Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

Hydrology and Earth System Sciences
Open Access
Discussions

Manuscript Title

Monitoring the variations of evapotranspiration due to the land use/cover changes in a semiarid shrubland

Tingting Gong, Huimin Lei, Dawen Yang, Yang Jiao, Hanbo Yang

State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China

Correspondence to: Huimin Lei (leihm@tsinghua.edu.cn)

Abstract

Evapotranspiration (E_T) is an important process in the hydrological cycle, and vegetation change is a primary factor that affects E_T. In this study, an attempt is made to analyze the annual and inter-annual characteristics of E_T using continuous observation data from eddy-covariance (EC) measurements over four periods (1st July 2011 to 30th June 2015) at a study site located in the Mu Us Sandland of China. Normalized vegetation index (NDVI) was demonstrated as the predominant factor that influences the seasonal variation in E_T. Normalization method was adopted to exclude the effects of potential evapotranspiration (E_{TP}) and soil water stress (f_s) on E_T. Vegetation phenological process was validated to have a remarkable positive effect on normalized E_T in a rate of 1.86 (the slope of normalized E_T per NDVI) along with vegetation greening. Both on the land degradation process and vegetation rehabilitation process, E_T and normalized E_T increased. We discussed several possibilities that might lead to the increase. Our work may promote our knowledge about the characteristics of

E_T of the mix land use/cover condition (sparse shrubland and grassland) in the fragile ecosystem of Mu Us Sandland.

Key words: evapotranspiration; vegetation phenology; land use/cover change; eddy covariance; Mu Us Sandland

1 Introduction

Arid and semiarid biomes cover about 40% of the Earth's terrestrial surface (Fernández, 2002). Previous studies have shown that more than 50% of precipitation (P) is consumed by E_T (Yang et al., 2007; Liu et al., 2002), and that the ratio of E_T/P could increase to even 90% or more in semiarid and arid areas (Mo et al., 2004; Glenn et al., 2007). Therefore, a slight change in E_T would have significant influences on water cycle in arid and semiarid regions. E_T is not only affected by climatic factors (e.g., radiation, temperature, and relative humidity), but also affected by vegetation conditions (Tian et al., 2015; Wang et al., 2011; Piao et al., 2006; Mackay et al., 2007). As such, there has been an important push to understand how E_T responds to vegetation conditions in these regions.

Vegetation change mainly integrates the phenological change (temporal) and land use/cover change (spatial). The phenological change reflects the response of plants to climate change (vegetation greening and browning process) (Ge et al., 2015), which actively controls E_T process through internal physiology such as stomatal conductance (Pearcy et al., 1989) and stomatal numbers and sizes (Turrell, 1947). In general, transpiration is in direct proportion to stomatal conductance at the leaf-level scale (Leuning et al., 1995). Meanwhile, at canopy scale, E_T is positively proportional to surface conductance that is an integration of stomatal conductance and leaf area (Ding et al., 2014). Thus, as a good indicator of vegetation phenological change, many studies have found that E_T was positively related to vegetation index such as Normalized difference vegetation index (NDVI) (Gu et al., 2007). Land use/cover change influences

E_T by means of modifying vegetation species with different transpiration rates, radiation transfers within canopy (Martens et al., 2000; Panferov et al., 2001), topography (Lv et al., 2006), albedos (Zeng et al., 2009), soil texture (Maayar and Chen, 2006), litter coverage (Wang, 1992), and biological soil crusts (Yang et al., 2015, Fu et al., 2010; Liu, 2012; Eldridge and Greene, 1994). These complex processes result in no consensus about the effects of land use/cover changes on E_T. For example, during the land degradation process, some researchers found that warming air temperature increase was the dominant cause to make E_T increase (Zeng and Yang, 2008; Li et al., 2000; Deffema and Freire, 2001). In contrary, E_T was found to decrease along with deforestation because of less transpiration (Snyman, 2001; Souza and Oyama, 2011) or higher albedos (Zeng et al., 2002). Moreover, no differences of E_T during land degradation was also reported (Hoshino et al., 2009). Therefore, the impacts of land use/cover changes on E_T still deserve further investigations.

The Mu Us Sandland is a semiarid shrubland ecosystem at the northern margin of the Loess Plateau in China, covering an area of only 40,000 km^2 (Dong and Zhang, 2001). The region is ecologically fragile (Yang et al., 2007). Shortage of water is the critical limiting factor on vegetation, and drought-enduring vegetation are prevailed as a result of common droughts (Wang et al., 2002; Wu, 2006). There are at least 117 shrub and semi-shrub species have been found within the Mu Us Sandland (Dong and Zhang, 2001). In such arid and semiarid ecosystem, sand dunes and biological soil crusts (BSCs) are commonly observed (Gao et al., 2014; Yang et al., 2015; Li and Li, 2000; Liu, 2012). Due to the exists of BSCs (Yang et al., 2015; Fu et al., 2010; Liu, 2012) and dry sand layers (Wang et al., 2006; Feng, 1994; Liu et al., 2006; Yuan et al., 2007), soil evaporation have been effectively retained, therefore, the Mu Us Sandland holds abundant groundwater (Li and Li, 2000). During the past decades, rapid land use/cover change has taken place in this region due to agricultural reclamation (Wu et al., 1997; Wu and Ci, 2002; Wang et al., 2009; Ostwald and Chen, 2006; Zhang et al., 2007), leading to a dramatic change in vegetation conditions. With respect to the specific question of whether land use/cover changes will lead to increases in E_T or not, a continuous measurement of E_T under different land use/cover conditions is needed in this region.

