Cultivation and grazing altered evapotranspiration and dynamics in Inner Mongolia steppes

Haixia Miao, Shiping Chen, Jiquan Chen, Wenli Zhang, Ping Zhang, Long Wei, Xingguo Han, Guanghui Lin

1. Introduction

Evapotranspiration (ET) is an essential component of global energy and the water balance. Many important ecosystem processes, such as vegetation photosynthesis, soil water content, biogeochemical cycling and energy partitioning, are all affected by ET (Wever et al., 2002). However, the magnitude and dynamics of ET vary greatly with plant functional type, weather and soil properties (Baldocchi et al., 2004). Therefore, it is of great interest to invest ET in a variety of ecosystems to better understand its link with other ecosystem processes (Wever et al., 2002), the ecosystem functions (Williams et al., 2004) and the water balance of terrestrial ecosystems (Yunusa et al., 2004).

Land-use change is one of the most important aspects of global change. In steppes, the dominant vegetation type of grassland in the semiarid region of southeastern Europe and Asia, crop cultivation and grazing represent the two major land-use practices due to rapidly increasing human populations (Lal, 1998; Wang, 2000). The increasing agricultural and grazing uses of steppes could affect ET by altering the species composition, removing substantial amounts of vegetation, modifying soil texture and changing the microclimate (Wraith et al., 1987). Consequently, these practices will alter the water balance of the region (Bremer et al., 2001). Previous studies concerning the potential effects of grazing on steppes ET have shown inconsistent results, with some demonstrating that grazing reduced seasonal ET (Bremer et al., 2001; Frank, 2003), while others found no significant effect (Stewart and Verma, 1992). Additionally, some reported an elevated ET associated with heavy grazing compared with light grazing when soil water became limiting (Day and Detling, 1994). Although, the reasons for such inconsistency are not clear but could be attributable to different grazing intensities, vegetation characteristics, soil physical properties and climate. As for the effects of crop cultivation on ET, there have been a very limited number of reports. Burbay and Verma (2005), however, did report a significantly lower annual ET in a cultivated wheat site than that of...
the native prairie when there was no moisture stress, but significantly higher annual ET in the wheat field in drought years. Mahmood and Hubbard (2003) found that rain-fed maize evapotranspired at a higher rate than a neighboring grass ecosystem based on a water balance model.

Over the past century, northern China, especially the semiarid region where water is the most crucial variable for ecosystem function, has experienced large changes in land-use due to sharp increases in the human population (Wang, 2000). Over-grazing and intensive farming have led to the degradation of large amounts of steppes. Quantifying the effects of cultivation and grazing on the water balance is critical for better understanding the consequences of land conversion. However, there is little detailed information about the effects of different land-use types on ET in this region. In this study, we conducted a field study using eddy-covariance towers to quantify the effects of grazing and cultivation on ET by comparing with the native steppe ecosystems. Our objectives were to examine the effects of cultivation and grazing on ecosystem ET by comparing the differences in potential evapotranspiration (PET), ET and ET/PET ratio between paired EC towers in two latitudinal regions and identify the biological and environmental drivers responsible for controlling ET dynamics.

2. Materials and methods

2.1. Study sites

We selected two representative regions in Inner Mongolia: Duolun and Xilinhot. Duolun is a typical agriculture-pasture transition region and Xilinhot is a typical steppe region in northern China. Two ecosystems were chosen within each region to represent the typical steppe ecosystem and the disturbed ecosystem to address the effects of major land-use practices. In Duolun, our paired sites are a typical steppe ecosystem (DS, 42°02′48″N, 116°17′01″E, elevation 1350 m) and a cropland (DC, 42°02′44″N, 116°16′47″E, elevation 1350 m). In Xilinhot, a fenced steppe (XF, 43°33′02″N, 116°40′20″E, elevation 1250 m) and a degraded steppe (XD, 43°33′16″N, 116°40′17″E, elevation 1250 m) ecosystem by long-term grazing were used.

