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Evapotranspiration from a Mongolian steppe under grazing and its environmental constraints

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Raise

Summary The magnitude and seasonal dynamics of evapotranspiration (ET) for a steppe in central Mongolia was estimated over a full year period (from 25 March 2003 to 24 March 2004, 366 days) using the eddy covariance (EC) technique. The steppe, typical of central Mongolia, is dominated by temperate C_3 plants and experiences moderate grazing. The environmental constrains over ET for the steppe were evaluated by examining the responses of ET to biotic (leaf area index) and abiotic (atmospheric evaporative demand and soil moisture condition) factors. Seasonal variations in ET followed closely the variation in leaf area index. Change in soil moisture was the most important environmental factor controlling the dynamics of ET in this grassland ecosystem, indicated by the strong susceptibility of ET and the Priestley–Taylor parameter (α, calculated as the ratio of the measured ET to the equilibrium ET) to soil water content. The α also showed a distinct seasonal variability, but its value on average was lower than 0.5 during most of the measurement period, suggesting that the steppe was limited in water supply. The maximum daily ET rate was 2.8 mm d^{-1}. Cumulative ET during the study period estimated directly by the EC method was 163 mm, which was 66% of the precipitation received at the site during the same time period (248 mm).

Introduction

Apart from precipitation, water vapor exchange (also called evapotranspiration, ET or latent heat flux, *LE*) between the atmosphere and terrestrial ecosystems is the major

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component of the terrestrial hydrological budget (Brutsaert, 1982). ET, by definition, is the process by which ecosystems return soil water, initially charged from precipitation (PPT), to the atmosphere to balance regional and global water cycling through two pathways: soil evaporation and plant transpiration (Brutsaert, 1982). ET at a given site depends largely on the availability of water and energy, and thus is site-specific. For example, in arid and semiarid environments across the world, limitations due to soil moisture are believed to be the most important factor affecting ET (Noy-Meir, 1973; Sala et al., 1992). ET is also controlled by canopy architecture and development, soil characteristics, and a variety of in situ environmental variables (Kelliher et al., 1995; Wilson et al., 2002a).

In Mongolia, steppe covers 83% of the territory ($\sim 1.3 \times 10^6$ km^2) (World Resources Institute, 2003). It lies mainly in the central part of the country, the transitional zone bordering the Gobi deserts to the south and mountain taiga forests to the north (Hilbig, 1995; Batjargal and Enkhbat, 1998). The steppe ecosystems are associated with the semiarid and arid continental temperate climates of the region, and are ecologically fragile and sensitive to climate change and anthropogenic disturbances. Recent studies have shown that in central and southeastern Mongolia, the annual mean temperature has shown an increasing trend (Yatagai and Yasunari, 1994; Dagvadorj and Mijiddorj, 1996) while summer precipitation has shown a decreasing trend over the past half century (Yatagai and Yasunari, 1995). The Mongolian steppe ecosystems play an important role in mitigating regional and even global climate through their interaction with the atmosphere (Yatagai and Yasunari, 1994, 1995). In turn, climate change may give rise to a modification in surface boundary conditions with respect to water vapor and energy exchange (Houghton et al., 2001). However, our knowledge of the ecosystem functioning of the Mongolian steppe is still lacking (Sugita et al., 2006). Therefore, it is crucial that information about water vapor and energy exchange is obtained in order to improve understanding of the coupling among water and carbon cycling, steppe management, and climate change in Mongolia. Only a few studies have assessed the hydrological processes of the steppe ecosystems in Mongolia (e.g. Ma et al., 2003; Miyazaki et al., 2004; Zhang et al., 2005). By using multiyear growing season measurements of hydrometeorological elements and surface energy fluxes from the Automatic Weather Station at a steppe in central Mongolia, Miyazaki et al. (2004) have found that ET and grass growth are highly associated with precipitation and soil water storage before July. By using observations obtained with microlysimeters, Zhang et al. (2005) have evaluated the growing season eco-hydrological characteristics of a sparse steppe at the edge of the Eurasian cryosphere in Mongolia, and have found that for grass growth, atmospheric heat stress is weaker than soil water stress, and soil evaporation is the prime contributor to ET. These works provide valuable information about the functioning of Mongolian steppe ecosystems. As part of the RAISE project, this study is designed to quantify water vapor exchange for a full year period and to establish its relationship to biotic and abiotic variables above a steppe in central Mongolia by means of the eddy covariance technique, which is now widely used for continuous flux measurements (Baldocchi, 2003).

Materials and methods

Site information

The study site is located at Kherlenbayan-Ulaan (KBU), Hentiy province, Mongolia (lat. 47°12.838′N, long. 108°44.240′E). The elevation is 1235 m above sea level. The soil is Kastanozem. For the surface horizon (top 30 cm), the bulk density is 1.45 g cm^{-3} on average, the hydraulic conductivity at 15 °C averages 0.01–0.08 mm s^{-1}, and the overall porosity is about 45% (Asano, 2004). There are scattered stones on the ground surface and in the top 2-m of soil profiles.The climate is continental in the temperate zone. Average annual air temperature is 1.2 °C and average annual precipitation is 181 mm, of which 88% falls from June through September. The climate data are from the report (1993–2002) of the meteorological station at KBU operated by the Institute of Meteorology and Hydrology (IMH) of Mongolia (around 10% of data are missing and the averages are from the remaining data). The vegetation at the site belongs to the dry steppe. In terms of biomass and leaf area index, about 75% of the vegetation is dominated by temperate C_3 plants (e.g. *Stipa krylovii*, *Carex duriuscula*, and *Artemisia frigida*). The steppe has experienced grazing over centuries. The site has been described in more detail by Li et al. (2005) and Li et al. (2006).

