Journal of
Plant Ecology

VOLUME 4, NUMBER 1–2,
PAGES 49–60

MARCH 2011

doi: 10.1093/jpe/rtq035

available online at
www.jpe.oxfordjournals.org

# Evapotranspiration and soil water relationships in a range of disturbed and undisturbed ecosystems in the semi-arid Inner Mongolia, China

*Nan Lu*[1,2,]*, *Shiping Chen*[3], *Burkhard Wilske*[1], *Ge Sun*[4] *and Jiquan Chen*[1]

[1] *Department of Environmental Sciences, University of Toledo, Toledo, OH 43606, USA*
[2] *Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Beijing 100085, China*
[3] *State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, The Chinese Academy of Sciences, 20 Xiangshan Nanxincun, Beijing 100093, China*
[4] *USDA Forest Service Southern Research Station, 920 Main Campus, Venture II Building, Suite 300, Raleigh, NC 27606, USA*
*Correspondence address. Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Beijing 100085, China. Tel: +86 10-62849102; Fax: +86 10-62849102; E-mail: nanlv@rcees.ac.cn

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

## Abstract

*Aims*

Evapotranspiration (ET) is a key component of water balance and is closely linked to ecosystem productivity. In arid regions, large proportion of precipitation (PPT) is returned to the atmosphere through ET, with only a small amount available to plants. Our objective was to examine the variability in ET–soil water relationship based on a set of ecosystems that are representative for semi-arid Inner Mongolia and its main land use practices.

*Methods*

This study used Eddy covariance (EC) data of water vapor (i.e. ET, mm), PPT (mm), soil volumetric water content (VWC, %), root biomass density and soil properties from three paired sites in semi-arid Inner Mongolia: cropland (Cropland-D) versus undisturbed grassland (Steppe-D), grazed grassland (Grazed Steppe-X) versus fenced grassland (Fenced Steppe-X) and poplar plantation (Poplar-K) versus undisturbed shrubland (Shrubland-K). The paired sites experienced similar climate conditions and were equipped with the same monitoring systems.

*Important Findings*

The ET/PPT ratio was significantly lower at Cropland-D and Grazed Steppe-X in comparison to the undisturbed grasslands, Steppe-D and Fenced Steppe-X. These differences are in part explained by the lower VWC in the upper soil layers associated with compaction of surface soil in heavily grazed and fallow fields. In contrast, the ET/PPT ratio was much higher at the poplar plantation compared to the undisturbed shrubland because poplar roots tap groundwater. The VWC of different soil layers responded differently to rainfall events across the six study sites. Except for Poplar-K, ET was significantly constrained by VWC at the other five sites, although the correlation coefficients varied among soil layers. The relative contribution of soil water to ET correlated with the density of root biomass in the soil ($R^2 = 0.67$, $P < 0.01$). The soil water storage in the upper 50 cm of soil contributed 59, 43, 64 and 23% of total water loss as ET at Steppe-D, Cropland-D, Shrubland-K and Poplar-K, respectively. Our across-site analysis indicates that the site level of soil water for ET differs between land use and land cover type due to altered root distribution and/or soil physical properties. As a result, we recommend that ecosystem models designed to predict the response of a wide variety of vegetation to climatic variation in arid regions include more detail in defining soil layers and interactions between evaporation, infiltration and root distribution patterns.

***Keywords:*** evapotranspiration • soil water storage • land use • Inner Mongolia • semi-arid region • eddy-flux measurements

Received: 13 June 2010 Revised: 16 November 2010 Accepted: 18 November 2010

© The Author 2011. Published by Oxford University Press on behalf of the Institute of Botany, Chinese Academy of Sciences and the Botanical Society of China.
All rights reserved. For permissions, please email: journals.permissions@oup.com

# INTRODUCTION

In semi-arid environments, the availability of water is the single most important factor in limiting ecosystem processes (Noy-Meir 1973). In water-limited regions, water loss is dominated by evapotranspiration (ET) (Sun *et al.* 2010), which can account for >95% of annual precipitation (PPT) (Huxman *et al.* 2005; Kurc and Small 2004). Variability in ET in semi-arid environments is therefore important to quantify as it affects not only productivity but also energy balance of the region.

Monthly and annual ET can be predicted reasonably well with data on PPT, vegetation type and its cover (Sun *et al.* 2010). In arid regions, ET is seasonally often limited by the availability of soil water (Kurc and Small 2007; Wilske *et al.* 2010). It therefore is generally included in most of process-based ET simulation models such as the Food and Agriculture Organization (FAO) method (Glenn *et al.* 2007). Because rainfall events are usually sporadic with only a few large storms each year in the semi-arid region, soil water storage ($\Delta S$) is a critical resource during non-rainy periods. When $\Delta S$ is high, a higher proportion of rainfall will be routed to surface runoff or recharge the ground water reservoir than when low (Brandes and Wilcox 2000).

The dynamic interactions between ET and soil water are key to understand soil–plant–atmosphere relations and the regional hydrological balance (Brutsaert and Chen 1995; Granier *et al.* 2000a, 2000b; Shuttleworth 1991). However, quantifying these relationships can be difficult. One of the reasons is that measurements of ET and soil water are rarely available at resolutions required to gain fuller insight on the interactions. For this reason, hydrological models often assume that plants access water from all soil layers equally, or only measure to <20 cm depth (Feddes *et al.* 2001; Porporato *et al.* 2001), which disregards in the latter case, the possible importance of root access to deeper soil layers (Nilsen *et al.* 1983; Schlesinger *et al.* 1990).

Land cover change in semi-arid regions has been occurring globally over the past century (Archer *et al.* 1995; Van Auken 2000). The major causes of the change are probably anthropogenic, associated with increased population and socio-economic development, which have also affected the frequency and intensity of fire regime and in some cases the climate. The world's largest extra-tropical semiarid and arid land, dominantly covered by grassland and barren deserts, is in the Inner Mongolia region. This region has experienced intensive land use practices during the recent decades, with cultivation and grazing being two representative disturbance types on the natural steppe (John *et al.* 2009). Under natural conditions, trees are only present in scattered areas with shallow groundwater. Recently, large plantations of poplars have been established within a sequence of large-scale projects to block the extension of desertification in this region such as the 'Three North Project' (launched in 1978), the 'Combating Desertification Project' (1991) and the 'Great Green Wall Project' (initiated in 2002). It is expected that the land use-associated disturbances affect soil water status, ET and the ET–soil water relationship, and consequently alters the regional water balance due to changes in species composition, vegetation cover and soil properties (Grayson and Western 1998; Zhang and Schilling 2006).

The objective of this study is to examine the relationships between PPT, soil water content/storage and ET in different ecosystems in semi-arid Inner Mongolia. Six representative ecosystems were selected to serve as three sets of paired sites for direct comparison (grassland vs. cropland, recovered grassland vs. grazed grassland, and undisturbed shrubland vs. poplar plantation). The paired sites are close to each other in location and they have similar meteorological conditions. Specifically, the objectives are to evaluate the effects of the three types of land use practices on: (i) the dynamics of soil water content responding to rainfall events, (ii) the interactions between soil water content and ET, and (iii) soil water balance and the relative contribution of $\Delta S$ in vertical soil profile to ET.

# METHODS

## Study sites

The six paired sites are located in three different areas (Duolun, Xilinhot and Ordos) in Inner Mongolia (Table 1). The first pair of sites was located in Duolun County, which was under free grazing before it was changed to an agriculture–pasture transition region in recent years. A steppe site (Steppe-D) and a rainfed cropland site (Cropland-D), which are ~500 m apart, were selected for this study. The Steppe-D site was fenced by the Duolun Restoration Ecology Research Station as a long-term study site in 2001 before that it was degraded due to grazing. The vegetation has greatly but not fully recovered to its original vegetation with *Stipa krylovii* being the dominant species and *Artemisia frigida* (an indicating species for degradation) still present. Cropland-D was converted to the conventional agricultural land in 1972. The major crop species were *Triticum aestivum*, *Avena nuda* and *Fagopyrum esculentum*, which were planted in mid-May and harvested in mid-September every year (Chen *et al.* 2009).

The second pair of sites was located in Xilinhot, where the native vegetation is typical steppe and grazing is the primary land-use manner during the last few decades. A fenced steppe site (Fenced Steppe-X) and a degraded steppe site (Grazed Steppe-X), which are 500 m apart, were selected in the study. The Grazed Steppe-X site was converted to *Stipa grandis* and *A. frigida* due to extensive grazing. The Fenced Steppe-X site was fenced by the Inner Mongolia Grassland Ecosystem Research Station in 1999 and it has recovered to the structure of typical steppe dominated by *S. grandis* and *Leymus chinensis* (Chen *et al.* 2009; Miao *et al.* 2009).

