7-2-2018

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Journal of Hydrology: Regional Studies 18 (2018) 80–91

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

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ARTICLE INFO

Keywords:
Nebraska
High plains aquifer
Evapotranspiration
Energy balance
Bowen ratio

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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https://doi.org/10.1016/j.ejrh.2018.06.009
Received 9 January 2018; Accepted 22 June 2018
Available online 02 July 2018

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

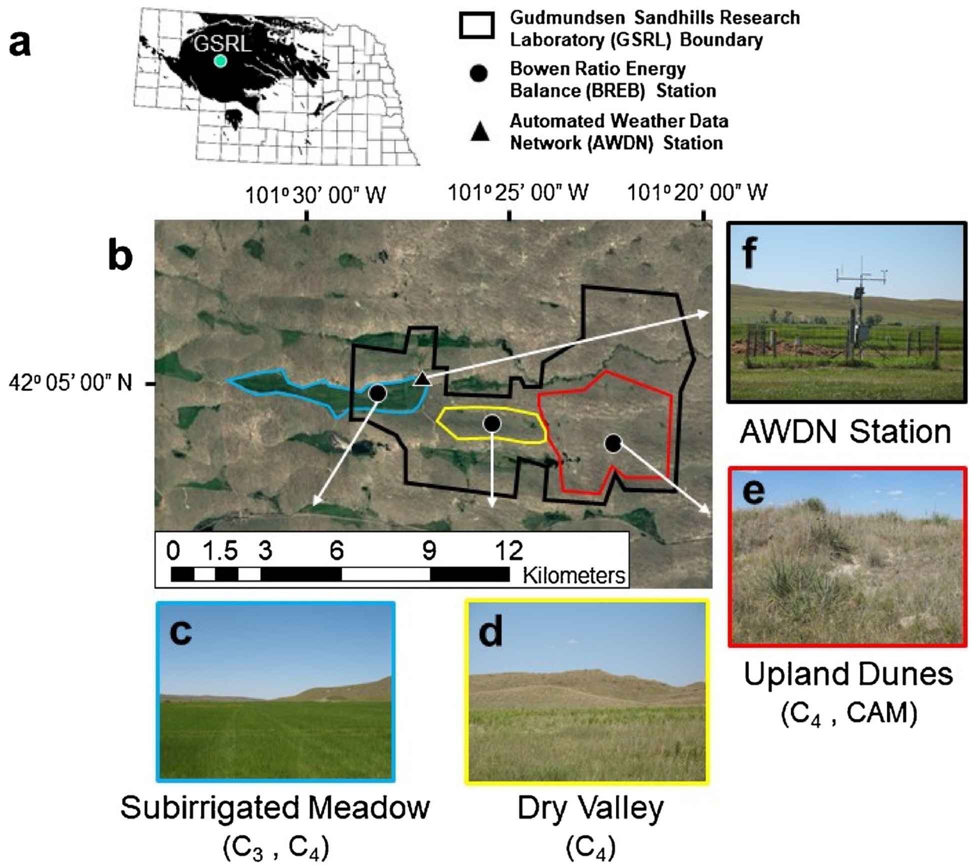

Fig. 1. Boundary of the Nebraska Sand Hills and (a) location of the Gudmundsen Research Laboratory (GSRL), (b) GSRL station locations, (c–f) images of each study site containing a BREB station and the Automated Weather Data Network (AWDN) station. A description of the mix of photosynthetic pathways present in the plants at each site in parentheses below. Example species present with common name and photosynthetic pathway: *Poa pretensis* (Kentucky bluegrass: C_3), *Medicago sativa* (Alfalfa; C_3), *Calamvilfa longifolia* (Prairie sandreed: C_4), *Andropogon hallii* (Sand bluestem: C_4), *Bouteloua gracilis* (Blue grama: C_4), and *Yucca glauca* (Yucca: CAM).

groundwater is typically between one to ten meters from the surface (Gosselin et al., 2006). The upland dune site at GSRL, where the water table is often located more than ten meters from the surface, exhibits pronounced topographic undulations and an abundance of exposed soil (sand) with high hydraulic conductivity. Table 1 describes the soil properties for each of the three land cover types.

Plant community composition varies at each site, largely determined by soil moisture and texture differences. The subirrigated meadow contains a dense canopy, where the maximum growing season leaf area index (LAI) is near three (Healey et al., 2011). This site supports a mix of mosses, shallow rooted (0–30 cm deep) C_3 grasses and deeper (> 30 cm) rooted C_4 grasses, forbs, and sedges (*e.g. Medicago sativa, Bromus inermis Leyss, Poa pratensis L., Spartina pectinata, Calamagrostis* spp., numerous *Carex* spp., *Cyperus* spp., *Scirpus* spp., and *Eleocharis spp*.). In spring, the abundant C_3 grasses and sedges in the subirrigated meadow optimally photosynthesize when leaf temperatures reach 20–30 °C, although Yamori et al. (2014) determined a much broader range of optimal temperatures for C_3 species (10–35 °C). Leaf temperatures are often 1–10 °C above (below) air temperature when air temperature is below (above) optimum, depending on leaf-level thermodynamics related to ambient wind speed, vapor pressure deficit, and solar irradiance (Campbell and Norman, 1998). The dry valley supports a sparser canopy with a maximum growing season LAI of just over one (Healey et al., 2011) and a higher proportion of C_4 grasses and forbs with deeper root systems. Albertson (1937) found that C_4

Table 1
Soil properties for the three Bowen ratio energy balance (BREB) system locations at the Gudmundsen Sandhills Research Laboratory, Nebraska. (Soil Water Information Source: Allen et al., 1998; Soil Type Information Source: USDA-NRCS, 2011).

	BREB Location at the Gudmundsen Sand Hills Research Laboratory		
	Meadow	Valley	Upland
Soil Type	Gannett–Loup fine sandy loam	Elsmere loamy fine sand	Valentine fine sand
Wilting Point ($m^3\,m^{-3}$)	0.06–0.16	0.03–0.10	0.02–0.07
Field Capacity ($m^3\,m^{-3}$)	0.18–0.28	0.11–0.19	0.07–0.17

Table 2
Instrumentation specifications for each of the Bowen ratio energy balance (BREB) systems at the Gudmundsen Sand Hills Research Laboratory, Nebraska.