Duolun County has a semiarid continental temperate climate and cultivation is the primary land-use practice. According to the local climate data (1994–2004) from a meteorological station, the mean annual temperature is 3.3 °C, with a mean monthly temperature ranging from 15.9 °C in January to 19.9 °C in July. The mean annual precipitation is 399 mm, with 88% falling during the growing season, which is from May to September in this area. The annual precipitation varies greatly (e.g., 490 mm in 1998 and 255 mm in 2001). The native vegetation is typical steppe ecosystems and dominated by Stipa krylovii and Artemisia frigida. The steppe study site selected in this study was located at a long-term study plot (>50 ha) fenced in 2001, with vegetation dominated by Stipa krylovii, A. frigida, Agropyron cristatum, Cleistogenes squarrosoa and Leymus chinensis. The cropland site was located about 500 m to the west of the steppe and was planted annually in mid May and harvested in mid September. The agricultural field was converted from the native steppe 35 years prior to the study; the primary crop species included Triticum aestivum, Avena nuda and Fagopyrum esculentum. The soils in the study area are chestnut soils (Table 1).

Xilinhot, 240 km north of Duolun, is also within the semiarid continental temperate climate zone and has chestnut soils (Table 1) similar to Duolun. However, livestock grazing is the primary land-use in this area. According to the climate data (1982–1998), the mean annual temperature is 0.6 °C, with the lowest mean monthly temperature (−21.4 °C) in January and the highest mean monthly temperature (18.5 °C) in July. The mean annual precipitation is 350 mm, with the highest precipitation in 1998 (507 mm) to the lowest in 1980 (182 mm) (Chen and Wang, 2000). Similar to Duolun, the growing season (from May to September) of local plants usually starts in late April and ends in late September. The native vegetation is typical steppe ecosystems dominated by L. chinensis, S. grandis, A. cristatum and C. squarrosoa. At our fenced site, grazing had been excluded since 1999. A large amount of dead plant material (litter) remained on the ground. Dominant vegetation species included L. chinensis, S. grandis, Achnatherum sibiricum and A. cristatum. The degraded steppe was located 500 m north of the fenced steppe and dominated by S. grandis and C. squarrosoa. The grazed steppe has experienced intensive grazing over the last few decades and was fenced in 2005 as a long-term experimental site. This site has been clipped annually in mid September to mimic the grazing by sheep after it was fenced, although no fertilization was added to simulate sheep manure, and no concerted attempt was made to simulate compaction from sheep hooves.

2.2. Microclimate measurements

Meteorological data was measured at 30-min intervals from December, 2005 to September, 2007. Net radiation (Rn, W m⁻²) was measured with a four-component radiometer (CNR-1, Kipp and Zonen, Delft, Netherlands). Photosynthetic photon flux density (PPFD, μmol s⁻¹ m⁻²) was measured with a quantum sensor (LI-190SB, LI-COR, USA). Air temperature (Ta, °C) and relative humidity (RH, %) were measured at heights of 1.5 m, 2.5 m and 4 m above the ground using HMP45C temperature and relative humidity probes (Campbell Scientific Inc., CSI, Logan, USA) with radiation shields. Soil temperature (Ts, °C) was measured at 5 cm depth using a temperature probe (107, CSI). A soil water content reflectometer (CS616, CSI) was installed 10 cm below the soil surface to measure the volumetric soil moisture content (θ, m³ m⁻³). Wind speed (U) and wind direction were measured at 3 m above the ground using a propeller anemometer (CSI) and precipitation (mm) was measured with a tipping bucket rain gauge (TES525MM, CSI). Snowfall was not recorded during freezing conditions by the instrument. Linear interpolation and redundant measures (Falge et al., 2001) were used to fill gaps in the meteorological data due to equipment malfunctions.

Table 1

<table>
<thead>
<tr>
<th>Area</th>
<th>Ecosystem</th>
<th>Bulk density (g cm⁻³)</th>
<th>Specific gravity</th>
<th>Total porosity (%)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duolun</td>
<td>DS</td>
<td>1.38 ± 0.04</td>
<td>2.42 ± 0.03</td>
<td>42.8</td>
<td>76.8 ± 0.6</td>
<td>16.7 ± 0.4</td>
<td>6.5 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>1.24 ± 0.03</td>
<td>2.41 ± 0.00NS</td>
<td>48.6</td>
<td>75.6 ± 1.2NS</td>
<td>14.4 ± 1.0NS</td>
<td>10.0 ± 0.6NS</td>
</tr>
<tr>
<td>Xilinhot</td>
<td>XF</td>
<td>1.22 ± 0.05</td>
<td>2.27 ± 0.04</td>
<td>46.6</td>
<td>67.5 ± 0.4</td>
<td>27.0 ± 0.2</td>
<td>5.5 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>XD</td>
<td>1.33 ± 0.03NS</td>
<td>2.38 ± 0.02NS</td>
<td>43.8</td>
<td>74.9 ± 0.3 **</td>
<td>15.2 ± 0.6 **</td>
<td>9.8 ± 0.6 **</td>
</tr>
</tbody>
</table>

The significant level reflects the comparison between two ecosystems with different land-use at each area (n = 4), with NS for P > 0.05.