The third pair of sites was located in Kubuqi Desert, which belongs to Ordos city. The selected shrubland site (Shrubland-K) is an undisturbed shrubland dominated by *Artemisia ordosica*. The poplar plantation site (Poplar-K), which was 20 km apart from Shrubland-K, was established in 2003 to immobilize the

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

**Table 1:** a summary of the characteristics of the six study sites in Inner Mongolia

| Site | Steppe-D | Cropland-D | Shrubland-K | Poplar-K | Fenced Steppe-X | Grazed Steppe-X |
|---|---|---|---|---|---|---|
| Location | | | | | | |
| N | 42°02′48″ | 42°02′44″ | 40°22′51″ | 40°32′18″ | 43°33′02″ | 43°33′16″ |
| E | 116°17′01″ | 116°16′47″ | 108°32′55″ | 108°41′37″ | 116°40′20″ | 116°40′17″ |
| PPT | 398 | 398 | 318 | 318 | 350 | 350 |
| $T_a$ | 13.8 | 13.3 | 19 | 19.2 | 14.2 | 14.6 |
| VPD | 0.6 | 0.7 | 1.4 | 1.3 | 1.0 | 0.9 |
| Land use/cover | Fenced in 2001, greatly recoveredto native vegetation | Reclaimed since 1965 | Native shrubland | Planted in 2003 | Fenced in 1999, recovered to native vegetation | Degraded steppe by grazing |
| Vegetation | *Stipa* sp., *Artemisia* sp. | *Triticum* sp. | *Artemisia* sp. | *Populus* sp. | *Stipa* sp., *Leymus* sp. | *Stipa* sp., *Artemisia* sp. |
| LAI | 0.5 | 1.15 | 0.3 | 0.38 | 0.29 | 0.25 |
| V cover % | 72 | na | 17–23 | na | 56 | 58 |
| AGB | 213.7 ± 25.4 | 660.5 ± 76.3 | na | na | 129.3 ± 14.9 | 129.5 ± 11.1 |
| BGB | | | | | | |
| 0–10 | 1228 ± 127 | 595 ± 168 | na | na | 773 ± 63 | 1112 ± 128 |
| 10–20 | 285 ± 56 | 349 ± 132 | na | na | 313 ± 40 | 462 ± 84 |
| 20–40 | 175 ± 17 | 274 ± 81 | na | na | 279 ± 87 | 292 ± 36 |
| Soil type | Chestnut soil | Chestnut soil | Sandy soil | Sand | Chestnut soil | Chestnut soil |
| SOM[a] | 1.14 ± 0.15 | 1.33 ± 0.06 | 0.17 ± 0.01 | 0.06 ± 0.004 | 1.91 ± 0.01 | 1.61 ± 0.01 |
| Texture[a] | | | | | | |
| Sand | 76.8 ± 0.6 | 75.6 ± 1.2 | >85 | >85 | 67.5 ± 0.4 | 74.9 ± 0.3 |
| Silt | 16.7 ± 0.4 | 14.4 ± 1.0 | na | na | 27.0 ± 0.2 | 15.2 ± 0.6 |
| Clay | 6.5 ± 0.2 | 10.0 ± 0.6 | na | na | 5.5 ± 0.2 | 9.8 ± 0.6 |
| BLK and (Pt) | | | | | | |
| 0–10 | 1.46 (42.5) | 1.46 (41.9) | 1.29 (48.4) | 1.53 (37.8) | 1.42 (42.1) | 1.46 (42.5) |
| 10–20 | 1.50 (40.7) | 1.56 (37.9) | 1.42 (47.2) | 1.54 (39.1) | 1.44 (41.8) | 1.50 (40.7) |
| 20–30 | 1.56 (37.7) | 1.66 (34.1) | 1.35 (44.4) | 1.54 (39.3) | 1.47 (42.1) | 1.56 (37.7) |
| 30–40 | 1.64 (34.0) | 1.77 (29.8) | 1.37 (44.4) | 1.55 (39.2) | 1.47 (42.8) | 1.64 (34.0) |
| 40–50 | 1.74 (32.2) | 1.81 (28.5) | 1.42 (42.7) | 1.57 (39.1) | 1.54 (42.1) | 1.74 (32.2) |

PPT = mean annual precipitation (mm); $T_a$ = annual mean air temperature (°C); VPD = annual mean vapor pressure deficit (kPa); V cover (%): vegetation cover; AGB = aboveground biomass (g $m^{-2}$); BGB = belowground (root) biomass (g $m^{-2}$); SOM = soil organic matter (%); texture = shown with percent of composed particles; BLK = soil bulk density (g $cm^{-3}$); Pt = soil total porosity in volume percent (%).

[a] Measurements were taken for 0–10 cm of soil in Steppe-D, Cropland-D, Fenced Steppe-X and Grazed Steppe-X and 0–30 cm of soil in Shrubland-K and Poplar-K.

sand dunes that stretched out between the southern side of the Yellow River and the northern part of the MuUs Sand land. The water table was 1–4 m below the ground depending on the microtopography of the sand dunes. Drip irrigation was applied to the young trees several times a year, but the amount of water was negligible (equivalent to 1.46 mm of PPT in 2005) for such a large area of plantation (3.73 $km^2$) (Wilske *et al.* 2009). The characteristics of all sites are summarized in Table 1.

## Eddy-covariance and micrometeorological instrumentation

The open-path eddy covariance (EC) and typical micrometeorological systems were installed at each site: the turbulent flux of latent heat (LE, W $m^{-2}$) was measured with the EC systems, comprised of an LI-7500 open-path infrared gas analyser (Licor, Inc., Lincoln, NE), a CSAT3 3D sonic anemometer (CSI), and a CR5000 data logger (CSI); net radiation (Rn, W $m^{-2}$) was measured with CNR net radiometers (Kipp and Zonen, Delft, Netherlands) at 3.5 m above the canopy; soil heat flux (G) was measured using soil heat plates with three replicates (HFT-3, CSI); PPT (mm) was measured with a tipping bucket rain gauge (TE525, CSI); soil VWC (%) was measured at 0–10, 10–20, 20–30 and 30–50 cm depth with EasyAC50 probes (Sentek Sensor Technologies, Stepney, Australia); air temperature ($T_a$, °C) and relative humidity (%) were measured using HMP45C probes (Vaisala, Helsinki, Finland).

## Vegetation and soil measurements

The leaf area index (LAI) was estimated using hemispherical photography (Nikon Coolpix with a FC-E8 fisheye lens) and

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

Gap Light Analyser software (GLA Version 2.0). Aboveground biomass was sampled in August and belowground biomass was sampled in May using 4 replicates of 0.25 $m^2$ plots at Steppe-D, Cropland-D, Fenced Steppe-X and Grazed Steppe-X, respectively. The soil samples were dried in an oven (105°C) till constant weight and sifted the dried grounded soil samples through a 2-mm sieve for estimation of bulk density and total porosity. The soil organic carbon was measured by NC analyser (KDY-9820; Tongrun Ltd, China) (Miao *et al.* 2009; Xie *et al.* 2009; Zhang *et al.* 2007).

### Data processing and gap filling

The fluxes and micrometeorological data were obtained from the six sites for the growing season of 2006 (i.e. May to September). LE was adjusted using the planar fit formulation (Leuning 2004). Half-hour means of ET were calculated as ET = LE/λ, with the vaporization heat λ (cal $g^{-1}$) = 597–0.564 × $T_a$. Quality control was applied to exclude non-representative measurements of ET. The data removed in the screening procedure included: (i) outliers, (ii) rainy periods, (iii) when the friction velocity $u^* < 0.1$ m $s^{-1}$, (iv) when the stationary index of $CO_2$, $H_2O$ and $T_a > 1$ and (v) when the automatic gain control > 75%. The energy balance closure (EBC) was an additional criterion used to assess the quality of the flux measurements of ET. The EBC was 89, 79, 81, 82, 75 and 87%, respectively, at Steppe-D, Cropland-D, Shrubland-K, Poplar-K, Fenced Steppe-X and Grazed Steppe-X (Chen *et al.* 2009; Wilske *et al.* 2009).

The dynamic linear regression (DLR) method was applied to fill ET data gaps on a half-hour basis. In the DLR algorithm, the regression model was expressed as the relationship between ET, Rn and the vapor pressure deficit (VPD):

$$ET(t) = \alpha(t) \cdot (Rn(t) - G(t)) + \beta(t) \cdot VPD(t) + \zeta(t)$$

with α and β being parameters of the linear regression model, and ζ being the regression model error series for the zero mean (Alavi *et al.* 2006).

