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Annual, seasonal, and diel surface energy partitioning in the semi-arid Sand Hills of Nebraska, USA

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ABSTRACT

Study Region: The Nebraska Sand Hills consisting of four major land cover types: (1) lakes and wetlands (~5% for both), (2) subirrigated meadows (~10%), (3) dry valleys (~20%), and (4) upland dunes (~65%).

Study Focus: Examination of surface energy and water balances on multiple temporal scales with primary focus on latent heat flux (λE), and evapotranspiration (*ET*), to gain a better understanding of the annual, seasonal, and diel properties of surface energy partitioning among different Sand Hills ecosystems to improve regional water resource management.

New Hydrological Insights for the Region: Based on surface energy and water balance measurements using Bowen ratio energy balance systems at three locations during 2004, we find a strong spatial gradient between sites in latent (λE) and sensible (*H*) heat flux due to differences in topography, soils, and plant community composition on all timescales. Seasonally, all land covers show the greatest λE in summer. Our results show that subirrigated meadows, dry valleys, and upland dunes allocate roughly 81%, 50%, and 41% of available energy to λE, respectively, during the growing season. The subirrigated meadow was the only cover type where cumulative annual *ET* surpassed cumulative annual precipitation (*i.e.* net loss of water to the atmosphere). Therefore, the dry valleys and upland dunes are where net groundwater recharge to the High Plains Aquifer is occurring.

1. Introduction

Fresh water is vital for human society, and proper management of this resource will continue to gain importance in areas where scarcity is increasing. It is a fundamental necessity for consumption by municipalities, irrigation for agriculture, and natural ecosystem function that requires careful consideration in both short- and long-term management strategies. Short-term benefits include sustaining ample drinking water, ensuring abundant food supplies, flood control, and habitat for plants and wildlife. Long-term benefits include sustainable resource management and adaptive capacity in the context of climate change. One of the most valuable sources of fresh water that supports human populations and agricultural production is groundwater stored in aquifers. In the United States, the High Plains (Ogallala) Aquifer (HPA) supports more than one fourth of the Nation's agricultural production (McMahon et al., 2007), as this immense hydrologic feature underlies roughly 448,000 km^2 of land extending from South Dakota to Texas (McGuire et al., 2000). The primary region of recharge to the HPA is in the semi-arid Sand Hills region of Nebraska (Bleed and

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Flowerday, 1989; United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS, 2006; Wang et al., 2008, 2009), which is the largest grass-stabilized sand dune field in the western hemisphere (Loope and Swinehart, 2000). Nebraska ranks first amongst the 50 states in overall area irrigated (United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS, 2013), and the HPA provides roughly 30% of irrigation resources for all United States agriculture (United States Geological Survey (USGS, 1997; Weeks and Gutentag, 1989; Nativ, 1992). Sustaining irrigation supply is vital to the Nebraskan economy which relies heavily on agriculture. Some areas overlying the HPA are experiencing groundwater declines (Kisekka and Aguilar, 2016; McGuire, 2009). Recent projections indicate that if current rates of extraction continue to exceed recharge, parts of the High Plains will face exhausted groundwater supplies within the next 100 years (Tidwell et al., 2016; United States Department of Homeland Security (USDHS, 2015). In fact, the southern HPA has already experienced significant depletion, and it is estimated that roughly 35% of the southern High Plains may not be able to sustain irrigation within the next 30 years if current extraction rates continue (Haacker et al., 2015; Scanlon et al., 2012).

The Nebraska Sand Hills region consists of four major land cover types: (1) lakes and wetlands (~5%), (2) subirrigated meadows (~10%), (3) dry valleys (~20%), and (4) upland dunes (~65%). Rolling topographic relief of grass-stabilized sand dunes in this region alter microclimatic conditions and affect connections between plant communities and groundwater (Gosselin et al., 1999, 2006). Understanding hydrologic connections between groundwater, soils, vegetation, and the atmosphere is critical for water resource managers that rely on the HPA. Improved seasonal and diel estimates of water's role in energy partitioning among dominant land cover types in this region will benefit estimates of the regional water balance and aquifer recharge (Szilagyi et al., 2005; Xu and Chen, 2005), irrigation scheduling (George et al., 2000; Ray and Dadhwal, 2001), and regional climate modeling (Radell and Rowe, 2008; Sridhar and Wedin, 2009). Thus, there is a need to improve our ability to manage different land cover types on different temporal scales for improved water conservation (Pruegar et al., 1997; Power, 2010).

