mV) and volumetric soil moisture samples collected from the field sites. The soil samples were oven-dried to derive volumetric soil moisture content (θ_V). The analysis of multiple samples produced the linear calibration shown in Figure 2.3. The linear curve chosen for sensor output calibration has an R^2 of 0.94 and $s_{y,x}$ of 0.91, which exceeds the manufacturer's average achievable accuracy of ±1% for soil-specific calibration. We adopted one calibration curve for both sites because the individual calibration curves for the active and stabilized sites differed by less than the minimum achievable error of the sensors.

To compliment the high-resolution measurements we acquired auger samples from all four sites at 50 cm increments, down to 500 cm below the ground surface. Because we attempted to acquire the auger samples during dry periods, we were unable to establish a consistent time interval for the augering due to the variable nature of precipitation throughout the 2010 growing season. In total, we collected samples on ten occasions between 11 May 2010 and 20 October 2010. The samples represent the average gravimetric soil moisture over a narrow depth range (± 10 cm) centered at each 50 cm increment. Care was taken to minimize contamination from sloughing during the insertion of the auger to retrieve a sample at each interval. Samples were weighed immediately after their collection and again after they were dried so as to minimize measurement errors. In all cases the auger samples were acquired within a 25 m^2 area with 1-2 m separation between boreholes. We assume the spatial distribution of soil moisture within the vertical profile of the sample area was consistent. After extracting the samples, each borehole was backfilled. The samples were dried and the gravimetric soil moisture content was determined following the protocols outlined by ASTM D2216-10. Gravimetric soil moisture content was then converted to

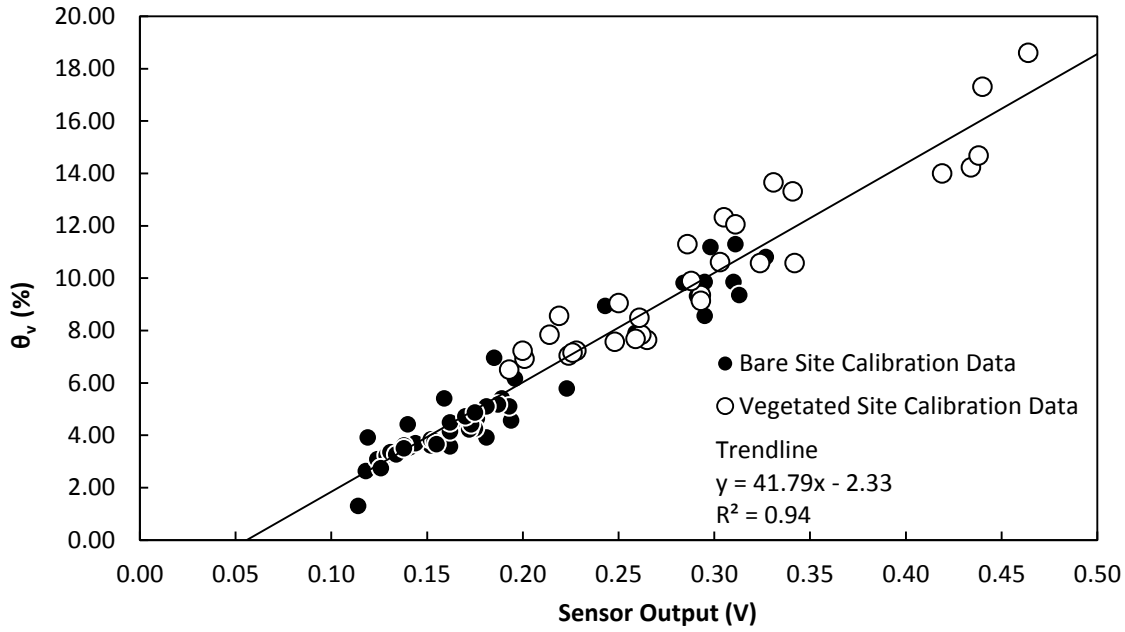


Figure 2.3. Calibration data for the soil moisture probes.

volumetric soil moisture content, by multiplying by the bulk density of the soil sample (Tan, 2005). This conversion was performed so that soil moisture data from the TDR probes and the auger samples could be compared.

In order to characterize the effects of dune stabilization on surface infiltration rate, we used a Decagon Mini Disk Tension Infiltrometer. To obtain the infiltration measurements, smooth soil surfaces devoid of vegetation were selected. At the vegetated sites, this meant taking measurements in the small bare spaces between vegetation stem clusters, to ensure a smooth contact between the ceramic base of the infiltrometer and the soil surface. For each measurement, the surface was carefully cleared of all overlying litter to create a clean surface contact for the infiltrometer. The infiltrometer was then placed over the cleaned soil patch and infiltration depth as a function of time was recorded. Infiltration rates for both the active and stabilized sites were then calculated in the lab using procedures

outlined by the manufacturer. In total, 30 infiltration measurements were acquired at each of the instrumented sites on 31 August 2010. We acquired soil samples following each measurement, to test our hypothesis about the role of texture and organic content in modifying infiltration rates. Soil samples from the top 5 cm of the soil profile were collected at each infiltrometer measurement site and stored for later laboratory analysis.

Soil samples from the pits and the surface were analysed in order to determine the relative proportions of sand, silt, clay, and organic content. To determine these soil properties, we followed standard testing procedures for the textural analysis (ASTM D422 - 63), and for the organic content measurements (ASTM F1647 - 11).

2.5 Data analysis

We re-sampled the raw, high-resolution (1 min) soil moisture measurements obtained with the TDR sensors to daily, monthly, and growing season averages. Results of Kolmogorov-Smirnov Goodness-of-fit tests determined that the soil moisture and precipitation data were non-normally distributed; therefore, we used a non-parametric test to determine inter- and intra-site differences in soil moisture and precipitation. Specifically, for comparisons between multiple (≥3) measurement depths, a Friedman non-parametric repeated measures test using a 0.05 significance level was employed. Post-hoc Wilcoxon Rank-Sum tests at the 0.05 significance level were then utilized to determine when, and at which depths, soil moisture distributions were significantly different between the active and stabilized sites. In addition, we applied a Wilcoxon Rank Sum test to determine if there was any significant difference in surface soil properties. The Wilcoxon Matched-Pairs Signed-Ranks test was used to determine inter-site differences in precipitation. The Matched-Pairs

test was used to determine if there was a consistent difference in the daily precipitation amount falling on each site. Finally, to correct for multiple comparisons between the same sampling groups on different dates, a Dunn - Sidak procedure was used to modify the significance level at which the null hypothesis was rejected.

2.6 Results

2.6.1 Infiltration Rates

As anticipated, surface soil moisture infiltration rates were higher at the active dune (Figure 2.4). The active dune site exhibited an average infiltration rate of 0.091 cm s^{-1}, whereas the stabilized dune site exhibited an average infiltration rate of approximately 0.009 cm s^{-1}. This indicates that the infiltration rate at the former was one order of magnitude higher than the latter. The linear nature of the infiltration curve suggests that infiltration did not slow as moisture infiltrated into the soil profile, which indicates that the soils at both the active and stabilized sites were well drained.

The TDR probes at 25 cm provide another perspective on the inter-site differences of infiltration in the shallow subsurface. Figure 2.5 shows a representative example of the soil moisture response to an intense convective rainfall event on 31 July 2010. Both stations recorded the event, yielding an average of 19.2 mm of rainfall over a 30 minute period (0.64 mm min^{-1}). At the active dune, the TDR signal at 25 cm increased abruptly approximately 25 minutes after the onset of rainfall, whereas at the same depth in the stabilized dune the sensor began responding more slowly at 50 minutes. Thus, it took approximately twice as

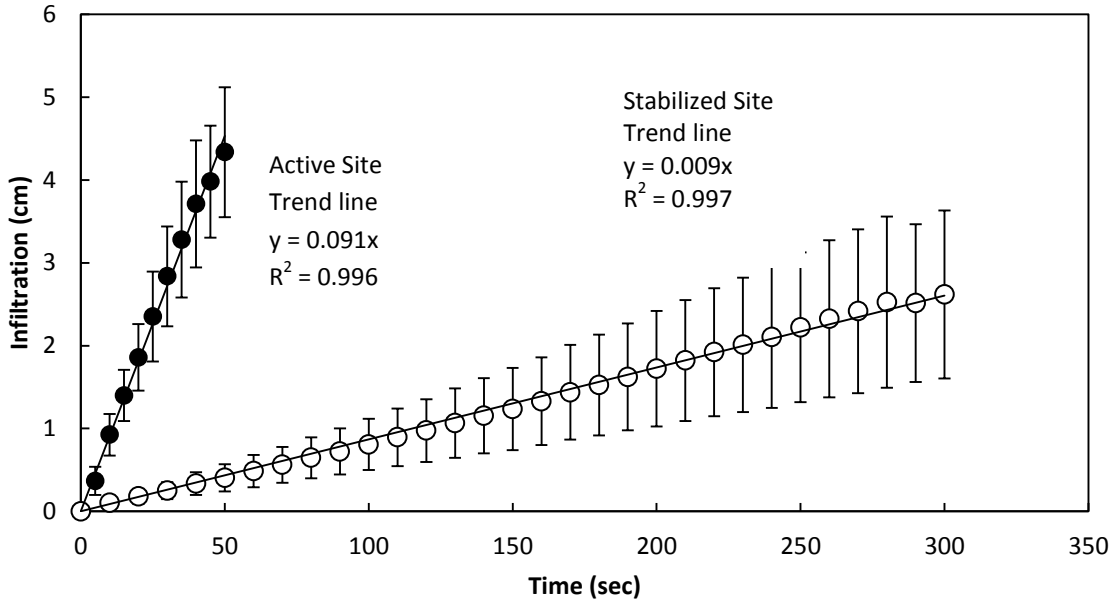


Figure 2.4. Infiltration data for the active and stabilized sites measured with the Mini Disk Infitrometer on 31 August 2010. Error bars represent one standard deviation from the mean observed infiltration depth.

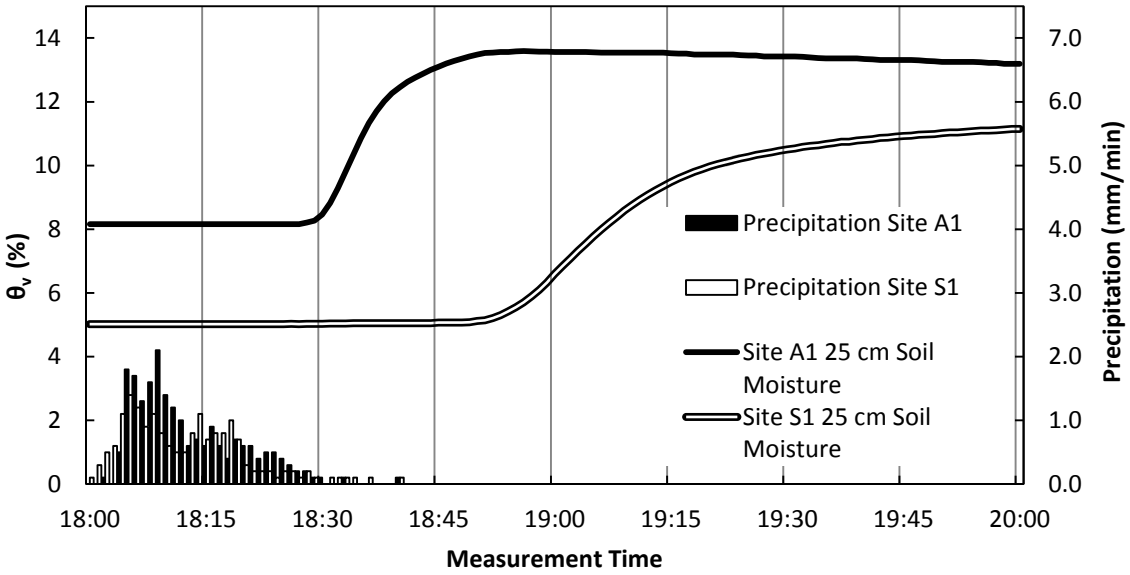


Figure 2.5. Soil moisture response to infiltration at 25 cm depth after an intense precipitation event July 31st, 2010. Precipitation and soil moisture data were collected at instrumented sites A1 and S1.

much time for a soil moisture response to be registered at the stabilized dune than at the active dune site after the onset of the rainfall event.

2.6.2 Temporal Soil Moisture Dynamics: TDR measurements

Figure 2.6 shows vertical variations of average daily volumetric soil moisture through time at the instrumented sites. An initial visual comparison of the soil moisture and precipitation time series indicates that there is some correspondence in the overall pattern of changes throughout the growing season. Initially, both soil moisture and precipitation are low, but as the frequency and duration of precipitation events increased, the soil moisture increased and fluctuated in a similar broad-scale pattern. The decrease in precipitation towards the end of the growing season coincided with a gradual decrease in soil moisture. Low magnitude precipitation events recharged soil moisture only within those layers nearest to the surface, whereas higher-magnitude events (>20 mm day^{-1}) allowed moisture to penetrate and recharge deeper layers within the soil profile. At the stabilized dune, it appears that multiple high magnitude precipitation events in close succession were required for soil moisture recharge at depths below 25 cm (Figure 2.6B). Despite similar growing season precipitation, there are marked differences at the inter- and intra-site scale that suggest fundamentally different soil moisture regimes in the near surface of the active and stabilized dunes.

At the beginning of the growing season soil moisture increased with depth down to 100 cm at the active dune, then decreased down to 200 cm (Figure 2.6A). At a seasonal time scale, soil moisture was relatively similar between the 25 cm, 50 cm, and 100 cm depths,

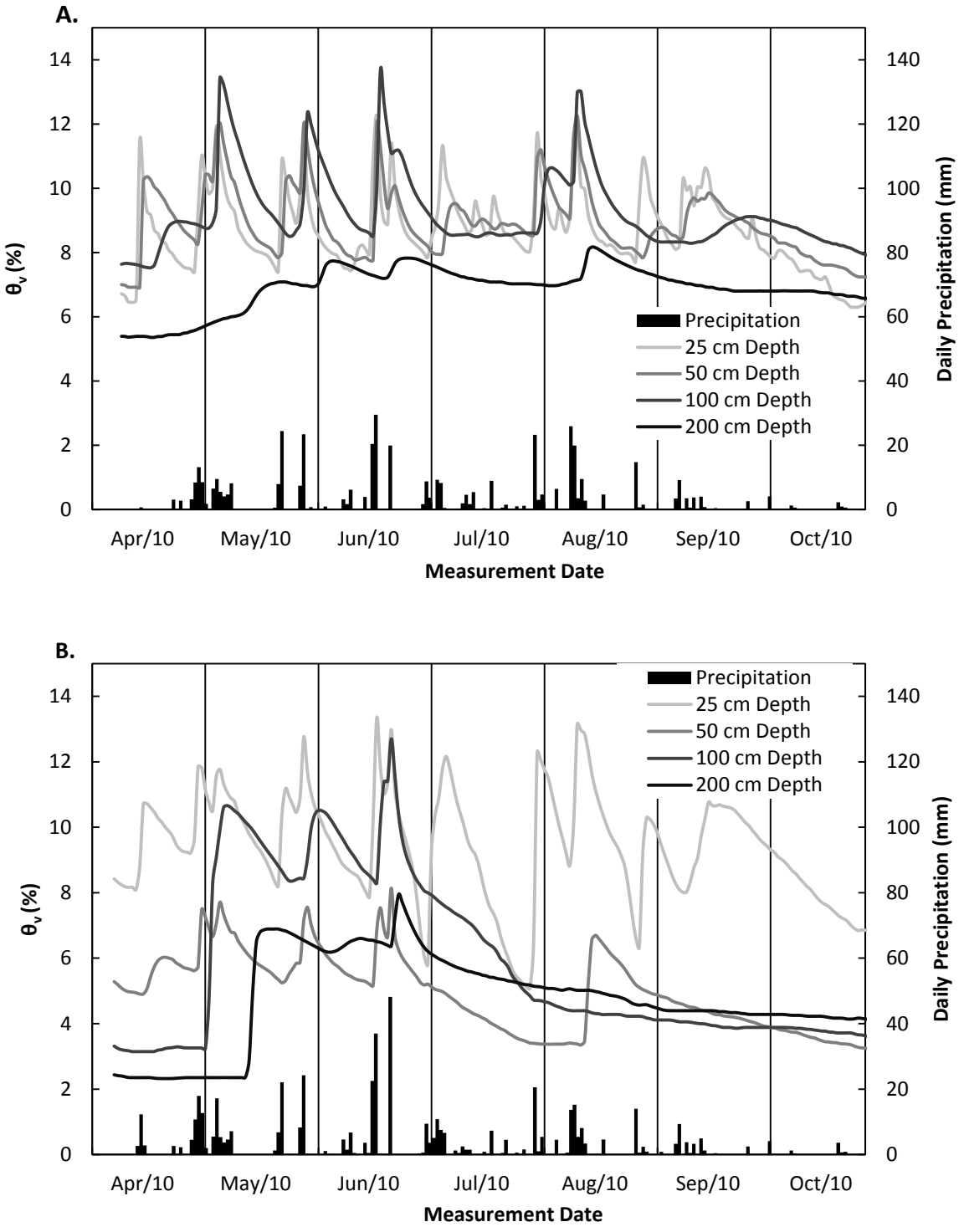


Figure 2.6. Daily volumetric soil moisture content (θ_V) and precipitation as measured over the study period at the active dune (A) and stabilized dune (B). Changes in soil moisture levels within the deeper soil layers were delayed and more gradual when compared to shallower soil layers.

with the 200 cm depth exhibiting lower soil moisture levels (Figure 2.7). However, by the end of the growing season Figure 2.6A shows that the soil moisture series at 25 cm decreased to levels similar to those measured at 200 cm. Over the growing season, the most frequent soil moisture fluctuations occurred at 25 cm, presumably due to greater drying potential near the surface. Below 25 cm, the frequency of soil moisture fluctuations decreased with increasing depth, but the amplitude of the fluctuations increased to a maximum at 100 cm, and then decreased substantially at 200 cm. Friedman statistical tests suggest that there are significant soil moisture differences between the four sampling depths throughout the sampling period (see Table 2.1A). Post-hoc results of the Wilcoxon Rank Sum tests shown (Table 2.1A) indicate that soil moisture at 25 cm, 50 cm, and 100 cm depth was similar at monthly intervals and over the entire growing season, whereas the 200 cm depth was significantly different at the 0.05 significance level.

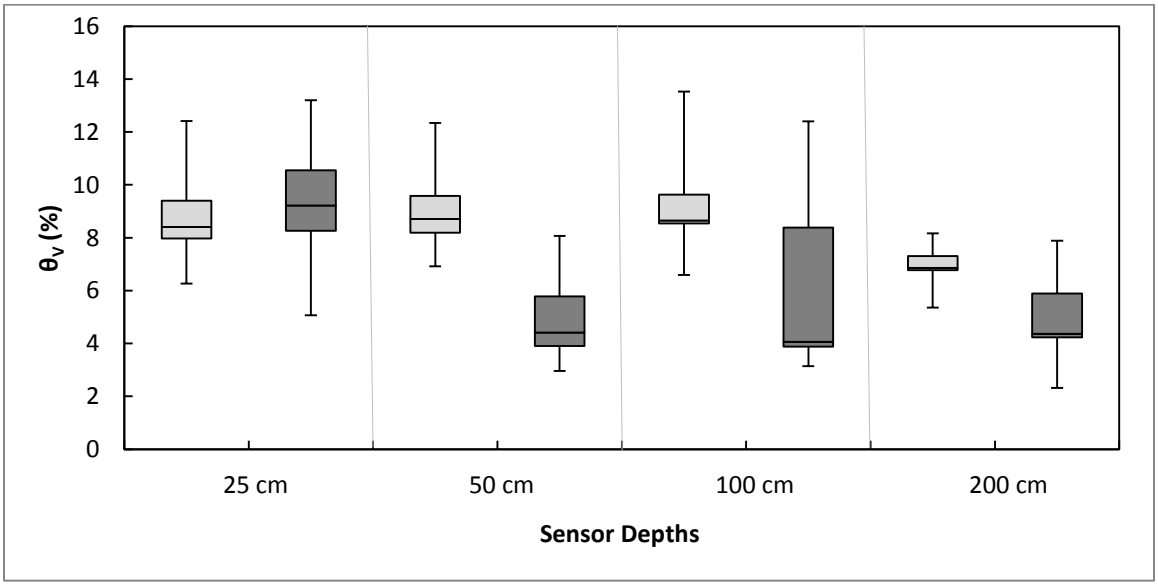


Figure 2.7 A comparison of measured volumetric soil moisture (θ_V) distributions at 25 cm, 50 cm, 100 cm, and 200 cm levels at instrumented sites A1 and S1. Light grey box plots represent soil moisture measured at site A1, whereas dark grey box plots represent soil moisture measured at site S1. Maximum, minimum, median, and quartiles are displayed.