### Water balance

We assumed surface runoff was negligible at all the six sites because the ground was flat at the crop and steppe sites and PPT was low in the sandy shrub and poplar sites. Therefore, a simplified water balance equation is written as:

$$\text{PPT} = \text{ET} + \Delta \text{S},$$

where ΔS is total soil water storage. ΔS in the 0- to 50-cm soil layer ($\Delta S_{0-50\ cm}$) was calculated based on the VWC measurements in the top 50 cm soil layers; and ΔS below 50 cm ($\Delta S_{>50\ cm}$) was estimated by subtracting $\Delta S_{0-50\ cm}$ from (PPT − ET), i.e.

$$\Delta S_{>50cm} = (\text{PPT} - \text{ET}) - \Delta S_{0-50\ cm}$$

We used the Crop Reference ET to represent potential evapotranspiration (PET). It was calculated with the FAO Penman–Monteith equation (Allen *et al.* 1994). And ET to PET ratio was used to characterize the degree of ecosystem water stress.

## RESULTS

### Temporal changes of daily VWC

The VWC of different soil layers responded distinctively to rainfall events across the six study sites. As expected, larger rain events led to increased soil moisture in deeper soil layers. The VWC pulses at 0–10 cm and 10–20 cm of soil followed all rainfall events >10 mm at Steppe-D and Cropland-D. Daily rainfall <6 mm did not cause any sustained changes in VWC but it quickly returned to the atmosphere through ET. During the entire growing season, only four large rainfall events in June and July resulted in VWC pulses at 30–50 cm at Steppe-D and 20–30 and 30–50 cm of soil at Cropland-D (Fig. 1, Steppe-D and Cropland-D) (Fig. 1, Steppe-D and Cropland-D). The magnitude of the VWC pulses was larger in upper 0- to 30-cm soil layers at Steppe-D compared to Cropland-D, although the amount and frequency of rainfall were almost identical at the two sites.

The VWC at Poplar-K was very low (2–8%) compared to that of Shrubland-K, and it had very small pulses throughout the soil layers of the upper 50 cm, even after relatively large rainfalls (Fig. 1, Shrubland-K and Poplar-K). For example, a rainfall of 13.2 mm in mid-July affected only the upper 10 cm of soil, where the daily mean VWC increased 2.0%. A rainfall of 25.7 mm in mid August affected the soil layers of the upper 50 cm; however, the daily mean VWC of 30–50 cm increased only 0.9%. The VWC of the 0- to 10-cm layer was constantly lower than that of the 10–20 cm ($P = 0.02$) and 20–30 cm ($P = 0.04$) layers at Shrubland-K, where the maximum VWCs were as high as to 34% in the growing season. Similarly, the VWC of the 0–10 cm soil layer at Fenced Steppe-X was constantly higher than Grazed Steppe-X throughout the growing season ($P = 0.05$) (Fig. 1, Fenced Steppe-X and Grazed Steppe-X).

### Controlling effects of soil moisture on ET

Daily ET showed positive correlations with VWC at all six sites (Fig. 2, upper six panels). However, the strength of the correlation varied among different soil layers. Based on the total growing-season observations, the regression of ET versus VWC yielded $R^2$ values of 0.13–0.46, 0.23–0.50 and 0.13–0.57 for different soil layers at Steppe-D, Cropland-D and Shrubland-K, respectively. At Steppe-D and Cropland-D, the VWC of the 10- to 20-cm and 20- to 30-cm soil layers showed the best correlations with ET ($R^2 = 0.46$ and $R^2 = 0.53$, respectively) (Fig. 3). At Shrubland-K, the VWC of the 0–10 cm provided the best correlation with ET ($R^2 = 0.57$). In contrast, the correlations were very weak for all soil depths above 50 cm at Poplar-K ($R^2 < 0.05$). This indicated that VWC from the upper 50 cm soil depths did not account for most of the ET variations at Poplar-K. The VWC of the upper 10 cm also accounted for a fair proportion of variations in ET at Fenced Steppe-X (29%) and Grazed Steppe-X (43%).

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

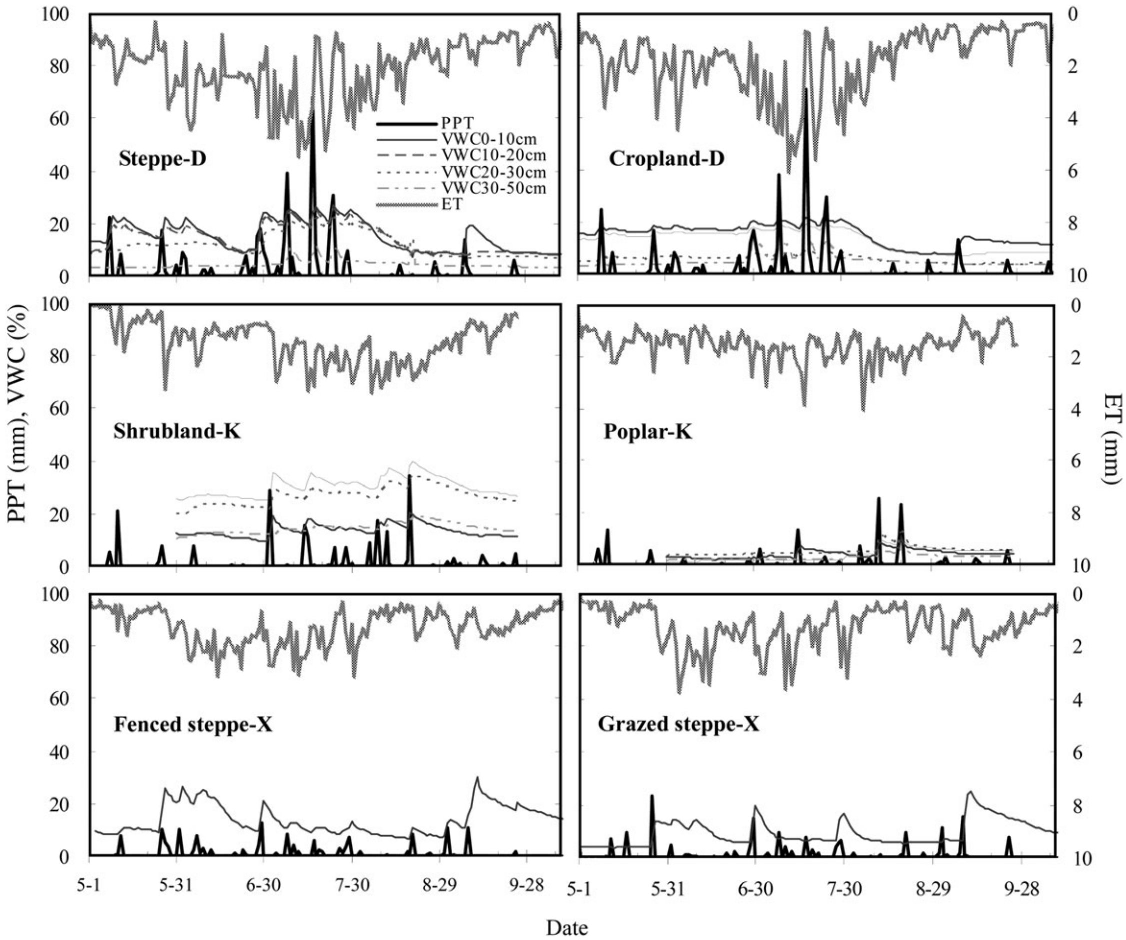


**Figure 1:** temporal dynamics of daily PPT, VWC of different soil layers and ET over the 2006 growing season at three paired sites. The *Y*-axis on the left represents PPT (mm) or VWC (%) while the *Y*-axis on the right represents ET (mm). All the six panels have the same scales for both left *Y*-axis (0–100) and right *Y*-axis (0–10). VWC data were not available for soil layers deeper than 10 cm at Fenced Steppe-X and Grazed Steppe-X.

The exclusion of rainy days improved the relationships between ET and VWC for all soil layers (Fig. 3). The VWC at 0–50 cm of soil explained 72, 68 and 47 variations of ET at Steppe-D, Cropland-D and Shrubland-K during the non-rainy period, respectively. And VWC at 0–10 cm of soil explained 45 and 44% variation of ET at Fenced Steppe-X and Grazed Steppe-X, respectively. The ET/PET ratio also showed positive correlations with VWC at all sites (Fig. 2, lower six panels). However, the relationships were less clear than those between ET and VWC as reflected in the relatively lower $R^2$ values (Fig. 3). Most of the outliers were also from the rainy days.