Variable	Instrument Type	Model	Quantity	Height of Sensor (m)	Units	Accuracy
Temperature	Platinum resistance thermometer	Vaisala Humitter 50-Y	2	1.9 and 3.3	°C	± 0.6 °C
Relative Humidity	Capacitive RH sensor	Vaisala Humitter 50-Y	2	1.9 and 3.3	%	± 4 %
Wind Speed	Cup anemometer	MET-One model 014A	2	1.9 and 3.3	$m\ s^{-1}$	± 0.11 $m\ s^{-1}$
Wind Direction	Wind vane	Met-One 024	1	3.3	degrees	± 5°
Atmospheric Pressure	Pressure transducer	Vaisala PT105B	1	1.9	mbar	± 0.3 at + 20 °C
Precipitation	Tipping bucket	Texas Instruments TE525	1	1	mm	± 10 mm $hour^{-1}$
Incoming/ Outgoing shortwave/ longwave radiation	Net Radiometer	Kipp & Zonen NR-lite	1	2.2	$W\ m^{-2}$	± 30 $W\ m^{-2}$
Soil Heat Flux	Thermopile gradient	REBS HFT3	2	0.03-0.05 (below surface)	$W\ m^{-2}$	± 5%
Soil Moisture	Probe	Delta-T ML-2 theta	2	0.10, 0.25, 0.50, 1 (below surface)	$m^3\ m^{-3}$	± 0.05 $m^3\ m^{-3}$
Incoming shortwave radiation	Thermopile	LiCor LI-200	1	2.2	$W\ m^{-2}$	± 5%
PAR	Thermopile	LiCor LI-190 PAR	1	2.2	$\mu mol\ s^{-1}\ m^{-2}$	± 1.7%

tallgrass prairie species can have root systems that extend over two meters into the soil profile. The upland dune ecosystem has a very sparse canopy with a maximum growing season LAI < 0.3, consisting mostly of deep rooted C_4 grasses and, with the exception of species like *Yucca glauca*, shallow rooted **Crassulacean Acid Metabolism** (CAM) plants, and some isolated forbs, succulents, and shrubs (*e.g. Andropogon scoparius, Calamovilfa longifolia, Andropogon hallii, Panicum virgatum* L.*, Eragrostis trichoides, Bouteloua gracillis, and Opuntia fragilis*). This site is a grass-stabilized upland sand dune ecosystem, where soil water holding capacity is increasingly limited due to increased infiltration potential (*i.e.* high permeability), heightened aridity, coarse sandy soils, and no upward vertical flow of groundwater. Thus, these species must be opportunistic in capturing soil water that travels quickly through the sandy soil horizon. Previous research shows that the species distribution from the dry valley bottom to the upland dunes differs based on the topography (Pool, 1914; Barnes and Harrison, 1982), soil texture (Burzlaff, 1962), and most importantly the spatial and temporal distribution of soil moisture (Tolstead, 1942).

3. Materials and methods

The surface energy balance at each of the three land cover types was calculated using BREB systems, using instrumentation described in Table 2. At each of the three sites, data were logged by Campbell CR23X data loggers using Campbell Scientific AM25 T solid-state multiplexers to provide additional analog input channels. Observations were made once per second, and 30-minute averages were recorded. Because a psychrometer exchanging mechanism was not available, inherent biases between the individual temperature/relative humidity sensors were removed by calibrating them using a precision platinum resistance thermometer and a reference dew point hygrometer. For validation, calculated energy fluxes were compared to values obtained from eddy covariance instrumentation installed at the dry valley site. The procedure was also tested against eddy covariance instrumentation in a fallow Oklahoma wheat field, where flux system errors are estimated to be ± 15% $W\ m^{-2}$ (Billesbach et al., 2004). Bowen ratio energy fluxes in this study were estimated to be within about 10% of the eddy covariance observations, and positive (negative) flux values denote movement of matter or energy away from (toward) the land surface. Thus, the overall surface energy balance can be written as:

$$R_n = \lambda E + H + G \tag{1}$$

where λE is the latent heat flux; R_n is net radiation; H is the sensible heat flux; G is the surface heat flux; and all units are in $W\ m^{-2}$. The Bowen ratio (Bowen, 1926) is then computed as:

$$\beta = \left(\frac{H}{\lambda E}\right) \tag{2}$$

To calculate ET, we divide λE by $\lambda\rho_w$ where ρ_w is the density of water ($kg\ m^{-3}$). In this study we report fluxes of both λE and ET in terms of energy ($W\ m^{-2}$) and water ($mm\ day^{-1}$), respectively. Reference evapotranspiration (ET_o) was calculated using the FAO-56 Penman-Monteith equation (Allen et al., 1998; ASCE-EWRI, 2005), using grass as the reference crop. For growing season analyses, we examined the snow-free period from April-October. For seasonal analyses, we defined spring as extending from April-May, summer as June-August, and fall as September-October. Using daytime values of λE and ET only, we show a filtered time series of energy balance components for each of the three sites using a 7-day running mean to reduce noise associated with synoptic weather variability, focusing instead on the seasonal variability.

All data were checked against a set of quality control criteria for validity. Data were flagged if the measured or calculated 30-

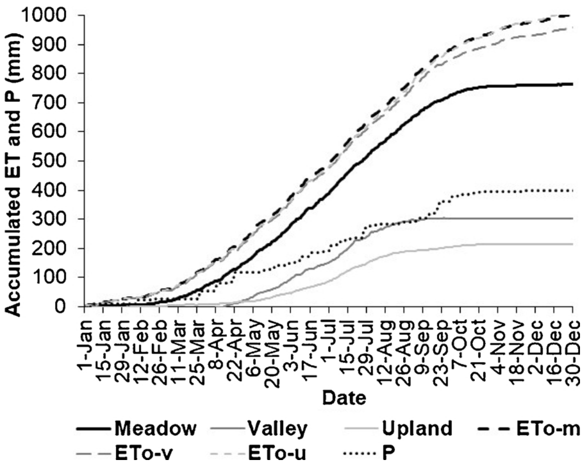

Fig. 2. Cumulative Reference Evapotranspiration at the Subirrigated Meadow (*ETo-m*), Dry Valley (*ETo-v*), and the Upland Dune (*ETo-u*), Precipitation (*P*) from the Automated Weather Data Network (AWDN) station, and Actual Evapotranspiration (*ET*) at the Subirrigated Meadow, Dry Valley, and Upland Dune sites within the Gudmundsen Sand Hills Laboratory, Nebraska in 2004.

minute BREB values fall outside a set of limits. For daily data, questionable values were replaced by the arithmetic mean of the preceding and proceeding acceptable values. When calculating totals for longer periods (monthly or growing season), the same procedure was applied for single missing days, but linear interpolation was used for multiple missing days.