Measurements

The site was set up and instrumented in March 2003 as a component of the RAISE project for measuring microclimatic variables, water vapor, CO_2, and energy fluxes by using the eddy covariance (EC) technique. The EC system included a 3-D ultrasonic anemometer–thermometer (SAT-550, Kaijo Sonic Co., Tokyo, Japan, 15-cm path length) and an open path infrared gas (CO_2/H_2O) analyzer (IRGA) (Li7500, LICOR Inc., Lincoln, NE, USA, 15-cm path length). Two sensors were installed side by side aligned in the E–W direction around 3.5 m above the ground. The tower was also equipped to measure four components of radiation (up and down, long and short wave radiation) (CNR1, Kipp & Zonen BV, Delft, the Netherlands) at 2.5 m, and air temperature and humidity (HMP-45D, Vaisala Inc., Helsinki, Finland) at 2.5 m above the ground. Output signals of wind speed and gas concentration were sampled at 10 Hz while output signals of radiation, temperature and humidity were scanned at 0.2 Hz. The IRGA was calibrated three times during the measurement period following the procedure in the LI-COR Instruction Manual (LI-COR Inc, 2000). The half-hourly means of scalar radiation fluxes, temperature and humidity were computed online and recorded continuously by a CR23X datalogger (Campbell Scientific, Logan, UT, USA).

We also measured the soil temperature profile at 5, 10, 20, 30, 50, 70, 100, and 150 cm depths by platinum resistance thermometers (C-PT, CLIMATEC Inc., Tokyo, Japan), soil heat flux at 2 and 10 cm depths by soil heat plates (PHF-1.1, REBS, Inc., Seattle, WA, USA), the soil moisture profile at 10, 20, 30, 50, 70, 100 and 150 cm depths by time domain reflectometry probes (CS616, Campbell Scientific, Logan, UT, USA), and precipitation by a tipping bucket rain gauge (CYG-52202, RM Young Company, Traverse City, MI, USA). They were sampled at 0.1 Hz and the 30-min mean data were logged on a CR10X datalogger (Campbell Scientific, Logan, UT, USA). The measurements were carried out from 25 March 2003 to 24 March 2004, and are expected to continue at least until the end of 2006.

Leaf area index (LAI) and mean canopy height were measured in June, July, August and September during the 2003 growing season by the clipping method. LAI gaps were linearly interpolated to daily intervals. For a detailed account of the measurements see Li et al. (2005) and Sugita et al. (2006).

Data processing

The net all-wave radiation (R_n) above the steppe is partitioned between sensible heat flux (H), latent heat flux (LE), soil heat flux (G), and the energy storage within the canopy (ΔS) (Monteith and Unsworth, 1990):

$$R_n = LE + H + G + \Delta S. \quad (1)$$

The storage term is omitted in this study since it usually accounts for a fairly small fraction in R_n relative to other components. G was directly measured with a soil heat plate at a depth of 2 cm, and LE and H were quantified by the EC technique (Monteith and Unsworth, 1990):

$$H = \rho c_P \overline{w'T'}, \quad (2)$$

$$LE = \rho L \overline{w'q'}, \quad (3)$$

where ρ is the air density at a given air temperature; c_P is the specific heat capacity of air at constant pressure; L is the latent heat of vaporization of water; w', T' and q' denote fluctuations of vertical wind speed (w), air temperature (T) and specific humidity (q), respectively; and over bars indicate the average of the product over the sampling interval. Positive scalar fluxes denote mass and energy transfer from the canopy surface to the atmosphere while negative fluxes signify the reverse.

Data post-processing included (1) the cospectral correction for the CO_2 and water vapor fluxes using the algorithm proposed by Eugster and Senn (1995), and (2) the correction of the scalar fluxes for the density effect following the algorithm described by Webb et al. (1980) and Leuning and Moncrieff (1990).

Following the method proposed by Falge et al. (2001), we filled the data breaks caused by sensor malfunctioning, precipitation events, sensor maintenance, IRGA calibration, power failure, etc.: (1) linear interpolation was used to fill the gaps that were less than two hours by calculating an average of the values immediately before and after the data gaps; (2) other data gaps were filled using empirical relationships (look-up tables), such as the regressions of H or LE vs. air temperature (T_a) or atmospheric water vapor pressure deficit (VPD) in cases where those relationships could be established; and (3) if these relationships could not be established due to missing meteorological data, we used mean daily variations to fill the gaps. Gaps in the precipitation data in the winter season when the precipitation gauge failed were filled with data from the IMH meteorological station at KBU.

We assessed the overall performance of the EC system by checking the closure of the surface energy budget in terms of (Wilson et al., 2002b):

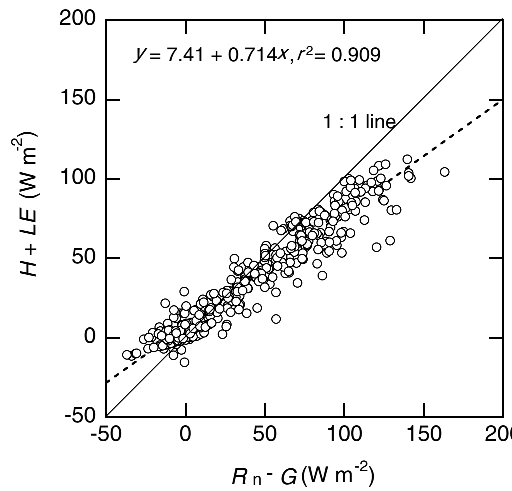

Figure 1 Test of energy balance closure: the daily sums of sensible (H) and latent heat fluxes (LE) are plotted against the daily differences between net radiation (R_n) and soil heat flux (G).

$$LE + H = a_0 + a_1(R_n - G), \quad (4)$$

where a_0 (W m^{-2}) and a_1 are intercept and slope, respectively. Since the storage term was not measured, the cumulative values for 24-h periods were used to minimize the possible effect of the energy storage upon the closure. During the measurement period from 25 March 2003 to 24 March 2004 (366 days), a_0, a_1 and the coefficient of determination (r^2) were 7.41 W m^{-2}, 0.714 and 0.909, respectively (Fig. 1). The ratio of $(LE + H)/(R_n - G)$ was 0.81. In the annual total, $(LE + H)$ accounted for about 87% of $(R_n - G)$.