Table 2.1. Results of the Wilcoxon Rank Sum and Friedman non-parametric repeated-measures (F) test for resolving intra-site differences in daily average soil moisture values for each month and across the entire growing season (bottom row). The *p*-values show the probability of getting a test statistic value as extreme as the one observed if soil moisture variations are similar between depths (H_0). Because the same samples were repeatedly measured at different time intervals, a modified Dunn-Sidak significance level of 0.0036 was used, representing the equivalent significance of a 0.05 significance level test repeated over seven monthly measurement periods. Non-shaded cells indicate a failure to reject H_0 at the 0.05 significance level. Grey shading indicates a rejection of H_0 at the 0.05 significance level. The results for the active dune are shown (A), while the stabilized dune results are shown in (B).

A.

Active Dune Intrasite Soil Moisture Comparison							
	Sensor Depths Compared						
Month	25 cm vs. 50 cm	25 cm vs. 100 cm	25 cm vs. 200 cm	50 cm vs. 100 cm	50 cm vs. 200 cm	100 cm vs. 200 cm	All 4 Classes (F)
April	0.065	0.428	0.000	0.141	0.000	0.000	0.000
May	0.145	0.068	0.000	0.486	0.000	0.000	0.000
June	0.294	0.000	0.000	0.000	0.000	0.000	0.000
July	0.751	0.120	0.000	0.028	0.000	0.000	0.000
August	0.588	0.005	0.000	0.024	0.000	0.000	0.000
September	0.647	0.001	0.000	0.000	0.000	0.000	0.000
October	0.000	0.000	0.034	0.000	0.000	0.000	0.000
Entire Season	0.035	0.004	0.000	0.482	0.000	0.000	0.000

B.

Stabilized Dune Intrasite Soil Moisture Comparison							
	Sensor Depths Compared						
Month	25 cm vs. 50 cm	25 cm vs. 100 cm	25 cm vs. 200 cm	50 cm vs. 100 cm	50 cm vs. 200 cm	100 cm vs. 200 cm	All 4 Classes (F)
April	0.000	0.000	0.000	0.000	0.000	0.000	0.000
May	0.000	0.000	0.000	0.000	0.018	0.000	0.000
June	0.000	0.768	0.000	0.000	0.000	0.000	0.000
July	0.000	0.014	0.000	0.000	0.000	0.000	0.000
August	0.000	0.000	0.000	0.486	0.741	0.000	0.000
September	0.000	0.000	0.000	0.000	0.745	0.000	0.000
October	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Entire Season	0.000	0.000	0.000	0.029	0.495	0.435	0.000

At the stabilized dune, soil moisture decreased with depth at the beginning of the growing season. Below 25 cm, this pattern reversed by the end of the growing season (Figure 2.6B). There was a long lag in the response at 100 cm and 200 cm early in the growing season, but once the moisture front reached these depths the response was rapid and substantial. Over the course of the growing season the frequency and amplitude of soil moisture fluctuations was greatest at 25 cm. There appears to be a transition in the time series sometime in June whereby the soil moisture at 100 cm and 200 cm steadily declined following a peak on 19 June. There also seems to high variability of soil moisture at 25 cm until September. Figure 2.7 shows the soil moisture was greatest nearest the surface throughout the growing season, but the greatest variation occurred at 100 cm.

Compared to the active dune, variations in soil moisture were much higher throughout the growing season at the stabilized dune (Figure 2.7). While soil moisture was slightly higher at 25 cm at the stabilized site, measurement depths below 25 cm were significantly drier than those at the equivalent depth at the active site. Table 2.1B shows that there was also less intra-site similarity, although at a seasonal time scale there is some similarity between the 50 cm, 100 cm, and 200 cm measurement depths (Table 2.1B).

When we compare inter-site differences for equivalent depths we find even fewer similarities, and more importantly, that soil moisture is statistically dissimilar at all depths for the entire growing season at the 0.05 significance level (Table 2.2). While there are some similarities between the measurement sites at some depths in some months, the prevailing soil moisture patterns are different between these sites down to 200 cm depth (Figure 2.7).

Section 2.6.3 extends the record to 500 cm below ground surface but at a much coarser temporal resolution that precludes rigorous statistical testing.

Table 2.2. Results of the Wilcoxon Rank Sum test for resolving inter-site differences in daily average soil moisture values for each month and across the entire growing season (bottom row). The *p*-values show the probability of getting a test statistic value as extreme as the one observed if soil moisture variations are similar between depths (H_0). Because the same samples were repeatedly measured at different time intervals, a modified Dunn-Sidak significance level of 0.0036 was used, representing the equivalent significance of a 0.05 significance level test repeated over seven monthly measurement periods. Non-shaded cells indicate a failure to reject H_0 at the 0.0036 significance level. Grey shading indicates a rejection of H_0 at the 0.0036 significance level.

Intersite Soil Moisture Comparison				
	Sensor Depth Compared			
Month	25 cm	50 cm	100 cm	200 cm
April	0.000	0.000	0.000	0.000
May	0.001	0.000	0.043	0.002
June	0.002	0.000	0.110	0.000
July	0.179	0.000	0.000	0.000
August	0.004	0.000	0.000	0.000
September	0.028	0.000	0.000	0.000
October	0.001	0.000	0.000	0.000
Entire Season	0.001	0.000	0.000	0.000

2.6.3 Soil Moisture Dynamics: Augered soil moisture measurements

Deeper profiles obtained through augering and gravimetric soil moisture determination are shown in Figure 2.8. Within the active dune profiles (A1 & A2) there was a modest yet consistent increase in soil moisture toward the base of the profile that stayed consistent throughout the season. This contrasted with the stabilized sites (S1 & S2), which exhibited higher variability throughout the profile, with a sharp decline in soil moisture below 300 cm at S1. At the beginning of the season, available soil moisture was depleted at depths as shallow as 100 cm (as also seen in Figure 2.6). Throughout the course of the season, soil moisture infiltrated the dry layer at depth, reaching 300 cm at S1 and 500 cm at

S2 by the beginning of August. Most of this infiltration occurred during late June / early July following intense precipitation events in mid-June.

2.6.4 Inter-site differences in precipitation and soil properties

As a first step to document factors that could account for inter-site differences in soil moisture we tested whether precipitation amounts at each site were similar. Since the distance between sites is relatively small (4.9 km), it was expected that any difference would be minimal. Although there are some disparities at the daily scale (Figure 2.2), especially in June, which is likely the result of spatial variability due to convective precipitation, the results of Wilcoxon Rank Sums test indicate that the total precipitation did not significantly differ between the active and stabilized dune sites at either seasonal (p = 0.80) or monthly scales (p = 0.31). The maximum monthly difference in precipitation occurred in June (87.1 mm vs. 127.2 mm). However, 70.6% (28.3 mm) of this difference is ascribed to one convective precipitation event that occurred on 22 June. Thus, consistent long-term differences in soil moisture between sites appear to be minimally-affected by variations in precipitation. Table 2.3 shows the soil texture and organic content of the soils obtained from auger samples at the two instrumented sites (A1 & S1). The only notable difference between sites is at the surface, as shown by the elevated silt, clay and organic content at the stabilized dune (S1). Statistical differences in sand, silt, clay, and organic matter between the active and stabilized sites were all significant at the 0.001 significance level for surface samples. Below the surface the two sites have relatively similar texture, organic content, and bulk density down to 500 cm. Both sites also have elevated organic content at 100 cm. Visual inspection of the pit

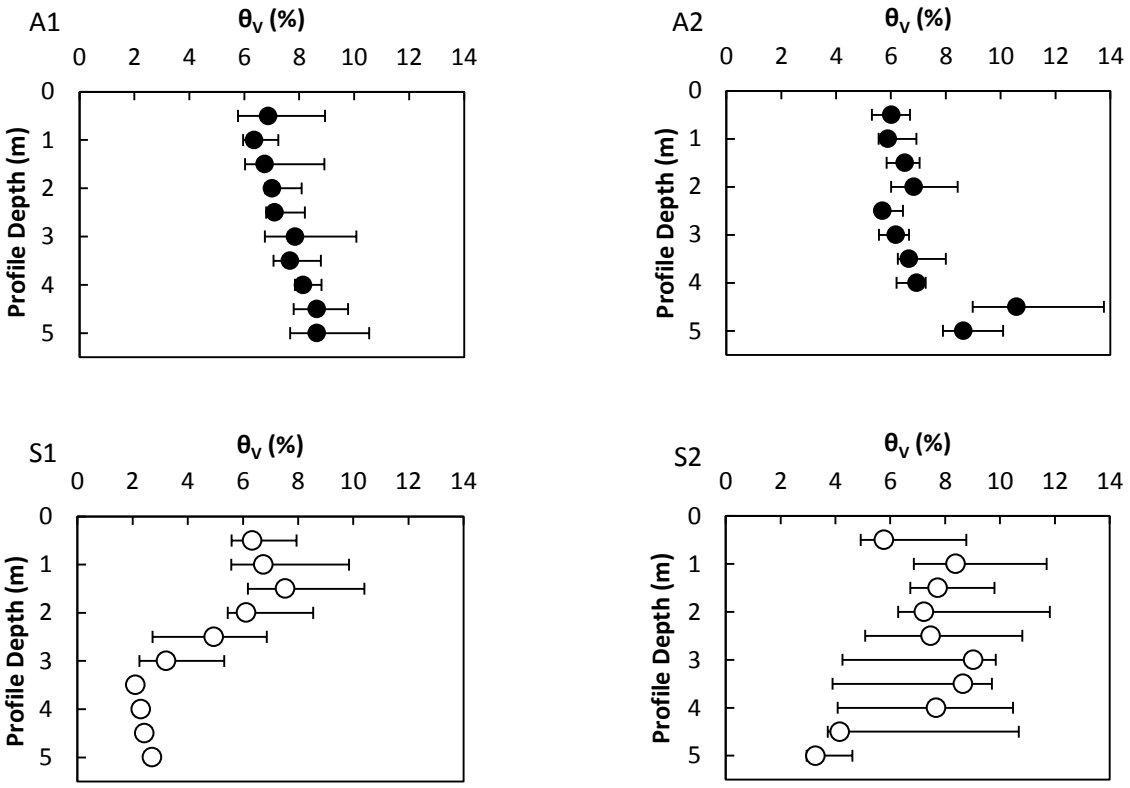


Figure 2.8. Volumetrically determined soil moisture beneath both active (A1 & A2) and stabilized (S1 &S2) dune sites throughout the 2010 field season. Dots represent the median soil moisture value observed. Error bars represent 25% and 75 % quartiles on either side of the median. n = 10 for each sample depth at each sample site.

walls did not identify evidence of a buried soil or other observable features that could account for the increased organic content. The source of the organic material is unknown at the active dune since the deposit is relatively young and historically devoid of vegetation. Elevated organic matter content at 100 cm depth at the stabilized site is potentially due to organic matter translocation along root macropores (Jenny, 1941; Rumpel *et al.*, 2002).

Table 2.3. Soil texture analysis of the active and stabilized dune sites. Silt and clay proportions were higher at the stabilized than at the active dune sites. Organic matter was higher at the surface and at 100 cm depth in the stabilized dune profiles. Elevated organic matter content was also observed at 100 cm depth at the active dune sites.

	Active Dune Sites					Stabilized Dune Sites				
	Texture			Organic Matter	Bulk Density	Texture			Organic Matter	Bulk Density
Sample Depth	Sand %	Silt %	Clay %	%	g*cm^{-3}	Sand %	Silt %	Clay %	%	g*cm^{-3}
Surface	96.87	1.12	2.01	0.63	1.32	91.39	3.37	5.25	2.40	1.20
25 cm	95.88	1.22	2.91	0.60	1.34	95.07	2.00	2.94	0.60	1.33
50 cm	96.35	0.87	2.78	0.40	1.61	96.30	1.36	2.35	0.99	1.60
100 cm	97.48	0.90	1.63	1.40	1.62	96.41	0.91	2.69	4.60	1.64
200 cm	96.87	1.49	1.65	0.59	1.61	95.41	0.82	3.78	1.40	1.63
300 cm	95.72	0.66	3.62	0.88	1.62	94.13	1.97	3.91	0.40	1.61
400 cm	97.48	1.10	1.43	0.69	1.63	93.49	2.06	4.46	0.20	1.63
500 cm	96.28	1.80	1.92	0.60	1.62	94.52	1.73	3.76	0.00	1.65

2.6.5 Vertical distribution of roots at instrumented stabilized dune

The distribution of roots at depths corresponding to TDR sensor placement was measured to better understand the impact of transpiration on soil moisture fluctuations. Root density at depth is reported as a percentage of root observations along the pit wall (Böhm, 1977; Mickovski & van Beek, 2009). Root density was greatest near the soil surface; 57.8% of all root deteections were observed 25 cm below the soil surface. At 50 cm and 100 cm depth root densities were 18.3% and 16.2% of total root observations, respectively. Only 7.7% of all root observations were observed at 200 cm depth, suggesting that many tap-roots beneath this vegetation community end between 100 cm and 200 cm depth.

2.7. Discussion

Despite record setting precipitation in the 2010 growing season, the results of this investigation show that the profile soil moisture regime was fundamentally different between active and stabilized dunes. Although rainfall varied between sites over short intervals (hours to days), we failed to statistically detect significant differences in precipitation between the two sites at monthly scales and across the entire growing season, suggesting that rainfall played a negligible role in explaining inter-site differences in soil moisture at these timescales. Thus, at monthly to seasonal scales, local factors are the most likely sources of inter-site diffferences; the most obvious being the presence of vegetation and its allied effects on soil.

Surface infiltration rates were one order of magnitude higher at the active dune compared to the stabilized dune site. This is qualitatively consistent with the relatively coarse texture and low organic content of the near-surface soils at the active dune, which promote rapid infiltration due to high porosity. In contrast, the near-surface soil at the stabilized dune exhibited higher clay, silt, and organic content, which reduce infiltration by collectively reducing porosity. Part of the difference may also be attributed to the stratigraphy at both sites. During installation of the TDR sensors inclined (25-28°) laminae were noted at A1, which are consistent with grainflow deposition (Hugenholtz *et al.*, 2008). There was very little indication of stratigraphy in S1, which is consistent with grainfall deposition onto vegetation during the early stages of stabilization (Hugenholtz *et al.*, 2008). Steeply dipping grainflow laminae can lead to anisotropic movement of soil water, which may enhance surface infiltration via preferential flow paths (Ritsema & Dekker, 1994). The difference owing to this effect may be somewhat muted, however, by the presence of vegetation, which disturbs the soil surface in such a way as to cause a relative enhancement of infiltration where plant

stems meet the soil surface, whereas at locations where there are no stems perturbing the soil surface infiltration is greatly reduced (Orradottir *et al.* 2008). This may explain why the infiltration rates inferred from the 25 cm TDR sensors were about twice as fast at the active dune than the stabilized dune.

Data from the instrumented sites show that soil moisture remained higher throughout the 2010 growing season at the active dunes, but was lower and more variable at depth in the stabilized dunes. Soil moisture increased in May and June at the active dunes and varied in response to precipitation events, but otherwise remained relatively consistent throughout the monitoring period as denoted by low dispersion in the data. This contrasts with the large amount of soil moisture variation observed at the stabilized dune sites. At one of the stabilized dunes (S1) there is evidence that soil moisture did not penetrate below 350 cm, while at the other stabilized site (S2) it appears to have penetrated down to 500 cm. This contrast is likely due to the presence of enhanced macroporosity at S2. Rodent burrows (*Dipodomys ordii and Thomomys talpoides*) were more prevalent at S2, while other site parameters such as vegetation cover species were largely similar. The burrows could have increased macroporosity, thus enhancing soil moisture infiltration within the profile and allowing moisture to percolate below the rooting zone more quickly than at S1. This may have enabled deep soil moisture recharge to occur more frequently and at greater intensities than at S1.

Vegetation is likely the primary discriminating factor between the soil moisture dynamics observed at the active and stabilized sites. While small variations in precipitation were observed between the active and stabilized sites, we failed to detect statistically significant differences in precipitation over monthly and seasonal time scales, ruling out

precipitation as a source of inter-site soil moisture differences. Organics and fine sediment particles were more prevalent near the surface of the stabilized dune, reducing infiltration rates and enhancing the soil moisture storage capacity of near-surface soils. This resulted in higher soil moisture content in the near-surface soil profile, while reducing soil moisture recharge in soils below 25 cm. The presence of transpiring vegetation depleted profile soil moisture more quickly at the stabilized sites than at the active sites, suggesting that the draw vegetation places on soil moisture resources is an important control on soil moisture dynamics in this ecosystem. While vegetation growth enhanced the moisture storage capacity of near-surface soils, decreased infiltration and enhanced evapotranspiration create a negative overall impact on deeper soil moisture resources at the stabilized dune sites.

According to the results of this research the transformation of dunes in the BSH from active to vegetation-stabilized has reduced deep soil moisture recharge. This is demonstrated by the lower frequency and intensity of deep soil moisture recharge at the stabilized dunes compared to the active dunes. With soil moisture content being lower throughout the season below 25 cm depth at the stabilized dune site the susceptibility of vegetation to drought conditions is enhanced (Fearnehough *et al.*, 1998; Li *et al.*, 2004B). In contrast, active dune sites exhibited higher overall profile soil moisture levels throughout the season. Given the anomalous growing season precipitation in 2010 soil moisture recharge at depth in stabilized dunes is less likely under more typical precipitation conditions.

Overall, the results of this investigation are unique because they extend the understanding of soil moisture dynamics during the natural stabilization of sand dunes. Shay *et al.* (2000) looked at near-surface (< 30 cm) soil moisture dynamics in another Canadian sandhill ecosystem and documented higher soil moisture levels near the surface beneath stabilized dunes. Other studies in sandhill ecosystems have focussed on soil moisture

dynamics only on fully stabilized sand dunes to depths of 100 cm (Sridhar & Wedin, 2009; Hubbard *et al.*, 2009). Those studies were conducted under average precipitation conditions and found that vegetation could deplete soil moisture resources by the end of the growing season. Like Berger (1992) and Wilcox & Thurow (2005) this study establishes that a significant reduction in deep soil moisture recharge occurs with the establishment of vegetation on active dunes. In addition, this study confirms the effects of stabilization on infiltration, thereby broadening the context of stabilization to a greater range of hydrological processes.