4. Results and discussion

4.1. Growing season energy partitioning

With the highest net radiation, precipitation, and soil moisture, the subirrigated meadow exhibited the highest growing season average λE (216 W m^{-2}) and total accumulated evaporative water loss (total $ET = 763$ mm). In fact, the total *ET* was nearly double that of precipitation (399 mm) (Fig. 2), indicating that the soil receives a regular replenishment of water from local groundwater sources, even when precipitation is lacking. As noted by Gosselin et al. (2006), this site is characterized by groundwater flow that has seasonally sustained upward vertical gradients and discharge, with consistent replenishment by flow into the meadow from the north and south. We estimated that the subirrigated meadow produced a growing season average *ET* of 3.5 ± 1.6 mm day^{-1}, with the maximum rate of 6.4 mm day^{-1} occurring on June 14, which compares closely with results from Burba et al. (1999a, 1999b), who estimated *ET* rates of 3.8–4.1 mm day^{-1} for open water in north-central Nebraska, as well as Lenters et al. (2011), who measured *ET* to equal 4.4 mm day^{-1} for a riparian wetland in central Nebraska.

Gosselin et al. (2006) described the dry valley as an area where groundwater flows laterally, and when vertical gradients of flow exist here, they are typically downward. Dry valleys have a stronger dependence on precipitation to recharge soil moisture in the root zone and support λE, rather than supplemental groundwater connections. Here, accumulated precipitation (359 mm) surpassed the annual cumulative *ET* (276 mm) (Fig. 2). Average growing season λE in the dry valley was 127 W m^{-2} (*ET* of 2.0 ± 1.4 mm day^{-1}), and the maximum rate of *ET* (5.9 mm day^{-1}) occurred a month later (July 14) than in the subirrigated meadow. These results are similar to a study by Christie (1981) in an Australian semi-arid grassland, who found growing season *ET* to average around 2.7 mm day^{-1}.

The upland dune site is slightly windier, hotter, and less humid on average than the subirrigated meadow and dry valley (Table 3). Despite the higher evaporative demand at this site (higher air temperature, vapor pressure deficit, and wind speed), the upland dune

Table 3
Average April-October daytime micrometeorological values at the three ecosystems within the Gudmundsen Sand Hills Research Laboratory, Nebraska in 2004.

Variable	Units	Meadow	Valley	Upland
Net Radiation (R_n)	W m^{-2}	273	261	255
Sensible Heat Flux (*H*)	W m^{-2}	52	125	128
Soil Heat Flux (*G*)	W m^{-2}	5	10	38
Latent Heat Flux (λE)	W m^{-2}	213	120	78
Bowen Ratio (β)	unitless	0.2	1	1.6
Air Temperature (T_a)	°C	17.55	17.65	17.84
Relative Humidity (*RH*)	%	60.7	62	53.8
Vapor Pressure Deficit (*VPD*)	kPa	1.049	1.033	1.102
Wind Speed (*U*)	m s^{-1}	4.7	4.9	5.4

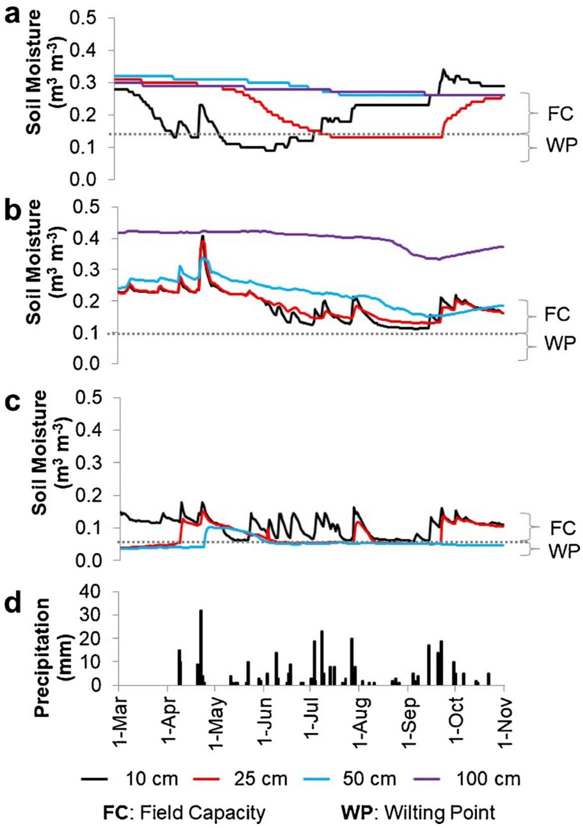

Fig. 3. Daily soil moisture measurements from the Automated Weather Data Network (AWDN) station located adjacent to the (a) subirrigated meadow, from the Bowen ratio energy balance (BREB) station located at the (b) dry valley site and (c) upland dune site, and (d) precipitation at the Gudmundsen Sand Hills Research Laboratory, Nebraska in 2004. Ranges of moisture representing field capacity (FC) and the wilting point (WP) for each soil type are defined in the right margin (a–c). Note: 100 cm soil moisture data were unavailable at the upland dune site. Also the AWDN location is adjacent to the subirrigated meadow which is slightly elevated from the BREB location and, thus, the 100 cm soil water content in panel a is likely underrepresented and closer to the 100 cm soil water content at the dry valley.

produced the lowest growing season average λ*E* of 89 W m^{-2} (*ET* of 1.4 ± 0.8 mm day^{-1}), with a maximum *ET* rate of 3.8 mm day^{-1} occurring on July 9. Accumulated precipitation in the upland dune site totaled 371 mm, and accumulated *ET* (213 mm) was lowest among the three sites (Fig. 2). However, sensible heat flux, *H*, was higher, and the average 2004 growing season T_a was also warmest at this site (by ~0.2 °C).

From April – October energy partitioning gradients are noticeable among sites where the subirrigated meadow, dry valley, and upland dune sites partitioned 81% (3.4 ± 1.6 mm day^{-1} of *ET*), 50% (2.0 ± 1.4 mm day^{-1} of *ET*), and 41% (1.4 ± 0.8 mm day^{-1} of *ET*), of available energy to λ*E*, and 19%, 50%, and 59% to *H*, respectively. When combining the growing season *ET* with the precipitation in 2004, the subirrigated meadow system represents a net loss (*i.e.*, *P* – *ET*) of -364 mm of water, while the dry valley and upland dune represent net gains of +83 mm and +158 mm of water, respectively. Scaled up according to the fraction of areal coverage for the different land cover types in the Sand Hills region (10% subirrigated meadows, 20% dry valley, and 65% upland dunes), the overall net recharge of water to the HPA is found to be 87.3 mm in 2004.

4.2. Seasonal variability

4.2.1. Spring

In the transition from winter to spring, ample soil water throughout the soil column and root zone (Fig. 3a) of the subirrigated meadow allows for commencement of noticeable *ET* increase as opposed to the dry valley and upland dune sites (Fig. 2). In fact, *ET* increased by 39% at this time even though precipitation decreased by roughly 50%. Although, measurements of noticeable *ET* in spring are primarily a reflection of ample soil moisture in the top 10–25 cm (Fig. 2, 3). During spring in the subirrigated meadow, 217 W m^{-2} (3.5 mm day^{-1}), or 77% of available energy (282 W m^{-2}) is partitioned to λ*E*, and 65 W m^{-2}, or 23%, to *H* (Figs. 4 and 5).