Results and discussion

Daily patterns of energy partitioning in relation to canopy development and precipitation

The daily pattern for energy partitioning was clearly affected by precipitation (PPT) at the site. Fig. 2 illustrates the three day ensemble mean diurnal cycles of the energy components (LE, H and G) and the Bowen ratio ($\beta = H/LE$) prior to and immediately after the PPT at two canopy development stages: the early growth stage (Stage I; day of year, DOY 129–138) and the peak growth stage (Stage II, DOY 221–231). Both stages experienced a shift from dry to wet due to PPT (12.2 mm from DOY 132 to 135 for Stage I, and 0.7 mm on DOY 224 and 17.3 mm from DOY 226 to 228 for Stage II). Soil water content (SWC) at a depth of 10 cm increased from 7.0% (7.5%) prior to the PPT to 8.6% (11.7%) after the PPT for Stage I (Stage II). Regardless of the growth stage and the PPT effect, the ensemble diurnal trends of R_n and its components in Fig. 2 exhibit similar shaped pattern. The R_n was mainly partitioned to H and G (Fig. 2), suggesting the available energy was primarily used for heating the air and the soil. Relative to G and H, LE was rather small in magnitude (<40 W m^{-2} when the canopy was dry, and <100 W m^{-2} when the canopy was wet). The nighttime energy fluxes were all quite small (<50 W m^{-2}), and among them G was the major contributor to R_n (Fig. 2).

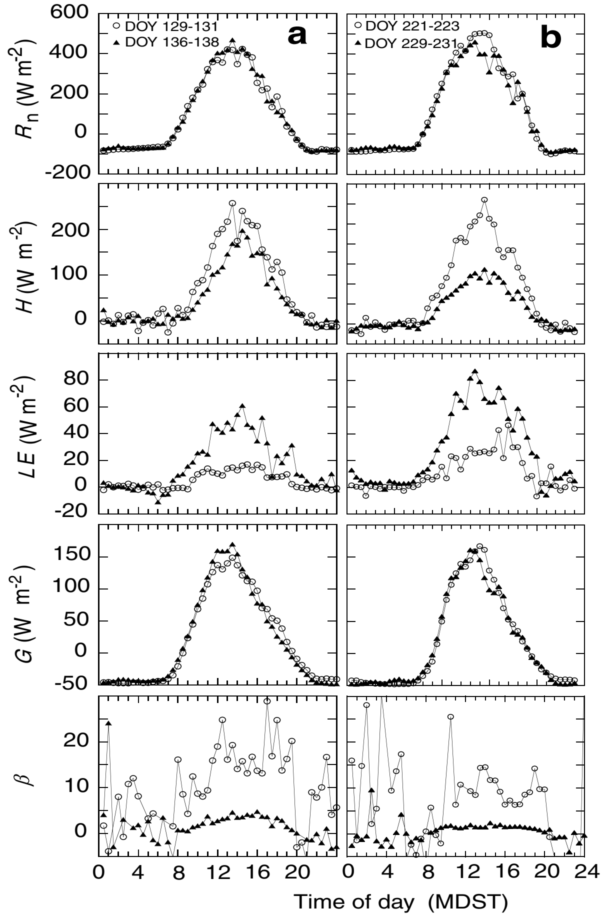

Figure 2 Three day ensemble half-hourly average of net radiation (R_n) and its partitioning between sensible (H), latent (LE) and soil heat flux (G) as a function of time of day prior to (open circles) and immediately after (solid triangles) the precipitation event: (a) Stage I, and (b) Stage II. Time of day is Mongolian Daylight-saving Standard Time (MDST). The time difference between MDST and local solar time is 1.8 h. Data are summarized in Table 1.

To account for the differences in the energy partitioning between the two growth stages, we computed the partitioning fraction of H, LE, and Gin R_n, i.e. the ratios H/R_n, LE/R_n and G/R_n (Table 1). Irrespective of the PPT effect, a greater fraction of R_n was partitioned to LE at Stage II than at Stage I while the proportions of H and G in R_n were reduced at Stage II relative to Stage I. This modification in the pattern of energy partitioning is principally due to changes in LAI. The larger LAI at the Stage II appeared to increase evaporative consumption of the available energy. At both the growth stages, the PPT did not significantly affect the fraction of R_n consumed in G, but considerably affected the relative contribution of H and LE to R_n. For example, at Stage I, the differences between the daily average energy fluxes prior to and after PPT indicate that H/R_n (LE/R_n) decreased (increased) by 29% (260%) but that G/R_n did not change (Table 1).