The current vegetation-stabilized state that now dominates more than 99% of Canadian Prairie sandhill ecosystems has the potential to reduce soil moisture resources over time. Most current global circulation models (GCM's) predict a reduction in the precipitation to potential evapotranspiration ratio (P:PE) throughout the Canadian Prairies (Wolfe & Thorpe, 2005; McGinn, 2010). A decrease in the P:PE would put more stress on soil moisture resources, especially in the most arid regions of the Canadian Prairies. As the growing season lengthens, there is potential for vegetation to increase total seasonal moisture usage (Sridhar & Wedin, 2009). Not only could seasonal moisture usage increase but the period of vegetation dormancy could decrease, reducing the period during which soil moisture recharge is most effective (Gosselin *et al.*, 1999). Long periods of drought within the study area have been linked to periods of increased dune activity within Canadian Prairie sandhill ecosystems as recently as the mid 1980's (Wolfe *et al.*, 2001). Should these deeper moisture reserves be sufficiently depleted the vegetation present within Canada's sandhill ecosystems would be more susceptible to drought thereby increasing the probability of dune surface blowouts and dune reactivation during prolonged drought periods. This type of scenario has been demonstrated in the US southwest where Laity (2003) reported dune

reactivation in response to a lowering of the groundwater table. In addition, there is increasing pressure on water resources in these ecosystems by the agricultural and energy (natural gas) industries. Should increased ecological and anthropogenic moisture usage exceed soil moisture recharge there is the potential to deplete the ecologically important soil moisture resources of this region.

2.8 Conclusion

The results of this field study confirm the hypothesis: sand dune stabilization reduces infiltration and soil moisture storage in a northern Great Plains sandhill ecosystem. The infiltrometer measurements show that the surface and near-surface infiltration rates were lower on the stabilized dune compared to the active dune. This is explained by the higher clay, silt, and organic content in the former. Despite receiving approximately equivalent rainfall at monthly to seasonal scales, the vertical distribution of soil moisture in the upper 200 cm of the soil profile was higher and significantly less variable throughout the 2010 growing season in the active dune compared to the stabilized dunes. Deeper measurements (500 cm) also showed substantially higher soil moisture at the active dunes throughout the growing season, although by October deep soil moisture at one of the stabilized dunes increased, presumably due to enhanced infiltration from rodent burrows. The key difference between sites is the presence of vegetation, which reduces surface infiltration rate by altering soil texture and organic content and also reduces soil moisture storage through evapotranspiration. Overall, despite the anomalously high precipitation in the 2010 growing season, these results indicate that active dunes can absorb and retain greater moisture than

the stabilized dunes that now dominate prairie sandhill ecosystems. It is anticipated that these differences will be more pronounced during typical (drier) growing seasons.

By extension, the broader implication of this investigation is that the progressive stabilization of this landscape has potentially reduced groundwater recharge. This long-term effect may be of concern to various stakeholders who rely on the shallow groundwater resources of these unique areas, such as ranchers and the energy companies. Thus, continued stabilization coincident with climate warming may require greater regulation of water resources in these unique areas.

CHAPTER 3: EFFECTS OF DUNE STABILIZATION ON SPATIOTEMPORAL PATTERNS OF NEAR-SURFACE SOIL MOISTURE, NORTHERN GREAT PLAINS, CANADA

3.1 Abstract

This Chapter reveals the effects of sand dune stabilization on the spatiotemporal distribution of near-surface soil moisture. Previous studies have recognized that spatial variations of soil moisture influence plant community development in dune landscapes; however, the effects of vegetation colonization and dune topography on near-surface soil moisture variability are not well-known. To document these effects, the spatiotemporal patterns of near-surface soil moisture were measured ten times throughout the 2010 growing season on active and a stabilized dune (sites A1 & S1; see Chapter 2). The effects of vegetation cover type on intra-site soil moisture variability were stronger than those related to dune topography. Nonparametric statistical tests show that near-surface (< 6 cm) soil moisture was higher and more variable at the stabilized dune than at the active dune. Effects of topography (slope and aspect) were also more pronounced at the stabilized dune, with consistently higher near-surface soil moisture on north-facing slopes and footslopes than elsewhere on the dune during a wet year. The primary differences between sites are related to direct and indirect influences of vegetation. Direct influences are related to the roughness effects of the vegetation, which reduce evaporative losses from the soil surface at the stabilized dune, resulting in higher near-surface soil moisture. Indirect influences include pedogenic alterations associated with vegetation that increase the moisture-holding capacity of soil at the stabilized dune, as a result of higher clay, silt and organic matter content. Near-

surface intra-site soil moisture exhibited little spatial variation on the active dune, but significant differences were observed between the moister on north-facing slopes and other slope aspects at the stabilized dune, in association with differences in vegetation cover and solar insolation. Higher soil moisture was also observed along the stabilized dune footslope, consistent with lateral soil moisture flow or hydraulic redistribution of soil moisture by plant roots. Overall, this study suggests that the establishment of vegetation and the allied process of soil genesis have a feedback effect on soil moisture, increasing near-surface soil moisture availability at stabilized dunes, and enhancing topographic effects on soil moisture variations.

3.2 Introduction

The sand hill regions of the southern Canadian Prairies are comprised of parabolic aeolian sand dunes that have become stabilized by vegetation growth. The transformation from active, mobile dunes to vegetation-stabilized dunes began approximately 200 years BP, under the influence of warmer and drier conditions (Wolfe & Hugenholtz, 2009). Currently, less than 1% of the area comprising Canadian Prairie sandhills maintains active sand dunes devoid of stabilizing vegetation (Epp & Townley-Smith, 1980; Wolfe & Hugenholtz, 2009). Active dunes are ecologically important in largely stabilized sandhill ecosystems because they provide habitat for a variety of endangered species. Furthermore, Chapter 2 showed that they are important pathways for moisture recharge at depth. This Chapter expands the understanding of soil moisture dynamics in Canadian Prairie sandhill ecosystems by investigating the effect of dune stabilization on the spatiotemporal variations of near-surface soil moisture. We also examine how dune topography affects the distribution of near-surface soil moisture, including variations in slope angle, aspect, and slope position.

The availability of soil moisture in the soil layers nearest the surface is one of the primary controls on vegetation establishment in active dune ecosystems (Barnes and Harrison, 1982; Maun, 1994; Moran *et al.*, 2010). Whereas previous studies have demonstrated that the spatial distribution of dune vegetation is correlated with the spatial availability of soil moisture resources (Hulett *et al.*, 1966; Barnes and Harrison, 1982; Berger, 1992; Shay *et al.*, 2000), the ability of vegetation to create temporal heterogeneity has received little attention. Moreover, topographic effects on dune soil moisture are poorly resolved, especially at middle latitudes where differences in solar insolation are more pronounced between north and south-facing slopes. Vegetation uses soil moisture for transpiration (Schlesinger *et al.*, 1987; Lawrence *et al.*, 2007). However, vegetation also reduces soil heat flux, thereby reducing soil moisture evaporation (Kustas *et al.*, 2000). Slope aspect significantly modifies the amount of incoming solar radiation received on different slopes (Holland & Steyn, 1975; Bennie *et al.*, 2008). In addition, the presence of vegetation traps windblown fines and adds organic matter to the near-surface soil profile, thereby reducing infiltration while increasing the moisture storage capacity of dune soils (Barnes & Harrison, 1982; Dunkerley, 2002).

As in Chapter 2, this Chapter also applies an ergodic (space-for-time) approach to determine the effects of dune stabilization on the spatiotemporal dynamics of near-surface soil moisture. The goal was to test for differences in the spatiotemporal variability of soil moisture between active and stabilized dunes (sites A1 & S1; see Chapter 2), and to examine the contributions of dune topography to any observed differences. We relate the differences between the active and stabilized dunes to direct and indirect influences of vegetation, while topographic effects manifest in terms of slope steepness, aspect and relative slope position. The novelty of this research is that it is the first to resolve spatiotemporal variations of near-

surface soil moisture in the context of dune stabilization, and to relate these variations to the effects of vegetation colonization on sand dunes.

3.3 Study Area

This study was conducted in the Bigstick Sand Hills, located approximately 40 km northeast of Maple Creek, Saskatchewan (Figure 3.1). The landscape is characterized by parabolic sand dunes largely stabilized by vegetation. The dunes within the study area are composed of former glacio-fluvial sands deposited 13,000 years BP that have been reworked intermittently by aeolian processes up to present (Wolfe & David, 1997). Currently less than 1% of the dunes in the study area are active (Wolfe & Hugenholtz, 2009). Since the beginning of the last stabilization period, approximately 200 years ago, the number of active dunes has substantially decreased (Hugenholtz and Wolfe, 2005; Hugenholtz *et al*., 2008). Initial dune colonizing species observed during this study include lance-leaved psoralea [*Psoralea lanceolata* (Pursh) Rydb.], veined dock [*Rumex venosus* Pursh], and Russian thistle [*Salsola kali* L.]. Later colonizing vegetation types most commonly observed include thickspike wheatgrass [*Elymus lanceolatus* (Scribn, & J.G. Sm.) Gould ssp. *lanceolatus*], needle-and-thread speargrass [*Hesperostipa comata* (Trin. & Rupr.) Barkworth ssp. *comata*], prairie Junegrass [*Koeleria macrantha* (Ledeb.) Schult.], woods' rose [*Rosa woodsii* Lindl.], prairie sagewort [*Artemesia frigida* Willd.], and western snowberry [*Symphoricarpos occidentalis* Hook.].

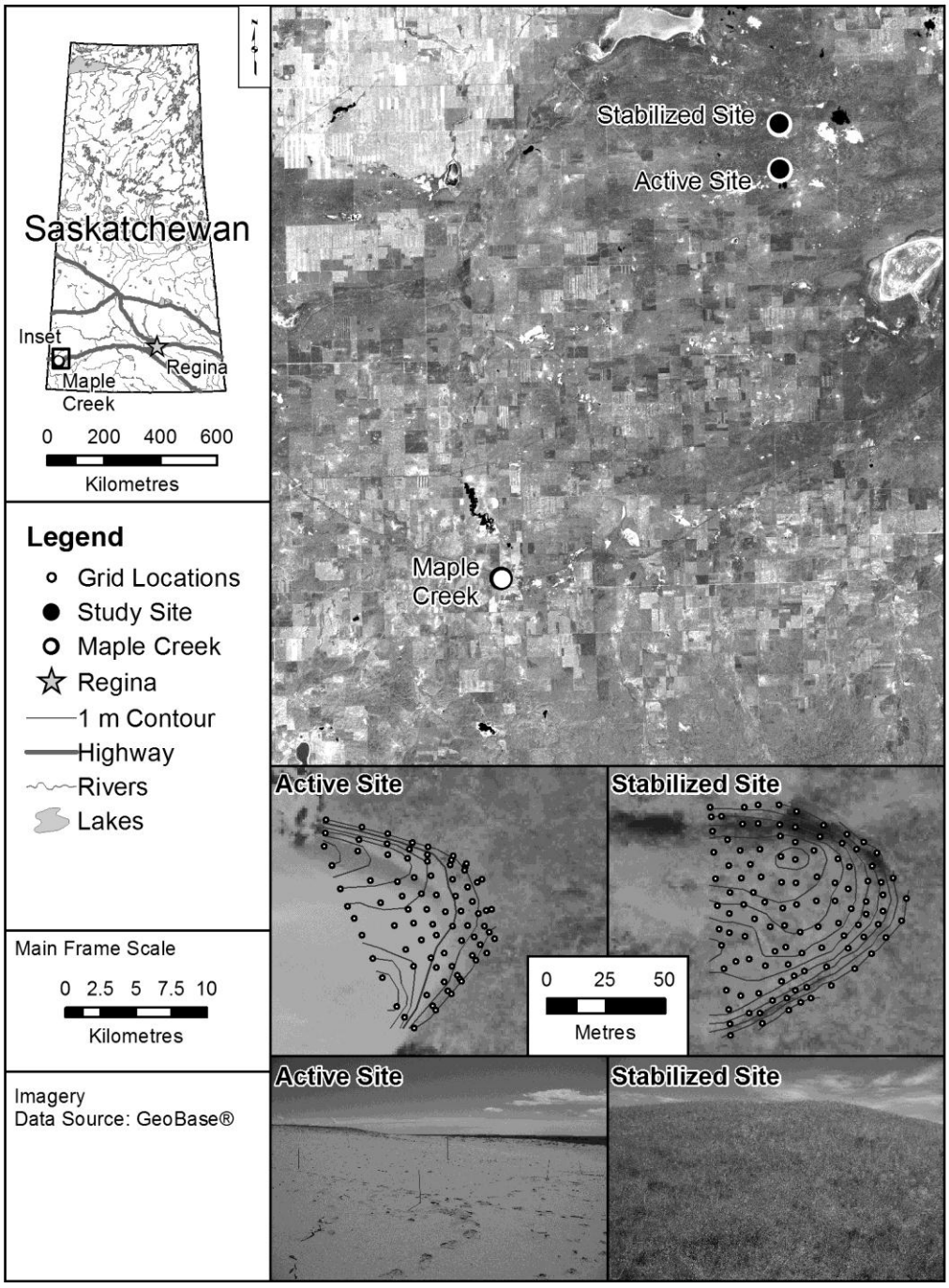


Figure 3.1. Overview of the study area, located 40 km NE of Maple Creek, Saskatchewan, depicting the sampling grid arrangement at the active and stabilized dune sites.

The climate of the Bigstick Sand Hills is cool, dry sub-humid, with long, cold winters and short, warm summers. However, during severe drought, the area is distinctly semi-arid (Wolfe, 1997). Average daily temperatures in the study area range from -10.4 °C in January to 19.3 °C in July. According to the nearest meteorological station 40 km to the southwest (Maple Creek), yearly precipitation totals average 379.3 mm, with 109.6 mm on average falling as snow (Environment Canada, 2011). Convective precipitation is the dominant contributing precipitation type during the mid to late growing season (Kim & Wang, 2007).

Field measurements during the 2010 growing season coincided with lower than normal temperatures and above average precipitation. Total precipitation in the study area was 423 mm from April to August, which is 110% above the 1971-2000 Maple Creek station mean (Figure 3.2; Environment Canada, 2011). Measureable precipitation was recorded during 72 of the 131 days in this study, with no rain-free periods exceeding eleven days (May 10-20). Cool spring temperatures, above average snowpack (>200%), record precipitation in April and May, and consistent, high intensity precipitation events throughout most of June saturated soils in areas surrounding the sandhills, leading to a 1:3,700 year flood event (Pentland *et al.,* 2011). However, within the sandhills, the soil profile quickly absorbed this moisture in most areas.

Data were collected at two sites in this study, including an active, largely bare sand dune and a nearby vegetation-stabilized dune exhibiting common final stage dune vegetation types across most of its surface (sites A1 & S1, respectively; see Chapter 2). The total distance between these sites is 3.2 km. The north-facing slopes of the stabilized dune exhibited shrubs such as prairie sagewort, western snowberry, and Woods' rose, making this dune a reasonable representative of stabilized dunes within the Bigstick Sand Hills. Soils at

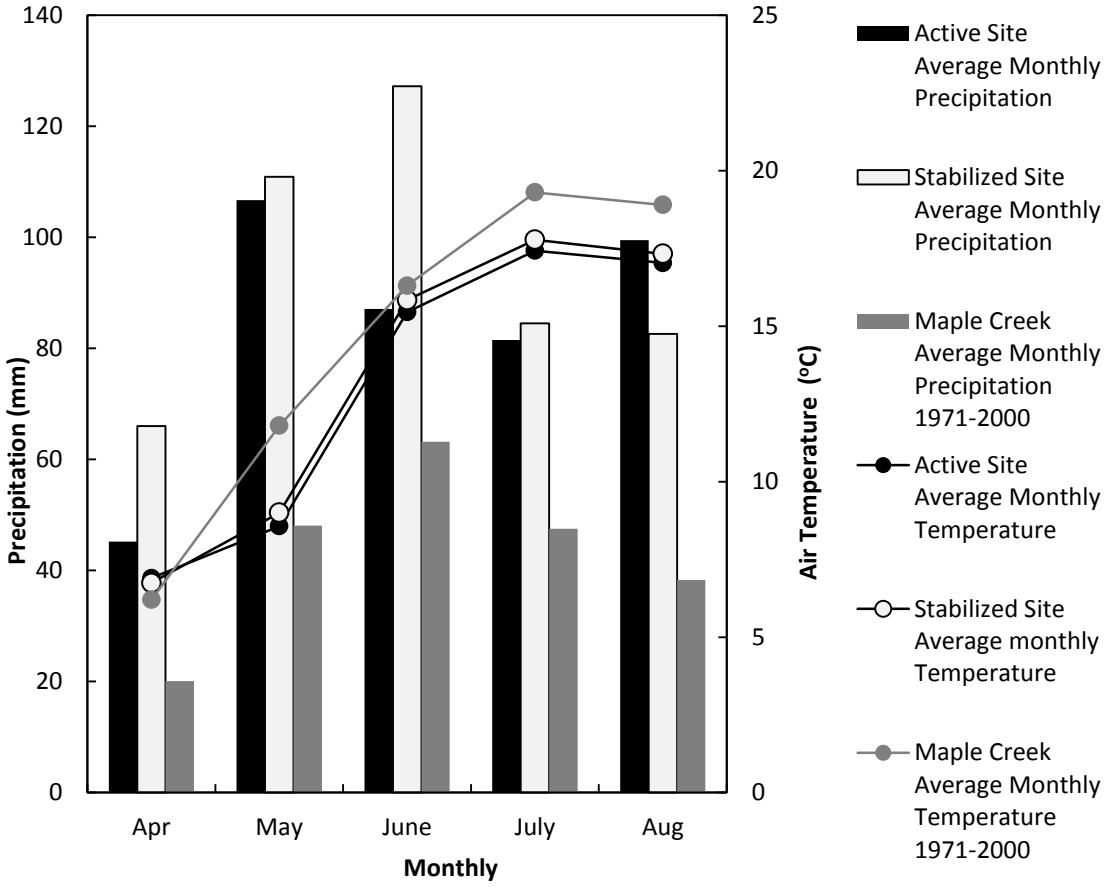


Figure 3.2. Monthly precipitation totals and air temperatures during the study period. Observed precipitation during the study period was more than double that recorded in an average year. Observed air temperatures were below average for most of the study period.

all sites are classified as sand based on USDA soil texture classification (Davis & Bennett, 1927). Sand typically comprised 95% of sediment samples by mass. Silts, clays, and organic matter were more prevalent at the stabilized dune but still made up a small proportion of all soil constituents.

3.4 Methodology

This study focuses on soil moisture dynamics and dune topography, and excludes the surrounding inter-dune areas. This was done so as to minimize the influence of vegetated inter-dune areas that have access to near-surface groundwater resources. Groundwater resources in inter-dune areas enhance vegetation growth thereby enhancing the rate at which organic matter is added to the soil (Miller *et al.*, 1985). Through limiting this study to dune forms and avoiding lower elevation interdune regions, the effects of groundwater on vegetative growth and soil genesis were minimized, thereby enabling a more clear comparison to be made between the near-surface soil moisture dynamics present at the active and stabilized dune sites.

In order to acquire soil moisture measurements, an array of narrow aluminum pins was established on each dune (Figure 3.1). The pins served as reference points for the soil moisture measurements. The array of pins extended to the base of the dune slopes but did not extend onto the surrounding inter-dune area. In order to reconcile changes in soil moisture resulting from differences in the upslope contributing area pins were placed at three locations along dune slopes: crest, midslope and footslope. This order coincides with an increase in the upslope contributing area from crest to footslope. To create a spatiotemporal dataset of soil moisture variation across both dunes we measured near-surface soil moisture ten times throughout the 2010 growing season.