For P < 0.05.

For P < 0.01.
power failures (see summary in Table 2). We used the same precipitation data for paired stations at each area because they are within 0.5 km of distance.

2.3. Water vapor exchange

The eddy-covariance technique was used to measure the exchange rate of water vapor continuously in the four ecosystems (DS, DC, XF and XD) from December, 2005 to September, 2007. Each system included an open-path infrared gas analyzer (LI-7500, LICOR), a fast response 3-dimensional sonic anemometer (CSAT3, CSI) and a CR5000 datalogger (CSI). The fetch of the observation sites was at least 100 sensor heights in all directions (Zhang et al., 2007). The LI-7500 was used to measure water vapor concentration, CO₂ concentration and barometric pressure. The CSAT3 was installed to measure the mean and fluctuating values of vertical, streamwise and lateral wind speed and sonic temperature. The 30-min mean latent heat flux was calculated as the product of the mean covariance of vertical wind speed fluctuations and the scalar fluctuation of water vapor concentration. The Webb–Peerman–Leuning density correction was used in the calculation of latent heat flux. Then, a 2-dimensional coordinate rotation was used to adjust the x-axis to be parallel with the local main wind direction. Daily ET (mm day⁻¹) was derived by dividing the latent heat flux (LE) by the latent heat of vaporization (ΔL = 2.45 MJ kg⁻¹).

2.4. Gap filling for eddy-covariance data

A data-screening procedure was used to remove anomalous values due to system failures. The data screening consisted of removing those periods with (1) rainfall, (2) excessive spikes in the sonic anemometer and infrared gas analyzer (IRGA) data due to precipitation, moisture, frost and dirt on the sensors, (3) friction wind speed (u*) values less than 0.15 (Zhang et al., 2007), indicating low turbulence conditions, and (4) spikes outside a range of latent heat flux from –100 to 500 W m⁻².

We filled the data gaps following the method proposed by Falge et al. (2001): (1) a mean diurnal variations (MDV) procedure was used to fill gaps based on previous and subsequent days and (2) other data gaps were filled using a semi-empirical method (i.e., look-up tables). For look-up tables, the average LE was compiled for four seasons: December 1–February 28, March 1–May 31, June 1–August 31 and September 1–November 30. In each season, the average LE was compiled according to PPFD and VPD classes. PPFD classes were defined through 100 μmol m⁻² s⁻¹ intervals with a separate class for PPFD = 0. Similarly, vapor pressure deficit (VPD) classes consisted of 0.15 kPa intervals. The gaps were filled using the average LE with the corresponding PPFD and VPD class.

2.5. Aboveground biomass and leaf area index (LAI)

Aboveground biomass and LAI were quantified by harvesting the vegetation in small plots around eddy-covariance towers. In 2006, the vegetation was harvested every two weeks from May to September in DS, every two weeks from mid-May to late June and every week from July to September in DC and once a month from May to September in XF and XD. Four 0.5 m × 0.5 m quadrants were harvested in each sampling period in DS, XF and XD. In DC, T. aestivum, A. nuda and F. esculentum were planted this year in which A. nuda and F. esculentum were planted at different times by different farmers. Three quadrants were sampled for each crop species and therefore, fifteen 0.5 m × 0.5 m quadrants were harvested each sampling period due to different crops and different cultivation periods. In 2007, LAI and aboveground biomass were determined every 20 days in DS, XF and XD and every ten days in DC. The aboveground parts of the vegetation were clipped to the ground surface and transported to the laboratory for measurements of leaf area and dry weight. The plants were separated into live and dead, oven-dried at 70 °C for 48 h and weighed. Leaf areas of green were measured using a Portable Area Meter (LI-3000A, LI-COR Inc.) and LAI was calculated as the ratio of leaf area to ground surface area.