The study sites were under water stress during most of the growing season. There were, respectively, only 7, 9, 1 and 2 days when ET was not limited by soil water availability (i.e. ET to PET ratio was $\geqslant$1.0) at Steppe-D, Cropland-D, Fenced Steppe-X and Grazed Steppe-X. These days usually followed relatively large rainfall events. The mean ET/PET ratio of the growing season was 0.64, 0.54, 0.36 and 0.44 at Steppe-D, Cropland-D, Fenced Steppe-X and Grazed Steppe-X, respectively. There were considerable more days without water limitation at Shrubland-K (18 days) and Poplar-K (30 days). As a result, the mean ET/PET ratio was 0.64 and 0.77 at Shrubland-K and Poplar-K, respectively.

## Water balance in the growing season

The accumulated PPT and ET were almost balanced in May and June at Steppe-D and Cropland-D. However, the accumulated PPT exceeded accumulated ET from July and lasted to the end of the growing season at both sites (Fig. 4A and B). The total ET in the growing season was 37.5 mm more at Steppe-D than Cropland-D, although the growing-season total PPT only had a difference of 9.5 mm (Steppe-D > Cropland-D). The ET/PPT ratio was 0.85 and 0.78 at Steppe-D and Cropland-D, respectively. $\Delta S_{0\text{–}50\text{cm}}$ was almost balanced at Steppe-D and Cropland-D in the growing season with a decrease of only 9.4 and 12.1 mm, respectively. Whereas, the deeper soil layers below 50 cm obtained sizable recharges: 59.5 mm at Steppe-D and 90.6 mm at Cropland-D. Thus, the net changes in $\Delta S$ were positive at the end of the growing season: 50.1 and 78.5 mm at Steppe-D and Cropland-D, respectively.

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

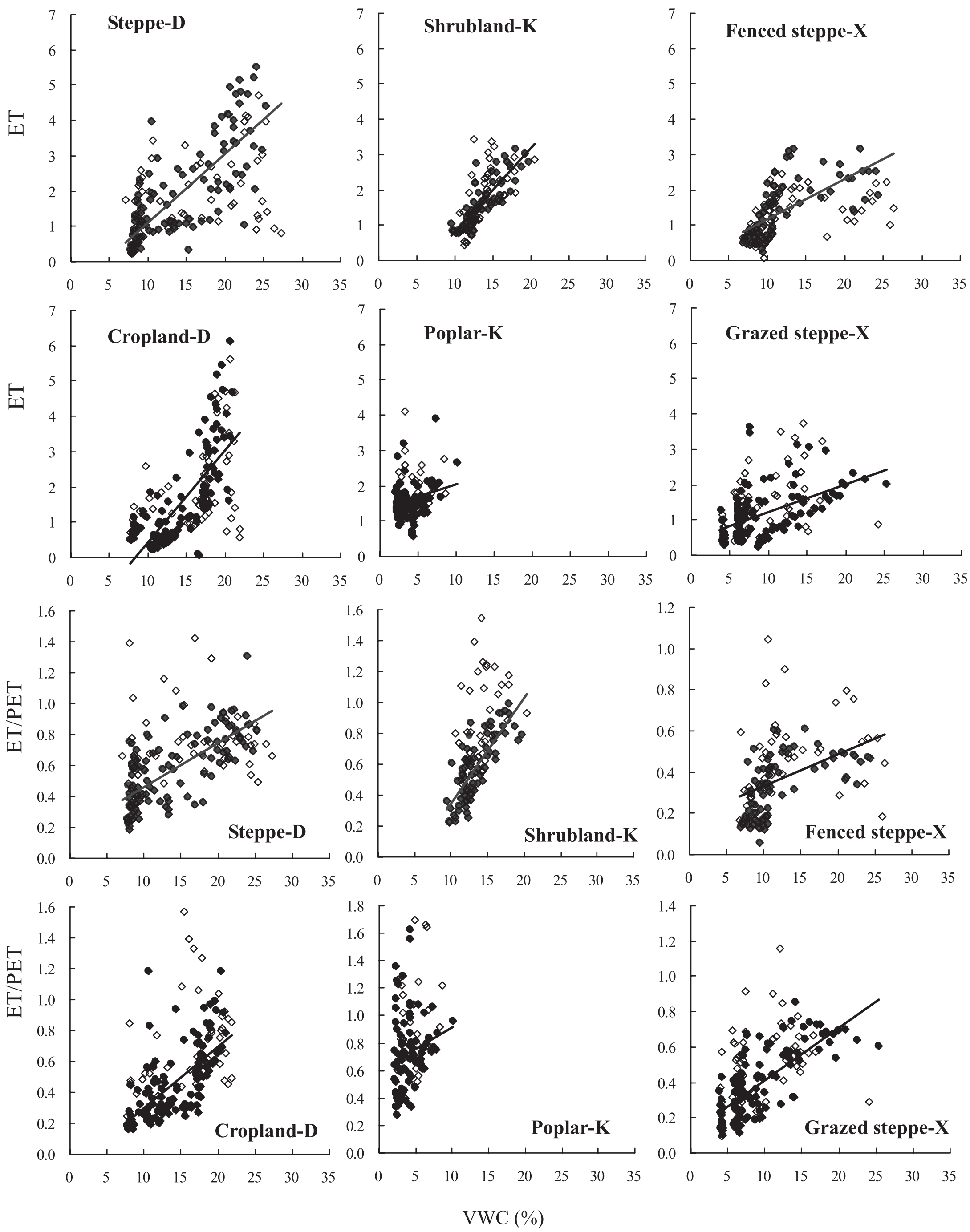


**Figure 2:** relationships between soil VWC (%), ET (mm) and ET/PET at the six sites. Solid dots represent data from the non-rainy days; the linear fits (solid line) are based on these days. Data from rainy days are represented with hollow circles. Data are only shown for VWC of the top 0–10 cm of soil.

The total ET was almost identical in the growing season at Poplar-K and Shrubland-K, with a difference of only 12.1 mm (Poplar-K < Shrubland-K); however, the total PPT was 72.7 mm less at Poplar-K than Shrubland-K. The ET/PPT ratio was 1.50 and 1.01 at Poplar-K and Shrubland-K, respectively (Wilske *et al.* 2009). At Shrubland-K, the accumulated PPT was larger than ET before mid-June; they were balanced at a few dates in the following months and almost balanced at the end of the growing season (Fig. 4C and D). In contrast, the accumulated PPT had a deficit of 87.6 mm compared to ET at Poplar-K. The accumulated $\Delta S_{0–50cm}$ from June to September were close to zero at both Shrubland-K and Poplar-K (representing almost no recharge); the negative value of accumulated $\Delta S_{0–50cm}$ indicated substantial water

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

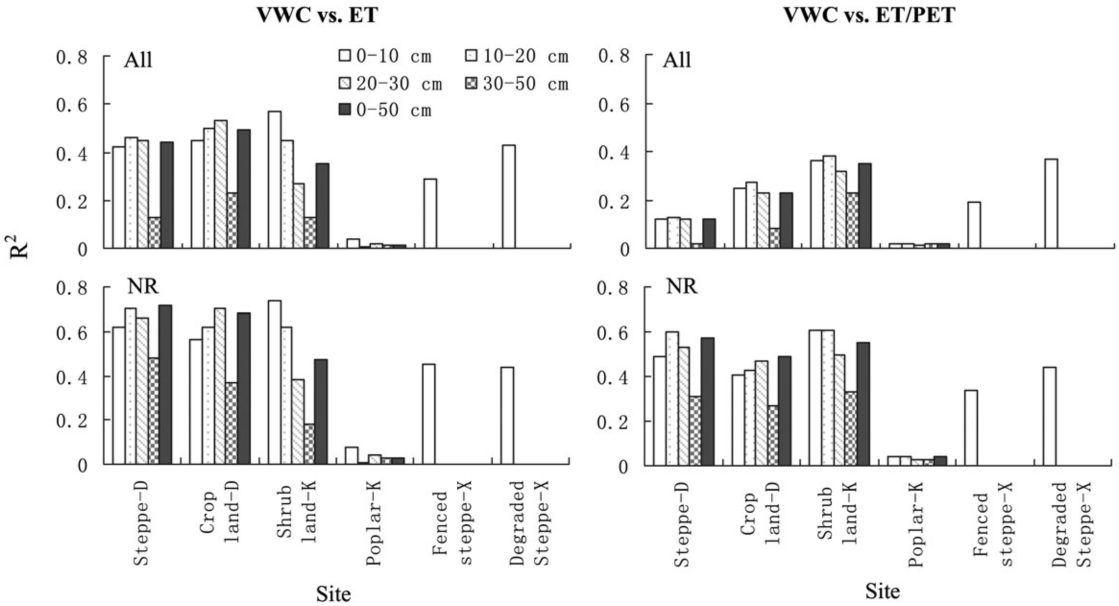


**Figure 3:** coefficient of determination ($R^2$) of linear correlation between ET, ET/PET and VWC in different soil layers at three paired sites at the daily scale. 'All' means data points from all observation days (with gap filling); 'NR' (no rain) means data points during rainy days were excluded.