Three methods were usually employed to assess the impacts of land use/cover change on E_T: numerical models, paired comparative approaches and the in situ filed observations. In these methods, numerical models are widely used (Twine et al., 2003; Feddema et al., 2005; Kim et al., 2005; Li et al., 2009; Cornelissen et al., 2013; Mo et al., 2004). However, model parameterization of vegetation condition is a big challenge as the complex underlying mechanisms mentioned above cannot be completely considered in the models. Therefore, the simulated impacts of land use/cover change on E_T is highly dependent on the model parameterizations, and the resulting conclusions may be doubtful (Cornelissen et al., 2013; Li et al., 2009). Paired comparative approach is often considered as the best method, but it is difficult to find two similar medium and large-sized sites with different land use/cover conditions (Li et al., 2009; Lorup et al., 1998). In situ observation is also a widely used method for long-term land-atmosphere exchange measurements. However, the land use/cover conditions at the sites are usually

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

Hydrology and Earth System Sciences
Discussions
Open Access

stable, and only the responses of E_T to vegetation phenology change can be studied. For example, the characteristics of E_T under grassland (Zhang et al., 2005), mixed plantation (cork oak, black locust and arborvitae) (Tong et al., 2014), vineyard (Li et al., 2015) and grazed steppe (Chen et al., 2009; Vetter et al., 2012). To our knowledge, there is little learned of E_T under native sparse shrubland and continuous filed observations under land degradation and vegetation rehabilitation conditions are not documented.

Our study site is at the edge of the Mu US Sandland. Coincidentally, land degradation and vegetation rehabilitation has occurred at this site, which provides us a unique opportunity to study the effects of land use/cover change on E_T. Based on the 4-year measurements of E_T by eddy covariance technique, this study analyzed the seasonal and inter-annual variations of E_T, and discussed the possible reasons for the responses of E_T to land use/cover changes.

2 Materials and methods

2.1 Site description

The study was carried out at Yulin flux site (N 38°26´, E 109°47´, 1233 m), which was established in June 2011 and is in a landform transition zone change from Mu Us Sandy land to north Shaanxi Loess Plateau (Fig. 1). The study site is in a temperate semiarid continental temperate monsoon climate. According to the long-term climate data (1951-2012) from a meteorological station in Yulin (Fig. 1), the annual precipitation varies from 235 mm to 685 mm, with a mean of 402 mm, and more than 50% of annual precipitation is falling in the monsoon season (July-September). The mean annual air temperature is 8.4 ℃ during the past 61 years. The dominant soil type is sand (98% sand) (saturated soil water content: 0.43 m^3m^{-3}, field capacity: 0.16 m^3m^{-3}, residual moisture content: 0.045 m^3m^{-3}). There are widely distributed fixed dunes and semi-fixed dunes around the site, and the depth of dry sand layer is 10 cm (Wang et al., 2006). The mean groundwater depth of our study site from 1st July 2011 to 30th June 2015 was 3.5 m.

[Figure 1 is to be inserted here]

The experimental site is mainly covered with mixed vegetation, one kind of vegetation is the native drought-enduring shrubs with low water demands such as *Artemisia ordosica* and *Salix psammophila* (Fig.2a); the other kind is the sparse grassland that mainly distributed at the bottom of sand dunes because of better soil moisture condition (Lv et al., 2006). They constitute the dominant vegetation in Mu Us Sandland (An et al., 2011) and are adapted well to semiarid and arid sites. According to our observations around the flux tower on 14th June 2011, the maximum root depth of the shrubs was approximately 160 cm. Xiao et al. (2005) reported that the growing season of *Artemisia ordosica* and *Salix psammophila* spanned from late April to late September. Therefore, we defined the period from 1st May to 30th September as vegetation growing season for data analysis in this study. On 15th August 2011 and 7th September 2011, we did surveys about the vegetation coverage with randomly selected 7 samples around the flux tower (5 × 500 cm × 500 cm and 2 × 1000 cm × 1000 cm), and found that the vegetation coverage was 28.2% and 27.9%, respectively.

[Figure 2 is to be inserted here]

At the end of June 2012, the land use/cover condition around the east area of flux tower began to be changed by farmers (the natural vegetation including the leaves and branches was cut-off, and the sand dunes were bulldozed) (Fig. 2c), converting part of the natural vegetated land to bare soil, with the planning of planting potatoes in the future. As time goes on, natural grass grew out gradually in the bare land before planting potatoes. Thus, our study period can be divided into four periods according to the land use/cover conditions: Period I (1st July 2011 to 30th June 2012) was the natural land use/cover condition (i.e., mixed sparsely distributed shrubs and grass) (Fig.2a and Fig.2b); Period II (1st July2012 to 30th June 2013) was the transitional period with land use/cover condition starting to change with partial natural vegetation being cut-off and sand dunes being bulldozed; Period III (1st July 2013 to 30th June 2014) was the period when the land use/cover condition constituted two parts, one was the natural vegetation zone and the other was the bare soil zone (Fig.2c); Period IV (1st July 2014 to 30th June 2015) was the period when the bare soil zone was gradually covered by re-growing grass (Fig.2d).