2.6. Model coefficients

Potential ET (PET) is an index that can be calculated from the meteorological data without considering the effects of water supply and biotic factors. PET is then used to calculate the ET/PET ratio for assessing whether a limitation in water supply exists for each ecosystem (Li et al., 2007). ET was measured by the eddy-covariance technique and PET (mm day⁻¹) was estimated using the Penman–Monteith equation of the United Nations Food and Agriculture Organization (FAO) (Allen et al., 1994):

\[
E_{\text{PET}} = \frac{0.408 \Delta (R_n - G) + y(900/(T + 273))\tau(e_s - e_a)}{\Delta + y^*}
\]

where \(E_{\text{PET}}\) is potential ET, \(\Delta\) is the slope of the saturation water vapor pressure curve with respect to air temperature (kPa C⁻¹), evaluated at the 24-h mean air temperature, \(R_n\) is 24-h net radiation (MJ m⁻² day⁻¹), \(G\) is 24-h soil heat flux (MJ m⁻² day⁻¹), \(y\) is the psychrometric constant (kPa C⁻¹), \(\gamma^*\) is the modified psychrometric constant (kPa C⁻¹), \(e_s\) is the saturation vapor pressure (kPa) at the 24-h mean ambient air temperature \(T\) (°C), \(e_a\) is the 24-h mean actual vapor pressure (kPa) and \(u\) is the mean 24-h wind speed (m s⁻¹) at 2 m height.
Biological control was assessed from changes in ET with canopy surface conductance \( (g_c) \), which was calculated using the inverted form of the Penman–Monteith equation (Arain et al., 2003):

\[
g_c = \frac{1}{\left( \frac{\rho c_p}{\gamma} \right) \left( \frac{g_a}{\Delta} \right)} \left( \frac{l_E}{D_e} - 1 \right) \left( \frac{D_e}{g_a} \right) \left( \frac{1}{C_0} \right)
\]

Where \( \Delta \) is latent heat, \( \rho \) (kg m\(^{-3}\)) is air density, \( c_p \) (J kg\(^{-1}\) K\(^{-1}\)) is the specific heat of the air, \( \Delta \) (kPa K\(^{-1}\)) is the change of saturation vapor pressure with temperature, \( \gamma \) (kPa K\(^{-1}\)) is the psychrometric constant, \( \beta \) is the Bowen ratio (H/L.E), \( D_e \) (kPa) is the vapor pressure deficit of air and \( g_a \) (m s\(^{-1}\)) is the aerodynamic conductance of the air layer between the canopy and the flux measurement height. \( g_a \) was calculated as Gu et al. (2005):

\[
g_a = \frac{1}{(u/u^*) + 6.2u^* - 0.67}
\]

where \( u \) (m s\(^{-1}\)) is wind speed and \( u^* \) (m s\(^{-1}\)) is friction velocity.

### 2.7. Statistical analysis

Statistical analysis was conducted using SAS 8.2. Significant differences in daily ET and soil moisture between the paired ecosystems at each area were tested using mixed procedure with repeated measurements. The significance of regression functions was tested by SAS PROC REG. Analysis of covariance (ANCOVA) was used to test the significance of the differences in regression function slopes for ET and soil moisture between the two ecosystems at each study area.

### 3. Results

#### 3.1. Leaf area index and biomass

Seasonal changes in LAI were clearly different between DS and DC (Fig. 1a). In 2006, the grasses of DS started to grow in late April and increased growth until mid-August, when the LAI reached its maximum of 0.97 ± 0.05 m\(^2\) m\(^{-2}\). In contrast, the crops of DC reached their peak LAI (2.42 ± 0.4 m\(^2\) m\(^{-2}\)) in mid-July and then decreased rapidly until the harvesting in mid-September. LAI of DS and DC in 2007 were much lower than those in 2006. Additionally, the peak values of the LAI of DS and DC in 2007 were delayed to August 24 and August 14, respectively. In Xilinhot, the XF and XD steppes exhibited similar seasonal changes of LAI, with peak values in mid-July in 2006 and in early August in 2007 (Fig. 1c). The maximum LAI for XF and XD were 0.52 ± 0.05 m\(^2\) m\(^{-2}\) and 0.44 ± 0.02 m\(^2\) m\(^{-2}\) in 2006, and 0.52 ± 0.03 m\(^2\) m\(^{-2}\) and 0.68 ± 0.04 m\(^2\) m\(^{-2}\) in 2007, respectively.

The seasonal changes in aboveground biomass were similar to those of LAI but the timing of the peaks lagged LAI at all ecosystems except DS (Fig. 1b and d). At DS, the maximum value of the aboveground biomass (213.7 ± 25.4 g m\(^{-2}\)) occurred in mid-August in 2006 (i.e., similar to LAI dynamics). Obviously higher aboveground biomass was found at the cropland, with a peak value of 660.5 ± 76.3 g m\(^{-2}\) in mid-August in 2006. Similar to LAI dynamics, the aboveground biomass in DS and DC were much lower in 2007 than in 2006. Seasonal changes in the aboveground biomass were similar for the fenced and degraded steppe ecosystems. The litter biomass in DS, XF and XD were clearly higher in 2007 than those in 2006.