The relative contribution of LE and H to R_n was also well illustrated by β which displayed a broad plateau shape when

Table 1 Daily totals of net radiation (R_n), sensible heat (H), latent heat (LE) and soil heat (G) fluxes, and derived ratios of H/R_n, LE/R_n, G/R_n and H/LE (i.e. the Bowen ratio) at two canopy development stages of a steppe in central Mongolia with respect to the precipitation (PPT) effect

Stage	DOY	LAI (m^2 m^{-2})	R_n (MJ m^{-2} d^{-1})	G (MJ m^{-2} d^{-1})	H (MJ m^{-2} d^{-1})	LE (MJ m^{-2} d^{-1})	H/R_n (MJ m^{-2} d^{-1})	G/R_n (MJ m^{-2} d^{-1})	LE/R_n (MJ m^{-2} d^{-1})	H/LE (MJ m^{-2} d^{-1})
Stage I, before PPT	129–131	0.08	7.50	1.63	5.78	0.39	0.77	0.22	0.05	14.7
Stage I, after PPT	136–138	0.12	7.87	1.73	4.02	1.44	0.51	0.22	0.18	2.8
Stage II, before PPT	221–223	0.55	9.56	1.37	6.81	0.91	0.71	0.14	0.10	7.5
Stage II, after PPT	229–231	0.57	8.67	1.35	3.11	2.47	0.36	0.16	0.28	1.3

the canopy was wet but fluctuated substantially when the canopy was dry (Fig. 2). Values of β were significantly reduced as a result of PPT events. For example, at Stage I, the daily β value was decreased by 80% from 16.2 before PPT to 3.3 after PPT (Table 1).

The effect of moisture conditions on the pattern of energy partitioning in this study is similar to those reported for tussock grassland in New Zealand (Hunt et al., 2002) and for tall grass prairie in the USA (Kim and Verma, 1990; Verma et al., 1992; Bremer et al., 2001). However, as compared with these grasslands, the partitioning of R_n among H, LE and G were somewhat different in magnitude. For the Mongolian steppe, whether it was moisture limited or non-moisture limited, the LE/R_n ratios were comparatively low and the H/R_n ratios were correspondingly high. Also, on a daily basis the G/R_n ratios were noticeably higher (>0.3 in general) at our site than for the above-mentioned grasslands, which generally have G/R_n ratios ranging from 0.06 to 0.20 (Kim and Verma, 1990; Verma et al., 1992; Bremer et al., 2001; Hunt et al., 2002). Differences in the pattern of energy partitioning are caused by differences in surface conditions that characterize different grassland ecosystems, for example, climate, vegetation cover, and soil moisture availability (Stull, 1988; Bremer et al., 2001; Hunt et al., 2002). Hence, relatively high ratios of H/R_n and G/R_n are indicative of the sparse vegetation cover and arid climate at the site.

Evapotranspiration during the growing season

According to phenological data from the IMH meteorological station at KBU, the steppe started growing around 23 April (DOY of 113) and stopped growing around 21 October (DOY 294) in 2003. LAI increased rapidly from late April to late July (Fig. 3a). The maximum LAI occurred in late August when it reached a value of 0.57 $m^2\ m^{-2}$. Values of LAI decreased precipitously from late August through late October, indicating senescence (Fig. 3a). The mean canopy height (h_c) was 12 ± 7.5 SD cm measured in early July 2003, and the maximum h_c reached 45 cm (mean 20 ± 12 SD cm) after *Stipa krylovii* eared in late July.

Evapotranspiration (ET) was associated with the seasonal development of leaf area. The daily ET rate exhibited an increasing trend with an increase of LAI before July, corresponding to the rapid growth of the grasses. When the canopy entered the peak growth period (LAI >0.5, from late July to mid August), due to the deficiency in water supply, ET was pronouncedly reduced. After late August, ET decreased with senescence (Fig. 3a).

The growing season (DOY 113—294, 182 day) was in phase with the rainy season at the site. During this 182-day period, the steppe received 243 mm of PPT (Fig. 3b), about 5% higher than that (232 mm) recorded by the IMH meteorological station at KBU. Temporal variation of volumetric SWC in the upper soil layers was highly associated with PPT. SWC at a depth of 10 cm traced PPT spells rather closely, while SWC at a depth of 30 cm was delayed with respect to PPT. SWC at a depth of 30 cm displayed only a slight increase before September. SWC beneath a depth of 70 cm remained at a near-constant value below 5%, suggesting that the ground water recharge was very limited.

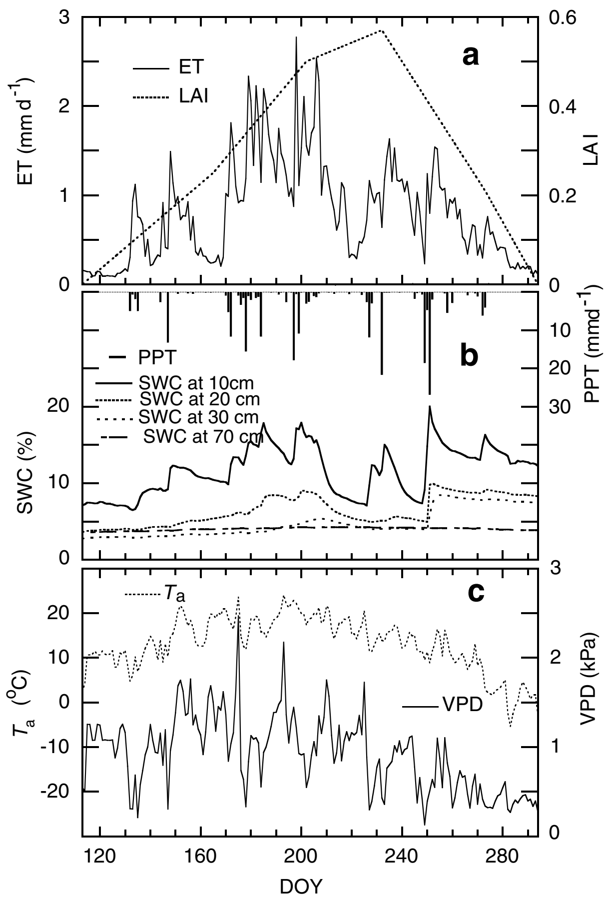

Figure 3 Temporal variation of (a) daily evapotranspiration rate (ET) and leaf area index (LAI), (b) daily precipitation (PPT) and daily mean soil water content (SWC) at depths of 10, 20, 30 and 70 cm, and (c) daily mean air temperature (T_a) and corresponding atmospheric vapor pressure deficit (VPD) during the growing season.