Soil moisture in the dry valley is at or above field capacity throughout the top 1 m of soil until the end of spring (Fig. 3b), indicating that a large portion of *ET* at this time is evaporation from the soil, rather than transpiration *via* photosynthesis. This is also evident in the difference between ET_o and *ET* (Fig. 2). During spring, 120 W m^{-2} (1.9 mm day^{-1}), or 46% of available energy (261 W m^{-2}) is partitioned to λ*E*, and 141 W m^{-2}, or 54%, to *H* (Fig. 4, 5).

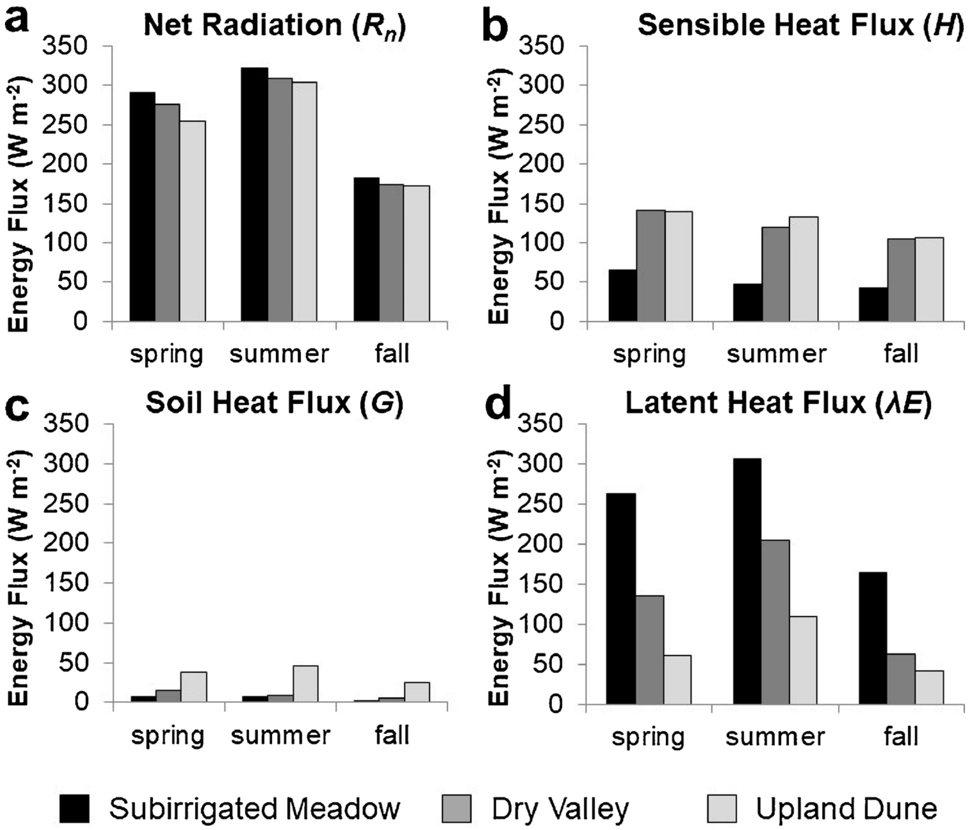

Fig. 4. Average daytime seasonal energy balance components at the subirrigated meadow, dry valley and upland dune Bowen ratio energy balance (BREB) locations at the Gudmundsen Sandhills Research Laboratory, Nebraska. (Spring: April-May; Summer: June-August; Fall: September-October).

Being the most arid of the three sites, the upland dune area shows minimal *ET* accumulation in spring. Rapid increases in soil moisture within the top 10 cm occur shortly after sporadic spring precipitation events (Fig. 3c). Transpiration is driven by these rapid pulses of precipitation because soil water quickly migrates to depths deeper than 1 m, or beyond the root zone. Although seasonal precipitation events provide water for *ET*, the coarse sandy soils and (assumed) depth to groundwater requires plant species to (1) rapidly take advantage of limited soil water in the topmost layers of the soil profile with shallow root systems (*e.g.,* CAM), or (2) extend roots deeper in order to endure dry periods (*e.g.,* C_4) to increase transpiration rates. Although soil moisture in the top 10 cm is at field capacity in spring (likely due to snowmelt), all other layers are at or near the permanent wilting point. Thus, *ET* in spring is 84% below the ET_o value, which implies moisture stress in the root zone and/or species that are not physiologically active at this time. In the spring, only 77 W m^{-2} (1.2 mm day^{-1}), or 35% of available energy (217 W m^{-2}) is partitioned to λE, and 140 W m^{-2}, or 65%, to *H* (Fig. 4, 5).

4.2.2. Summer

Sustained soil moisture in the root zone and a consistently wet surface make evaporative losses at the subirrigated meadow energy limited, so peak *ET* occurred in July due to high net radiation during summer months (Table 1, Fig. 3a). The groundwater table in the subirrigated meadow can decrease by roughly 0.8–1.3 m between late July and late September (Gosselin et al., 1999, 2006), although ample soil water in the root zone determines that *ET* is energy limited at this site. In early summer during our study period, shallow soil depths (0–50 cm) remain at field capacity throughout the growing season (Fig. 3a). On average, 268 W m^{-2} (4.3 mm day^{-1}), or 85% of available energy (316 W m^{-2}) is partitioned to λE, and 48 W m^{-2}, or 15%, to *H* over summer (Fig. 4, 5).

By summer, cumulative *ET* in the dry valley has caught up to and nearly surpassed precipitation (Fig. 2), due to high soil evaporation from shallow soil water (Fig. 3b), and (3) the topographic position of the station (valley bottom), where soil water may collect and maintain high soil moisture. Soil moisture in the 10 and 25 cm depths was near field capacity from summer until the end of the year (Fig. 3b), but more drying events occurred when compared to the subirrigated meadow (Fig. 3a). In the dry valley, high summer *ET* is due to and ample soil moisture and maximum seasonal energy availability. Here, 180 W m^{-2} (2.9 mm day^{-1}), or 60% of available energy (300 W m^{-2}) is partitioned to λE, and 120 W m^{-2}, or 40%, to *H* (Fig. 4, 5).