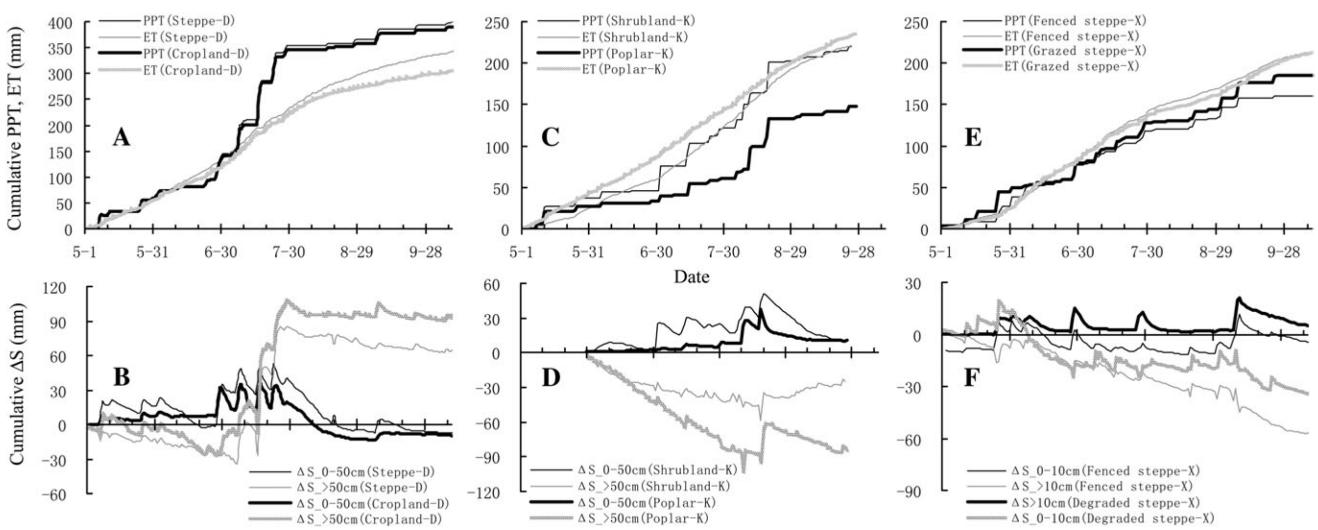


**Figure 4:** comparison of cumulative PPT, ET (A, C, E) and soil water storage (ΔS) (B, D, F) (mm) in the 2006 growing season at three paired sites. ΔS is shown for 0–50 cm of soil layer and deeper soil layer (>50 cm), respectively.

was extracted by plants from below 50 cm of soil depth, especially at Poplar-K.

The total PPT were 34.8 mm less at Fenced Steppe-X than Grazed Steppe-X, but the total amounts of ET were very close. The ET/PPT ratio was 1.39 and 1.12 at Fenced Steppe-X and Grazed Steppe-X, respectively. The accumulated PPT exceeded ET in May and they were mostly balanced at the end of June at both Fenced Steppe-X and Grazed Steppe-X. However, PPT was not sufficient for ET later in the growing season at either sites and the water deficit was 66.6 and 32.2 mm at Fenced Steppe-X and Grazed Steppe-X, respectively (Fig. 4E and F). The ΔS in the 0–10 cm of soil was almost balanced, indicating that both sites depleted water from below 10 cm.

## ΔS dynamics and its fractional contribution to ET

During the rainy days, PPT was distributed to the soil layers in different percentages, depending on the amount of PPT. Under

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

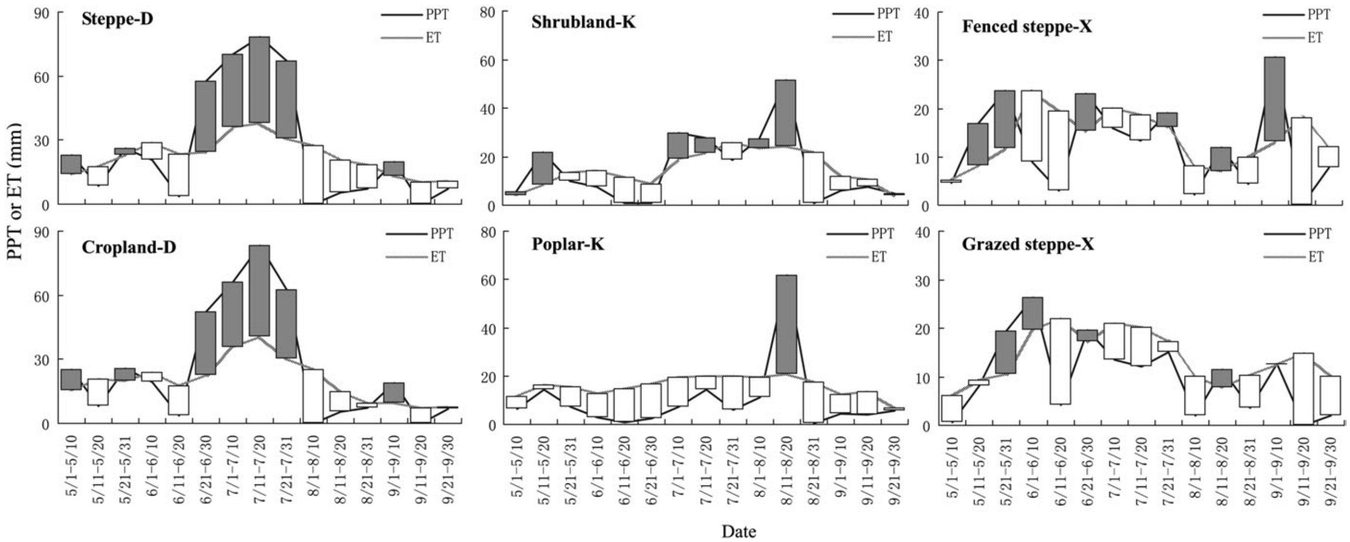


**Figure 5:** comparison of the temporal dynamics of PPT (smooth line) and ET (dot line) at three paired sites for the 2006 growing season. The bars represent differences between PPT and ET, gray for PPT > ET and white for PPT < ET. The water flux components are shown in 10-day intervals.

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

the non-runoff assumption, the PPT that exceeded ET on rainy days was stored and returned to the atmosphere through ET during non-rainy periods (Figs 5 and 6). The ΔS of shallower soil layers was mainly recharged immediately following rainfall, and only later did deeper soil layers respond, after the upper soil was saturated. This was most clearly shown at Steppe-D and Cropland-D from late June to July when the rainfall continued to over a period of days. The recharge and depletion of ΔS were not synchronous for different soil layers. The ΔS decreased in some layers while increasing in other layers. For example, at Shrubland-K water percolation into the 0- to 50-m layer, while at the same time, roots in the >50 cm layer extracted water that contributed to transpiration. This phenomenon was observed at the daily as well as the 10-day intervals (Fig. 6), reflecting the complexity of water redistribution in the soil profile when both the replenishment and extraction of water occurred simultaneously.

The changes in ΔS in a certain soil layer reflected the net results of rainfall recharge, water consumption by ET and soil water redistribution across soil layers at finer time scales, e.g. within a day; but in the long term, the accumulated loss of water can be regarded as extraction by ET. Thus, the relative contribution of ΔS from a soil layer can be calculated by summing the accumulated decrease in its ΔS compared to total ET. We found that the contributions of ΔS to ET were not identical for different soil layers. On non-rainy days, it was 29, 18, 9 and 3% at Steppe-D and 15, 10, 5 and 13% at Cropland-D in 0–10, 10–20, 20–30 and 30–50 cm soil layers, respectively. In total, ΔS of the upper 50 cm of soil contributed 59 and 43% of water to ET at Steppe-D and Cropland-D, respectively. The ΔS of the upper 50 cm of soil contributed 64% of water to ET at Shrubland-K and only 23% at Poplar-K. The ΔS of 0–10 cm of soil contributed 38% to ET at Fenced Steppe-X and 26% at Grazed Steppe-X.