Soil moisture data were collected using an ML2x Theta time domain reflectometry (TDR) probe connected to an HH2 moisture meter (Delta-T Devices). The TDR probe estimates the volumetric soil moisture content (θ_v) of the soil, based on the relation between volumetric soil moisture content and the apparent dielectric constant (Topp *et al.,* 1980). At

each pin location, the TDR probe was fully inserted into the soil surface to a depth of 6 cm. Two measurements were taken within 100 cm of each pin, averaged, and then recorded. Because the manufacturer's recommended calibration procedure does not perform well in sandy soils (see Schmutz, 2007), a soil-specific calibration curve was created using raw sensor output (mV) and volumetric soil moisture samples collected from the field sites (A1: n = 15; S1: n = 18). The soil samples were oven-dried to derive volumetric soil moisture content (θ_V). The analysis of multiple samples produced the linear calibration shown in Figure 3.3. The linear curve chosen for sensor output calibration has an R^2 of 0.94 and $s_{y,x}$ of 0.91, which exceeds the manufacturer's average achievable accuracy of ±1% for soil-specific calibration. We adopted one calibration curve for both sites because the individual calibration curves for the active and stabilized sites differed by less than the minimum achievable error of the sensor.

Soil texture was determined on all samples collected for the TDR probe calibration, using the Bouyoucos (1962) hydrometer method (ASTM D422 - 63 (2007)). Soils were classified by percentage sand, silt, and clay based on USDA soil texture classification (Davis & Bennett, 1927). The percent organic matter content of each sample was determined using loss on ignition (LOI) methodology (ASTM F1647 - 11).

Precipitation data collected at dunes A1 and S1 (see also Chapter 2) were used to quantify temporal variations in precipitation between the active and stabilized sites since those instrumented sites are centrally located within the array of pins delineating soil moisture measurement locations. These data were aggregated to a daily timescale and analysed using a Wilcoxon Matched-Pairs Signed-Ranks test to detect significant differences in precipitation between the sites.

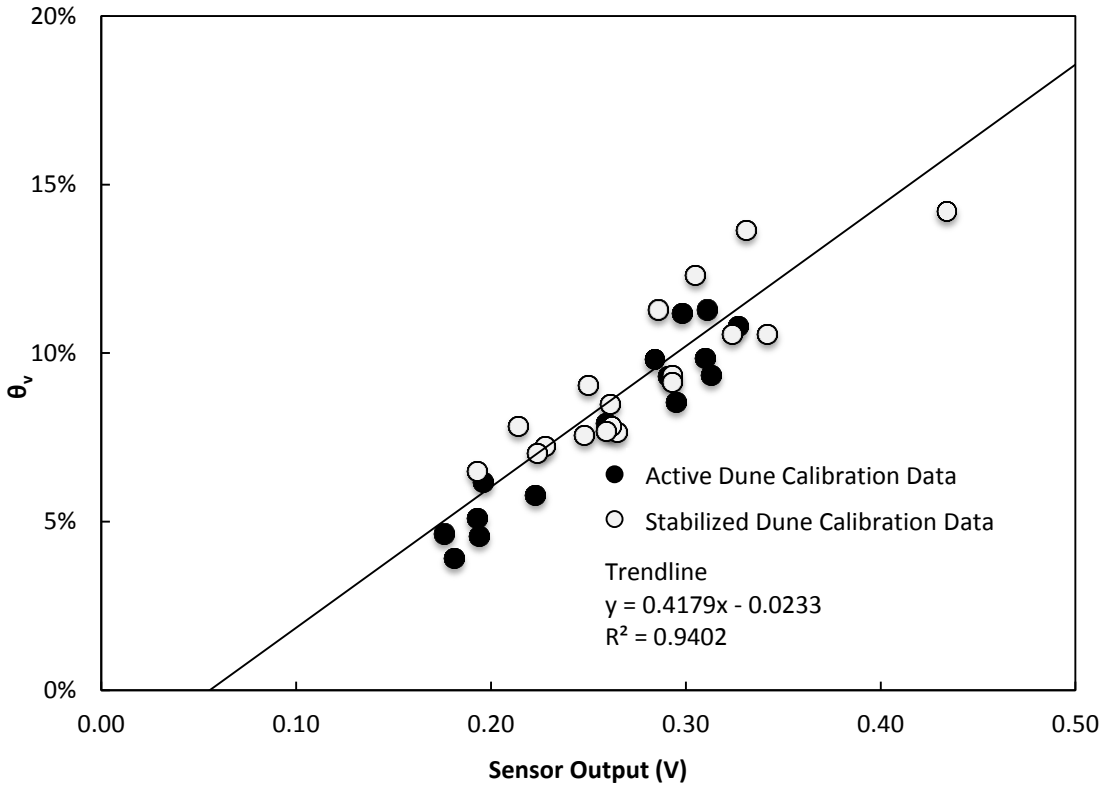


Figure 3.3. Instrument calibration of the TDR probe for the soils present at the active and stabilized dune sites.

Each pin location was classified according to the surrounding vegetation functional group (grass or shrub) and topographic position. Sparse vegetation on the active dune coincided with five pins, but given the limited sample size, was not included in any statistical testing. On the stabilized dune a 2 x 2 m quadrat was placed on the ground, centred on each pin, and the dominate functional group was noted. Grasses occupied the majority of the pin sites (72.5% or 79/109) followed by shrubs (27.5% or 30/109). Since shrubs and grasses often occurred together, sites with greater than 10% shrub cover were classified as shrub.

The topographic properties (slope steepness, aspect) of each pin were determined using GIS procedures following a detailed survey of pin locations on both dunes with a real-

time kinematic GPS. The positional error of the GPS measurements was sub-centimetre in the horizontal plane and less than 2 cm in the vertical plane. From the survey data a 25 cm resolution digital elevation surface was generated for each dune using a spline algorithm in ArcGIS 9.3. The algorithm was set so that only the nearest five points were used in the interpolation. Increased tension was used to minimize unknown surface curvatures between survey points. For each pin location the slope steepness, aspect, and slope position (crest, mid-slope, and footslope) were calculated from the corresponding digital elevation surface. At the active dune, surface accretion/deflation was also measured at each pin, enabling analyses of the effects of dune surface change on near-surface soil moisture availability.

Near surface (< 6 cm) soil moisture data was collected at both dunes ten times throughout the 2010 growing season. Intervals between measurement dates ranged from 5 to 30 days. The longest period between measurements, from 11 May to 10 June, consisted of an extended period of heavy rainfall. Shorter measurement intervals were used during drier periods. The shortest interval corresponded to a warm (19.7 °C) and dry period between 24 June and 29 June, which followed 89 mm of rainfall between 16 June and 22 June.

Soil moisture data were classified according to the land cover and topographic properties of each pin. The three land cover classes were: bare sand, grass and shrub. The topographic data were also classified by slope steepness (< 5^o, 5^o - 10^o, 10^o - 20^o, 20^o - 30^o and > 30^o) and site aspect (flat (< 5^o), north, south, east, and west). The flat aspect was added as a control class, enabling comparisons between pin locations exhibiting steep slopes and those with relatively gentle slopes. Pins located on the outer slopes of the dunes were also classified according to their relative position (crest, midslope and footslope), similar to Sulebak *et al.* (2000). The data were classified and aggregated into land cover and topographic

classes for each survey date and also aggregated on a seasonal scale to compare soil moisture dynamics among sites with different land cover and topographic characteristics.

3.5 Data Analysis

Nonparametric statistical analyses were chosen because the soil moisture data did not satisfy the normal population distribution and equal variance requirements of parametric tests such as *t*-tests and analysis of variance (ANOVA). We used the Wilcoxon Rank Sum (W), the Kruskal-Wallis (H) and Friedman non-parametric repeated-measures tests (F) at the 0.05 significance level. The Wilcoxon Rank Sum test is the nonparametric alternative to the two-sample *t*-test and is used to determine differences in the distributions of two repeatedly measured samples. At the active dune a Wilcoxon Rank Sum (W) was also used to determine whether surface accretion or deflation affected near-surface soil moisture measurements. In addition, a Wilcoxon Matched-Pairs Signed Ranks test was used to determine if precipitation differed between the two dunes. The Kruskal Wallis (H) test is a nonparametric alternative to the ANOVA and is used to determine differences in the distributions of three or more independent samples on individual measurement dates. The Friedman non-parametric repeated measures test is a nonparametric alternative to the ANOVA and is used to determine differences in the distributions of three or more repeatedly measured samples at the seasonal scale. The goal of these tests was to detect statistically significant variations in near-surface soil moisture for different land cover and topographic properties. Because soil moisture was repeatedly measured at the same measurement sites on ten different occasions over the season, a Dunn - Sidak procedure was used to modify the significance level at which the null hypothesis was rejected for season-scale comparisons.

3.6 Results

Prior to describing differences in soil moisture between and across dunes, the site-specific factors that may influence the spatiotemporal variability of near-surface soil moisture between the two dunes are outlined. Recall that the total distance between the dunes is 3.2 km. The focus of sections 3.6.1 and 3.6.2 is on differences in precipitation and soil properties (texture and organic content). Following the description of these controls, the soil moisture data and results of statistical tests that reveal inter- and intra-site differences relating to the effects of vegetation and topography are presented in section 3.6.3.

3.6.1 Precipitation

As explained in Chapter 2, above average precipitation fell throughout the 2010 study period (April-August), with record precipitation in the watershed during April and May, 2010 (Pentland *et al.*, 2011). Total precipitation during the study period was 423 mm, which is 110% more than the 1971-2000 mean of 203 mm (Figure 3.2; Environment Canada, 2011). Frequent precipitation precluded assessment of drought or dry spell effects on soil moisture distribution in active and stabilized dunes. To narrow the list of variables that may influence inter-site soil moisture variations, a Wilcoxon Matched-Pairs Signed Ranks test was used to determine if there was a significant difference in precipitation at both monthly and seasonal time scales. Results show that total precipitation volumes did not vary significantly between the sites at either the monthly ($p = 0.31$) or seasonal ($p = 0.80$) scales, suggesting that any long-term differences in soil moisture were minimally impacted by variations in precipitation input. Of the 40.4 mm precipitation difference between the sites, 28.3 mm (70.0 %) of this difference is accounted for during a single precipitation event on

22 June. Thus, consistent long-term differences in soil moisture between sites appear to be minimally-affected by variations in precipitation.

3.6.2 Soil properties

Soil texture was finer and more variable at the stabilized dune (Table 3.1). Clay and silt made up 8% of the near-surface sediment, whereas clay and silt made up only 3% of near-surface sediment at the active dune. Silt and clay contents are higher on all aspects of the stabilized dune compared to the active dune. Organic content was also higher at the stabilized dune. Intra-site variation of organic content was slightly more pronounced at the stabilized dune, with higher organic content on the north- and south-facing slopes. Differences in soil texture and organic matter content between the dunes were all significant at the 0.001 significance level. Increased variation of near-surface soil properties at the stabilized dune may be linked to effects of vegetation. For instance, enhanced organic content was observed beneath shrubs (3.09%) compared to grasses (1.69%). Most shrubs

Table 3.1. Summary of near-surface soil texture and organic content at the active (n = 6) and stabilized (n = 6) dunes for each class.

Study Site	Aspect	Soil Texture			Organic Matter
		Sand %	Silt %	Clay %	%
Active	North	96.85	1.27	1.87	0.67
Active	South	97.42	0.86	1.72	0.00
Active	East	98.57	0.66	0.77	0.60
Active	Flat	94.68	1.37	3.95	1.20
Active	Average	96.88	1.04	2.08	0.62
Stabilized	North	89.08	5.68	5.24	3.61
Stabilized	South	91.99	3.12	4.90	2.48
Stabilized	East	94.75	1.72	3.53	1.39
Stabilized	Flat	91.32	4.17	4.52	1.20
Stabilized	Average	91.79	3.67	4.55	2.17

were located on the north-facing slopes (53%), which could explain the enhanced organic matter, as well as the elevated silt and clay content.

3.6.3 Effects of vegetation on the spatiotemporal dynamics of soil moisture

The highest near-surface soil moisture variability was observed early in the growing season (9 April & 22 April) at both dunes (Figure 3.4). On a seasonal scale, the average soil moisture across the active dune was less variable than across the stabilized dune. Wider ranges of soil moisture were observed during periods when median soil moisture was high (Figure 3.5). While a smaller number of soil moisture measurement intervals coincided with extended dry periods, the coefficient of variation did not change significantly for shorter dry periods, suggesting that the relative soil moisture variability during all measurement intervals was similar (Table 3.2).

The near-surface soil moisture data collected at the stabilized dune was higher and more variable than at the active dune (Table 3.2). Maximum soil moisture variation was observed on 9 April, following snowfall on 8 April. While the snow melted before measurements were taken on 9 April, redistribution of the snow by high winds may have played a role in enhancing soil moisture heterogeneity at both dunes. Wilcoxon Rank Sum W tests suggest that near-surface soil moisture was significantly different between the two dunes during most measurement intervals. The smallest difference between the dunes occurred on 29 June, which also corresponded to the driest measurement interval of the study.

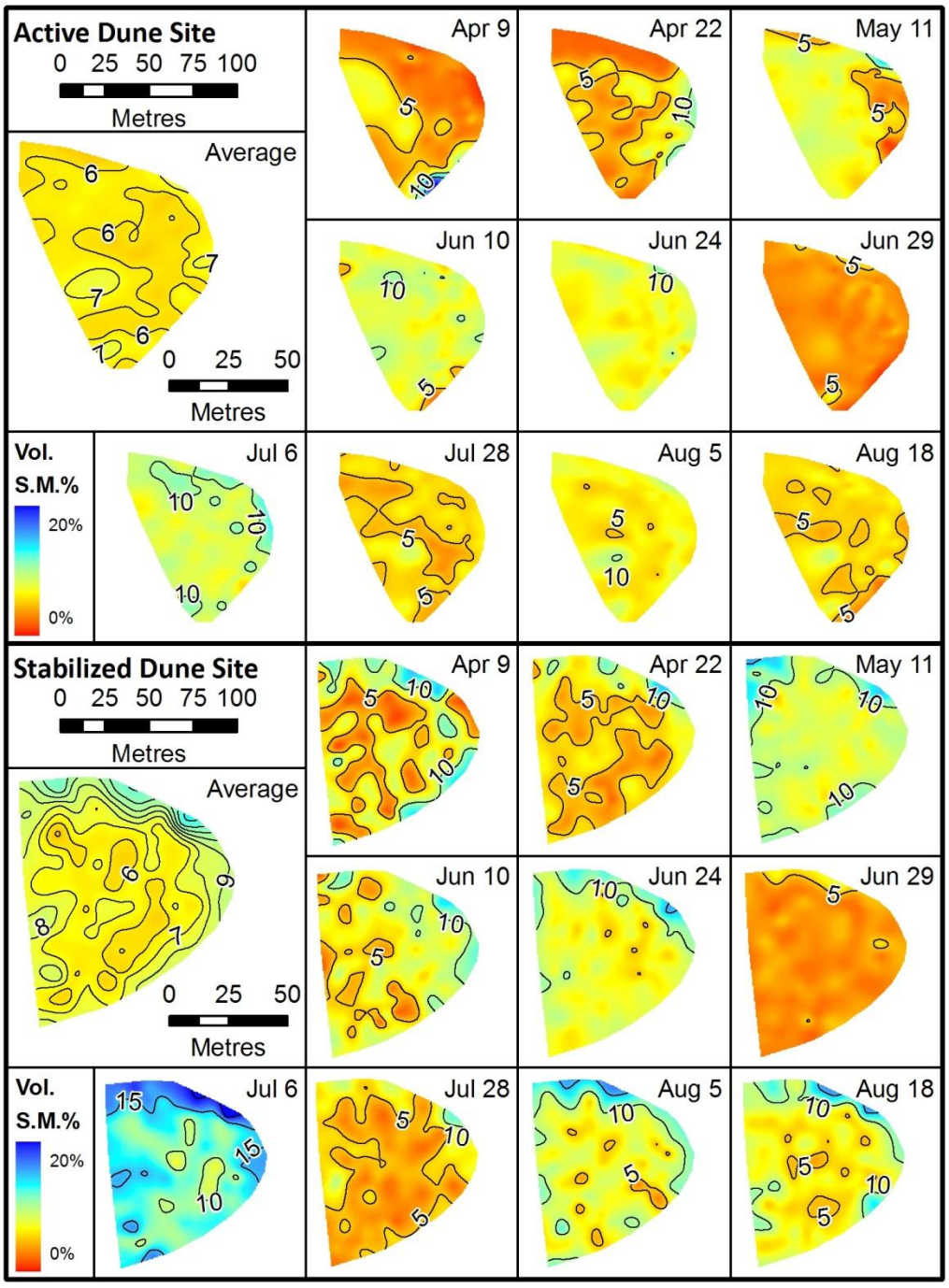
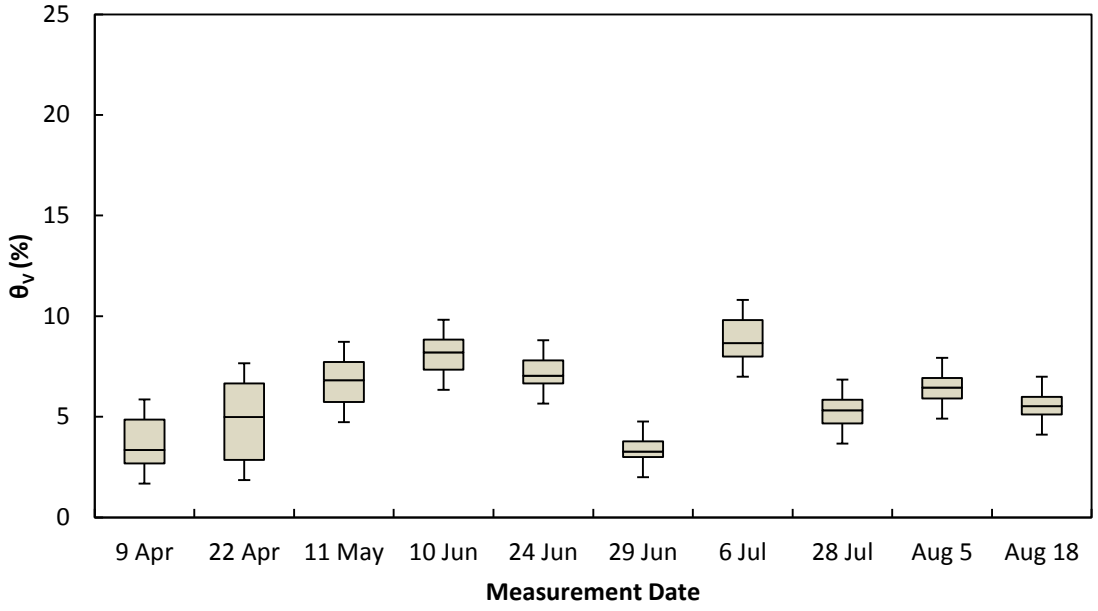


Figure 3.4. Spatio-temporal distribution of near-surface (< 6 cm) soil moisture at the active and stabilized dune sites.

A.