At the upland dune site, the greatest water loss also occurs at the height of the summer when available energy is at a maximum and water is available (though not abundant relative to the other two sites). In the upland dunes, 124 W m^{-2} (2.0 mm day^{-1}), or 48%

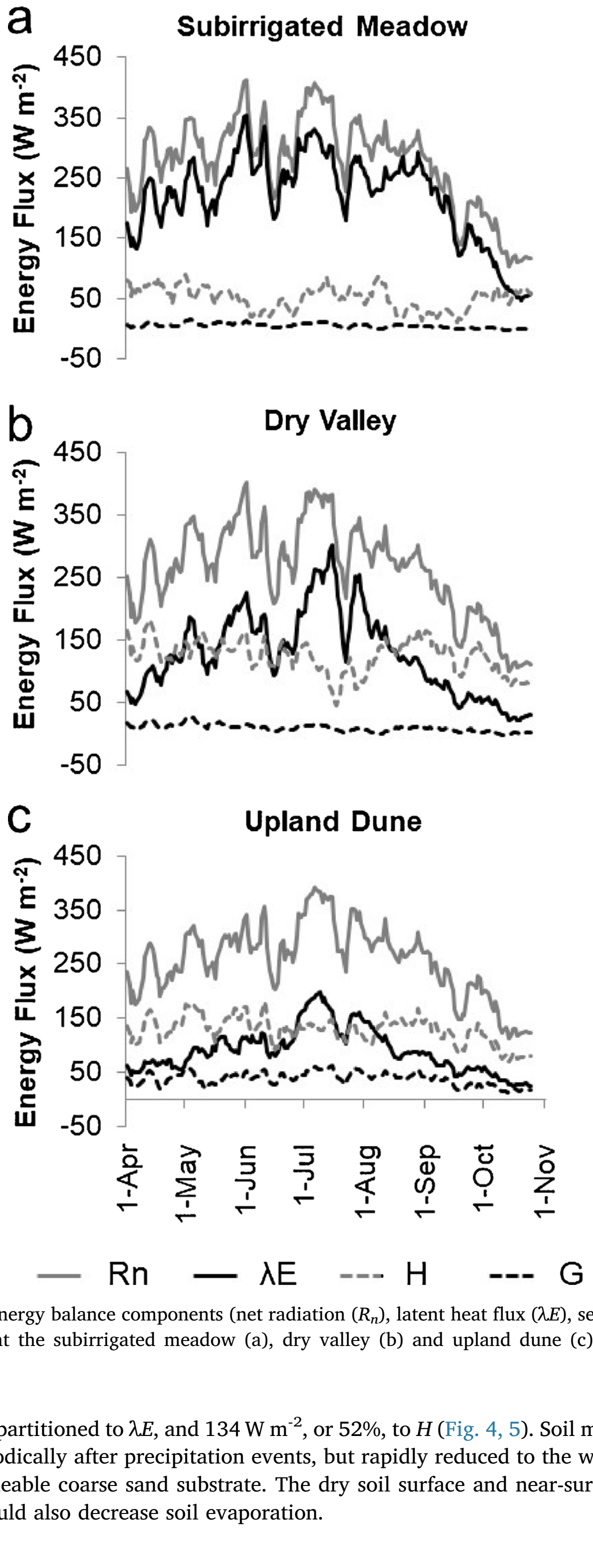

Fig. 5. 7-day running mean daytime energy balance components (net radiation (R_n), latent heat flux (λE), sensible heat flux (H), and soil heat flux (G)) from the three BREB locations at the subirrigated meadow (a), dry valley (b) and upland dune (c) sites at the Gudmundsen Sand Hills Laboratory, Nebraska, 2004.

of available energy (258 W m^{-2}) is partitioned to λE, and 134 W m^{-2}, or 52%, to H (Fig. 4, 5). Soil moisture in the top 50 cm of the soil profile reached field capacity periodically after precipitation events, but rapidly reduced to the wilting point during summer due to the abundance of the highly permeable coarse sand substrate. The dry soil surface and near-surface that existed most of the time during the summer at this site would also decrease soil evaporation.

4.2.3. Autumn

In the fall, 138 W m^{-2} (2.2 mm day^{-1}), or 76% of available energy (181 W m^{-2}) is partitioned to λE, and 43 W m^{-2}, or 24%, to H in the subirrigated meadow (Fig. 4, 5). Similar to spring and summer, fall energy partitioning is still dominated by λE due to the dense plant cover utilizing easily accessible soil moisture near the surface soil layer. However, the difference between ET and ET_o increases in the fall, as photoperiod (*i.e.* day length) diminishes and air temperatures decrease.

In fall, available energy is increasingly limited, which results in a reduction of *ET* at the dry valley site even though substantial precipitation occurred. At this time virtually all precipitation either briefly replenishes soil moisture or infiltrates the soil profile to greater depths than were measured, potentially adding groundwater to the HPA. This is important in understanding how groundwater recharge is distributed both spatially and temporally in the HPA region. In the dry valley, 64 W m^{-2} (1.0 mm day^{-1}), or 38% of available energy (169 W m^{-2}) is partitioned to λE, and 105 W m^{-2}, or 62%, to *H* (Fig. 4, 5). These seasonal results are comparable to a study conducted at another tallgrass prairie overlying the HPA in north central Oklahoma who found an *ET* estimate of 1.5 mm day^{-1} (Burba and Verma, 2001).

In early fall, a greater fraction of precipitation rapidly infiltrates the upland dunes whereby water quickly moves through the root zone without being lost as evaporation from the soil or used in transpiration. At this time, only 40 W m^{-2} (0.6 mm day^{-1}), or 27% of available energy (147 W m^{-2}) is partitioned to λE, and 107 W m^{-2}, or 73%, to *H* (Fig. 4, 5). Although substantial precipitation occurred in the fall season, local topography and soil properties allow for greater infiltration, causing less water to be lost to the atmosphere and the potential for more water to recharge the HPA. Therefore, since the upland dunes represent ~70% of the Sand Hills land cover, the spring and fall seasons represent the time periods with the greatest potential for recharge to the HPA.

4.3. Diel variability

On diel time scales (Fig. 6), λE remains the dominant component of energy partitioning in subirrigated meadows (Fig. 6a), with a maximum value of 343 W m^{-2} at 1500 h CST, roughly one hour after the time of peak R_n. At sunrise, total water potential within the vegetation is closer to equilibrium with soil moisture content than at any other time of the day (Tiaz and Zeiger, 2006). Because there is virtually no water limitation in the subirrigated meadow, 89% of available energy is partitioned to λE over the course of the day, leaving only 11% partitioned to *H* (Fig. 6a). Average hourly *G* is only slightly positive in the afternoon and evening (1300–2100 h CST) and, overall, is quite minimal at this site (maximum of 16 W m^{-2} at 1600 h) on a diel basis. Thus, the subirrigated meadow partitions nearly all available energy to λE, acting as a constant source of atmospheric moisture throughout the day as long as R_n is positive.