2.2 Measurements

2.2.1 Eddy covariance system

Net exchange of water vapor between atmosphere and canopy at this site is measured by the eddy-covariance (EC) flux measurements, which assess the fluxes of land-atmosphere (such as water and energy) (Baldocchi et al., 2001). The data are essential for the estimation of the water and energy balance (Franssen et al., 2010). At our site, EC system is installed at a height of 7.53 m above the ground surface, using CSAT3 three-dimensional sonic anemometers (Campbell Scientific Inc., Logan, UT, USA) for wind and temperature fluctuations measurements and a LI-7500A open-path infrared gas analyzer (LI-COR, Inc., Lincoln, NE, USA) for water vapor content measurement.

2.2.2 Other measurements

Net radiation (R_n) is measured by a net radiometer (CNR-4; KIPP&ZONEN, Delft, the Netherlands), including four radiometers measuring the incoming and reflected short-wave radiation (R_S), and incoming and outgoing long-wave radiation (R_L). Wind speed and direction (05103, Young Co. Traverse City, MI, USA) are measured at 10 m above the ground surface. Precipitation (P, mm) is recorded with a tipping bucket rain gauge (TE525MM; Campbell Scientific Inc., Logan, UT, USA) installed at a height of 0.7 m above the ground surface. Air temperature (T_a) and relative humidity (R_H) are measured by a temperature and relative humidity probe (HMP45C; Campbell Scientific Inc., Logan, UT, USA) at a height of 2.6 m above the ground surface. Soil water content (θ) is measured by Time Domain Reflectometry (TDR) sensors (CS616; Campbell Scientific Inc., Logan, UT, USA), soil temperature (T_s) is measured by thermocouples (109; Campbell Scientific Inc., Logan, UT, USA), and soil heat flux (G) is measured by heat flux plates (HFP01SC; Campbell Scientific Inc., Logan, UT, USA) at a depth of 0.03 m below the ground surface. These ground variables (G, θ, T_s) are measured beneath the surface at two profiles (1) a plant canopy patch and (2) a bare soil patch. θ and T_s are measured at depths of 5, 10, 20, 40, 60, 80, 120 and 160 cm below the ground surface. Groundwater table is measured by an automatic sensor (CS450-L; Campbell Scientific Inc., Logan, UT, USA), which is installed in a groundwater well close to the tower.

2.3 Data and methodology

2.3.1 Flux data processing

The half-hourly latent heat flux (λE_T) data were calculated by EddyPro software (www.licor.com/eddypro) based on the raw data collected from the EC technique, and it is widely used because it is comprehensive, freely available and use-friendly (Fratini et al., 2014). The calculated half-hourly flux datasets were filtered for spikes, instrument malfunctions, and poor quality, according to the following criteria (Papale et al., 2006): (1) incomplete half-hourly measurement, mainly caused by power failure or instrument malfunction; (2) rainy events; and (3) outliers caused by occasional spikes for unknown reasons. The ratios of data removed through this procedure are 17.3% in Period I, 20.2% in Period II, 16.5% in Period III and 18.6% in Period IV.

Daily averaged flux data were calculated by firstly gap-filled half-hourly data. Linear interpolation was used to fill gaps less than 1-h by calculating an average of the values immediately before and after the data gap. Larger gaps (gaps more than 1-h but less than 7-days) in flux data were replaced by average values using mean diurnal variation (MDV) methods (Falge et al. 2001). This method is adopted by FLUXNET for standardized gap-filling. We found that the daily λE_T had the best correlation with daily available energy ($R_n - G$) rather than other environmental variables such as vapor pressure deficit (VPD) and NDVI. Therefore, for some large gaps more than 7-days and less than 15 days in daily λE_T, we fitted the relationship between daily λE_T and daily available energy flux (R_n-G) in each period. Then we used the fitted function f to estimate the daily λE_T of gaps. We chose the function f with the highest coefficient of correlation (R) in each period (Yan et al., 2013). The function f of each period was $\lambda E_T = 0.0014\,(Rn-G)^2 + 0.0746\,(Rn-G) + 10.69$ (Period I, R = 0.77), $\lambda E_T = 0.0012(Rn-G)^2 + 0.0559(Rn-G) + 17.69$ (Period II, R = 0.67), $\lambda E_T = 0.0014(Rn-G)^2 + 0.16(Rn-G) + 13.244$ (Period III, R = 0.75), and $\lambda E_T = 0.0015(Rn-G)^2 - 0.0834(Rn-G) + 25.868$ (Period IV, R = 0.69), respectively. Large gaps of more than 7-days did occur in the winter.

2.3.2 Footprint model

In order to determine the contributing source area of flux at our site, scalar flux footprint model proposed by Heish et al. (2000) was used. The analytic model accurately described the relationship between footprint, observation height, surface roughness, and atmospheric stability. The footprint fetch F_f is calculated by,

$$F_f/Z_m = D/(0.105 \times k^2)\, Z_m^{-1}|L|^{1-Q} Z_u^Q \quad (1)$$

where k is the von Karman constant (=0.40), D and Q are the similarity constants (stable conditions: D = 0.28, Q = 0.59; near neutral and neutral conditions: D = 0.97, Q = 1; unstable conditions: D = 2.44, Q = 1.33), L is the Obukhov Length, Z_m is the height of wind instrument (=7.53 m), Z_u is defined as (Heish et al, 2000),

$$Z_u = Z_m(\ln(Z_m/Z_0) - 1 + Z_m/Z_0) \quad (2)$$

where Z_0 is the height of momentum roughness (0.05 m).