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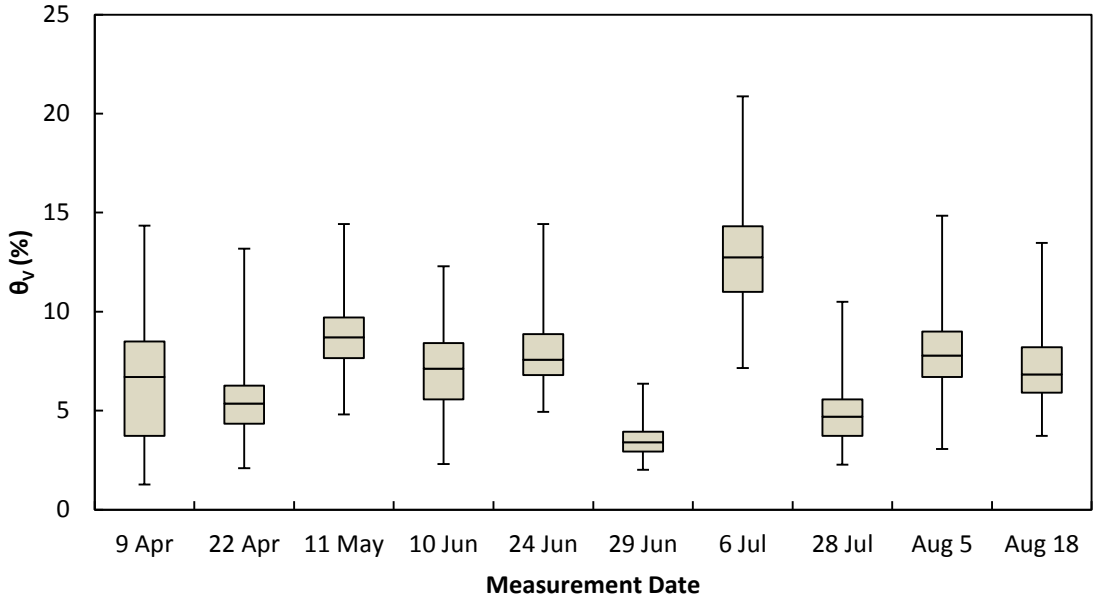


Figure 3.5. Statistical distribution of volumetric soil moisture (θ_V) measurements captured at the active (A) and stabilized (B) dunes on each measurement date. Maximum, minimum, median, and quartiles are displayed. n = 83 for each active dune site measurement date. n = 109 for each stabilized dune measurement date.

Table 3.2. A comparison of the mean, standard deviation (St. Dev.), and coefficient of variation (Co. Var.) of soil moisture values measured at the instrumented active (n = 83) and stabilized (n = 109) dune sites over the entire study period. p-values were derived using the Wilcoxon W Rank Sum test and show the probability of getting a test statistic value as extreme as the one observed if soil moisture varies similarly across the surface of the active and stabilized dunes (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates for the season-level comparison.

	Active			Stabilized			
	Mean	St. Dev.	Co. Var.	Mean	St. Dev.	Co. Var.	p-values
9 Apr	4.02	2.02	0.50	6.74	2.87	0.43	0.000
22 Apr	4.91	2.14	0.44	5.71	1.97	0.35	0.073
11 May	6.51	1.65	0.25	8.90	1.83	0.21	0.000
10 Jun	8.08	1.18	0.15	7.20	2.11	0.29	0.000
24 Jun	7.31	0.99	0.14	8.14	1.81	0.22	0.025
29 Jun	3.47	0.73	0.21	3.56	0.85	0.24	0.893
6 Jul	8.84	1.24	0.14	12.98	2.42	0.19	0.000
28 Jul	5.29	0.94	0.18	4.94	1.65	0.33	0.001
5 Aug	6.52	0.93	0.14	8.24	2.40	0.29	0.000
18 Aug	5.66	0.87	0.15	7.41	2.05	0.28	0.000
Entire Season	6.06	2.12	0.35	7.35	3.16	0.43	0.000

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

Statistical differences between the three land cover classes shown in Table 3.3 provide additional detail on the effects of vegetation on near-surface soil moisture. In some cases the difference between these classes is less pronounced than when all measurements for each dune are used as a basis for comparison. For example, on several measurement dates the differences between bare sand and grass, and between bare sand and shrub are weaker than when the data are aggregated for each dune. Grass and shrub classes had very few strong differences. At the seasonal scale, however, each of the pairings showed a strong

Table 3.3. *p*-values depicting the results of the Wilcoxon Rank Sum test (W), Kruskal-Wallis (H), and Freidman non-parametric repeated-measures (F) test for resolving differences in near-surface (< 6 cm) soil moisture values between and among bare, grass and shrub classes. *p*-values show the probability of getting a test statistic value as extreme as the one observed if soil moisture varies similarly beneath different vegetation cover types (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates at the seasonal scale. n = 78, n = 79 and n = 30 on each measurement date for the bare, grass and shrub classes respectively.

	Vegetation Classes Compared			
Date	Bare vs. Grass (W)	Bare vs. Shrub (W)	Grass vs. Shrub (W)	All 3 Classes (H)
9-Apr	0.000	0.000	0.022	0.000
22-Apr	0.226	0.041	0.153	0.000
11-May	0.000	0.000	0.206	0.000
10-Jun	0.000	0.088	0.181	0.000
24-Jun	0.260	0.001	0.012	0.000
29-Jun	0.769	0.366	0.291	0.132
6-Jul	0.000	0.000	0.024	0.000
28-Jul	0.000	0.331	0.250	0.000
5-Aug	0.000	0.000	0.221	0.000
18-Aug	0.000	0.000	0.041	0.000
Entire Season	0.000	0.000	0.000	0.000 (F)

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

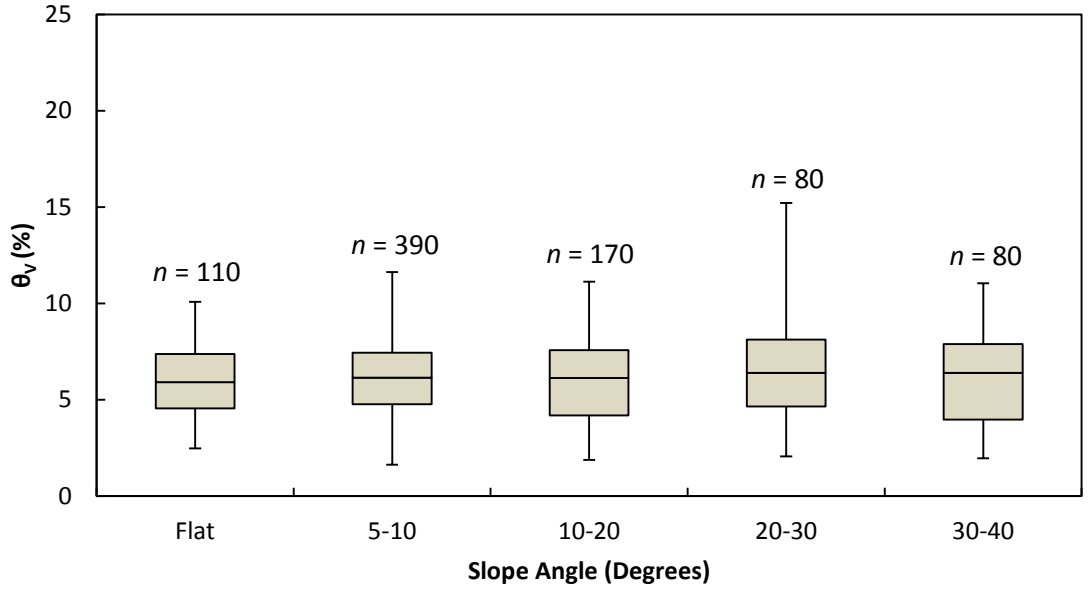
statistical difference. The Kruskal-Wallis (H) tests indicate that soil moisture was most similar (p = 0.132) beneath all three vegetation classes on 29 June, corresponding with the driest measurement date of the field season. On a seasonal scale, the Friedman test statistic confirms that statistically significant soil moisture differences are present between all three vegetation classes.

3.6.4 Effects of topography on the spatiotemporal dynamics of soil moisture

On a seasonal scale, the median and range of soil moisture measurements were very similar for each slope steepness class across each dune (Figure 3.6). We failed to detect significant differences in soil moisture between different slope steepness's on most measurement dates at either the active dune (Table 3.4) or the stabilized dune (Table 3.5) sites. While statistically significant differences were observed between some classes on some individual measurement dates, on a seasonal scale significant soil moisture differences were not observed at either site between the slope steepness classes.

Soil moisture measurements classified according to aspect exhibited significant variation at a seasonal scale at the stabilized dune, whereas soil moisture distributions were similar at a seasonal scale between aspect classes across the surface of the active dune (Figure 3.7). Soil moisture on the north-facing slope of the stabilized dune was higher and more variable than soil moisture measured on other aspects. Because none of the measurement sites on the active dune were located on a west-facing aspect, statistics could not be compiled for that aspect. Soil moisture was significantly different among aspects on several measurement dates at both the active (Table 3.6) and stabilized (Table 3.7) dunes. At both of these sites, the north-facing aspect was significantly wetter on most measurement dates, accounting for most of the intra-site variability. At the stabilized site, the drier south-facing slope had significantly lower soil moisture on several measurement intervals compared to other aspects. However, at the seasonal scale, only the stabilized dune exhibited a statistically significant difference in soil moisture between aspects. The flat, east, and west aspects at the

A.



B.

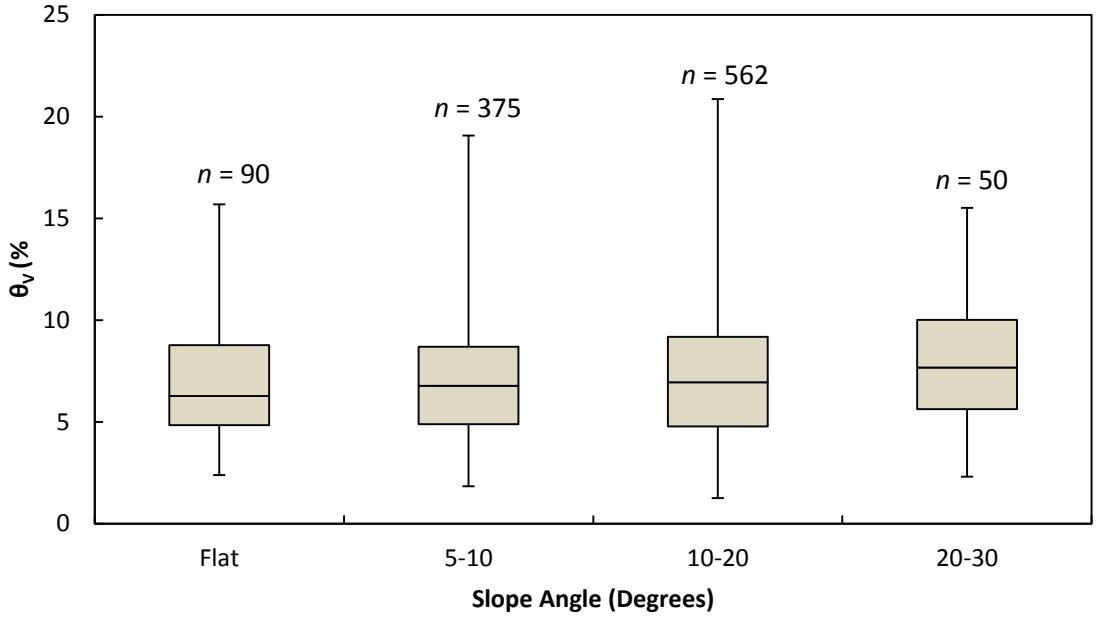


Figure 3.6. Statistical distribution of volumetric soil moisture (θ_V) measurements at different slope angles on the active (A) and stabilized (B) dunes over the entire field season. Maximum, minimum, median, and quartiles are displayed.

Table 3.4. *p*-values depicting the results of the Wilcoxon Rank Sum test (W), Kruskal-Wallis (H), and Freidman non-parametric repeated-measures (F) test for resolving differences in near-surface (< 6 cm) soil moisture between and among five different slope classes on the active dune. The *p*-values derived show the probability that the compared slope classes exhibited similar surface soil moisture distributions (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates at the seasonal scale. n = 11, 39, 17, 8 and 8 on each measurement date for the <5, 5-10, 10-20, 20-30 and 30-40 degree slope classes respectively.

Date	Downslope Angle (Degrees)										
	<5 vs. 5-10 (W)	<5 vs. 10-20 (W)	<5 vs. 20-30 (W)	<5 vs. 30-40 (W)	5-10 vs. 10-20 (W)	5-10 vs. 20-30 (W)	5-10 vs. 30-40 (W)	10-20 vs. 20-30 (W)	10-20 vs. 30-40 (W)	20-30 vs. 30-40 (W)	All 5 Class (H)
9 Apr	0.033	0.165	0.650	0.021	0.190	0.040	0.562	0.232	0.081	0.000	0.011
22 Apr	0.051	0.173	0.043	0.000	0.004	0.001	0.000	0.415	0.000	0.000	0.000
11 May	0.003	0.100	0.322	0.283	0.289	0.145	0.246	0.727	0.816	0.160	0.027
10 Jun	0.331	0.438	0.934	0.342	0.735	0.533	0.921	0.560	0.727	0.768	0.825
24 Jun	0.219	0.082	0.039	0.026	0.297	0.033	0.033	0.130	0.466	0.595	0.004
29 Jun	0.287	0.384	0.117	0.173	0.831	0.428	0.428	0.268	0.162	0.000	0.152
6 Jul	0.406	0.760	0.058	0.063	0.378	0.018	0.021	0.097	0.130	0.346	0.012
28 Jul	0.308	0.029	0.483	0.026	0.105	0.921	0.039	0.415	0.322	0.022	0.030
5 Aug	0.125	0.067	0.107	0.003	0.247	0.358	0.003	0.930	0.039	0.284	0.000
18 Aug	0.007	0.095	0.137	0.006	0.702	0.745	0.068	0.816	0.116	0.035	0.002
Entire Season	0.747	0.825	0.250	0.744	0.994	0.224	0.806	0.280	0.870	0.459	0.092 (F)

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

stabilized dune exhibited similar soil moisture on most measurement dates. When soil moisture on all aspects is analysed simultaneously using the Kruskal-Wallis (H) statistic, significant differences are observed throughout most of the season at both dunes, suggesting that at least one aspect at each site exhibits significantly different soil moisture dynamics from the others on most measurement dates.

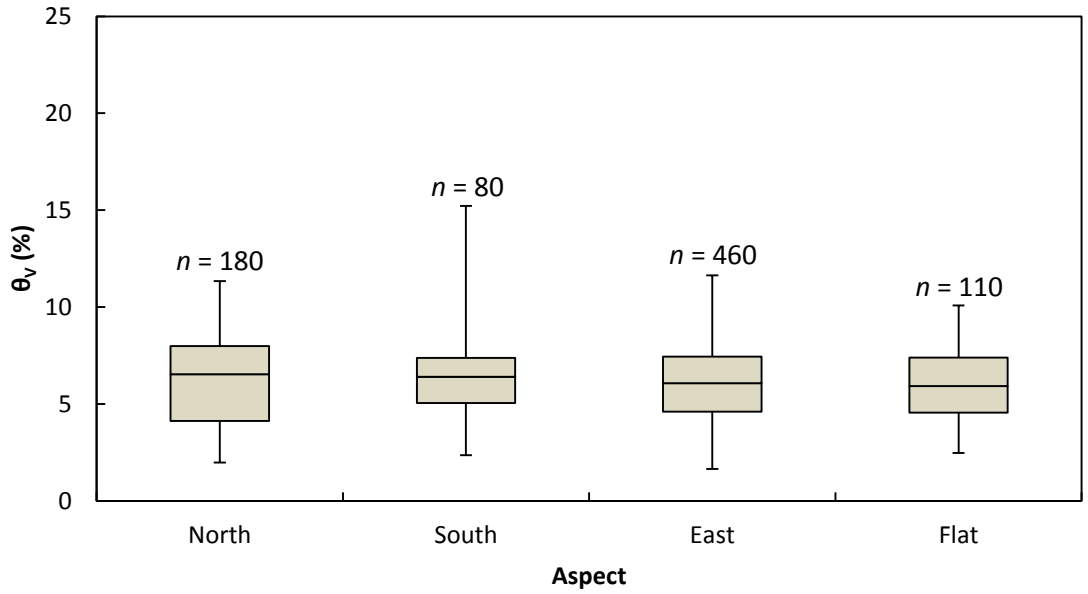
Table 3.5. *p*-values depicting the results of the Wilcoxon Rank Sum test (W), Kruskal-Wallis (H), and Freidman non-parametric repeated-measures (F) test for resolving differences in near-surface (< 6 cm) soil moisture between and among four different slope classes on the stabilized dune. The *p*-values derived show the probability that the compared slope classes exhibited similar surface soil moisture distributions (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates at the seasonal scale. n = 9, 38, 57 and 5 on each measurement date for the <5, 5-10, 10-20, and 20-30 degree slope classes respectively.

Date	Downslope Angle (Degrees)						
	<5 vs. 5-10 (W)	<5 vs. 10-20 (W)	<5 vs. 20-30 (W)	5-10 vs. 10-20 (W)	5-10 vs. 20-30 (W)	10-20 vs. 20-30 (W)	All 4 Classes (H)
9 Apr	0.491	0.062	0.009	0.067	0.079	0.162	0.023
22 Apr	0.964	0.704	0.643	0.439	0.025	0.293	0.616
11 May	0.761	0.772	0.165	0.841	0.004	0.112	0.356
10 Jun	0.646	0.449	0.165	0.835	0.036	0.210	0.472
24 Jun	0.715	0.802	0.877	0.342	0.011	0.717	0.761
29 Jun	0.482	0.859	0.217	0.991	0.005	0.149	0.510
6 Jul	0.797	0.919	0.316	0.615	0.027	0.455	0.786
28 Jul	0.292	0.794	0.877	0.258	0.011	0.965	0.537
5 Aug	0.925	0.562	0.877	0.679	0.015	0.942	0.926
18 Aug	0.925	0.702	0.758	0.427	0.016	0.896	0.842
Entire Season	0.598	0.394	0.235	0.693	0.302	0.399	0.160 (F)

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

Relative slope position was the most significant topographic control in determining the spatiotemporal distribution of soil moisture. The median and range of soil moisture measurements collected at the active dune were similar at a seasonal scale at crest, mid-slope, and footslope positions (Figure 3.8). However, along the footslope of the stabilized dune soil moisture was higher and more variable than other slope positions. In contrast, soil moisture

A.



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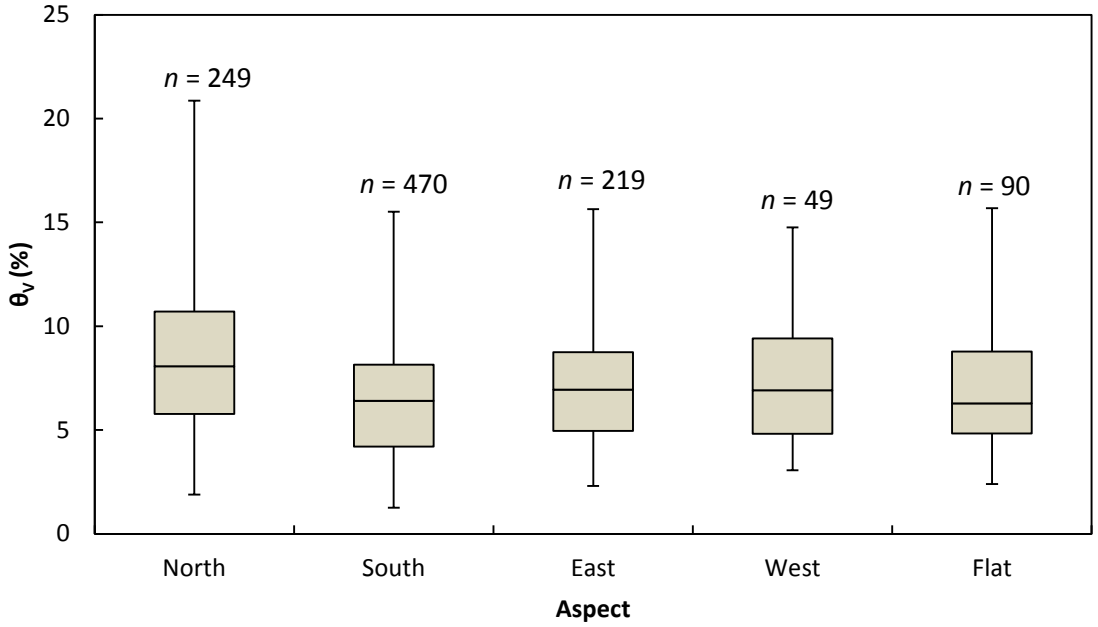


Figure 3.7. Statistical distribution of volumetric soil moisture (θ_V) measurements on different slope aspects at the active (A) and stabilized (B) dunes over the entire field season. Maximum, minimum, median, and quartiles are displayed.