Ecohydrological connections are often climate dependent (Rodriguez-Iturbe, 2000) and are especially important to agricultural producers in areas prone to drought like the semi-arid Sand Hills region of Nebraska (Sridhar and Hubbard, 2010). The two-way connection between groundwater and the atmosphere is controlled by precipitation inputs and losses *via* soil and plants in the form of latent heat flux (λE). Terrestrial λE occurs as a combination of evaporation (E) and transpiration (T), collectively referred to as evapotranspiration (ET). Regional climatology determines the energy and water available for λE that, in turn, influences the rate of recharge to the HPA. Although previous research has investigated regional-scale satellite remote sensing estimates of ET in the Sand Hills region (Szilagyi and Jozsa, 2013; Szilagyi et al., 2011; Healey et al., 2011), these analyses were restricted spatially and/or temporally.

In this research, we focus on the following research question that has not yet been addressed: How does the surface energy balance at three of the four major land cover types in the Nebraska Sand Hills region differ across timescales, from diel to seasonal to annual? The objective of this study is to expand the findings of Healey et al. (2011) and Billesbach and Arkebauer (2012) to establish a new understanding of how the dominant land cover types in the Sand Hills of Nebraska partition available energy, with primary focus on energy consumed in the processes of soil evaporation and plant transpiration, on diel, seasonal and growing season timescales. We aim for our results to inform rangeland managers about differences in hydrologic characteristics of the major regional land cover types on different time scales to improve determination of the best land use practices (*i.e.* grazing rotations, grazing capacity, planting and harvest timing of crops such as hay, *etc.*).

This research also aims to expand on results from modeling efforts by Sridhar and Wedin (2009) on upland dune ecosystems in the Nebraska Sand Hills, while providing new insight into energy partitioning in dry valley and subirrigated meadows on different temporal scales initiated by Sridhar (2007) and Healey et al. (2011). These previous studies (1) provided remote sensing estimations of ET from high resolution satellite imagery representing "snapshots" of energy partitioning at the times of satellite overpasses and (2) implemented statistical models to interpolate ET estimations between sites in the Sand Hills. This current study provides *in situ* observations at three of the four dominant ecosystems in the Sand Hills that have not been closely examined at different timescales, thus extending beyond instantaneous estimations of ET and utilizing observations instead of spatial interpolation to better understand the hydrologic behavior of the Sand Hills region.

2. Site description

The regional climate of the Nebraska Sand Hills is semi-arid, with a significant precipitation gradient from about 450 mm yr^{-1} in the west to over 650 mm yr^{-1} in the east (Szilagyi et al., 2003). Based on the 30-year climatology for this mid-latitude region (High Plains Regional Climate Center (HPRCC, 2010), maximum precipitation normally occurs during the month of June (105 mm). In general, the area can be characterized as a continental climate (hot summers and contrastingly cold winters), with most precipitation falling in the summer season. Over the growing season (April-October), the mean air temperature is 15.8 °C, with an average low temperature of 8.6 °C, and average high temperature of 22.9 °C. Annual maximum temperatures typically occur in July.

The Gudmundsen Sand Hills Research Laboratory (GSRL) is a 52 km^2 multidisciplinary research facility located in the heart of the Sand Hills region near Whitman, Nebraska (Latitude: 42.06 °N, Longitude: 101.52 °W, Elevation: 1098 m a.s.l.), and the laboratory also serves as a livestock ranch (Fig. 1). At GSRL, three micrometeorological Bowen ratio energy balance (BREB) stations were established in 2002 and 2003 at an interdunal subirrigated meadow, a dry shortgrass valley, and an upland dune ecosystem. The subirrigated meadow at GSRL (roughly 6.5 km long and 800 m wide) is flanked by dunes to the north and south that discharge soil water to the meadow (Gosselin et al., 2006), where the water table often rises to the soil surface. Hay is harvested from the meadow to feed winter cattle and supplement dormant-season grazing on dry valley and upland range sites. The dry valley at GSRL (roughly 4 km long and about 600 m wide) is a flow-through area where ground water typically flows parallel to the land surface, and