2.3.3 Methods of analyzing controlling factors on E_T

It is generally recognized that potential evapotranspiration (E_{TP}), vegetation condition and soil water content are the three main factors controlling E_T (Lettenmaier and Famiglietti, 2006; Chen et al., 2014). In order to decouple the effect of vegetation change from the integrated effects of these three factors on E_T, we used a simple equation which is similar with the FAO single crop coefficient method (Irrigation and Drainage Paper No. 56 (FAO-56)) and is expressed as,

$$E_T = E_{TP} \times f_v(\text{vegetation}) \times f_s(\text{soil water}) \quad (3)$$

where $f_v(\text{vegetation})$ represents the effect of vegetation change on E_T, and $f_s(\text{soil water})$ represents the effect of soil water content on E_T. By transforming the Eq.3, $f_v(\text{vegetation})$ can be expressed as,

$$f_v(\text{vegetation}) = E_T / [E_{TP} \times f_s(\text{soil water})] \quad (4)$$

where $f_v(\text{vegetation})$ can also be regarded as the normalized E_T which eliminates the effects of atmospheric and soil water content. E_{TP} (mm day^{-1}) was estimated by the following equation (Maidment, 1992) which is a modification of Penman equation,

$$E_{TP} = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\rho_a c_p / r_a}{\Delta+\gamma}\frac{VPD}{\lambda} \quad (5)$$

where the units of R_n and G are mm d^{-1}; ρ_a is the air density ($= 3.486 \frac{P_a}{275+T}$, kg m^{-3}, where P is the atmospheric pressure in kPa and T is air temperature in degrees Celsius); c_p is the specific heat of moist air (=1.013 kJ kg^{-1} ℃$^{-1}$); Δ is the slope of saturation vapor-pressure-temperature curve (kPa ℃$^{-1}$); γ is the psychrometric constant (kPa ℃$^{-}$

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

[1]); VPD is the difference of the mean saturation vapor pressure (e_s, kPa) and actual vapor pressure (e_a, kPa); U_2 is the daily wind speed at a height of 2.0 m (m s^{-1}), which was simulated by the wind speed at the height of 10.0 m (m s^{-1}),

$$U_2 = U_{10} \frac{4.87}{\ln(67.8*10-5.42)} \quad (6)$$

r_a is the aerodynamic resistance, which was calculated as (Penman, 1948; 1963),

$$r_a = \frac{4.72[ln(\frac{Z_h}{Z_0})][ln(\frac{Z_h}{Z_0})]}{1+0.536U_2} \quad (7)$$

where Z_h is the height at which meteorological variables are measured (2 m), and Z_0 is the aerodynamic roughness of surface (0.00137 m) (Penman, 1948; 1963).

The effects of soil water content on E_T can be described in three stages (Idso et al., 1974), stage 1: the soil water is enough to satisfy the potential evaporation rate (f_s=1); stage 2: the soil is drying and water availability limits E_T (0<f_s<1); and stage 3: the soil is dry and evaporation can be considered negligible (f_s=0). We used daily soil water content of the root depth (θ_r) to estimate f_s by the following expression (Hu et al., 2006),

$$f_s = \begin{cases} = 1 & \theta_r > \theta_k \\ = 0 & \theta_r < \theta_w \\ = \frac{\theta_r - \theta_w}{\theta_k - \theta_w} & \theta_w \le \theta_r \le \theta_k \end{cases} \quad (8)$$

where θ_w is the wilting value, θ_k is the stable field capacity which is considered to be equivalent to 60% of the field capacity (Lei et al., 1988; Wang et al., 2008). θ_r (m^3 m^{-3}) is the mean soil water content from surface to the depth of 160 cm (root zone) and was calculated by measured soil water contents at different depths,

$$\theta_r = \frac{0.5[10\theta_5+15\theta_{10}+30\theta_{20}+40(\theta_{40}+\theta_{60})+60\theta_{80}+80\theta_{120}+40\theta_{160}]}{160} \quad (9)$$

Site-averaged soil water content of each depth (θ_i; i =5, 10, 20, 40, 60, 80, 120,

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

and 160 cm) was calculated by taking a weighted average of the measured values in the canopy and bare surface patches,

$$\theta_i = M \times \theta_{i,c} + (1 - M) \times \theta_{i,b} \quad (10)$$

where $\theta_{i,c}$ and $\theta_{i,b}$ refer to the measured soil water content of canopy patch and bare soil patch at the depth of i cm, respectively; M is the monthly vegetation coverage of undisturbed zone, and it was calculated by monthly Normalized Difference Vegetation Index (NDVI) values (Gutman and Ignatov, 1998),

$$M = (NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (11)$$

where $NDVI_{max}$ is the maximum value (0.8 in this study); $NDVI_{min}$ is the minimum value (0.05 in this study) (Gutman and Ignatov, 1998). The calculated monthly M (27.6% and 24.2%) was consistent with the measured vegetation coverage in August 2011 (28.2%) and September 2011 (27.9%) at our study site.