Table 3.6. *p*-values depicting the results of the Wilcoxon Rank Sum test (W), Kruskal-Wallis (H), and Freidman non-parametric repeated-measures (F) test for resolving differences in near-surface (< 6 cm) soil moisture between and among four different aspect classes on the active dune. The *p*-values derived show the probability that the compared aspect classes exhibited similar surface soil moisture distributions (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates at the seasonal scale. n = 18, 8, 46, and 11 on each measurement date for the north, south, east and flat aspect classes respectively.

	Aspects Compared - Active Dune						
Date	Flat vs. North (W)	Flat vs. East (W)	Flat vs. South (W)	North vs. East (W)	North vs. South (W)	East vs. South (W)	All 4 Aspects (H)
April 9	0.029	0.010	0.007	0.748	0.001	0.000	0.000
April 22	0.000	0.176	0.934	0.000	0.001	0.162	0.000
May 11	0.669	0.001	0.302	0.002	0.487	0.033	0.000
June 10	0.048	0.606	0.934	0.039	0.012	0.503	0.039
June 24	0.004	0.169	0.483	0.003	0.008	0.503	0.000
June 29	0.041	0.253	0.837	0.160	0.030	0.201	0.007
July 6	0.164	0.864	0.620	0.115	0.075	0.495	0.178
July 28	0.009	0.249	0.386	0.008	0.017	0.932	0.005
Aug 5	0.004	0.089	0.342	0.013	0.026	0.618	0.001
Aug 18	0.001	0.012	0.650	0.031	0.004	0.050	0.000
Entire Season	0.290	0.939	0.462	0.148	0.602	0.453	0.029 (F)

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

was similar at footslope, mid-slope, and crest positions for almost all measurement intervals at the active dune (Table 3.8). However, at the stabilized dune, significant differences in soil moisture between the footslope and the other two slope positions was evident on most measurement dates. Soil moisture at crest and mid-slope positions at the stabilized dune could not be statistically differentiated.

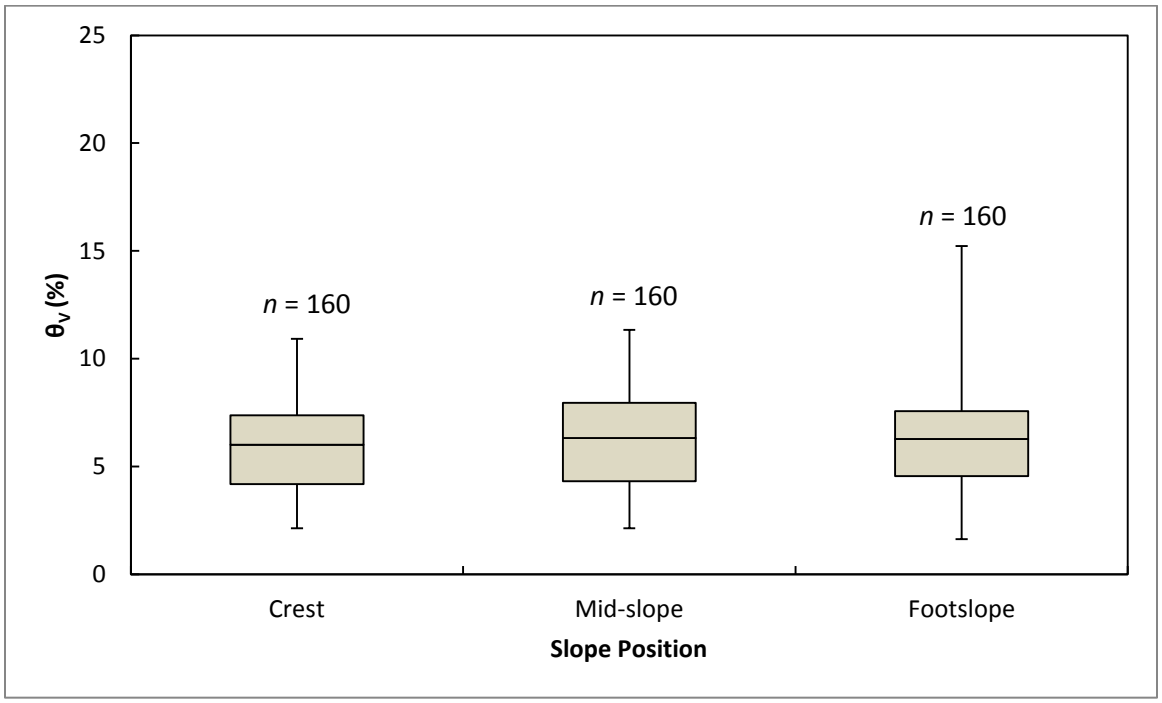
Table 3.7. *p*-values depicting the results of the Wilcoxon Rank Sum test (W), Kruskal-Wallis (H), and Freidman non-parametric repeated-measures (F) test for resolving differences in near-surface (< 6 cm) soil moisture between and among five different aspect classes on the stabilized dune. The *p*-values derived show the probability that the compared aspect classes exhibited similar surface soil moisture distributions (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates at the seasonal scale. n = 25, 48, 22, 5 and 9 on each measurement date for the north, south, east, west and flat aspect classes respectively.

	Aspects Compared - Stabilized Dune										
Date	Flat vs. North (W)	Flat vs. East (W)	Flat vs. South (W)	Flat vs. West (W)	North vs. East (W)	North vs. South (W)	North vs. West (W)	East vs. South (W)	East vs. West (W)	South vs. West (W)	All 5 Aspects (H)
Apr 9	0.007	0.025	0.555	0.894	0.159	0.001	0.037	0.059	0.061	0.605	0.002
Apr 22	0.013	0.408	0.232	0.440	0.001	0.000	0.046	0.739	0.943	0.823	0.000
May 11	0.258	0.215	0.372	0.641	0.006	0.007	0.616	0.575	0.057	0.065	0.008
June 10	0.274	0.003	0.622	0.549	0.159	0.043	0.290	0.000	0.034	0.773	0.000
June 24	0.109	0.483	0.608	0.841	0.001	0.000	0.221	0.414	0.242	0.420	0.001
June 29	0.598	0.528	0.140	0.947	0.881	0.026	1.000	0.031	0.755	0.171	0.000
July 6	0.015	0.663	0.189	0.182	0.000	0.000	0.141	0.331	0.134	0.015	0.000
July 28	0.049	0.296	0.498	0.083	0.163	0.001	0.597	0.021	0.134	0.028	0.000
Aug 5	0.053	0.862	0.678	0.947	0.004	0.000	0.126	0.397	0.950	0.543	0.001
Aug 18	0.033	0.931	0.477	0.841	0.001	0.000	0.266	0.343	0.553	0.394	0.000
Entire Season	0.000	0.360	0.352	0.576	0.000	0.000	0.024	0.009	0.930	0.128	0.000 (F)

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

Surface elevation change at the active dune was greatest in April, when average wind speeds where greater than at any other point during the study (> 5 m s^{-1}). However, an analysis of active dune surface change versus soil moisture did not show any distinguishable differences in surface soil moisture between accreting and deflating surfaces at any point during the study period ($p > 0.05$).

A.



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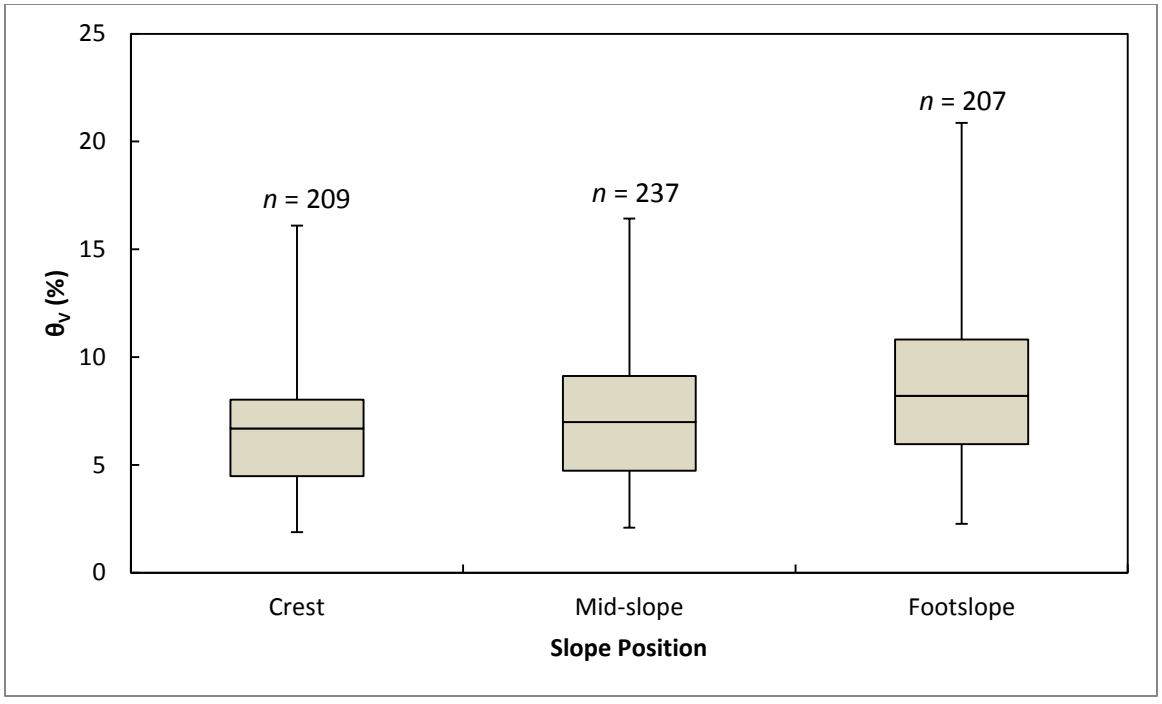

Figure 3.8. Statistical distribution of volumetric soil moisture (θ_V) measurements at different slope positions captured at the active (A) and stabilized (B) dunes over the entire field season. Maximum, minimum, median, and quartiles are displayed.

Table 3.8. *p*-values depicting the results of the Wilcoxon Rank Sum test (W), Kruskal-Wallis (H), and Freidman non-parametric repeated-measures (F) test for resolving differences in near-surface (< 6 cm) soil moisture between and among five different slope positions (crest, mid-slope, footslope) at the active and stabilized dune sites. The *p*-values derived show the probability that the compared slope position classes exhibited similar surface soil moisture distributions (H_0). A Dunn-Sidak modified significance value of 0.0025 was used to determine whether H_0 should be rejected at the 0.05 significance level for ten repeated measurement dates at the seasonal scale. n = 16 for all slope position classes on each measurement date at the active dune site. n = 21, 24 and 21 on each measurement date for the crest, mid-slope and footslope classes respectively at the stabilized dune site.

	Active Dune Slope Position Comparison				Stabilized Dune Slope Position Comparison			
Date	Crest vs. Footslope (W)	Crest vs. Mid-slope (W)	Mid-slope vs. Footslope (W)	All 3 Slope Positions (H)	Crest vs. Footslope (W)	Crest vs. Mid-slope (W)	Mid-slope vs. Footslope (W)	All 3 Slope Positions (H)
9 Apr	0.910	0.572	0.665	0.836	0.004	0.357	0.032	0.011
22 Apr	0.283	0.109	0.792	0.280	0.005	0.329	0.065	0.017
11 May	0.207	0.880	0.283	0.380	0.002	0.207	0.030	0.004
10 Jun	0.638	0.940	0.865	0.917	0.174	0.547	0.317	0.342
24 Jun	0.083	0.012	0.337	0.020	0.000	0.259	0.007	0.000
29 Jun	0.880	0.585	0.638	0.797	0.191	0.219	0.030	0.034
6 Jul	0.318	0.221	0.851	0.415	0.001	0.116	0.017	0.001
28 Jul	0.221	0.266	0.763	0.358	0.011	0.433	0.114	0.036
5 Aug	0.070	0.073	0.806	0.109	0.001	0.811	0.006	0.002
18 Aug	0.706	0.207	0.181	0.188	0.001	0.776	0.004	0.002
Entire Season	0.650	0.264	0.499	0.150 (F)	0.000	0.146	0.000	0.000 (F)

Note:
White cells indicate failure to reject H_0 at the 0.05 significance level
Grey cells indicate a rejection of H_0 at the 0.05 significance level

3.7 Discussion

The results of this study indicate that near-surface soil moisture was higher and more variable on a stabilized dune than on an active dune during a relatively wet growing season. For a given environment with active and stabilized dunes, the active dunes typically

experience higher wind speeds near the surface, greater fluctuation of ground surface temperature, higher surface evaporation, erosion and deposition of sand, as well as lower fine sediment and organic matter content (Lichter, 1998). By contrast, vegetation-covered dunes experience lower wind speed due to increased roughness, little to no erosion, lower ground surface temperature fluctuation, reduced evaporation, especially on north-facing and lee slopes, and increased soil moisture holding capacity due to increased organic matter content and deposition of finer sediment (Li, 2005; Zhao *et al.*, 2007).

Intra-site soil moisture variation resulting from dune topography influenced the spatiotemporal distribution of soil moisture less strongly than land cover type. Slope steepness did not have a strong impact on soil moisture distributions at either dune. At the stabilized dune, soil moisture was consistently higher at pins coinciding with shrub cover. Soils associated with shrubs had higher organic, silt, and clay content than those associated with grasses and bare sand. Enhanced soil moisture, shrub cover, and organic content were all measured on the north-facing slope of the stabilized dune. More pronounced differences in soil moisture distributions between north- and south-facing slopes were anticipated at the active dune owing to differences in insolation and its effect on evaporation; however, this did not materialize to the extent expected, presumably because aspect alone is not as significant without vegetation, or because there simply wasn't enough drying to establish aspect-related differences on the active dune during the 2010 growing season. Instead, stronger differences due to aspect were found on the stabilized dune, but this appears to be more closely related to different vegetation functional groups rather than aspect. It is possible that the higher proportion of shrubs on the north-facing slope of the stabilized dune is related to aspect, but a causal connection is difficult to resolve from the short measurement period. Strong differences in soil moisture at footslope positions at the

stabilized dune may either be associated with lateral soil moisture redistribution toward the footslopes or that plant roots may be accessing deeper soil moisture reserves from the adjacent inter-dune area (Caldwell *et al.*, 1998).

Surface accretion and deflation were not significant controls on the spatial distribution of near-surface soil moisture at the active dune site in this study. This was likely due to the high frequency of precipitation events during the field season, which limited sediment transport while frequently recharging near-surface soil moisture on both freshly accreted and eroded surfaces, thereby minimizing the potential for the detection of soil moisture differences. In addition, 78.6% of all measured accretion was less than 6 cm deep between measurement dates. Because the top 6 cm of the soil profile was measured during soil moisture sampling, most soil moisture measurements on accreting surfaces would comprise a mixture of recently deposited and previously extant sand, thus potentially reducing observed soil moisture differences between accreting and deflating surfaces during the study period.

As stated, record precipitation fell during the 2010 growing season, preventing an assessment of near-surface soil moisture dynamics under drought or dry spell conditions, when spatiotemporal differences are most likely to manifest under different land cover types and topographic positions (Mahmood & Hubbard, 2007). While daily precipitation varied between the two sites by up to 28 mm, no significant bias in daily precipitation volumes was observed over longer monthly or seasonal timescales, suggesting that rainfall played a negligible role in creating inter-site differences in near-surface soil moisture at the seasonal scale. Therefore, while spatially variable precipitation could influence soil moisture measurements at individual measurement intervals, these differences were likely negated at

the seasonal time scale, making other factors such as vegetation, pedogenic modifications and topographic effects the most likely sources of both inter and intra-site variability.

The presence of vegetation at the stabilized dune promotes the fining of dune sediments through the settling of fine wind-borne sediment particles (Muhs & Wolfe, 1999). Increased silt, clay, and organic matter content were all detected at the stabilized dune site, which collectively increase the available water holding capacity of those soils (Feustal & Byers, 1936; Li, 2005; Zhao *et al.*, 2007). In addition, vegetation shades the sediment surface and reduces wind velocity near the soil surface, thereby reducing evaporation from the soil surface (de Castro Teixeira *et al.*, 2008). Because the soil composition at the two dunes is significantly different, higher near-surface soil moisture content is expected at the stabilized sites under similar weather conditions, despite the negative effect of plant water-use on soil moisture availability that is commonly observed in non-dune environments (James *et al.*, 2003). These results are similar to those of Shay *et al.* (2000), which demonstrated higher soil moisture in the upper 5 cm at stabilized dunes compared to active dunes.

The heterogeneous distribution of different vegetation types across different aspects of the stabilized dune has likely enhanced soil moisture variability. Shrubs occupied north- (53%), east- (23%) and south- (20%) facing slopes, with shrub cover on the south-facing slope concentrated near the footslope. While organic matter, clay, and silt content were higher across the stabilized dune than the active dune regardless of vegetation type, measured organic matter was 100-200% greater on average beneath shrub cover. Distinct seasonal transpiration patterns have been observed beneath shrubs and grasses (Schlesinger *et al.*, 1990; Pockman & Small, 2010). Plant water extraction tends to be more gradual for shrub-dominated sites than grassed sites, because the latter exhibit more profligate water use

during periods when soil moisture is available (Kurc & Small, 2007; Letts *et al.*, 2010). Furthermore, grasses tend to have shallower rooting networks that extract water more rapidly from the uppermost soil horizons, whereas woody species use water over a greater range of depths (Sala *et al.*, 1989; McLaren *et al.*, 2004). High rates of water-use during periods of moisture availability, combined with higher insolation and lower roughness may explain the tendency for more rapid near-surface moisture depletion at sites with grass-dominated rather than shrub-dominated vegetation. The net effect of this process is enhanced spatiotemporal soil moisture variability at the stabilized dune, due to the effect of heterogeneous vegetation functional groups on near-surface soil water extraction and evaporation.

Higher soil moisture variability is often observed under dry conditions (Qiu *et al.* 2001; Mahmood & Hubbard, 2007). By contrast, soil moisture variability was lowest on the driest measurement date in the Bigstick Sandhills in 2010. We also found that slope steepness was not a significant control on soil moisture distribution, whereas previous studies have demonstrated a slope effect (Sulebak *et al.*, 2000; Qiu *et al.*, 2001). Runoff is typically enhanced at steeper slope angles, resulting in lower rates of soil moisture recharge (Dalrymple *et al.*, 1968; Sulebak *et al.*, 2000). Thus, we interpret that dune stabilization in the southern Canadian Prairies has increased near-surface soil moisture relative to active dunes. The stabilizing vegetation creates a feedback effect by altering the near surface soil texture and organic content, which, in turn, enhances shallow soil moisture. Even at pin locations with the steepest slope angles, infiltration rates were sufficiently high to prevent runoff, thereby minimizing the effect of slope angle on soil moisture variability.