![Fig. 1. Temporal variation of leaf area index (LAI) and biomass at four eddy-covariance tower sites in two regions of Inner Mongolia (steppe [DS] and cropland [DC] in Duolun; fenced steppe [XF] and degraded steppe [XD] in Xilinhot) during the growing season of 2006 and 2007. The total litter for DS, XF, and XD during the growing season is shown in the inset of (b and d). There was no litter remainder for DC due to plow. Values represent the mean ± S.E. (n = 4).](image-url)
3.2. Microclimate

The precipitation during the growing season in Duolun in 2006 was higher than the 11-year average (345 mm) (Table 2), while the precipitation was lower than the average in 2007. Precipitation in Xilinhot during both years was much lower than the long-term mean for this area, indicating that 2006 and 2007 were abnormally dry years for this region.

Changes in soil volumetric water content ($\theta$) at the four study ecosystems were, as expected, coupled to precipitation (Fig. 2a and e). The $\theta$ of DS was higher than DC in both the dormant season and the growing season in 2006 and 2007 ($P < 0.01$). The $\theta$

![Seasonal changes in precipitation (PPT) and soil volumetric water content ($\theta$), net radiation ($R_n$), vapor pressure deficit (VPD), and evapotranspiration (ET) at four eddy-covariance tower sites in two regions of Inner Mongolia (steppe [DS] and cropland [DC] in Duolun; fenced steppe [XF] and degraded steppe [XD] in Xilinhot) from December 1, 2005 to September 30, 2007.](image)
values of XF were also higher than those of XD in both years ($P < 0.01$).

Net radiation ($R_n$) at all four-study ecosystems was unimodal, with peak values occurring in July (Fig. 2b and f). The annual average $R_n$ was similar for DS and DC in 2006 but higher in DS than that in DC in 2007 (Table 2). In Xilinhot, XF had higher $R_n$ than XD in both years. There were little differences in air temperature, relative humidity, VPD and wind speed between DS and DC, or between XD and XF. Daily mean VPD varied dramatically during the growing season (Fig. 2c and g), with peak VPD in May at DS and DC in 2006. In contrast, VPD remained at a relatively high level from May to August at XD and XF in 2006. VPD values at all four ecosystems were significantly higher in 2007 than that in 2006, with peak values in June. The soil temperature of DS was lower than that of DC, with a difference of 0.4°C. Similarly, the soil temperature of XF was lower than that of XD and the annual average difference was 1.6°C.

### 3.3. PET and ET

In all ecosystems, relatively high rates of ET were recorded during the growing season, while they were low (near zero) during the winter months (Fig. 2d and h). The daily average ET during the growing season in 2006 in DS was $2.25 \pm 0.10$ mm day$^{-1}$, 0.34 mm day$^{-1}$ greater than that in DC ($P < 0.05$). The daily average ET in XF was $1.52 \pm 0.06$ mm day$^{-1}$, 0.20 mm day$^{-1}$ greater than that of XD ($P < 0.05$). However, there was similar daily average ET during the growing season of 2007 between DS and DC and between XF and XD ($P > 0.05$). The peak ET values occurred in early August of 2007 in Duolun, a delay of about thirty days compared with that of 2006. The peak ET values occurred from mid-June to mid-July in 2006 in Xilinhot, while around mid-July in 2007.

In July, when crops experienced a peak growth period, DC had higher ET and ET/PET values than those in DS for both 2006 and 2007, while DS showed higher ET and ET/PET values in most of other months (Fig. 3). Monthly ET and ET/PET values of XF were higher than those of XD in most of the months in both years. With similar microclimatic conditions in the same region, PET values during the growing season were quite similar among the ecosystems at each study area (Table 3). The ET values of DS (344.4 mm and 204.1 mm in 2006 and 2007, respectively) were higher than those of XD (292.0 mm and 190.5 mm in 2006 and 2007, respectively) during the entire growing seasons of both years. Similarly, higher ET values were found at XF (230.3 mm and