# DISCUSSION

## VWC and ET relations

The differences between the paired sites in VWC under similar rainfall events may be in response to the changes of soil properties associated with land use practices, at least in regard to the upper soil depths. The VWC in the surface soil at Cropland-D was lower than Steppe-D, perhaps from a decrease in soil total porosity associated with an increase in bulk density following furrowing activities (Mitchell 1991). Similarly, grazing may cause the compaction of surface soil and decreased the VWC (Schlesinger *et al.* 1990). For the tree plantation (Poplar-K), the relatively high soil bulk density and low organic matter compared with Shrubland-K may partly account for the low VWC in the upper soil depths, although it is unknown how much difference was associated with vegetation type.

Some of the outliers in ET and VWC correlation may be caused by the small rainfalls of short duration (for the case of high ET but low VWC). In such cases, evaporation from the soil or leaf surface may have been sufficient to prevent wetting below the surface soil. Whereas, the other instance of low ET but high VWC may follow relatively large PPT, during when the evaporative demand remains low, and so that soil recharge is rapid.

The stronger relationships between VWC and ET compared to VWC and ET/PET were for the steppe and crop sites, which is consistent with other studies in arid regions, where ET was mainly constrained by VWC rather than the evaporative demand of the atmosphere (including net solar energy) (Brutsaert and Chen 1995; Yamanaka *et al.* 2007). The differences in VWC–ET relationships for different soil depths were in part a function of rainfall, the more the rainfall, the better the relationship. For a grassland in central New Mexico, Kurc and Small (2007) found that ET was strongly related to

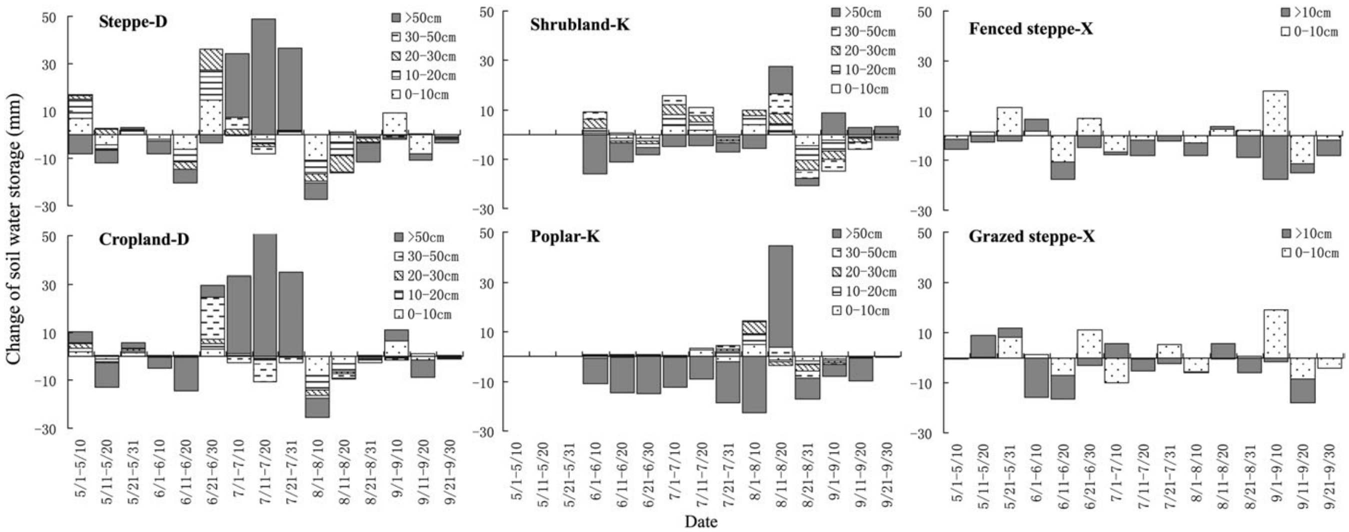


**Figure 6:** comparison of the temporal dynamics of soil water storage (ΔS, mm) in different soil layers at three paired sites during the 2006 growing season. The data are presented at 10-day intervals, based on VWC averaged from 30-min means. The values above the zero line represent water recharge to a soil layer; and the values below the zero line represent water loss from a soil layer.

VWC of the upper 5 cm of soil and ΔS of the 0- to 10-cm layer was the main water reservoir. The importance of a much shallower soil layer in their study may reflect a difference in PPT, which was only 137 mm during growing season in their study compared to ours (213–343 mm). If the lower soil layers were not fully recharged, roots would be expected to extract water from surface layers with higher (less negative) water potentials (Doussan *et al.* 1998).

In contrast, as fast-growth plantations of trees, such as at the Poplar-K site, are much less tolerant to drought than the native shrubs (Monclus *et al.* 2006) and prospered only when a water source was readily available. This observation would explain the high ET/PPT ratio of up to 1.50 at Poplar-K where roots access groundwater 1–3 m below the surface (Wilske *et al.* 2009). The contrast between poplars exploiting of groundwater and *A. ordosica* relying on the availability of soil water in the surface horizons (Ohte *et al.* 2003) may explain why VWC had no correlation with ET at Poplar-K but a strong correlation at Shrubland-K. Regardless of what caused the differences in ET–VWC relationships among soil depths in our study, it suggests that acquiring more information from deeper soil layers will improve our understanding of the interactions between ET and ΔS. With the additional knowledge, more comprehensive simulation models can be constructed and evaluated (Glenn *et al.* 2007).

## Water balance of the growing season

Native plants have developed various adaptations to avoid or tolerate water deficits. These adaptations include: seasonal control of leaf stomata, resistance to cavitation, deep rooting to exploit groundwater, reduction in leaf area, and different photosynthetic pathways (C-3 vs. C-4) that affect water use efficiency (Gaze *et al.* 1998; Nilsen *et al.* 1983; O'Grady *et al.* 1999; Wang *et al.* 2004; Webb 1978). In the early growing season, the ratio between ET and PPT at our steppe and shrub sites clearly reflect the native vegetation's success in adapting to the limited water. Shrubland-K maintained an almost closed balance between PPT and ET from May to September with a total PPT of 220.5 mm and total ET of 221.7 mm. In contrast, fast growing tree plantations (usually composed of non-native species), as noted above, are intolerant of drought. In arid environments, plantations survive and grow well only if they obtain access to groundwater or receive irrigation (Moore *et al.* 2004; Myers *et al.* 1996). Because of these differences in adaptation, large plantations can draw down ground water resources, which can be detrimental or beneficial, depending on the degree that salt might accumulate on the surface soil (Edraki *et al.* 2007; Harper *et al.* 2005; Wilske *et al.* 2009).

The findings about water use of cropland and degraded grassland relative to native vegetation are inconsistent due to differences in crop species, grazing intensity, annual rainfall as well as soil conditions (Burba and Verma 2005; Mahmood and Hubbard 2003; Miao *et al.* 2009). The total ET during the growing season was smaller at Cropland-D than Steppe-D, as a result of the lower VWC in the upper soil layers and shorter growing period compared to the undisturbed grassland (Miao *et al.* 2009). Thus, less water loss through ET led to more water storage in the soil during the relatively wet growing season (total PPT > ET) at Cropland-D. An increase in soil water storage by conversion of semi-arid pasture to cropland was also reported by Snyman (2000) in South Africa, where cultivation increased ΔS by 31%. Grazing tended to decrease ecosystem ET similar to cultivation. Aside from lower LAI, lower VWC in the surface soil was also a major contributor to the lower ET/PET (i.e. normalized ET) at Grazed Steppe-X (Miao *et al.* 2009). The ET/PPT ratio was higher at Fenced Steppe-X than

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

Grazed Steppe-X (both >1), although the total amounts of ET were almost the same. Consequently, there was more soil water depletion at Fenced Steppe-X than the Grazed Steppe-X.

### Effects of time lag

Scott and Cable (2004) observed that it took ~10 days for desert shrubs to respond to PPT at the beginning of the rainy season, whereas thereafter, the responses took <2 days. We observed the same differences in response to PPT in our study. Both Fenced Steppe-X and Grazed Steppe-X showed time lags in ET following PPT. $R^2$ values improved from 0.29 to 0.62 at Fenced Steppe-X and from 0.05 to 0.37 at Grazed Steppe-X when we shifted ET measurements 10 days forward to match PPT events. Similarly, the $R^2$ improved from 0.37 to 0.46 by shifting the time window for 10 days at Shrubland-K. The necessity to take account of a 10-day time lag in ET response to PPT was consistent at Fenced Steppe-X, Grazed Steppe-X and Shrubland-K. We believe this long time of time lag is a result of long periods between rain events. However, at Steppe-D and Cropland-D, where PPT was higher but still separated by long intervals, ET response still occurred 10 days following PPT (Fig. 5), with the $R^2$ being 0.52 and 0.65, respectively. The asynchronous changes in VWC or ΔS of different soil layers also were the result of time lags because PPT takes longer to infiltrate to deeper than to shallower soil layers. In contrast, the Poplar-K site was unresponsive to the moisture regime in surface soil layers as tree roots extracted water almost exclusively from deeper water sources.