The presence of vegetation has enhanced both the availability and variability of soil moisture resources at the stabilized dune relative to those observed at the active dune. As

Canadian Prairie sandhill regions progressively become more stabilized by vegetation, near-surface soil moisture resources should also increase as vegetation modifies soil conditions through the addition of fine soil particles and organic matter, enhancing moisture storage capacity (Jenny, 1961; Miller *et al.*, 1985). At a landscape scale, enhanced availability of near-surface soil moisture can enhance both vegetation growth and seedling establishment potential (Maun, 1994; Moran *et al.*, 2010). Other Canadian sandhill studies (Shay *et al.*, 2000) have also measured higher soil moisture near the surface of stabilized dunes than active dunes, suggesting that higher near-surface soil moisture associated with stabilized dunes is not uncommon in Canadian Prairie sandhill ecosystems. While topography did play a significant role in modifying soil moisture conditions at the stabilized dune, vegetation played a more significant role overall in modifying near-surface soil moisture conditions at both individual measurement intervals and over the entire field season.

Near-surface soil moisture availability has been enhanced by the presence of vegetation and allied soil-genesis processes. However, deeper soil moisture recharge was discovered to be negatively impacted by dune stabilization, as seen in Chapter 2. The establishment of vegetation in the Bigstick Sandhills has modified the soil moisture dynamics of this ecosystem. While the establishment of vegetation has led to enhanced near-surface soil moisture conditions through soil genesis, soil moisture recharge deeper within the stabilized dune soil profile has been negatively impacted. Through understanding how soil moisture dynamics have changed as vegetation has expanded in sandhill ecosystems, we may better manage those resources, thereby preserving the hydrological utility these regions well into the future.

3.8 Conclusion

The results of this field study confirm the hypothesis that the establishment of vegetation in Canadian Prairie sandhill ecosystems has significantly modified near-surface soil moisture dynamics during the transition from bare, active dunes to stabilized dune ecosystems. Lower and less variable soil moisture was measured across the active dune surface as compared to the stabilized dune. Enhanced soil moisture variability at the stabilized dune can be attributed to the spatial variability of vegetation types, relative slope position, and dune slope aspect. At the active dune, slope aspect was the only topographic control that influenced soil moisture distributions, but only on north-facing aspects. Active dune surface accretion and deflation did not significantly influence soil moisture distributions across the active dune surface on a seasonal scale. Slope angle affected spatial soil moisture distributions at neither the active nor stabilized dune, presumably because of the high infiltration rate and low potential for runoff on either dune surface. Overall, these results indicate that dune stabilization and the allied process of soil genesis have increased soil moisture availability in near-surface soil layers, thereby enhancing the conditions for vegetation establishment and growth within these ecosystems. As this period of stabilization progresses, continuing soil development may further enhance near-surface soil moisture conditions at stabilized dunes.

While the results of this chapter suggest that near-surface soil moisture availability is improved through dune stabilization and soil genesis, the results of Chapter 2 indicate that dune stabilization has negatively impacted deeper profile soil moisture recharge at the stabilized dune. While near-surface soil moisture is higher across vegetation-stabilized dunes, deeper profile soil moisture recharge is reduced by the presence of vegetation. The broader

implication of these findings is that anthropogenic water use must be considered in light of the historical landscape changes that have occurred, and how these changes have affected soil moisture resources within sandhill ecosystems.

CHAPTER 4: CONCLUSIONS AND FUTURE DIRECTIONS

4.1 Summary of conclusions and contributions

Soil moisture provides an important physical link between vegetation, topography, soil, and climate. However, because the controls on soil moisture dynamics are not consistent between different ecosystems, it is necessary to study soil moisture dynamics in individual ecosystems. This study looked at soil moisture dynamics in a sandhill ecosystem that has undergone recent vegetation stabilization, transforming the region from a once desert-like dune landscape, to the relatively verdant, ecologically diverse ecosystem that exists today. Specifically, this thesis used an ergodic (space-for-time) approach to examine how the establishment of vegetation in the study area has modified both near-surface and deeper profile soil moisture dynamics relative to soil moisture dynamics observed at active dunes, which represent the former condition of the landscape. The key conclusions of this study can be summarized as follows:

(1) Dune stabilization reduces infiltration and soil moisture storage within the soil profile (see Chapter 2). Soil genesis associated with sand dune stabilization results in higher silt, clay and organic matter content. In the Bigstick Sandhills, this caused lower infiltration rates at the stabilized dune, relative to the active dune. In the upper 200 cm of the soil profile, soil moisture content was higher and less variable at the active dune than at the stabilized dune, with the exception of the 25 cm measurement depth. Deeper measurements (500 cm) show that soil moisture was significantly lower beneath stabilized dunes, although soil moisture infiltrating from the surface reached 500 cm depth at one stabilized dune by

October, presumably because rodent burrows enhanced macroporosity. A broader study implication is that the progressive stabilization of this sandhill landscape may have reduced groundwater recharge. This could impact the various stakeholders reliant on shallow groundwater resources in this area. As the last active dunes stabilize and soil genesis progresses, the continuing reduction in profile soil moisture recharge may necessitate greater regulation of water resource consumption in sandhills with comparable climate and vegetation characteristics.

(2) Dune stabilization enhances near-surface (< 6 cm) soil moisture storage and soil moisture variability (see Chapter 3). Near-surface soil moisture content was significantly higher at the stabilized dune than at the active dune. At the stabilized dune, soil moisture content was higher beneath shrubs than grasses. Higher near-surface soil moisture content was highly correlated with increasing organic matter, silt, and clay content resulting from soil genesis at the stabilized dune. Topography played a lesser role in modifying the spatial distribution of soil moisture at the sites. Downslope angle did not have a statistically significant impact on soil moisture, whereas aspect produced significant differences only between the moister north-facing aspect and the rest of the stabilized dune. The broader implications of this study are that enhanced near-surface soil moisture availability at stabilized dunes improves conditions for vegetation establishment and growth, reducing the likelihood of dune reactivation as vegetation-associated soil genesis develops soil moisture storage potential through the addition of silt, clay, and organic matter to the near-surface soil profile.

The establishment of vegetation across more than 99% of the study area has modified soil moisture dynamics. Near the dune surface, higher and more variable soil moisture resources are present at the stabilized dune than at the active dune. However, below 25 cm depth, soil moisture resources were lower and more variable beneath stabilized dunes than active dunes. While soil genesis has enhanced the soil moisture storage capacity near the surface, it has also reduced the ability of soil moisture to infiltrate deeper within the soil profile toward the groundwater table. The presence of transpiring vegetation has also created a draw on soil moisture resources to depths below 200 cm, depleting profile moisture resources more quickly after recharge events at stabilized dunes than active dunes. While the presence of vegetation enhances soil moisture availability near the dune surface, vegetation growth also detrimentally affects deeper profile and possibly groundwater recharge.

There are positive ecological and anthropogenic implications for increased near-surface soil moisture following vegetation establishment. Soil moisture storage capacity is enhanced by soil genesis, thereby improving conditions for the establishment and maintenance of vegetation growth across stabilized dune surfaces. Plant growth within the sandhills is critically important for the ranching industry, making improved soil conditions following vegetation establishment desirable. However, as the last few remaining active dunes become stabilized by vegetation, species reliant on dune activity could become extirpated from this ecosystem.

Natural and anthropogenic water users that rely on deeper sources of soil moisture and groundwater may be negatively impacted by progressive vegetation stabilization and soil genesis. The reduction of infiltration rates and deep profile recharge events, coupled with the

draw transpiring vegetation puts on soil moisture resources have combined to reduce and occasionally prevent soil moisture recharge at greater depths within the soil profile. A further reduction in deeper soil moisture recharge as the last active dunes stabilize and soil genesis progresses could have further negative impacts on deep profile soil moisture infiltration and storage within sandhill regions than those observed in this study. In addition, past (and potentially future) reductions in deep profile soil moisture recharge resulting from continuing dune stabilization and allied processes have likely reduced groundwater recharge in sandhill ecosystems. In these regions, groundwater is utilized by deep-rooting vegetative species in interdune locations and is also utilized by the ranching and petrochemical industries. If soil moisture depletion exceeds soil moisture recharge either now or at some point in the future, water resources in these ecosystems may become depleted, necessitating greater regulation of anthropogenic water use in these regions.

4.2 Future research directions

This study investigated soil moisture beneath active and stabilized dunes, encompassing the two end-members of the dune stabilization continuum. Dune vegetation cover within this ecosystem encompasses a range from barren, to initial colonizers, to grassland, to shrubs, up to fully treed sites at interdune locations. Interdune regions exhibit different vegetation cover types from those associated with dunes, and could potentially exhibit different soil moisture dynamics than those observed in this study. In addition, vegetation access to groundwater resources could be enhanced at the topographically lower interdune positions, increasing the potential for the hydraulic redistribution of soil moisture by plant roots within the soil profile. At sites where the groundwater table is at a shallower

depth, precipitation may better infiltrate and reach the groundwater table, enabling groundwater recharge at some interdune sites when groundwater recharge is not possible through stabilized dune crests. Studies examining profile and near-surface soil moisture dynamics at interdune locations and beneath landcover types not examined in this study would complement this research, enabling a more complete assessment of soil moisture dynamics within the study area.

Plant water-use data were not collected as part of this study. Individual plant species are likely to use soil moisture at different rates and at different times of the year. Differential transpiration rates among species could explain some of the enhanced soil moisture variation observed across the surface of the stabilized dune in Chapter 3. Further studies could help determine the moisture utilization characteristics of individual plant species, enabling analyses of soil moisture usage beneath all sandhill land cover classes.

Precipitation during this study was anomalously high. Ideally, the precipitation regime during the study period would have been more representative of climate normals. Soil moisture infiltration was likely much higher than would have been observed under average precipitation conditions. More importantly, it was not possible to observe soil moisture during prolonged rain-free periods, which are common in dryland regions. Additional soil moisture measurements conducted during a drought or dry spell would add to our understanding of soil moisture dynamics when soil moisture input is lower.

In this study, it was assumed that soil moisture infiltrated and flowed vertically within the soil profile, with limited horizontal soil moisture redistribution. The soil moisture profile study sites used in Chapter 2 were selected at topographically-prominent high-points, to prevent confounding influences on soil moisture, such as lateral flow, groundwater intrusion

and capillary rise. However, it is possible for soil moisture to be redistributed laterally at the profile sites, especially if a flow impediment such as a buried soil were present. Ideally, tensiometers would have been deployed to estimate lateral soil moisture movement potential. However, the deployment of tensiometers was beyond the scope of this study.

Lastly, continuous profile soil moisture monitoring was limited to one active site and one stabilized site for this study. Ideally, other monitoring locations could have been located at different dune locations and possibly beneath different landcover types at interdune locations. While extending the continuous soil moisture monitoring program to other sites of interest would be informative, those benefits would have to be weighed off against the costs of developing a more intensive monitoring program.

4.3 Concluding remarks

Throughout the time I have spent designing, implementing, analyzing, and writing up my research I have been asked "why are you studying soil moisture in a small remnant ecosystem," and "what do you hope to add to the body of scientific knowledge through your study." To answer these questions, I will begin by saying that the Great Sand Hills of Saskatchewan (of which the Bigstick Sand Hills are an extension) comprise by far the largest contiguous undisturbed tract of prairie grassland in Saskatchewan (Epp & Townley-Smith, 1980). Far from being a small, remnant ecosystem, the ecological diversity of the study area provides habitat for rare, dune-dwelling species (*Dipodomys ordii*), endangered avian species (*Falco peregrines*), and large mammals (*Odocoileus hemionus*, *Antilocapra americana*). Because of minimal human interference in these landscapes, sandhill regions have become important for the preservation of biological diversity on the Canadian Prairies. The study of soil moisture

in sandhill regions adds to our understanding of how the availability of soil moisture, one of the primary limiting factors for life in these former dune landscapes, varies at both seasonal and longer time scales as these landscapes become stabilized by vegetation.

My research began with the hypothesis that the active (bare) dunes would have higher profile soil moisture content than the stabilized dunes because the presence of vegetation on the latter reduces infiltration and removes soil moisture through evapotranspiration. While the occurrence of depleted soil moisture below vegetation stabilized sandhills has been observed in other studies, this study has looked deeper within the soil profile than other comparable studies (500 cm) and observed a lack of soil moisture recharge below 300 cm at one stabilized dune and a large reduction of soil moisture recharge at the other. That these observations were made during one of the wettest recorded growing seasons adds strength to the hypothesis that vegetation significantly reduces soil moisture recharge in sandhill ecosystems. While the combination of dune stabilization and soil genesis have combined to enhance near-surface soil moisture conditions on stabilized dunes, these factors have also reduced soil moisture recharge at greater depth. Even as enhanced near-surface soil moisture conditions improve conditions for seedling establishment, vegetative growth, and dune stability, it comes with the trade-off of lower soil moisture and, possibly, groundwater recharge.

Understanding the consequences of changes to the spatiotemporal distribution of soil moisture in sandhill ecosystems is of great importance. This is especially true given that anthropogenic utilization has been increasing, potentially straining sandhill groundwater resources. Understanding how sandhill soil moisture dynamics have changed since the onset

of vegetation stabilization will help us better manage water resources and enhance ecosystem sustainability within Canadian Prairie sandhill ecosystems.

REFERENCES

Allison, G.B., Stone, W.J., Hughes, M.W. (1985). Recharge in Karst and Dune Elements of a Semi-arid Landscape as indicated by Natural Isotopes and Chloride. *Journal of Hydrology*, 76, 1-25.

ASTM D422-63. (2011). Standard Test Method for Particle-Size Analysis of Soils. Retrieved June 14th, 2011 from: http://www.astm.org/Standards/D422.htm

ASTM D2216-10. (2011). Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. Retrieved June 20th, 2011 from http://www.astm.org/Standards/D2216.htm

ASTM F1647-11. (2011). Standard Test Methods for Organic Matter Content of Athletic Field Rootzone Mixes. Retrieved June 14th, 2011 from: http://www.astm.org/Standards/F1647.htm

Aston, A.R. (1978). Rainfall Interception by Eight Small Trees. *Journal of Hydrology*, 42, 383-396.

Bagnold, R.A. (1941). The physics of blown sand and desert dunes. Methuen and Co. Ltd., London.

Baldwin, K.A. & M.A. Maun (1983). Microenvironment of Lake Huron sand dunes. *Canadian Journal of Botany*, 61, 241-255.

Barnes, P.W. & T.A. Harrison. (1982). Species Distribution and Community Organization in a Nebraska Sandhills Mixed Prairie as Influenced by Plant/Soil-Water Relationships. *Oecologia*, 52, 192-201.

Bennie, J., Huntley, B., Wiltshire, A., Hill, M.O., Baxter, R. (2008). Slope, aspect and climate: Spatially explicit and implicit models of topographic microclimate in chalk grassland. *Ecological Modeling*, 216, 47-59.

Berger, D.L. (1992). Ground-Water Recharge through Active Sand Dunes in Northwestern Nevada. *Water Resources Bulletin*, 28, 959-965.

Berndtsson, R., Nodomi, K., Yasuda, H., Persson, T., Chen, H., Jinno, K. (1996). Soil water and temperature patterns in an arid desert dune sand. *Journal of Hydrology*, 185, 221-240.

Böhm, W. (1977). Development of soybean root systems as affected by plant spacing. *Z. Acker-Pflanzenbau*, 144, 103-112.

Böhm, W. & U. Kopke. (1977). Competitive root investigations with two profile wall methods. *Z. Acker-Pflanzenbau*, 144, 297-303.

Bouma, J. (1977). Soil survey and the study of water in the unsaturated soil. Soil Survey Paper 13, Netherlands Soil Survey Institute, Wageningen.

Bouyoucos, G.J. (1962). Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal,* 54, 464-465.

Bowers, J.E. (1982). The plant ecology of inland dunes in western North America. *Journal of Arid Environments*, 5, 199-220.

Bridge, J.S. & J.L. Best (1988). Flow, sediment transport and bedform dynamics over the transition from dunes to upper-stage plane beds: implications for the formation of planar laminae. S*edimentology*, 35, 753-763.

Caldwell, M.M., Dawson, T.E., Richards, J.H. (1998). Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia*, 113, 151-161.

Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D. (1996). Maximum rooting depth of vegetation types at the global scale. *Oecologia*, 108, 583-595.

Canton, Y., Sole-Benet, A., Domingo, F. (2004). Temporal and spatial patterns of soil moisture in semi-arid badlands of SE Spain. *Journal of Hydrology*, 285, 199-214.

Chadwick, H.W. & P.D. Dalke. (1965). Plant succession on dune sands in Fremont County, Idaho. *Ecology*, 46, 765-785.

Chen, X. & X. Chen. (2004). Simulating the effects of reduced precipitation on ground water and streamflow in the Nebraska sand hills. *Journal of the American Water Resources Association*, 40, 419-430.

Chen, X., Chen, X., Rowe, C., Hu, Q., Anderson, M. (2003). Geological and Climactic Controls on Streamflows in the Nebraska Sand Hills. *Journal of the American Water Resources Association*, 39, 217-228.

Dalrymple, J.B., Blong, R.J., Conacher, A.J. (1968). A hypothetical nine unit landsurface model. *Z. Geomorphol.*, 12, 60-76.

Danin, A. (1991). Plant adaptations in desert dunes. *Journal of Arid Environments*, 21, 193-212.

David, P.P., Wolfe, S.A., Huntley, D.J., Lemmen, D.S. (1999). Activity cycle of parabolic dunes based on morphology and chronology from Seward sand hills, Saskatchewan. *GSC Bulletin*, 534, 223-238.

Davis, R.O.E. & H.H. Bennett. (1927). Grouping of soils on the basis of mechanical analysis. *United States Department of Agriculture Departmental Circulation*, 419.

de Castro Teixeira, A.H., Bastiaanssen, W.G.M., Ahmad, M.D., Moura, M.S.B., Bos, M.G. (2008). Analysis of energy fluxes and vegetation-atmosphere parameters in irrigated and natural ecosystems of semi-arid Brazil. *Journal of Hydrology*, 362, 110-127.

de Rosnay, P., Gruhier, C., Timouk, F., Baup, F., Mougin, E., Hiernaux, P., Kergoat, L., LeDantec, V. (2009). Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali. *Journal of Hydrology*, 375, 241-252.

Dincer, T., Al-Mugrin, A., Zimmermann, U. (1974). Study of the infiltration and recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium. *Journal of Hydrology*, 23, 79-109.

Douville, H. (2004). Relevance of soil moisture for seasonal atmospheric predictions: is it an initial value problem? *Climate Dynamics*, 22, 429–446.

Duan, Z., Xiao, H., Li, X., Dong, Z., Wang, G. (2004). Evolution of soil properties on stabilized sands in the Tengger Desert, China. *Geomorphology*, 59, 237-246.

Dunkerley, D. (2002). Systematic variation of soil infiltration rates within and between the components of the vegetation mosaic in an Australian desert landscape. *Hydrological Processes*, 16, 119–131.

Ensign, K.L., Webb, E.A., Longstaffe, F.J. (2006). Microenvironmental and seasonal variations in soil water content of the unsaturated zone of a sand dune system at Pinery Provincial Park, Ontario, Canada. *Geoderma*, 136, 788–802.

Environment Canada, 2011. Climate Normals and Averages 1971-2000 – Maple Creek, Saskatchewan. Retrieved January 15th, 2011 from: www.climate.weatheroffice.ec.gc.ca/climate_normals.

Epp, H.T. & L. Townley-Smith (1980). The Great Sand Hills of Saskatchewan. Report prepared for the Saskatchewan Department of the Environment.

Fearnehough, W., Fullen, M.A., Mitchell, D.J., Trueman, I.C., Zhang, J. (1998). Aeolian deposition and its effect on soil and vegetation changes on stabilised desert dunes in northern China. *Geomorphology*, 23, 171-182.

Feustal, I.C. & H.G.Byers. (1936). The comparative moisture-absorbing and moisture-retaining capacities of peat and soil mixtures. *USDA Technical Bulletin*, 532.

Gardner, R. & S. McLaren (1999). Infiltration and Moisture Movement in Coastal Sand Dunes, Studland, Dorset, U.K.: Preliminary Results. *Journal of Coastal Research*, 15, 936-949.