Daily ET rates were highly dependent upon the dry—wet fluctuations of the steppe, or variability in SWC caused by PPT events (Fig. 3a and b). Several peak values of ET were usually observed following PPT events that largely affected SWC. ET was thus observed to fluctuate in synchrony with SWC at a depth of 10 cm, increasing with an increase of SWC and decreasing with the desiccation of the soil (Fig. 3a and b). For example, when SWC at a depth of 10 cm from 15.6% on DOY 206 to 7.4% on DOY 222, ET decreased from 2.5 to 0.3 mm d^{-1} correspondingly.

Daily mean T_a and VPD also varied dramatically across the growing season (Fig. 3c). However, ET appeared to show an inconsistent relationship to variation in both T_a and VPD. When the canopy was wet, high ET rates coincided with high T_a or VPD values, whereas when the canopy suffered a water shortage, daily ET rates were inversely related to T_a or VPD (Fig. 3a and c).

During the growing season, the daily ET rate varied from 0.1 (early May) to 2.8 mm d^{-1} (DOY 198), with an average of 0.8 ± 0.6 mm d^{-1}. On most days of the growing season, ET was less than 1.5 mm d^{-1} (160 days, 88%, Fig. 4a). Among these 160 days, there were 71 days (44%) of ET <0.5 mm d^{-1} (Fig. 4a and the inset therein). There were only two days on

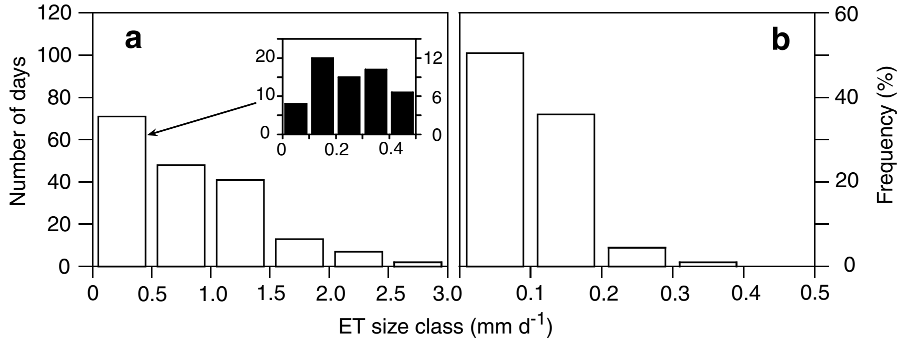

Figure 4 The size distribution of daily evapotranspiration (ET) rates for (a) the growing season (DOY 113-294 of 2003) and (b) the non-growing season (DOY 84-112 of 2003, DOY 295 of 2003 to DOY 84 of 2004). The inset shows the size distribution of daily ET rates for ET <0.5 mm d^{-1} for the growing season.

which ET exceeded 2.5 ± 0.6 mm d^{-1}. The total ET during the 182-day growing period was 145.7 mm, which was about 63% of PPT. During the non-growing season, ET was generally lower than 0.4 mm d^{-1}. The day number of ET <0.2 mm d^{-1} was 173 (94%), of which 101 days had ET <0.1 mm d^{-1} (Fig. 4b). The total ET during the non-growing period was 17.2 mm, with an average of 0.1 ± 0.1 mm d^{-1}.

The lower ET rates (0.1—2.8 mm d^{-1}) in this study were similar in magnitude to those (0.5—3.0 mm d^{-1}) reported for the northern temperate grassland in Canada at a similar latitude with similar peak LAI values (0.4—0.6) under conditions of PPT close to or significantly below the multiyear average of 378 mm (Wever et al., 2002). At a *stipa* steppe (LAI 0.4—1.3) at Arvaikheer, Mongolia (46.23°N, 102.82°E), about 460 km west of KBU, Miyazaki et al. (2004) also observed lower ET rates (0.2—1.8 mm d^{-1}), which are compatible with the ET rates at our steppe site. However, the ET rates at our site were relatively low compared with the ET (1.0—4.7 mm d^{-1}) from the grazed and non-grazed semi-arid grasslands of the Great Plains of the USA, which are at a similar latitude, have an annual mean PPT varying from 345 to 517 mm (multiyear mean of 404 mm) and a peak LAI varying from 0.38 to 0.59 (Frank, 2003). Also, the Mongolian steppe had lower ET rates than the tall grass native prairies of the USA (Verma et al., 1992; Weltz and Blackburn, 1995; Ham and Knapp, 1998; Dugas et al., 1999; Bremer et al., 2001), which have ET rates ranging from 2.1 to 9.5 mm d^{-1}. This is mainly due to the fact that the tall grass native prairies generally receive more PPT (over 600 mm) and have higher LAI (2.0—3.5) than the Mongolian steppe. The maximum ET rate of 2.8 mm d^{-1} (DOY 198) is considerably lower than the maximum ET rates (3.0—6.2 mm d^{-1}) for the global grassland ecosystems in the literature (Kelliher et al., 1993; Dugas et al., 1999; Meyers, 2001; Hunt et al., 2002 Wever et al., 2002). Therefore, lower ET rates may be the nature of the Mongolian steppe that has low stature and low leaf area index in association with low precipitation.