<p>| Table 3 |
| Evapotranspiration (ET), potential evapotranspiration (PET), ratios of ET to PET and ratios of ET to PPT at the four eddy-covariance tower sites in Inner Mongolia, China (steppe [DS] and cropland [DC] in Duolun; fenced steppe [XF] and degraded steppe [XD] in Xilinhot) during the growing seasons of 2006 and 2007. |</p>
<table>
<thead>
<tr>
<th>Growing season in 2006 (May–September)</th>
<th>Growing season in 2007 (May–September)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS DC XF XD</td>
<td>DS DC XF XD</td>
</tr>
<tr>
<td>ET (mm)</td>
<td>344.4 292.0 230.3 201.4</td>
</tr>
<tr>
<td>PET (mm)</td>
<td>505.0 510.2 598.6 556.0</td>
</tr>
<tr>
<td>ET/PET</td>
<td>0.68 0.57 0.38 0.36</td>
</tr>
<tr>
<td>ET/PPT</td>
<td>0.87 0.74 1.25 1.09</td>
</tr>
</tbody>
</table>
210.4 mm in 2006 and 2007, respectively) than those in XD (201.4 mm and 207.5 mm in 2006 and 2007, respectively). DS had higher ET/PET values than DC during the entire growing season in both years, while similar ET/PET values were found between XF and XD in both 2006 and 2007 (Table 3).

The annual ET of DS (426 mm) was equal (within experimental error) to the annual precipitation (427 mm) in 2006. In DC, the annual ET (376 mm) in 2006 was about 88% of the annual precipitation. The ET in the two ecosystems in Duolun in 2007 and the two ecosystems in Xilinhot in the two years were all higher than the precipitation during this period (Table 3).

### 3.4. Relationship between ET and biological properties

The mean ET, averaged over seven to 15 days around the sampling date in DS, XF, XD and DC, was significantly correlated with LAI when the data for all four ecosystems was pooled (P < 0.01) (Fig. 4a), while there was no significant correlation between ET and biomass (P > 0.05, Fig. 4b). The LAI data was pooled together because of the low sampling frequency in each ecosystem. ET also appeared to be significantly related to soil volumetric water content (θ) in the four ecosystems (Table 4). The slopes of the regression analysis for DC were higher than those at DS in 2007 (P < 0.01) but there was no significant difference in 2006 (P > 0.05). On the other hand, the slopes of the regression model for XD were significantly higher than those for XF both in 2006 and 2007 (P < 0.01). Canopy surface conductance (gsc) was significantly related to ET in all four ecosystems (P < 0.01), as expected from Eq. (2) because the conductance values of lower than 0.5 in a Mongolian steppe ecosystem. The high ratios of ET to PPT during the growing seasons indicated that ecosystem ET was limited by water supply (Table 3). Li et al. (2007) also found ET/PET values of lower than 0.5 in a Mongolian steppe ecosystem. The high ratios of ET to PPT of the two ecosystems (≥1) indicated that most or all of precipitation was returned to the atmosphere through ET.

### 4. Discussion

#### 4.1. Effects of cultivation on ET

The maximum daily ET rate (5.69 mm day⁻¹) of the typical steppe ecosystem in DS was within the range of the maximum rates found in other global steppe ecosystems (3–6.2 mm day⁻¹, Kelliher et al., 1993; Dugas et al., 1999; Meyers, 2001; Hunt et al., 2002). During the growing season, the daily ET of DS (0.20–5.69 mm day⁻¹) was relatively high compared to ET (0.1–2.8 mm day⁻¹) in a Mongolian steppe ecosystem, which had a peak LAI (0.57 m² m⁻²) under conditions of PPT (248.1 mm) higher than the multiyear average of 181 mm (Li et al., 2007). However, the ET rates in DS were lower than those (2.1–9.5 mm day⁻¹) reported for the native tallgrass prairies in the USA, where LAI reached 2.0–3.5 and PPT was over 600 mm (Weltz and Blackburn, 1995; Ham and Knapp, 1998; Bremer et al., 2001; Burba and Verma, 2005). The differences in ET between DS and other grassland ecosystems were thus most likely related to differences in precipitation and leaf area.

The ET of an ecosystem is affected by microclimate, soil moisture and vegetation characteristics (Weever et al., 2002; Li et al., 2007; Kelliher et al., 1995). ET/PET is generally greater than one (between 1.1 and 1.4) for well-watered crops or wet surfaces (Lhomme, 1997; Kim and Entekhabi, 1997; Wilson and Baldocchi, 2000). In our study, the low ET/PET values of the two ecosystems during the growing seasons indicated that ecosystem ET was limited by water supply (Table 3).
During the period of 1994–2004, the annual precipitation ranged from 255 mm to 490 mm. The observed difference in ET between 2006 and 2007 was likely caused by the variation in precipitation (Tables 2 and 3). Our results were consistent with the studies of Meyers (2001) and Weyer et al. (2002), who also found that ET varied in response to inter-annual variations in precipitation.