In this study, vegetation phenology is represented by Moderate Resolution Imaging Spectroradiometer (MODIS)-NDVI data when the land use/cover condition is fixed. NDVI is sufficiently stable to reflect the seasonal changes of any vegetation (Huete et.al, 2002). Higher NDVI usually represent greater photosynthetic capacity (greenness) of vegetation canopy (Gu et al., 2007; Tucker, 1979). The daily MODIS/Terra and MODIS/Aqua Surface Reflectance (at 250m) data within the footprint source area were chosen to calculate NDVI. The Surface Reflectance data of MODIS/Terra (MOD09GQ) and MODIS/Aqua (MYD09GQ) were downloaded from reverb (http://reverb.echo.nasa.gov). MODIS Reprojection Tool (MRT) (Kalvelage and Willems, 2005) was used to reject the daily Surface Reflectance data to the Universal

Transverse Mercator (UTM). The calculation of NDVI is based on its definition,

$$\mathrm{NDVI}_{\mathrm{Terra\ or\ Aqua}} = \frac{\mathrm{NIR-VIS}}{\mathrm{NIR+VIS}} \tag{12}$$

where $\mathrm{NDVI}_{\mathrm{Terra}}$ and $\mathrm{NDVI}_{\mathrm{Aqua}}$ are the NDVI values calculated from MODIS/Terra and MODIS/Aqua reflectance data, respectively; NIR is the spectral response in the near-infrared band (857 nm); VIS is the visible red radiation band (645 nm). In order to eliminate the poor quality data values, the calculated NDVI data series stack needs to be firstly filtered to remove anomalous hikes and drops (Lunetta et al., 2006). Hikes and drops were eliminated by removing the values that suddenly decreased or increased, and then smoothing spline was used to produce a smoother profile. In this study, daily NDVI value was averaged from $\mathrm{NDVI}_{\mathrm{Terra}}$ and $\mathrm{NDVI}_{\mathrm{Aqua}}$.

Theoretically, land use change can be evaluated by comparing the land use maps in two different periods. However, the transient land use maps are unavailable at our site. Therefore, we separated the study area within the footprint area into two zones: we assigned the undisturbed zone without any land use/cover change as zone A, and assigned the disturbed zone with land use/cover change as zone B. In zone A, vegetation condition change included only vegetation phenological change; however, in zone B, there were not only vegetation phenological change but also land use/cover change. By assuming that the phenological changes caused by climate in the two zones are same, we defined an indicator (D_{lu}) to be the measure of land use/cover change:

$$D_{lu} = M_{\mathrm{A}} - M_{\mathrm{B}} \tag{13}$$

where, M_{A} and M_{B} are the vegetation coverage of zone A and zone B, respectively.

3 Results

3.1 Footprint and energy balance closure

Based on the footprint model, we got the half-hourly scatter data of footprint fetch (Eq. (2)), and according to the wind rose (Fig. 3a), the prevailing wind direction in this site were northwest and southeast, so we chose an ellipse to enclose the scatters and simulated the footprint (Fig. 3b). The long axis of the simulated ellipse is 1682 m, and the short axis is 1263 m. There were 93% half-hourly flux data within the ellipse under unstable conditions. We measured the boundary of zone B in October 2013 when the land use/cover condition in zone B had stopped to change (Fig.3b). There were 11 pixels (250 m × 250 m) in zone A, while there are 19 pixels (250 m × 250 m) in zone B, and thus in the following part of calculating the weight-averaged NDVI ($NDVI_w$) within the footprint fetch, we chose the weighted coefficient as $\beta = 11/(11 + 19)$.

[Figure 3 is to be inserted here]

In order to validate EC measurements and examine the quality of flux data, we used daily data in period I to conduct the linear regression between available energy (R_n − G) and the sum of surface fluxes ($\lambda E_T + H$). The linear regression yielded a slope of 0.87, an intercept of -1.42 W m^{-2}, and R^2 of 0.82. These indicators indicated that the measurements at our experimental site provided reliable flux data, and that the EC measurements underestimated the sum of surface fluxes to the extent of 13%. A lot of researchers have investigated the energy imbalance (Barr et al., 2006; Wilson et al., 2002; Franssen et al., 2010), and there is a consensus that it is difficult to examine the exact reasons leading to the imbalance.

3.2 Characteristics of environmental variables

A brief summary of the key environmental variables will be presented in this section. Monthly *D*s was much higher than the normal value of 1954-2014 except in July and September. The highest value of monthly *D*s was in May (299.5 h) and the lowest was in February (206.6 h). Seasonal characteristics of *T*a showed a highly similar trend with the normal, and the differences were less than 1 ℃ except in July, January and March. The highest value of monthly *T*a was in July (22.1 ℃) and the lowest was in December (-8.1 ℃). The values of R_H showed almost lower than the normal, especially in March and April. The highest R_H was in September (65.4%) and the lowest was in March (35.1%). The seasonal distributions of *P* were consistent with the normal, and 89.7% of *P* happened in the growing season. The value of *P* in July was the highest (120.5 mm) and in January was the lowest (0.3 mm)

[Figure 4 is to be inserted here]

The inter-annual characteristics of daily *T*a, R_H, *D*s, θ_r, groundwater level (GWL) and total *P* in the growing season of each period were listed in Tab.1.

[Table 1 is to be inserted here]

The values of *T*a, R_H, *P* and θ_r in the growing season of Period IV were the lowest compared with other three periods. Period I~III are all wet year, while Period IV was the dry year. The values of θ_r in Period I~III were basically the same, however, θ_r decreased by 0.0113 m^3 m^{-3} in Period IV. The mean GWL in Period III was the shallowest.

3.3 Seasonal variations in E_T due to climate variability

Seasonal curve of E_T in each year had a single peak value (Fig.5a), with the higher E_T appearing mostly in the growing season while the lower appeared in the non-growing season. The daily E_T was in a range from 0.0 mm day^{-1} to 6.8 mm day^{-1} during the four periods, the highest E_T appeared on 22th June 2013. The highest E_T appeared at the day after a continual rainfall event start from 19th June 2013 to 21th June 2013 (90.3 mm), E_T rates normally increase rapidly after rainfall events. The lowest E_T was on 28th November 2012, which was in the frozen period (late November to early March in our study site). In rainy days, E_{TP} (Fig.5b) was much lower due to lower net radiation and air temperature. E_{TP} was in the range of 0.2 mm day^{-1} that appeared in December 2011 to 17.9 mm day^{-1} that appeared in September 2013.