Biotic and abiotic constraints over water vapor exchange

Evapotranspiration is principally associated with the complicated interaction between biotic and abiotic variables. The major biotic variables include the green leaf area index, ecophysiological features of plant functional type, and the phenological stage of the canopy. The major abiotic variables involve solar radiation, wind, temperature, humidity, and soil moisture availability (e.g. McNaughton and Jarvis, 1991; Kelliher et al., 1995; Wilson et al., 2002a). Since ET occurred dominantly in the growing period, our discussion on biotic (leaf area index) and abiotic (soil water conditions and atmospheric evaporative demand) controls over ET will be focused on this period, except as otherwise indicated.

Since ET was found to be highly linked with soil water conditions during the growing season (Fig. 3), we compiled the ET data with respect to SWC at a depth of 10 cm (SWC $\leqslant$ 10%, 10 < SWC $\leqslant$ 15%, and SWC > 15%), and then examined ET in response to LAI and VPD. At each SWC class, there was a significant linear relationship between ET and LAI (Fig. 5). The slope, i.e. an increase of ET per unit LAI, increased with an increase of SWC. Between 21% and 47% of the variance in ET at the site was associated with canopy development as represented by LAI.

The response of ET to VPD was more complicated. Except under conditions of SWC > 15%, only a small portion of the variance of ET could be accounted for by the variance in VPD (Fig. 6). When the steppe was under water stress (SWC $\leqslant$ 10%), the daily ET rate was inversely related to VPD (Fig. 6), suggesting that the water supply from the soil could not meet the atmospheric evaporative demand. Also, under water-stressed conditions, soil evaporation was likely to be the prime contributor to ET due to stomatal closure induced by drought stress. In contrast, when the steppe was not limited by water supply (SWC > 15%), ET was positively related to VPD (Fig. 6). Since vegetation cover was very low at the site, a linear increase of ET with increasing VPD under well-watered conditions could also come mainly from soil evaporation. Rapid decrease in surface soil water after a substantial PPT event proved such evidence for this trend (Fig. 3b).

To further assess the effect of water availability on ET, we compared actual ET with the equilibrium ET rate (ET_{eq}) (Priestley and Taylor, 1972), which is defined as:

$$ET_{eq} = \frac{\Delta}{L(\Delta + \gamma)}(R_n - G), \quad (5)$$

where Δ is the slope of the saturated vapor pressure—temperature curve of air, γ is the psychrometric constant. The ratio of ET/ET_{eq}, i.e. the Priestley—Taylor parameter α (Priestley and Taylor, 1972), can be used to depict whether

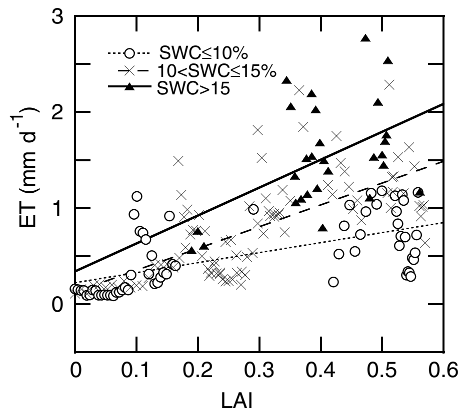

Figure 5 The relationship between daily evapotranspiration rate (ET) and leaf area index (LAI) during the growing season. The data were compiled into three classes of soil water content (SWC) at 10 cm and each class was fitted to a linear function ($ET = b_0 + b_1 \times LAI$):

SWC	b_0	b_1	n	Adjusted r^2	F	P
SWC ⩽10%	0.224 ± 0.058	1.044 ± 0.169	63	0.375	38.2	<0.001
10< SWC ⩽15%	0.128 ± 0.083	2.267 ± 0.253	91	0.468	80.1	<0.001
SWC >15%	0.342 ± 0.425	2.905 ± 1.023	28	0.207	8.06	<0.01

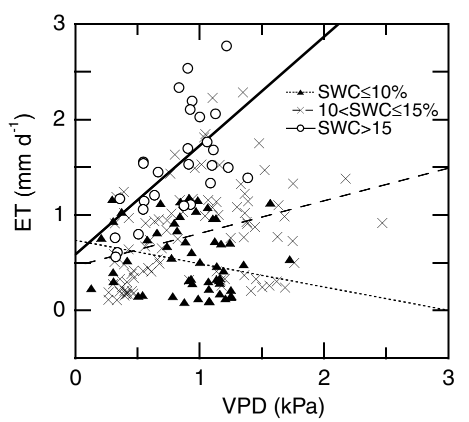

Figure 6 The relationship between daily evapotranspiration rate (ET) and daily mean vapor pressure deficit (VPD) during the growing season. The data were compiled into three classes of soil water content (SWC) and each class was fitted to a linear function ($ET = c_0 + c_1 \times VPD$):

SWC	c_0	c_1	n	Adjusted r^2	F	P
SWC ⩽10%	0.735 ± 0.138	−0.245 ± 0.138	63	0.033	3.14	<0.1
10< SWC ⩽15%	0.464 ± 0.107	0.342 ± 0.101	91	0.105	11.5	<0.005
SWC >15%	0.585 ± 0.247	1.141 ± 0.284	28	0.359	16.1	<0.001

a limitation in water supply exists for the canopy. A wet canopy surface has higher α values than a dry canopy surface (e.g. Price and Woo, 1988; Thompson et al., 1999).