Cultivation reduced ET by 15% during the growing season of 2006 (Table 3). On an annual basis, ET was reduced by 12%. Microclimatic factors associated with ET (e.g., air temperature, relative humidity, wind speed, VPD and solar radiation) were similar in the steppe and cropland. Li et al. (2007) reported that soil moisture was the most important environmental factor controlling the dynamics of ET in a Mongolian steppe ecosystem. In our study, the ET of the steppe and the cropland seemed highly correlated with soil moisture (Table 4). The lower soil moisture was likely to be responsible for the lower ET in the cropland. In addition, the ET of cultivation appeared more sensitive to soil moisture in 2007, indicating that ET might depend more on soil moisture than biological factors (e.g., LAI, canopy conductance) in a dry year.

Some studies assumed that surface runoff and downward infiltration could be ignored in semiarid ecosystems and that the precipitation remaining after ET would be stored in the soil (Schultz, 1995; Lauenroth and Bradford, 2006). Based on this concept, we would expect higher soil moisture content in the cropland than the steppe because of lowered ET. However, significantly lower soil water content was observed in the surface soil in the cropland (Fig. 2; Table 2). The decrease in soil water-holding capacity of the cropland compared with the steppe might increase storm infiltration into the deep soil layer and increase the evaporation loss to the atmosphere. Our data showed that the moisture of the deep soil layer (30–50 cm) was significantly lower (P < 0.01) in the cropland (5.1% and 4.1% in the growing season of 2006 and 2007, respectively) than the steppe (4.2% and 3.6% in the growing season of 2006 and 2007, respectively), which further confirmed that cultivation increased the infiltration of water in the surface soil. In addition, the vertical root distribution of annual crops leans more toward soil surface than the native perennial grasses, which causing more water in surface soil layer loss transpired by the crops, especially in the peak growth period. While in early and late growth stage and dormant season, more bare soil surface in the cropland might cause higher soil evaporation of soil surface. All of those would explain that why the cropland showed lower soil moisture in soil surface layer than the steppe, although the cropland had lower ET than the steppe.

Variation in LAI was another important factor influencing the ET variability of ecosystems in addition to soil moisture (Burba and Verma, 2005; Li et al., 2007). Low LAI in the steppe and cropland in 2007, likely due to lowered precipitation, resulted in less ET in the steppe and the cropland during the growing season of 2007 than 2006 (Table 3). Using a stable isotopic partitioning approach, Ypez et al. (2003) found that a major portion of ET was from plant transpiration in the semiarid savanna woodland of southwestern USA. Our stable isotope partitioning results also showed that plant transpiration contributed more than 85% of the ET during the growing season in this region (unpublished data). Because LAI can reflect the total transpiring area, we reason that the difference in LAI played a key role in the ET differences between DS and DC during the growing season. When there was higher LAI in DC than DS during the peak season, higher ETs were recorded in DC (Figs. 1 and 3a). In July 2006, LAI of the cropland was 3 times that of the steppe; however, ET of the cropland was similar to that of steppe. These indicated that the stomatal conductance of per leaf area played an important role in the limitation of crops transpiration. The shallower root systems at crops prevented the plants to access soil water at deeper layers; and limited water supply from the surface layer would lead to water stress for the crops. In addition, the growth period of the crops in our study area was from June to August, ET of the cropland was much lower in May and in September than that of steppe. Thus, over the growing season, the total ET in DC was lower than that in DS due to the shorter growth period for the crops (Table 3).
Canopy conductance ($g_c$) is influenced by several biotic and abiotic factors such as LAI, stomatal conductance, VPD, radiation and available soil moisture (Weyer et al., 2002). It not only represents the physiological stomatal conductance impacts, but also includes nonlinear effects of soil moisture and canopy turbulence (Raupach and Finnigan, 1988; Paw U and Meyers, 1989). A number of studies have indicated that $g_c$ primarily represents canopy-integrated stomatal conductance, granted that soil evaporation is low (Raupach, 1995; Baldocchi and Meyers, 1998). In our study, a higher contribution of plant transpiration to limitation of ET than soil evaporation. The higher regressive slopes of ET to $g_c$ for DS and DC in 2006 than those in 2007 (Fig. 5a and b) indicated that presumably lower humidities and higher canopy temperatures in the dry year (2006) increased the sensitivity of ET to $g_c$, as indicated in partial differentiating the ET equation with respect to the conductance. In addition, the slightly higher slopes for DS than DC in both 2006 and 2007 suggested that steppe canopy temperature was higher than that of the crops, and/or the aerodynamic conductance was greater for the steppe canopy than for the crop canopy.