At the dry valley, partitioning of λE and *H* on diel timescales is nearly balanced (maximums of 266 and 233 W m^{-2}, respectively) throughout an average day, with partitions of 45% and 55% of available energy, respectively (Fig. 6b). Daily maximum λE and *H* occur around the same hour as maximum R_n. Equal partitioning between λE and *H* is an indication that this site is more water limited and that *H* plays a larger role in the daily energy budget compared to the energy-limited subirrigated meadow. *G* was slightly higher at the dry valley, with an hourly average maximum of 25 W m^{-2} occurring at 1600 h CST. The fact that λE is reduced on a diel basis compared to the subirrigated meadow is indicative of increased soil water limitation.

On an average day during the growing season, 68% of available energy in the upland dune site is partitioned to *H* (maximum of 225 W m^{-2}), while only 32% is partitioned to λE (maximum of 118 W m^{-2}) (Fig. 6c). Interestingly, peak λE occurs one hour before maximum R_n here. Due to the abundance of exposed soil, *G* utilizes 18% (75 W m^{-2}) of available energy at the expense of λE throughout the day. Compared to the dry valley site, the diel cycle of *H* is nearly identical at the upland dune site.

5. Conclusions and future research

This research has investigated the surface energy partitioning of three of the four major ecosystems in the Nebraska Sand Hills region. Evapotranspiration is not uniform among our three sites because of varying microclimate and land cover type (*i.e.* vegetation cover, soil moisture availability, and topography), which were found to have a large influence on how water moves through the soil-plant-atmosphere continuum. Our results support the findings by Sridhar et al. (2006), in that precipitation and soil moisture availability are critical controlling factors in determining *ET* and, thus, the hydrologic cycle of the Nebraska Sand Hills region. Using our findings, we can now investigate the regional water budget with a better understanding of this semi-arid region's hydrologic behavior. The largest regional evaporative losses occur in the subirrigated meadows where groundwater is naturally discharged from the HPA, although it is limited in spatial extent (~10% of regional land cover). The main reason why the Nebraska Sand Hills is the main location for net recharge to the HPA is that the majority of the region's land cover (~85%) is comprised of dry valleys and upland dunes where groundwater recharge is occurring and *ET* is lowest.

Results from our energy balance elucidate intricate differences in how the plants at each site partition energy in order to utilize water most effectively with different soil moisture limitations. After combining annual precipitation with *ET*, the subirrigated meadows represent a net loss of water on the order of -364 mm of water, while the dry valleys and upland dunes represent net gains (83 mm and 158 mm, respectively) to soil moisture, and potential recharge to the HPA. Overall, we conclude that the overall recharge potential to the HPA was 87.3 mm in 2004.

Seasonal estimates of *ET* can be roughly calculated using regional climate modeling if sufficient input parameters are available, but this study provides *in situ* observations that do not rely on assumptions that are inherently embedded in hydrological models. This research provides a new understanding of the hydrologic behavior of the Sand Hills region on different time scales that can be utilized in future modeling efforts that examine how the seasonality of energy partitioning impacts regional hydrology if climate change alters the intensity and frequency of precipitation events. For example, a major finding from our study is that the greatest seasonal λE occurred during the summer primarily due to varying limitations of soil moisture where the subirrigated meadows partition 85%, while the dry valleys and upland dunes partition 60%, and 48% of available summer energy, respectively, to λE.

On a diel basis, the vast majority of energy is partitioned to λE in the subirrigated meadows, while λE and *H* are nearly balanced at the dry valleys and *H* dominates energy partitioning in the upland dunes on a diel basis. The upland dunes and the dry valleys begin

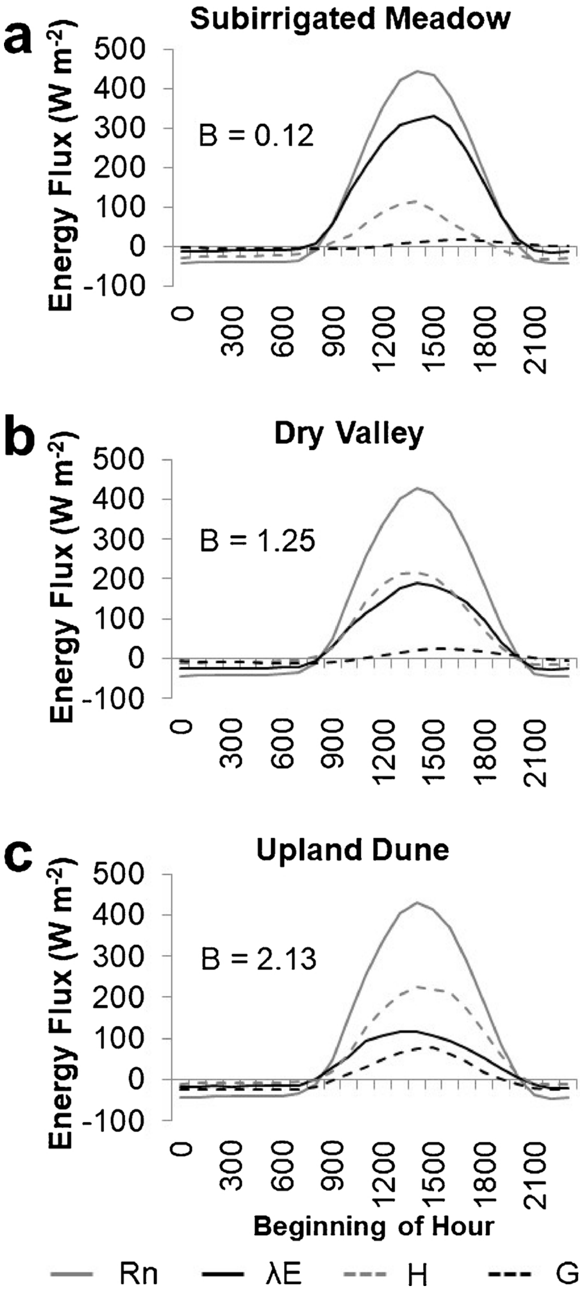

Fig. 6. Average diel cycle of net radiation (R_n), latent heat flux (λE), sensible heat flux (H), and soil heat flux (G) at the subirrigated meadow (a), dry valley (b) and upland dune (c) sites at the Gudmundsen Sand Hills Laboratory, Nebraska, 2004. Times are Central Standard Time (CST). Bowen ratio (B) is calculated as the ratio of the daily mean H to daily mean λE.

to shift energy partitioning away from λE and to H one hour prior to peak daily net radiation, where the subirrigated meadows make this shift one hour *after* peak net radiation. This is a direct reflection of (1) the variation in soil moisture limitation and (2) assumed differences in transpiration by the different plant communities (subirrigated meadow: C_3, C_4 mix; dry valley: C_4; upland dune: C_4, CAM mix) present at each site. Plants in the subirrigated meadows utilize ample soil water throughout the day, while those in the dry valleys and upland dunes likely decrease photosynthetic rates earlier in the day because of soil water limitation, not because radiation is lacking. Therefore, measurements of leaf-level gas exchange (photosynthesis and respiration) of control plots at each BREB study site would advance our findings about how C_3, C_4, and CAM species behave on the different time scales in the context of energy partitioning in this study. However, our results provide detailed information about connections between soil water availability and energy partitioning that will refine future modeling of plant physiological behavior on varying time scales which, in turn, impacts various land use practices (ex. irrigation scheduling, to planting and harvest timing, to grazing capacity) that rely on accurate estimations of regional hydrology and plant-water relationships.