### Relative contribution of ΔS to ET

VWC and ΔS are two different measures of soil water status. The former we used to assess the correlation with ET, while the latter provided a measure of the amount of water extracted or added to the measured soil profile. The amount of PPT in a given rainfall event was the major factor determining the depth that water infiltrated under natural vegetation. The mean depth that water infiltrates usually determined the vertical distribution of root biomass in arid areas (Rambal 1984). Others have suggested that the pattern of plant water uptake across soil depths may result from the non-uniform soil horizons that affect root penetration and density, as well as the rate and depth that water infiltrates (Li *et al.* 2002; Rambal 1984; van Genuchten 1980). At the same time, as suggested by our study, both water and root redistribution are affected by soil disturbances associated with the intensity and type of land use activities. The fraction of soil water contributing to ET was positively correlated with root biomass ($R^2$ = 0.67, $P <$ 0.01) within the 0–50 cm of depth at the grassland and cropland sites (Fig. 7), which suggested that root biomass was an important indictor of where water was extracted by herbaceous species.

The ΔS of below 50 cm of soil contributed substantial amounts of water to ET at Steppe-D and Cropland-D although the root biomass (~15% of total root biomass) was less than that of upper soil layers. This indicated that deep roots played

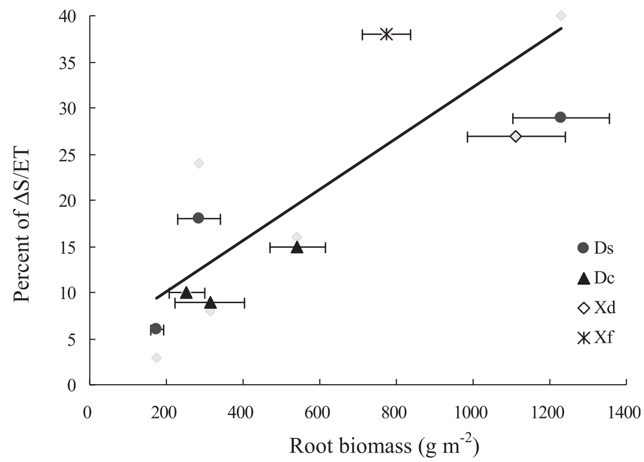


**Figure 7:** relationship between vertical distribution of root biomass and percentage of soil water contribution to ET by soil layer. Three data points are from Ds and Cropland-D (0–10, 10–20, 20–40 cm) and one data point from Grazed Steppe-X and Fenced Steppe-X, respectively (0–10 cm). Error bars are standard error. The solid line is the linear fit based on the eight data points. The coefficient of determination ($R^2$) between root biomass and percent of ΔS/ET is 0.67 ($P$ < 0.01).

a critical role in providing water for plants in the dry period to these water-limited ecosystems. Our interpretation corresponds to that offered by Rambal (1984) who states in a study of a *Quercus* scrub ecosystem that when soils were uniformly wet, the surface soil water contributed the most to ET, but as the soil dried, deeper soil layers contributed an increasing fraction of water despite having a lower root density.

The frequent occurrence of simultaneous recharge and depletion of soil water in different soil layers observed in our study indicated a very complex relationship between root water extraction and infiltration. At least three factors are involved in this process. Firstly, infiltration from the surface has a time lag to reach deeper soil horizons. Secondly, roots extract water at different rates from different layers. Thirdly, roots may permit hydraulic redistribution from moist to drier soil horizons. Even herbaceous plants may directly participate in this phenomenon as they have ability to extend roots to 1.5- to 2-m depths (Caldwell and Dawson 1998; Canadell *et al.* 1996; Izzi *et al.* 2008; Moroke *et al.* 2005). The maximum soil depth to which roots can access was beyond the limits of our sampling. Future studies need take measurements of VWC in deeper soil depth in such water-limited ecosystems.

In semi-arid and arid ecosystems, ET is often similar regardless of the type of vegetation because none of the PPT infiltrates below the rooting depth and is fully utilized (Wilcox *et al.* 2003). Different types of vegetation may, however, alter the relative contribution of evaporation and transpiration, especially for deeply rooted plants (Kizito *et al.* 2006). Transpiration was found to comprise 35–59% of ET in a Kherlenbayan-Ulaan grassland in eastern Mongolia (Tsujimuraa *et al.* 2007) and 96–98% of ET in a wheat field in Israel (Wang and Yakir 2000). Based on our findings, we believe that transpiration

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

contributed a large proportion of water to ET at the six sites during the growing season because evaporation was mainly restricted to losses from surface soil (Kurc and Small 2007; Sala *et al.* 1992). This is consistent with the stable isotope analysis which indicated that transpiration contributed an average of 73–88% to the total ET during the growing season at Steppe-D and Cropland-D (Miao 2008). The fraction that $\Delta S_{0-50\ cm}$ contributed to ET was 59% at the Steppe-D and 43% at the Cropland-D, with 14–45% from unconfirmed sources (possibly from below 50 cm and from evaporation off the surface of vegetation). Some error in measurement of VWC may also be involved as there was high variation among samples (Choler *et al.* 2009).

## CONCLUSIONS

Our study confirmed that land use manners such as cultivation, grazing and tree plantation can cause complex changes in the soil water dynamics and vegetation–ET–soil water feedbacks in the semi-arid Inner Mongolia. We also learned that our future studies should measure soil moisture at greater depths with more replication. To elucidate how the complex interrelationships between soil dynamics affect the regional hydrology and carbon cycle in arid regions, ecosystem models will need to include more detail in defining soil layers and water transport vertically and horizontally.

## FUNDING

Natural Science Foundation of China (30928002); National Aeronautics and Space Administration (NASA) - NEWS Program of US (NN-H-04-Z-YS-005-N); the Outstanding Overseas Scientists Team Project of CAS; the State Key Basic Research Development Program of China (2007CB106800); the National Basic Research Program of China (973 Program) (2010CB833501).

*Conflict of interest statement.* None declared.

## REFERENCES

Alavi N, Warland JS, Berg AA (2006) Filling gaps in evapotranspiration measurements for water budget studies: evaluation of a Kalman filtering approach. *Agric For Meteorol* **141**:57–66.

Allen RG, Pruitt WO, Wright JL, *et al.* (2006) A recommendation on standardized surface resistance for hourly calculation of reference ETO by the FAO56 Penman-Monteith method. *Agric Water Manage* **81**:1–22.

Archer S, Schimel DS, Holland EA (1995) Mechanisms of shrubland expansion: land use, climate or $CO_2$? *Clim Change* **29**:91–9.

Brandes D, Wilcox BP (2000) Evapotranspiration and soil moisture dynamics on a semiarid Ponderosa Pine hillslope. *J Am Water Res Assoc* **36**:965–74.

Brutsaert W, Chen D (1995) Desorption and the two stages of drying of natural tallgrass prairie. *Water Resour Res* **31**:1305–13.

Burba GG, Verma SB (2005) Seasonal and interannual variability in evapotranspiration of native tallgrass prairie and cultivated wheat ecosystems. *Agric For Meteorol* **135**:190–201.

Caldwell MM, Dawson TE (1998) Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia* **113**:151–61.

Canadell J, Jackson RB, Ehleringer JR, *et al.* (1996) Maximum rooting depth of vegetation types at the global scale. *Oecologia* **108**:583–95.

Chen S, Chen J, Lin G, Zhang W, Miao H, Wei L, Huang J, Han X (2009) Energy balance and partition in Inner Mongolia steppe ecosystems with different land use types. *Agric For Meteor* **149**:1800–9.

Choler P, Sea W, Briggs P, *et al.* (2009) A simple ecohydrological model captures essentials of seasonal leaf dynamics in semi-arid tropical grasslands. *Biogeosciences* **7**:907–20.

Doussan C, Pages L, Vercamber G (1998) Modelling of the hydraulic architecture of root systems: an integrated approach to water absorption-model description. *Ann Bot* **81**:213–23.

Edraki M, Kowsar SA, Mehrbakhsh AA, *et al.* (2007) Water Consumption of a Six-Year-Old River Red Gum Plantation in the Southern Zagros Mountains, Iran. *Journal of Mountain Science* **4**:136–45.

Feddes RA, Hoff H, Bruen M, *et al.* (2001) Modeling root water uptake in hydrological models and climate models. *Bull Am Meteorol Soc* **82**:2797–2809.