[Figure 5 is to be inserted here]

Seasonal NDVI curve with natural land use/cover condition (in zone A during Period I~IV and in zone B during Period I) represented the process of natural vegetation phenology and it had one single peak value in each year (Fig. 5c). In early May, seasonal NDVI curve began to increase and native vegetation began to enter the growing season and reached to the maximum value (0.27±0.01) in July or August. In winter, daily NDVI basically stayed at a constant value (0.13±0.01). f_s (Fig. 5d) increased rapidly in response to rainfall events of more than 5 mm a day, and also decreased rapidly one or two days later after rainfall events. During late November to early March, there was a frozen period in this site, and soil water content was below the wilting point. The groundwater level fluctuated obviously in monsoon season (July to

September) and mildly in winter (December to February).

The relationships between E_T and the three factors (E_{TP}, $\mathrm{NDVI_w}$ ($\mathrm{NDVI_w} = \mathrm{NDVI_A} \times \beta + \mathrm{NDVI_B} \times (1-\beta)$), f_s) were analyzed and were shown in Fig. 6 (a, b, c) by daily data in Period I. Because in Period I, the land use/cover condition within footprint was undisturbed. Data in rainy days was removed, because in rainy days, E_T was gap-filled instead of actual measured.

[Figure 6 is to be inserted here]

In order to figure out the major seasonal factor that control E_T at our study site, significant T-test was calculated to evaluate the degree of correlation. The linear correlations between E_T and the three factors both passed the 95% t-test confidence level. The determination coefficient (R^2=0.52) between E_T and $\mathrm{NDVI_w}$ was the largest, indicating that NDVI was a dominant factor that controlling the daily variations of E_T. To better quantify the effects of phenological process on E_T, daily normalized E_T (f_v) and $\mathrm{NDVI_w}$ in Period I were analyzed (Fig.7a).

[Figure 7 is to be inserted here]

Positive linear regression was found between f_v ($f_v = E_T/(E_{TP} \times f_s)$) and $\mathrm{NDVI_w}$ (Fig.7a). The slope of linear regression was used to evaluate the controlling degree between normalized E_T and vegetation phenological process. The positive regression stated the direct positive relationship between $\mathrm{NDVI_w}$ and normalized E_T, indicating that when $\mathrm{NDVI_w}$ increases one unit, it will contribute normalized E_T to increase about 1.86 units.

3.4 Inter-annual variations in E_T due to land use/cover changes

During the four periods, in zone A, the NDVI values of each period were basically the same because the land use/cover condition was not changed. While in zone B, the peak values of NDVI firstly declined from 0.28 to 0.15 (Period I to Period III) due to the land use/cover condition changed to bare soil and then increased to 0.22 due to the grass recovery (Figure 5(c)). An interesting phenomenon was found accompanied by the changing process of land use/cover condition: E_T in the growing season of each period was gradually observed to be increasing (Tab.2). E_T in Period IV increased strongly even with less precipitation, because a mass of soil water and ground water was consumed to satisfy the E_T demand (Fig.5e).

[Table 2 is inserted to be here]

Compared to Period I with natural land use/cover condition, D_{lu} of Period II and Period III gradually increased and D_{lu} of Period IV decreased. Taking August in each period as an example, in August of Period I, D_{lu} was 0.2%, while in August of Period II, Period III and Period IV, D_{lu} were 2.9%, 12.6% and 8.6%, respectively. In order to eliminate the influence of vegetation phenological change on E_T, we chose the growing season of each period to analyze the correlations between normalized E_T and D_{lu}.

Quantitative results of the relationship between D_{lu} and normalized E_T (f_v) are shown in Fig.7b. According to the dynamic path showed in Fig.7b, when the natural vegetation in Zone B was cut-off, the fixed and semi-fixed sand dunes were bulldozed, the BSCs and dry sand layers were disappeared (Period I~III), normalized E_T (i.e., f_v) increased and was more evident in Period III (from 78.5 to 88.1). When the land use/cover condition of zone B gradually changed to sparse grassland due to the self-restoring capacity of nature, normalization E_T (f_v) increased more significantly (from 88.1 to 111.3).

4 Discussion

4.1 Implications of the impacts of phenological change on E_T

The correlations between E_T and its controlling factors infer that at our experimental site, NDVI was the predominant factor that influence the seasonal variation on E_T. The positive linear relationship between normalized E_T and NDVI suggests that transpiration is mainly controlled by the stomatal conductance and the number of stomata, which is proportional to leaf area (Pearcy et al., 1989; Turrell, 1947), rather than the atmospheric water demand represented by E_{TP}.