Although a groundwater well is present at the subirrigated meadow and in various locations throughout the upland areas at GSRL, future research on this subject would be assisted by installation of groundwater wells to accompany the BREB stations at each of the study sites. This would provide direct means to investigate connections between groundwater depth fluctuations and the soil moisture available to plant communities present without the need for modeling. Our findings show that soil moisture dynamics in the Nebraska Sand Hills region are one of the most critical aspects to the organization of hydrology, plant community structure and composition, and resulting energy partitioning. Crop models that simulate growth, development, and water consumption by different species present in the Sand Hills, such as prairie grasses, could potentially benefit from the estimates of *ET* outlined in this research. Future estimates of groundwater recharge to the HPA will benefit from this research, since it provides insight into how the regional water budget behaves, which is commonly difficult to determine accurately by other, less direct, means.

Conflicts of interest

The authors of this research have no conflicts of interest to declare.

Acknowledgements

The authors of this research would like to thank the managers of the Gudmundsen Sandhills Research Laboratory for maintenance and upkeep of the facility. We also appreciate the independent peer reviews. This research was supported by internal funds associated with the University of Nebraska, Lincoln's Agricultural Research Division.

References

Albertson, F.W., 1937. Ecology of mixed prairie in west central Kansas. Ecol. Monogr. 7, 481–547. http://dx.doi.org/10.2307/1943101.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper no. 56, Rome, Italy.

ASCE-EWRI, 2005. In: Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., Snyder, R.L. (Eds.), The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers 69 p.

Barnes, P.W., Harrison, A.T., 1982. Species distribution and community organization in a Nebraska sandhills mixed prairie as influenced by plant/soil-water relationships. Oecologia (Berlin) 52, 192–201. http://dx.doi.org/10.1007/BF00363836.

Billesbach, D.P., Arkebauer, T.J., 2012. First long-term, direct measurements of evapotranspiration and surface water balance in the Nebraska Sand Hills. Agric. For. Meterol. 156, 104–110. http://dx.doi.org/10.1016/j.agrformet.2012.01.001.

Billesbach, D.P., Fischer, M.L., Torn, M.S., Berry, J.A., 2004. A portable eddy covariance system for the measurement of ecosystem-atmosphere exchange of CO2, water vapor, and energy. J. Atmos. Ocean. Technol. 21, 639–650. http://dx.doi.org/10.1175/1520-0426(2004)021 < 0639:APECSF > 2.0.CO;2.

Bleed, A.S., Flowerday, C.A. (Eds.), 1989. An Atlas of the Sand Hills. Conservation Survey Division, University of Nebraska, Lincoln, NE.

Bowen, I.S., 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Phys. Rev. 27, 779–787. http://dx.doi.org/10.1103/PhysRev.27.779.

Burba, G.G., Verma, S.B., 2001. Prairie growth, PAR albedo and seasonal distribution of energy fluxes. Agric. For. Meterol. 107 (3), 227–240. http://dx.doi.org/10.1016/S0168-1923(00)00233-1.

Burba, G.G., Verma, S.B., Kim, J., 1999a. Surface energy fluxes of *Phragmites australis* in a prairie wetland. Agric. For. Meterol. 94, 31–51. http://dx.doi.org/10.1016/S0168-1923(99)00007-6.

Burba, G.G., Verma, S.B., Kim, J., 1999b. A comparative study of surface energy fluxes of three communities (*Phragmites australis, Scirpus acutus, and open water*) in a prairie wetland ecosystem. Wetlands 19 (2), 451–457.

Burzlaff, D.F., 1962. A soil and vegetation inventory and analysis of three Nebraska sandhills range sites. Neb. Agric. Exp. Stn. Bull. 206.

Campbell, G.S., Norman, J.M., 1998. Environmental Biophysics, 2nd edition. Springer, New York.

Christie, E.K., 1981. Biomass and nutrient dynamics in a C4 dominated semi-arid Australian grassland community. J. Appl. Ecol. 18 (3), 907–918. http://dx.doi.org/10.2307/2402381.

George, B.A., Shende, S.A., Raghuwanshi, N.S., 2000. Development and testing of an irrigation model. Agric. Water. Manag. 46, 121–136. http://dx.doi.org/10.1016/S0378-3774(00)00083-4.

Gosselin, D.C., Drda, S., Harvey, F.E., Goeke, J., 1999. Hydrologic dynamics of two interdunal valleys in the central Sand Hills, Nebraska. Ground Water 37 (9), 24–33. http://dx.doi.org/10.1111/j.1745-6584.1999.tb01192.x.

Gosselin, D.C., Sridhar, V., Harvey, F.E., 2006. Hydrological effects and groundwater fluctuations in interdunal environments in the Nebraska Sand Hills. Great Plains Res. 16, 17–28.

Haacker, E.M.K., Kendall, A.D., Hyndman, D.W., 2015. Water level declines in the High plains aquifer: predevelopment to resource senescence. Groundwater 54 (2), 231–242. http://dx.doi.org/10.1111/gwat.12350.

Healey, N.C., Irmak, A., Arkebauer, T.J., Billesbach, D.P., Lenters, J.D., Hubbard, K.G., Allen, R.G., Kjaersgaard, J., 2011. Remote sensing and in situ-based estimates of evapotranspiration for subirrigated meadow, dry valley, and upland dune ecosystems in the semi-arid sand hills of Nebraska, USA. Irrig. Drain. Syst. 25 (3), 151–178. http://dx.doi.org/10.1007/s10795-011-9118-x.

High Plains Regional Climate Center (HPRCC), 2010. High Plains Regional Climate Center Station Data. Online at. Accessed 8 August 2009. http://www.hprcc.unl.edu/awdn.

Kisekka, I., Aguilar, J., 2016. Deficit irrigation as a strategy to cope with declining groundwater supplies: experiences from Kansas. Emerging Issues in Groundwater Resources. Springer International Publishing, pp. 51–66.

Lenters, J.D., Cutrell, G.J., Istanbulluoglu, E., Scott, D.T., Herrman, K.S., Irmak, A., Eisenhauer, D.E., 2011. Seasonal energy and water balance of a *Phragmites australis*-dominated wetland in the Republican River basin of south-central Nebraska (USA). J. Hydrol. 408 (1-2), 19–34. http://dx.doi.org/10.1016/j.jhydrol.2011.07.010.