4.2. Effects of grazing on ET

The ET/PET values of the two steppe ecosystems in Xilinhot were lower than those in Duolun in 2006 while similar to those in Duolun in 2007 (Table 3). The low ET/PET values at these sites also confirmed that water supply limited ET in steppe ecosystems. All of the ratios of ET/PPT in Xilinhot were greater than 1.0, indicating that all of the precipitation was lost by ET (Weyer et al., 2002; Frank, 2003).

Grazing reduced ET for the steppe in Xilinhot by 13% on average during the growing season of 2006, while there was similar ET between XF and XD in 2007 (Table 3). Bremer et al. (2001) reported that grazing reduced the seasonal evaporation of a steppe in Kansas by 6.1% from May to October in 1999. Frank (2003) reported uncertain variations in ET between ungrazed and grazed prairies. They found a 7% decrease in ET for a grazed prairie on average in three continued years; however, ET was higher in the grazed prairie than that in the ungrazed prairie in the year with higher soil water availability. Stewart and Verma (1992) found similar ET in both degraded and fenced steppes in wet years when soil moisture was not a limiting factor. Clearly, we could not explain why grazing has caused different effects on ET among different grass ecosystems or between different years. Further studies, especially those at multiple sites and over a longer term, are required to better understand these different results.

Tong et al. (2000) reported that grazing reduced soil water content in surface soil (0–20 cm) through increasing the infiltration velocity of water in the surface and aggravating the change of soil temperature in a typical steppe in Inner Mongolia. They attributed the increasing infiltration in the grazed steppe to lower root baffle and lower intercept of pant and litter than the fenced steppe. While Bremer et al. (2001) concluded that grazing could increase soil water content by increasing water-holding capacity and decreasing ET in degraded prairies. Meanwhile, Coronato and Bertiller (1996) found that grazing had no effect on soil water content. In our study, grazing decreased soil moisture likely due to reduced litter coverage and a more bare soil surface in XD (Fig. 1 and Table 2). In this case, surface runoff might occur in XD—another possible reason for the reduction of soil moisture. The significant relationships between ET and soil moisture in the two steppe ecosystems in Xilinhot (Table 4) indicated that the decrease in the soil moisture might be partially responsible for the reduction of ET. The greater sensitivity of ET to changes in soil moisture in XD further confirmed that soil moisture played an important role in determining ET in the degraded steppe ecosystem. Our results were different from those of Bremer et al. (2001) and Frank (2003), who reported that grazing decreased ET by changing canopy size (LAI) and energy budget components. Further studies are needed to explain these different results about the effects of grazing on ET.

The difference in the litter amount between XF and XD was another possible reason for the difference in ET between the two steppe ecosystems in dry years. Surface litter could increase the interception of precipitation and reduce the infiltration of water to the soil from small rain events (Couturier and Ripley, 1973). Therefore, there was probably much greater water loss directly from the canopy surface in XF than XD under small rain events due to a much greater amount of litter in XF (Fig. 1d). Moreover, elevated litter coverage in XF could increase water-holding capacity and decrease runoff under large rain events. We found similar LAI and $g_c$ values between XF and XD (Fig. 1c, Fig. 5c and d), which indicated that regulation of LAI and $g_c$ had little effect on the difference of ET in dry years. The similar slopes for XF and XD in 2006 and 2007 (Fig. 5c and d) also suggested that grazing did not change the sensitivity of ET to $g_c$ in dry years, indicating that the canopy temperature and aerodynamic conductances compensated for drier humidities.

5. Conclusions

In summary, anthropogenic disturbances to steppes (e.g., cultivation and grazing) have affected ET by altering vegetation, canopy surface conductance, canopy structure, and soil water-holding capacity and the response of ET to soil moisture. Cultivation has clearly reduced ecosystem ET. On one hand, plowing could lower soil moisture by decreasing soil water-holding capacity and increasing rain water infiltration, which limited ecosystem ET. On the other hand, based on the whole year, cultivation reduced ET by changing vegetation phenology, shortening the growth period and decreasing the sensitivity of ET to canopy conductance. Grazing decreased litter coverage and may have increased surface runoff, which reduced soil moisture in the degraded steppe ecosystem and then lead to a decrease in ET.

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