The daily α values at the site were consistently lower than unity, ranging between 0.04 and 0.70, throughout the growing season (Fig. 7). Differences in soil moisture/precipitation can explain most of the variation in α. The α value fluctuated closely with the drying or wetting of the surface soil, decreasing with depletion of soil moisture. Daily mean α values were significantly correlated with SWC at 10 cm in a linear way during the growing season ($\alpha = (0.031 \pm 0.003) \times SWC - (0.065 \pm 0.034)$, $n = 182$, adjusted $r^2 = 0.403$, $F = 123$, $P < 0.001$, see Appendix). The strong dependence of α on water availability at the site agrees well with the observation by Miyazaki et al. (2004) for another Mongolian steppe. Similar to the Mongolian steppe, a C_4 grassland in Oklahoma with a moist and sub-humid climate also displayed a decrease of α with an increase of SWC during the growing season, ranging from 0.2 to 0.6 (Meyers, 2001). This strong effect of water availability on ET for the grassland ecosystem was also reflected in the relationship between α and the canopy surface resistance (r_c, in $s\,m^{-1}$). The

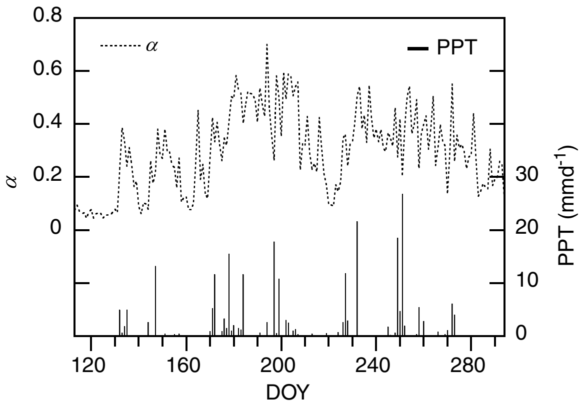

Figure 7 Temporal variation of daily Priestley—Taylor parameter (α) during the growing season. Daily precipitation rates (PPT) are also presented for convenience to explain the seasonal variability of α.

30-min mean values of r_c were derived from an algebraic arrangement of the Penman—Monteith equation after the aerodynamic conductance was computed from wind data (Monteith and Unsworth, 1990). The r_c data under low solar radiation (<100 W m^{-2}) were screened to minimize the effect of low solar radiation. Here we used daily means of 30-min g_c values. It was found that α decreased linearly with increases in r_c (Fig. 8). This is because a deficiency in water supply gives rise to an increase in r_c that restricted ET. On the contrary, when the soil moisture is ample, r_c decreases, and thus ET is enhanced, resulting in higher α values. Our findings with respect to the relationship between α and r_c are consistent with observations in the literature for other grasslands (e.g. McNaughton and Spriggs, 1986; Verma et al., 1992; Valentini et al., 1995; Burba et al., 1999; Wever et al., 2002).

The monthly average α was usually lower than 0.5 except for November 2003 (α = 1.5), December 2003 (α = −0.04),

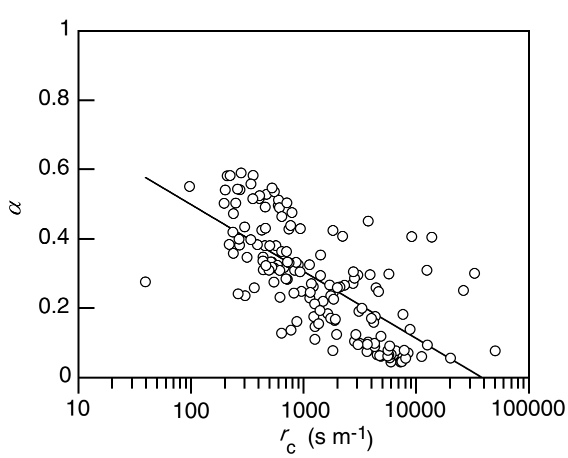

Figure 8 Daily means of the Priestley—Taylor parameter (α) plotted as a function of daily means of canopy surface resistance (r_c) during the growing season. The data were fitted to a logarithmic function (α = (0.886 ± 0.050) − (0.084 ± 0.007) × ln(r_c), n = 158, adjusted r^2 = 0.484, F = 149, P < 0.001).

and January 2004 (α = 1.2) (Table 2). The low α values further suggest that the hydrological conditions of the steppe ecosystem are characterized by the limitation in water supply.

Water balance for the steppe

A strong seasonal variation of ET was observed for the Mongolian steppe ecosystem. Monthly ET budgets are given in Table 2 for the study period. Monthly ET rates varied over an order of magnitude from 0.3 mm per month in December to 48.5 mm per month in July (Table 2). The maximum monthly ET rate was in accord with the maximum monthly PPT. Annually cumulative ET (from 25 March 2003 to 24 March 2004, 366 days) was 162.9 mm, with an average of 0.45 mm d^{-1}. The annual ET rate was considerably lower than the equilibrium ET rate (570.7 mm) (Table 2), typifying the canopy surface where water supply was insufficient. The total PPT during the measurement year measured by the IMH meteorological station at KBU was 248.1 mm. The annual PPT was less than 50% of the annual equilibrium ET.

Assuming that there is no downward infiltration of PPT water (this is probably true since the site is fairly flat with soil water content at 1 m depth nearly constant (<5%) throughout the measurement period), the water balance for the steppe can be approximated as:

$$\mathrm{PPT} - \mathrm{ET} - \Delta\mathrm{ST} = 0, \qquad (6)$$

where ΔST is the soil water storage. Computation using Eq. (6) yielded an annual ΔST of 97.4 mm. Thus, our year round EC measurements suggest that on an annual basis, 66% of PPT was returned to the atmosphere and joined the recycling of water, and the rest (33%) was used for soil water storage in the steppe (Table 2). In comparison with observations by Miyazaki et al. (2004) of another steppe in central Mongolia, soil storage flux at our site is overestimated. In their studies, ΔST varied from 0% to 15% of PPT.