Loope, D., Swinehart, J., 2000. Thinking like a dune field: geologic history in the Nebraska Sand Hills. Great Plains Res. 10, 5–35.

McGuire, V.L., 2009. Water-Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005-2006, and 2006-2007. United States Geological Survey Ground-Water Resources Program Scientific Investigations Report 2009-5019.

McGuire, V.L., Johnson, M.R., Schieffer, R.L., Stanton, J.S., Sebree, S.K., Verstraeten, I.M., 2000. Water in storage and approaches to ground-water management, high plains aquifer, 2000. United States Geological Survey (USGS) Circular, 1243.

McMahon, P.B., Dennehey, K.F., Bruce, B.W., Gurdak, J.J., Qi, S.L., 2007. Water-Quality Assessment of the High Plains Aquifer, 1999–2004 (US Geological Survey, Reston, VA), Professional Paper 1749.Water-Quality Assessment of the High Plains Aquifer, 1999–2004 (US Geological Survey, Reston, VA), Professional Paper 1749.

Nativ, R., 1992. Recharge into Southern High plains aquifer – possible mechanisms, unresolved questions. Environ. Geol. Water Sci. 19, 21–32. http://dx.doi.org/10.1007/BF01740574.

Pool, R.J., 1914. A study of the vegetation of the sandhills of Nebraska. Minnesota. Botany Stud. 4, 189–312.

Pruegar, J.H., Hatfield, J.L., Aase, J.K., Pikul, J.L.Jr., 1997. Bowen-ratio comparisons with lysimeter evapotranspiration. Agron. J 89 (5), 730–736. http://dx.doi.org/10.2134/agronj1997.00021962008900050004x.

Radell, D.B., Rowe, C.M., 2008. An observational analysis and evaluation of land surface model accuracy in the Nebraska Sand Hills. J. Hydromet. 9, 601–621. http://dx.doi.org/10.1175/2007JHM913.1.

Ray, S.S., Dadhwal, V.K., 2001. Estimation of crop evapotranspiration of irrigation command area using remote sensing and GIS. Agric. Water Manag. 49, 239–249. http://dx.doi.org/10.1016/S0378-3774(00)00147-5.

Rodriguez-Iturbe, I., 2000. Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamics. Water Resour. Res. 36 (1), 3–9. http://dx.doi.org/10.1029/1999WR900210.

Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., McMahon, P.B., 2012. Groundwater depletion and sustainability of irrigation in the US High plains and Central Valley. PNAS 109 (24), 9320–9325. http://dx.doi.org/10.1073/pnas.120031109.

Sridhar, V., 2007. Evapotranspiration estimation and scaling effects over the Nebraska sandhills. Great Plains Res. 17, 35–45.

Sridhar, V., Hubbard, K.G., 2010. Estimation of the water balance using observed soil water in the Nebraska Sandhills. J. Hydrol. Eng. 15 (1), 70–78. http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000157.

Sridhar, V., Wedin, D.A., 2009. Hydrological behavior of grasslands of the Sandhills of Nebraska: water and energy-balance assessment from measurements, treatments, and modeling. Ecohydrol. J. 2 (2), 195–212. http://dx.doi.org/10.1002/eco.61.

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. J. Irrig. Drain. Eng. 132 (5), 463–473. http://dx.doi.org/10.1061/(ASCE)0733-9437(2006)132:5(463).

Szilagyi, J., Jozsa, J., 2013. MODIS-aided statewide net groundwater-recharge estimation in Nebraska. Ground Water 51 (5), 735–744. http://dx.doi.org/10.1111/j.1745-6584.2012.01019.x.

Szilagyi, J., Harvey, E.F., Ayers, J.F., 2003. Regional estimation of base recharge to ground water using water balance and a base-flow index. Ground Water 41, 504–513. http://dx.doi.org/10.1111/j.1745-6584.2003.tb02384.x.

Szilagyi, J., Harvey, F.E., Ayers, J.F., 2005. Regional estimation of total recharge to ground water in Nebraska. Ground Water 43 (1), 63–69. http://dx.doi.org/10.1111/j.1745-6584.2005.tb02286.x.

Szilagyi, J., Zlotnik, V.A., Gates, J.B., Jozsa, J., 2011. Mapping mean annual groundwater recharge in the Nebraska Sand Hills, USA. Hydrogeol. J. 19 (8), 1503–1513. http://dx.doi.org/10.1007/s10040-011-0769-3.

Tidwell, V.C., Vargas, V.N., Jones, S.M., Dealy, B.C., Shaneyfelt, C., Smith, B.J., Moreland, B.D., 2016. Analysis of High Plains Resource Risk and Economic Impacts. Sandia National Laboratories Report, SAND2016-3405. pp. 1–175.

Tolstead, W.L., 1942. Vegetation in the northern part of cherry County, Nebraska. Ecol. Monogr. 12, 255–292. http://dx.doi.org/10.2307/1943543.

United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS), 2013. 2012 Census of Agriculture. Farm and Ranch Irrigation Survey, vol. 3 Part 1. AC-12-SS-1.

United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS), 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. United States Department of Agriculture Handbook. pp. 296.

United States Department of Homeland Security (USDHS), 2015. Analysis of High Plains Resource Risk and Economic Impacts. National Protection and Programs Directorate: Office of Cyber and Infrastructure Analysis Report. pp. 1–33.

United States Geological Survey (USGS), 1997. Groundwater Atlas of the United States, HA-730D.Groundwater Atlas of the United States, HA-730D.

USDA-NRCS, 2011. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture (USDA-NRCS). Available online at. Soil Survey Geographic (SSURGO) Database Accessed 8 August 2011. http://sdmdataaccess.nrcs.usda.gov.

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. J. Hydrol. 349, 88–97. http://dx.doi.org/10.1016/j.jhydrol.2007.10.027.

Wang, T., Wedin, D., Zlotnik, V.A., 2009. Field evidence of a negative correlation between saturated hydraulic conductivity and soil carbon in a sandy soil. Water Resour. Res. 45, W07503. http://dx.doi.org/10.1029/2008WR006865.

Weeks, J.B., Gutentag, E.D., 1989. The High plains regional aquifer-geohydrology in aquifers of the Midwestern area. Regional Aquifer Systems of the United States: American Water Resources Association Monograph Series No. 13. L.A. Swain and A.I. Johnson, Bethesda MD.

Xu, C.Y., Chen, D., 2005. Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. Hydrol. Process. 19, 3717–3734. http://dx.doi.org/10.1002/hyp.5853.

Yamori, W., Hikosaka, K., Way, D.A., 2014. Temperature response of photosynthesis in C_3, C_4, and CAM plants: temperature acclimation and temperature adaptation. Photosynth. Res. 119 (1), 101–117. http://dx.doi.org/10.1007/s11120-013-9874-6.