Various studies have tested the relationships between phenological change and E_T, and these results generally showed consistent and positive linear relationships (Nouri et al., 2014; Rossato et al., 2005; Duchemin et al., 2006; Glenn et al., 2008). However, with different vegetation species, phenological change have effects on E_T in different degrees. Loukas et al. (2005) have analyzed the relationships between NDVI and E_T in Greece, and relative strong regressions were found in forested sites (R^2=0.78). Kondoh and Higuchi (2001) investigated the correlation between NDVI and E_T in a grass-covered site at the university of Tsukuba, and a very high determination coefficient (R^2=0.92) was showed to reveal the strong control of phenological change on E_T. Nouri et al. (2014) have analyzed the relationships between NDVI and E_T in forests and grasses, and they found that determination coefficient of forests (R^2=0.94) was higher than the grassland (R^2=0.88). Chong et al. (2007) have found a strong relationship between NDVI and E_T in forests and moist savanna of Africa. Thus, we speculate that, for high dense vegetated ecosystems, phenological change might have a strong and significant control on E_T. However, in low vegetation cover condition such as sparse shrubland in this study, the relationship between E_T and seasonal vegetation change is thus positive but relative weak.

4.2 Possible reasons for the effects of land use/cover changes

During Period I~IV, the land use/cover condition of our experimental site has undergone two processes, one was the land degradation process (Period II~III), while the other was the vegetation rehabilitation process (Period IV). Interesting phenomenon was found that during these two processes: normalized E_T values were both increased, and normalized E_T increased much faster from Period III to IV than that from Period I to III.

The impact of phenological change on E_T demonstrated that E_T will decrease along with the leaf browning. Thus, we expect that E_T will also decease if only leaves were cleared by human activities. However, during Period I~III, not only leaves were cleared, but also all branches were cut-off, sand dunes (fixed and semi-fixed) were bulldozed, the dry sand layers and the biological soil crusts (BSCs) were destroyed, making the land use/cover condition complex. All these changed land surface properties might contribute to the increase of E_T. The exists of dry sand layers and BSCs were demonstrated to effectively restrained the soil evaporation rates (Wang et al., 2006; Lv et al., 2006; Liu et al., 2006; Chen and Dong, 2001; Yang et al., 2015; Fu et al., 2010; Liu, 2012). However, the bulldozing of sand dunes at our experimental site made the elevation of the flat soil surface be lower than the average elevation of the undisturbed soil surface (about 1.5 m, Figure 2(d)), which resulted that the groundwater depth was much shallower than before. Thus, it is hard for the formation of dry sand layers with shallower groundwater depth. In this situation with the destroyed BSCs and the disappeared dry sand layers, the sufficient groundwater supply (Li and Li, 2000) accelerated the loss of water that stored in shallow soil through evaporation. The enhancement effect of soil evaporation offset the inhibition effect of transpiration by leaves clearing, which made E_T increase.

A secondary reason for the enhancement of soil evaporation was that more solar radiation was absorbed by soil layer during land degradation process. In Period I with natural vegetation, the radiation absorbed by shadowed soil was the solar radiation transmitted into the canopy of shrub and grass. However, with the natural vegetation being cut-off, the leaves and the branches were also removed, which made the shadowed soil exposed and enhanced the radiation absorbed by soil, thus contribute to the increase of soil evaporation (Martens et al., 2000; Panferov et al., 2001). Besides, the removal of leaves and branches and the disappearance of sand dunes altered the land surface albedos. Various scholars have demonstrated that changes of land surface albedos could directly alter the solar radiation absorbed by the land surface (Dirmeyer and Shukla, 1994; Greene et al., 1999), subsequently leading to the change in E_T.

Some inconsistent results were found from the previous analyses that aim at studying the characteristics of E_T with land degradation. For instance, Li et al. (2013) have analyzed the features of E_T during land degradation process in Qinghai-Tibet Plateau, and they found that warming air temperature was the main cause to enhance E_T. However, some other scholars have opposite conclusions. For example, Snyman (2001) have compared E_T of natural grassland and degraded grassland resulted from overgrazing in a semi-arid are of South Africa, and he found that E_T was smaller of the degraded grassland due to less transpiration. Souza and Oyama (2011) have demonstrated that desertification in a semi-arid area of Northeast Brazil contributed to the decrease of E_T due to the loss of transpiration from natural vegetation. Lu et al. (2011) have found that E_T was lower in disturbed grazed grassland compared to the undisturbed grassland, and the lower soil water content was thought to be the explanation to result in the decrease of E_T. Mao and Cherkauer (2009) have demonstrated that E_T decreased when land use/cover condition was changed from forests to grass or cropland in the Great Lakes region. Furthermore, Hoshino et al. (2009) have demonstrated that there was no difference in E_T during the land degradation by overgrazing in a semi-arid Mongolian grassland, and they thought that the reason might be short time of grazing (2 years). Throughout the above researches of E_T under land degradation process, we found it was hard to accurately describe the features of E_T even when the land degradation was only performed by less vegetation coverage. Therefore, in our study site with complex land surface properties (sand dunes, dry sand layers and BSCs), the impact of land degradation on E_T was much more complicated.