Our EC system did not close the energy balance (Fig. 1). Although this energy imbalance is not avoidable, it might underestimate ET at the site (Wilson et al., 2002b). Taking the energy imbalance into consideration, we recomputed ET by enforcing the energy balance to close with two methods. First, assuming the convective sensible heat flux was correctly measured by the EC, we estimated ET as a residual of the energy budget (Eq. (1)) (Fitzjarrald and Moore, 1994). This method, called the eddy covariance energy balance method or the residual energy method, gave 241.0 mm of the annual ET rate (ET_1 in Table 2). Second, since a test of the energy closure showed that the EC system might underestimate H and LE by about 19% (Fig. 1), we assumed the proportion of underestimate by the EC technique could be equally distributed between H and LE, i.e. the Bowen ratio was correctly determined (Barr et al., 1994; Blanken et al., 1997), we then used this protocol, i.e. the Bowen ratio closure method (Twine et al., 2000), to close the energy balance and correct H and LE on a daily basis. This exercise produced an estimate of the annual ET rate at 202.6 mm (ET_2 in Table 2). These estimates of ET suggest that the steppe returned 82—97% of the PPT to the atmosphere. In addition, although we did not include downward filtration in Eq. (6), downward infiltration or recharge to the groundwater in the Kherlen River basin exits if there are strong precipitation events (Kamimera and Lu, not published data).

Table 2 Monthly distributions and annual budgets of measured evapotranspiration (ET), corrected ET by the residual energy method (ET_1) and by the Bowen ratio closure method (ET_2), the equilibrium evapotranspiration (ET_{eq}), precipitation (PPT), estimated soil water storage (Eq. (6), ΔST = PPT − ET), and derived ratios of ET/ET_{eq} (=α, the Priestley–Taylor parameter) and ET/PPT above a steppe in central Mongolia from 25 March 2003 to 24 March 2004 (366 days)

Month	ET (mm/month)	ET_1 (mm/month)	ET_2 (mm/month)	ET_{eq} (mm/month)	PPT (mm/month)	ΔST (mm/month)	ET/ETeq	ET/PPT
March, 2003 (7 days)	1.3	1.7	1.3	10.5	0	−0.2	0.12	0.00
April, 2003	4.7	5.7	4.8	57.3	0	−4.7	0.08	0.00
May, 2003	14.3	25.9	18.5	79.2	28.4	14.1	0.18	0.50
June, 2003	24.2	39.0	30.7	88.4	41.3	18.6	0.27	0.59
July, 2003	48.5	78.0	66.4	105.2	56.7	6.8	0.46	0.86
August, 2003	27.9	49.3	37.4	93.3	40.4	13.0	0.30	0.69
September, 2003	23.4	44.6	36.5	66.5	64.7	51.8	0.35	0.36
October, 2003	7.3	6.9	7.5	31.3	0	−7.3	0.23	0.00
November, 2003	2.5	−7.9	0.5	1.6	5.7	3.2	1.50	0.44
December, 2003	0.3	−8.8	−1.4	−7.8	0.5	0.2	−0.04	0.60
January, 2004	2.0	−2.4	2.5	1.7	1.5	−0.5	1.18	1.33
February, 2004	3.6	0.0	−5.8	10.7	1.6	−2.0	0.34	2.25
March, 2004 (24 days)	3.0	9.1	3.6	32.9	7.3	4.3	0.09	0.41
Annual sum (mm y^{-1})	162.9	241.0	202.6	570.7	248.1	97.4		
Annual mean (mm d^{-1})	0.45	0.66	0.55	1.56	0.68		0.29	0.66

Our results on the ratio of ET to PPT (66%) estimated by the EC method demonstrate that the magnitudes of ET and PPT were not equal on an annual basis. This ratio is low as compared with that for another steppe in central Mongolia (79–94%; Miyazaki et al., 2004), and that for a steppe close the edge of the Eurasian cryosphere in Mongolia (94%; Zhang et al., 2005). However, the ET to PPT ratio in this study is close to the ratios reported for annual grassland in California (54–59%; Baldocchi et al., 2004), and for the montane grasslands of South Africa (40–76%; Everson, 2001). Our values of the ET to PPT ratio lie in the lower end of the range (from 40% to 150%) for grassland ecosystems (Weltz and Blackburn, 1995; Lewis et al., 2000; Nouvellon et al., 2000; Reynolds et al., 2000; Everson, 2001; Meyers, 2001; Wever et al., 2002; Frank, 2003; Baldocchi et al., 2004). However, in the long-term, ET should balance PPT. Additionally, the annual ET rate of 162.9 mm at the site was equivalent to 407.2 MJ m^{-2} y^{-1} of LE, which was about 26% of the net radiation received at the site (1563.3 MJ m^{-2} y^{-1}), i.e. the bulk LE/R_n ratio averaged at 0.26. This value is very close to the LE/R_n ratios (0.24–0.29) for three semiarid grasslands in the northern Great Plains in the USA that are located at latitudes similar to the Mongolian steppe (Frank, 2003).

Conclusions

We quantified evapotranspiration (ET) over a year long period for a Mongolian steppe using the eddy covariance (EC) technique. ET occurred dominantly during the growing season, fluctuated in a close relationship with precipitation or variation in soil moisture, and followed a linear relationship with leaf area index. Therefore, canopy development and soil moisture conditions acted as major constraints on ET. This was also depicted by the Priestley–Taylor parameter (α), which also showed a strong dependence on soil moisture conditions. Relatively low α values (ranging from 0.04–0.70) for this steppe were observed during the growing season, indicating the restriction of water supply for ET. On an annual basis, the steppe returned 163 mm of water to the atmosphere through ET, accounting for 66% of the precipitation. However, the EC method might underestimate this percentage. If this underestimation is considered, then the annual ET rate accounted for 82–97% of the annual precipitation rate.

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Appendix

Daily means of the Priestley–Taylor parameter (α) could be expressed as a function of soil water content (SWC) at a depth of 10 cm during the growing season. This information is available as supplementary data to the online version of the article.

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