Gibbens, R.P. & J.M. Lenz (2001). Root systems of some Chihuahuan Desert plants. *Journal of Arid Environments*, 49, 221-263.

Gosselin, D.C., Drda, S., Harvey, F.E., Goeke, J. (1999). Hydrologic Setting of Two Interdunal Valleys in the Central Sand Hills of Nebraska. *Ground Water* , 37, 924-933.

Gupta, J.P. (1979). Some Observations on the Periodic Variations of Moisture in Stabilised and Unstabilised Sand Dunes of the Indian Desert. *Journal of Hydrology*, 41, 153-156.

Harvey, F.E., Swinehart, J.B., Kurtz, T.M. (2007). Ground Water Sustenance of Nebraska's Unique Sand Hills Peatland Fen Ecosystems. *Ground Water*, 45, 218-234.

Hennessy, J.T., Gibbens, R.P., Tromble, J.M., Cardenas, M. (1985). Mesquite (*Prosopis glandulosa* Torr.) dunes and interdunes in southern New Mexico: a study of soil properties and soil water relations. *Journal of Arid Environments*, 9, 27-38.

HilleRisLambers, R., Rietkerk, M., van den Bosch, F., Prins, H.H.T., de Kroon, H. (2001). Vegetation Pattern Formation in Semi-Arid Grazing Systems. *Ecology*, 82, 50-61.

Holland, P.G. & D.G. Steyn (1975). Vegetational Responses to Latitudinal Variations in Slope Angle and Aspect. *Journal of Biogeography*, 2, 179-183.

Hubbard, K.G., You, J., Sridhar, V., Hunt, E., Korner, S., Roebke, G. (2009). Near-surface soil-water monitoring for water resources in management on a wide-area basis in the Great Plains. *Great Plains Research*, 19, 45-54.

Hugenholtz, C.H. & S.A. Wolfe. (2005). Recent stabilization of active sand dunes on the Canadian Prairies and relation to recent climate variations. *Geomorphology*, 68, 131-147.

Hugenholtz, C.H., Wolfe, S.A., Bender, D. (2010). Declining sand dune activity in the southern Canadian prairies: historical context, controls and ecosystem implications. *Aeolian Research*, 2, 71-82.

Hugenholtz, C.H., Wolfe, S.A., Moorman, B.J. (2008). Effects of local sediment supply on the morphodynamics and stratigraphy of active parabolic dunes, Saskatchewan, Canada. *Canadian Journal of Earth Sciences*, 48, 1-15.

Hugenholtz, C.H., Wolfe, S.A., Moorman, B.J. (2007). Sand-water flows on cold-climate eolian dunes: environmental analogs for the eolian rock record and Martian sand dunes. *Journal of Sedimentary Research*, 77, 1-8.

Hulett, G.K., Coupland, R.T., Dix, R.L. (1966). The vegetation of dune sand areas within the grassland region of Saskatchewan. *Canadian Journal of Botany,* 44, 1307-1331.

James, S.E., Partel, M., Wilson, S.D., Peltzer, D.A. (2003). Temporal heterogeneity of soil moisture in grassland and forest. *Journal of Ecology*, 91, 234–239.

Jenny, H. (1941). *Factors of Soil Formation: A System of Quantitative Pedology*. Dover Publications Inc., New York.

Kim, Y. & G. Wang. (2007). Impact of Initial Soil Moisture Anomalies on Subsequent Precipitation over North America in the Coupled Land–Atmosphere Model CAM3–CLM3. *Journal of Hydrometoerology*, 8, 513-533.

Knapp, A.K., Beier, C., Briske, D.D., Classen, A.T., Luo, Y., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E., Fay, P.A., Heisler, J.L., Leavitt, S.W., Sherry, R., Smith, B., Weng, E. (2008). Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems. *BioScience*, 58, 811-821.

Kozak, J.A. & L.R. Ahuja. (2005). Scaling of Infiltration and Redistribution of Water across Soil Textural Classes. *Soil Science Society of America Journal*, 69, 816–827.

Kramer, P.J. (1944). Soil Moisture in Relation to Plant Growth. *Botanical Review,* 10, 525-559.

Kurc, S.A. & E.E. Small. (2007). Soil moisture variations and ecosystem-scale fluxes of water and carbon in semi-arid grassland and shrubland. *Water Resources Research*, 43, W06416.

Kustas, W.P., Prueger, J.H., Hatfield, J.L., Ramalingam, K., Hipps, L.E. (2000). Variability in soil heat flux from a mesquite dune site. *Agricultural and Forest Meteorology*, 103, 249-264.

Laity, J. (2003). Aeolian destabilization along the Mojave River, Mojave Desert, California: linkages among fluvial, groundwater, and aeolian systems. Physical Geography, 24, 196-221.

Lawrence, D.M., Thornton, P.E., Oleson, K.W., Bonan, G.B. (2007). The Partitioning of Evapotranspiration into Transpiration, Soil Evaporation, and Canopy Evaporation in a GCM: Impacts on Land–Atmosphere Interaction. *Journal of Hydrometeorology*, 8, 862-880.

Letts, M.G., Johnson, D.R.E., Coburn, C.A. (2010). Drought stress ecophysiology of shrub and grass functional groups on opposing slope aspects of a temperate grassland valley. *Botany*, 88, 850-866.

Li, X.R. (2005). Influence of variation of soil spatial heterogeneity on vegetation restoration. *Science in China Series D – Earth Sciences*, 48, 2020-2031

Li, X.R., Kong, D.S., Tan, H.J., Wang, X.P. (2007). Changes in soil and vegetation following stabilisation of dunes in the southeastern fringe of the Tengger Desert, China. *Plant Soil*, 300, 221-231.

Li., X.R., Ma, F.Y., Xiao, H.L., Wang, X.P., Kim, K.C. (2004A). Long-term effects of revegetation on soil water content of sand dunes in arid region of Northern China. *Journal of Arid Environments*, 57, 1-16.

Li, X.R., Xiao, H.L., Zhang, J.G., Wang, X.P. (2004B). Long-Term Ecosystem Effects of Sand-Binding Vegetation in the Tengger Desert, Northern China. *Restoration Ecology*, 12, 376-390.

Lichter, J. (1998). Primary succession and forest development on coastal Lake Michigan sand dunes. *Ecological Monographs*, 68, 487-510.

Loope, D.B., Swinehart, J.B., Mason, J.P. (1995). Dune-dammed palaeovalleys of the Nebraska Sand Hills: intrinsic versus climatic controls on the accumulation of lake and marsh sediments. *Geological Society of America Bulletin*, 107, 396-406.

Maestre, F.T., Cortina, J., Bautista, S., Bellot, J., Vallejo, R. (2003). Small-Scale Environmental Heterogeneity and Spatiotemporal Dynamics of Seedling Establishment in a Semiarid Degraded Ecosystem. *Ecosystems*, 6, 630-643.

Mahmood, R. & K.G. Hubbard. (2007). Relationship between soil moisture of near surface and multiple depths of the root zone under heterogeneous land uses and varying hydroclimatic conditions. *Hydrological Processes*, 21, 3449–3462.

Mamedov, A.I., Levy, G.J., Shainberg, I., Letey, J. (2001). Wetting rate, sodicity, and soil texture effects on infiltration rate and runoff. *Austrailian Journal of Soil Research*, 39, 1293-1305.

Mangan, J.M., Overpeck, J.T., Webb, R.S., Wessman, C., Goetz, A.F.H. (2004). Response of Nebraska Sand Hills Natural Vegetation to Drought, Fire, Grazing, and Plant Functional Type Shifts as Simulated by the Century Model. *Climatic Change*, 63, 49–90.

Mason, J.A., Swinehart, J.B., Goble, R.J., Loope, D.B. (2004). Late-Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, USA. *The Holocene*, 14, 209–217.

Maun, M.A. (1994). Adaptations enhancing survival and establishment of seedlings on coastal dune systems. *Vegetatio*, 111, 59-70.

McGinn, S.M. (2010). Weather and Climate Patterns in Canada's Prairie Grasslands. Biological Survey of Canada, In *Arthropods of Canadian Grasslands: (Volume 1): Ecology and Interactions in Grassland Habitats.* 105-119.

McLaren, J.R., Wilson, S.D., Peltzer, D.A. (2004). Plant feedbacks increase the temporal heterogeneity of soil moisture. *Oikos*, 107, 199–205.

Mickovski, S.B. & L.P.H. van Beek. (2009). Root morphology and effects on soil reinforcement and slope stability of young vetiver (*Vetiveria zizanioides*) plants grown in semi-arid climate. *Plant Soil*, 324, 43-56.

Miller, J.J., Acton, D.F., St. Arnaud, R.J. (1985). The effect of groundwater on soil formation in a morainal landscape in Saskatchewan. *Canadian Journal of Soil Science*, 65, 293-307.

Miller, P.C., Poole, D.K., Miller, P.M. (1983). The Influence of Annual Precipitation, Topography, and Vegetative Cover on Soil Moisture and Summer Drought in Southern California. *Oecologia*, 56, 385-391.

Moran, M.S., Hamerlynck, E.P., Scott, R.L., Stone, J.J., Holifield Collins, C.D., Keefer, T.O., Bryant, R., DeYoung, L. Nearing, G.S., Sugg, Z., Hymer, D.C. (2010). Hydrologic response to precipitation pulses under and between shrubs in the Chihuahuan Desert, Arizona. *Water Resources Research*, 46, W10509.

Muhs, D.R. & S.A. Wolfe. (1999). Sand Dunes of the northern Great Plains of Canada and the United States. *GSC Bulletin,* 534, 183-197.

Neave, M. & A.D. Abrahams. (2002). Vegetation Influences on Water Yields from Grassland and Shrubland Ecosystems in the Chihuahuan Desert. *Earth Surface Processes and Landforms*, 27, 1011–1020.

Nimlos, T.J., Van Meter, W.P., Daniels, L.A. (1968). Rooting patterns of forest understory species as determined by radioiodine absorption. *Ecology*, 49, 1146-1151.

Orradottir, B., Archer, S.R., Arnalds, O., Wilding, L.P., Thurow, T.L. (2008). Infiltration in Icelandic Andisols: the Role of Vegetation and Soil Frost. *Arctic, Antarctic, and Alpine Research*, 40, 412–421.

Pan, Y.X. & X.P. Wang. (2009). Factors controlling the spatial variability of surface soil moisture within revegetated-stabilized desert ecosystems of the Tengger Desert, Northern China. *Hydrological Processes*, 23, 1591–1601.

Pavlik, B.M. (1980). Patterns of Water Potential and Photosynthesis of Desert Sand Dune Plants, Eureka Valley, California. *Oecologia*, 46, 147-154.

Pentland, R.S., Abrahamson, B.T., Wiens. L.H. (2011). Maple Creek (Bigstick Lake) Watershed June, 2010 Flood. Report prepared by Water Resource Consultants Inc.

Pockman, W.T. & E.E. Small (2010). The Influence of Spatial Patterns of Soil Moisture on the Grass and Shrub Responses to a Summer Rainstorm in a Chihuahuan Desert Ecotone. *Ecosystems*, 13, 511-525.

Pye, K. & H. Tsoar (2009). Aeolian Sands and Sand Dunes. Springer-Verlag, Berlin Heidelburg.

Qiu, Y., Fu, B., Wang, J., Chen, L. (2001). Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. *Journal of Hydrology,* 240, 243–263.

Reynolds, J.F., Smith, M.S., Lambin, E.F., Turner, B.L. II, Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B. (2007). Global Desertification: Building a Science for Dryland Development. *Science*, 316, 847-851.

Ritsema, C.J. & L.W. Dekker. (1994). Soil moisture and dry bulk density patterns in bare dune sands. *Journal of Hydrology*, 154, 107-131.

Rosenthal, D.M., Ludwig, F., Donovan, L.A. (2005). Plant Responses to an edaphic gradient across an active sand dune/desert boundary in the Great Basin desert. *International Journal of Plant Science*, 166, 247–255.

Rummel, B. & P. Felix-Henningsen. (2004). Soil water balance of an arid linear sand dune. *International Agrophysics*, 18, 333-337.

Rumpel, C., Kögel-Knabner, I., Bruhn, F. (2002). Vertical distribution, age, and chemical composition of organic carbon in two forest soils of different pedogenesis. *Organic Geochemistry*, 33, 1131-1142.

Sala, O.E., Golluscio, R.A., Lauenroth, W.K., Soriano, A. (1989). Resource partitioning between shrubs and grasses in the Patagonian steppe. *Oecologia*, 81, 501–505.

Salve, R. & B. Allen-Diaz. (2001). Variations in Soil Moisture Content in a Rangeland Catchment. *Journal of Range Management*, 54, 44-51.

Schlesinger, W.H., Fonteyn, P.J., Marion, G.M. (1987). Soil moisture content and plant transpiration in the Chihuahuan Desert of New Mexico. *Journal of Arid Environments*, 12, 119-126.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., Whitford, W.G. (1990). Biological Feedbacks in Global Desertification. *Science*, 247, 1043-1048.

Schmutz, P.P. (2007). Investigation of the Utility of Delta-T Theta Probe for Obtaining Surficial Moisture Measurements on Beaches. M.Sc. Thesis: Louisiana State University, Baton Rouge, Louisiana, United States of America.

Schneider, G.W., Childers, N.F. (1941). Influence of Soil Moisture on Photosynthesis, Respiration, and Transpiration of Apple Leaves. *Plant Physiology*, 16, 565-583.

Schneider, K., Huisman, J.A., Breuer, L., Frede, H.G. (2008). Ambiguous effects of grazing intensity on surface soil moisture: A geostatistical case study from a steppe environment in Inner Mongolia, PR China. *Journal of Arid Environments*, 72, 1305-1319.

Shay, J.M., Herring, M., Dyck, B.S. (2000). Dune Colonization in the Bald Head Hills, Southwestern Manitoba. *The Canadian Field-Naturalist*, 114, 612-627.

Sridhar, V., Hubbard, K.G., Wedin, D.A. (2006). Assessment of Soil Moisture Dynamics of the Nebraska Sandhills Using Long-Term Measurements and a Hydrology Model. *Journal of Irrigation and Drainage Engineering*, 5, 463-473.

Sridhar, V.,Hubbard, K.G., You, J., Hunt, E.D. (2008). Development of the Soil Moisture Index to Quantify Agricultural Drought and Its "User Friendliness" in Severity-Area-Duration Assessment. *Journal of Hydrometeorology*, *9,* 660-676.

Sridhar, V. & D.A. Wedin. (2009). Hydrological behavior of grasslands of the Sandhills of Nebraska: Water and energy-balance assessment from measurements, treatments, and modeling. *Ecohydrology*, 2, 195–212.

Stephens, D.B. & R Knowlton (1986). Soil Water Movement and Recharge Through Sand at a Semiarid Site in New Mexico. *Water Resources Research*, 22, 881-889.

Sulebak, J.R., Tallaksen, L.M., Erichsen, B. (2000). Estimation of Areal Soil Moisture by Use of Terrain Data. *Geografiska Annaler. Series A, Physical Geography*, 82, 89-105.

Tan, K.H. (2005). *Soil Sampling, Preparation, and Analysis (Second Edition)*. Taylor & Francis Group, Boca Raton.

Tao, L., Honglang, X., Xinrong, L. (2001). Modeling the Effects of Crust on Rain Infiltration in Vegetated Sand Dunes in Arid Desert. *Arid Land Research and Management*, 15, 41-48.

Thorpe, J., Wolfe, S.A., Campbell, J., Leblanc, J., Molder, R. (2001). An Ecoregion Approach for Evaluating Land Use Management and Climate Change Adaptation Strategies on Sand Dune Areas in the Prairie Provinces. Saskatchewan Research Council Publication No. 11368-1E01.

Tolstead, W.L. (1941). Plant Communities and Secondary Succession in South-Central South Dakota. *Ecology*, 22, 322-328.

Topp, G.C., Davis, J.L., Annan, A.P. (1980). Electromagnetic determination of soil water content. *Water Resources Research*, 16, 574-582.

Tsoar, H. (2005). Sand dunes mobility and stability in relation to climate. *Physica A*, 357, 50–56.

van de Koppel, J., Rietkerk, M., van Langevelde, F., Kumar, L., Klausmeier, C.A., Fryxell, J.M., Hearne, J.W., van Andel, J., de Ridder, N., Skidmore, A., Stroosnijder, L., Prins, H.H.T. (2002). Spatial Heterogeneity and Irreversible Vegetation Change in Semiarid Grazing Systems. *The Amercian Naturalist*, 159, 209-218.

Wakindiki, I.I.C. & M. Ben-Hur (2002). Soil Mineralogy and Texture Effects on Crust Micromorphology, Infiltration, and Erosion. *Soil Science Society of America Journal*, 66, 897–905.

Wang, T., Zlotnik, V.A., Wedin, D., Wally, K.D. (2008). Spatial trends in saturated hydraulic conductivity of vegetated dunes in the Nebraska Sand Hills: Effects of depth and topography. *Journal of Hydrology*, 349, 88– 97.

Ward, R.C. & M. Robinson (2000). Principles of Hydrology. McGraw-Hill Publishing Company, London.

White, R.E. (1987). Introduction to the Principles and Practices of Soil Science. Blackwell Scientific Publications.

Wilcox, B.P. & T.L. Thurow. (2006). Emerging Issues in Rangeland Ecohydrology: Vegetation Change and the Water Cycle. *Rangeland Ecology and Management*, 59, 220–224.

Wind, G.P. (1961). Capillary rise and some applications of the theory of moisture movement in unsaturated soils. In TNO Committee for Hydrological Research. Proceedings and Information No. 5, Wageningen.

Winter, T.C. (1986). Effect of ground-water recharge on configuration of the water table beneath sand dunes and on seepage in lakes in the sandhills of Nebraska, U.S.A. *Journal of Hydrology*, 86, 221-237.

Wolfe, S.A. (1997). Impact of increased aridity on sand dune activity in the Canadian Prairies. *Journal of Arid Environments*, 36, 421-432.

Wolfe, S.A. & P.P. David. (1997). Canadian landforms example - 34. Parabolic dunes: examples from the Great Sand Hills, southwestern Saskatchewan. *The Canadian Geographer*, 41, 207-213.

Wolfe, S.A., Hugenholtz, C.H. (2009). Barchan Dunes Stabilized Under Recent Climate Warming on the Northern Great Plains. *Geology*, 37, 1039-1042.

Wolfe, S.A., Huntley, D.J., David, P.P., Ollerhead, D.J., Sauchyn, D.J., MacDonald, G.M. (2001). Late 18th century drought-induced sand dune activity, Great Sand Hills, Saskatchewan. *Canadian Journal of Earth Sciences*, 38, 105-117.

Wolfe, S.A., Thorpe, J. (2005). Shifting Sands: Climate Change Impacts on Sand Hills in the Canadian Prairies and Implications for Land Use Management. *Prairie Forum*, 30, 123-142.

Yair, A. (1990). Runoff generation in a sandy area – The NizzanaSands, Western Negev, Israel. *Earth Surface Processes and Landforms*, 15, 597-609.

Yamanaka, T. & T. Yonetani (2009). Dynamics of the evaporation zone in dry sandy soils. *Journal of Hydrology*, 217, 135-148.

Zhang, Z.S., Liu, L.C., Li, X.R., Zhang, J.G., He, M.Z., Tan, H.J. (2008). Evaporation properties of a revegetated area of the Tengger Desert, Northern China. *Journal of arid Environments*, 72, 964-973.

Zhao, H.L., Zhou, R.L., Su, Y.Z., Zhang, H., Zhao, L.Y., Drake, S. (2007). Shrub facilitation of desert land restoration in the Horqin Sand Land of Inner Mongolia. *Ecological Engineering*, 31, 1-8.