Gaze SR, Brouwer J, Simmonds LP, *et al.* (1998) Dry season water use patterns under *Guiera senegalensis* L. shrubs in a tropical savanna. *J Arid Environ* **40**:53–67.

Glenn EP, Huete AR, Nagler P, *et al.* (2007) Integrating Remote Sensing and Ground Methods to Estimate Evapotranspiration. *Crit Rev Plant Sci* **26**:139–68.

Granier A, Biron P, Lemoine D (2000*a*) Water balance, transpiration and canopy conductance in two beech stands. *Agric For Meteorol* **100**:291–308.

Granier A, Loustau D, Breda N (2000*b*) A generic model of forest canopy conductance dependent on climate, soil water availability and leaf area index. *Ann For Sci* **57**:755–65.

Grayson RB, Western AW (1998) Towards areal estimation of soil water content from point measurements: time and space stability of mean response. *J Hydrol* **207**:68–82.

Harper RJ, Smettem KRJ, Tomlinson RJ (2005) Using soil and climatic data to estimate the performance of trees carbon sequestration and recharge potential at the catchment scale. *Austr J Exp Agric* **45**:1389–401.

Huxman TE, Wilcox BP, Breshears DD, *et al.* (2005) Ecohydrological implications of woody plant encroachment. *Ecology* **86**:308–19.

Izzi G, Farahani HJ, Bruggeman A, *et al.* (2008) In-season wheat root growth and soil water extraction in the Mediterranean environment of northern Syria. *Agric Water Manage* **95**:259–70.

John R, Chen J, Lu N, *et al.* (2009) Land cover/land use change and their ecological consequences: lessons from Inner Mongolia. *Environ Res Lett* **4**:045010, doi:10.1088/1748-9326/4/4/045010.

Kizito F, Dragila M, Sene M, *et al.* (2006) Seasonal soil water variation and root patterns among two semi-arid shrubs coexisting with Pearl millet in Senegal, West Africa. *J Arid Environ* **67**:436–55.

Kurc SA, Small EE (2004) Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico. *Water Resour Res* **40**:W09305.

Kurc SA, Small EE (2007) Soil moisture variations and ecosystem-scale fluxes of water and carbon in semiarid grassland and shrubland. *Water Resour Res* **43**:W06416.

Leuning R (2004) Measurements of trace gas fluxes in the atmosphere using eddy covariance: WPL corrections revisited. In: Lee X, MassmanWJ, Law BE (eds). *Handbook of Micrometeorology. A Guide to Surface Flux Measurement and Analysis*. Boston, MA: Kluwer, 119–32.

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011

Li Y, Fuchs M, Cohen S, *et al.* (2002) Water uptake profile response of corn to soil moisture depletion. *Plant Cell Environ* **25**:491–500.

Mahmood R, Hubbard KG (2003) Simulating sensitivity of soil moisture and evapotranspiration under heterogeneous soils and land uses. *J Hydrol* **280**:72–90.

Miao H (2008) *Effects of cultivation and grazing on evapotranspiration of steppe ecosystems in Inner Mongolia, China. Doctoral dissertation.* Institute of Botany, Chinese Academy of Sciences, China.

Miao H, Chen S, Chen J, *et al.* (2009) Cultivation and grazing altered evapotranspiration and dynamics in Inner Mongolia steppes. *Agric For Meteorol* **149**:1810–9.

Mitchell AR (1991) Soil surface shrinkage to estimate profile soil water. *Irrig Sci* **12**:1–6.

Monclus R, Dreyer E, Villar M, *et al.* (2006) Impact of drought on productivity and water use efficiency in 29 genotypes of *Populus deltoids* × *Populus nigra*. *New Phytol* **169**:765–77.

Moore GW, Bond BJ, Jones JA, *et al.* (2004) Structural and compositional controls on transpiration in 40- and 450-year-old riparian forests in western Oregon, USA. *Tree Physiol* **24**:481–91.

Moroke TS, Schwartz RC, Brown KW, *et al.* (2005) Soil water depletion and root distribution of three dryland crops. *Soil Sci Soc Am J* **69**:197–205.

Myers BJ, Theiveyanathan S, O'Brien ND, *et al.* (1996) Growth and water use of Eucalyptus grandis and Pinus radiate plantations irrigated with effluent. *Tree Physiol* **16**:211–9.

Nilsen ET, Sharifi MR, Rundel PW, *et al.* (1983) Diurnal and seasonal water relations of the desert Phreatophyte *Prosopis Glandulosa* (Honey Mesquite) in the Sonoran desert of California. *Ecology* **64**:1381–93.

Noy-Meir I (1973) Desert ecosystems: environment and producers. *Annu Rev Ecol Syst* **4**:25–52.

O'Grady AP, Eamus D, Hutley LB (1999) Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia. *Tree Physiol* **19**:591–7.

Ohte N, Koba K, Yoshikawa K, *et al.* (2003) Water utilization of natural and planted trees in the semiarid desert of Inner Mongolia, China. *Ecol Appl* **13**:337–51.

Porporato A, Laio F, Ridolfi L, *et al.* (2001) Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress: III. Vegetation water stress. *Adv Water Res* **24**:725–44.

Rambal S (1984) Water balance and pattern of root water uptake by a *Quercus coccifera* L. evergreen scrub. *Oecologia* **62**:18–25.

Sala OE, Lauenroth WK, Parton WJ (1992) Long-term soil water dynamics in the shortgrass steppe. *Ecology* **73**:1175–81.

Schlesinger WH, Reynolds JF, Cunningham GL, *et al.* (1990) Biological feedbacks in global desertification. *Science* **247**:1043–8.

Scott RL, Cable WL (2004) The differential response of transpiration and bare-soil evaporation to precipitation in a Chihuahuan desert shrubland. *In: 26th Conference on Agricultural and Forest Meteorology, American Meteorological Society, 23–7 August, Vancouver, BC, Canada.*

Shuttleworth WJ (1991) Evaporation models in hydrology. In: Schmugge TJ, Andre J (eds). *Land Surface Evaporation*. New York: Springer-Verlag, 93–120.

Snyman HA (2000) Soil-water utilization and sustainability in a semi-arid grassland. *Water SA* **2**:333–42.

Sun G, Alstad K, Chen J, *et al.* (2010) A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecohydrology* (In press).

Tsujimuraa M, Sasaki L, Yamanaka T, *et al.* (2007) Vertical distribution of stable isotopic composition in atmospheric water vapor and subsurface water in grassland and forest sites, eastern Mongolia. *J Hydrol* **333**:35–46.

Van Auken O (2000) Shrub invasions of North American semiarid grasslands. *Annu Rev Ecol Syst* **31**:197–215.

Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci Soc Am J* **44**:892–898.

Wang XF, Yakir D (2000) Using stable isotopes of water in evapotranspiration studies. *Hydrol Process* **14**:1407–21.

Wang XP, Brown-Mitic S, Lauenroth W, *et al.* (1978) Productivity and Water Use in Native Forest, Grassland, and Desert Ecosystems. *Ecology* **59**:1239–47.

Webb W, Szarek CM, Lauenroth W, *et al.* (1978) Primary Productivity and Water Use in Native Forest, Grassland, and Desert Ecosystems. *Ecology* **59**:1239–47.

Wilcox BP, Seyfried MS, Breshears DD (2003) The water balance on rangelands. In: Stewart BA, Howell TA (eds). *Encyclopedia of Water Science*. New York: Marcel Dekker, 791–4.

Wilske B, Lu N, Wei L, *et al.* (2009) Poplar plantation has the potential to alter water balance in semiarid Inner Mongolia. *J Environ Manage* **90**:2762–70.

Wilske B, Kwon H, Wei L, *et al.* (2010) Evapotranspiration (ET) and regulating mechanisms in two semiarid Artemisia-dominated shrub steppes at opposite sides of the globe. *J Arid Environ* **74**:1461–70.

Xie J, Sun G, Chen J, Wang M, *et al.* (2009) Soil moisture characteristics of different types of vegetation in Xilingol grassland. *J Northeast For Univ* **37**:45–8.

Yamanaka T, Kaihotsu I, Oyunbaatar D, *et al.* (2007) Summer time soil hydrological cycle and surface energy balance on the Mongolian steppe. *J Arid Environ* **69**:65–79.

Zhang YK, Schilling KE (2006) Effects of land cover on water table, soil moisture, evapotranspiration, and groundwater recharge: a field observation and analysis. *J Hydrol* **319**:328–38.

Zhang W, Chen S, Chen J, *et al.* (2007) Biophysical regulations of carbon fluxes of a steppe and a cultivated cropland in semiarid Inner Mongolia. *Agric For Meteorol* **146**:216–29.

Downloaded from jpe.oxfordjournals.org by guest on March 13, 2011