During the vegetation rehabilitation process (Period IV), normalized E_T increased significantly due to the rehabilitation of grass in zone B, even though with less precipitation compared with other three periods. The rehabilitation of grass, rather than shrub, was due to the sufficient groundwater supply resulted from bulldozing the sand dunes. Previous researchers reported that sparse shrub more commonly grew at the top of sand dunes and grass grew at the bottom of sand dunes, because the differences between groundwater depth and the top of sand dunes was larger than that the that between groundwater depth and the bottom of the sand dunes (Lv et al., 2006; Chen and Dong, 2001). Because transpiration increases with the greening of vegetation (this was demonstrated in section 3.3), the regrowing grass will enhance plant transpiration supplied by the sufficient groundwater. More importantly, the transpiration rate of grass is higher than that of shrubs because shrubs are more tolerant to drought (Yang et al., 2014; Wang et al., 2002; Wu, 2006). Therefore, in the vegetation rehabilitation process, the increasing rate of transpiration in Period IV was much higher than that in Period I~III. Consistent conclusions of E_T increase during vegetation rehabilitation process were reported. For example, Qiu et al. (2011) have demonstrated that in the vegetation rehabilitation process, E_T increased and more water was consumed and less rainfall would infiltrate deeper soil layer. Yang et al. (2014) and Sun et al (2006) also considered E_T would increase with vegetation rehabilitation due to the increase of transpiration. Furthermore, Li et al. (2009) have reported that E_T increased when land use/cover condition converted from shrubland to grassland. Meanwhile, the regrowing grass can reduce the radiation absorbed by soil and hence reduce the soil evaporation. However, the intercept of radiation by grass canopy was expected to be smaller than that by mixed shrub and grass canopy in Period I~III because the leaf area index of grass is smaller than the sum of leaf area and stem area index of shrub. Therefore, the reduction of soil evaporation in Period IV may be small compared with the increment of soil evaporation in Period I~III.

We noticed that groundwater level decreased continuously from Period III due to the enhancement of E_T by the re-growth of grass and relative lower precipitation, and the regrowing grass has a high transpiration rate compared with the native mixed shrub and grass ecosystem. Therefore, we hypothesized that if the land use/cover condition of zone B continues to be grassland in several years, the groundwater level will decrease due to the larger consumption, making the soil water condition gradually become poor for the growing of grass. Then, in this situation, the grassland is expected to degrade to shrubland in zone B because shrubs are more tolerant to survive in water-starved ecosystems. On the other hand, potato is studied to consume more than 320 mm in the growing season (Qin et al., 2013; Liu et al., 2010) and the consumption is more than that of natural grass (Qin et al., 2013, 2014; Hou et al., 2010). Besides, planting potato needs to irrigate several times during the growing season (Fulton et al., 1970; Liu et al., 2010; Fabeiro et al., 2001). As potato consumes much more water than, our result implied that the groundwater level may continue to decrease faster with the growth of potato, which may lead to a more fragile ecosystem.

5 Conclusion

In this study, seasonal and inter-annual features of E_T were analyzed. The daily E_T

was in a range from 0.0 mm day^{-1} to 6.8 mm day^{-1} during the four periods. NDVI was the predominant factor that influences the seasonal variations in E_T. Vegetation greening had a positive effect on E_T. During land degradation process (Period I~Period III), when natural vegetation (including leaves and branches), sand dunes, dry sand layers and BSCs were all bulldozed by human activities, E_T was observed to increase with a mild rate. In vegetation rehabilitation process (Period IV) with sufficient groundwater, E_T also increased with a faster rate than that in the degradation process. When land use/cover changed by human activities, the underlying mechanisms that leads to the changes of E_T were complex, and vegetation types, topography and soil surface characteristics could contribute to the changes in E_T.

Acknowledgements

This research was supported by the National Key Research and Development Program (2016YFC0402404) and the Basic Research Fund Program of State key Laboratory of Hydroscience and Engineering (Grant No. 2014-KY-04). We thank A. W. Jayawardena for language and constructive suggestions of the manuscript.

References:

An, H., An, Y.: Soil moisture dynamics and water balance of Salix psammophila shrubs in south edge of Mu Us Sandy Land]. Journal of applied ecology 22, 2247-2252, 2011

Baldocchi, D. D., Wilson K. B.: Modeling CO_2 and water vapor exchange of a temperate broadleaved forest across hourly to decadal time scales, Ecological Modelling, 142, 155-184, 2001.

Barr, A. G., Morgenstern, K., Black, T. A., McCaughey, J. H., Nesic, Z.: Surface energy balance closure by the eddy-covariance method above three boreal forest stands and implications for the measurement of the CO_2 flux. Agricultural and Forest Meteorology, 140, 322-337, 2006.

Chen, S., Chen, J., Lin, G., Zhang, W., Miao, H., Wei, L., ... Han, X.: Energy balance and partition in Inner Mongolia steppe ecosystems with different land use types. Agricultural and Forest Meteorology, 149(11), 1800-1809, 2009.

Chen, Y., Xia, J. Z., Liang, S. L., Feng, J. M., Fisher, J. B., Li, X., Li, X. L., Liu, S. G., Ma, Z. G., Miyata, A., Mu, Q. Z., Sun, L., Tang, J. W., Wang, K. C., Wen, J., Xue, Y. J., Yu, G. R., Zha, T. G., Zhang, L., Zhang, Q., Zhao, T. B., Zhao, L. and Yuan, W. P.: Comparison of satellite-based evapotranspiration models over terrestrial ecosystems in China. Remote Sensing of Environment, 140, 279-293, 2014.

Chong. Lo Seen, D., Mougin, E., Gastellu-Etchegorry, J. P.: Relating the global vegetation index to net primary productivity and actual evapotranspiration over Africa. TitleREMOTE SENSING, 14(8), 1517-1546, 1993.

Cornelissen, T., Diekkrüger, B., Giertz, S.: A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment, Journal of Hydrology, 498, 221-236, 2013.

Dong, X. J., Zhang, X. S.: Some observations of the adaptions of sandy shrubs to the arid environment in the Mu Us Sandland: leaf water relations and anatomic features. Journal of Arid environments, 48:41-48, 2001.

DeFries, R., Eshleman, K. N.: Land‐use change and hydrologic processes: A major focus for the future. Hydrological processes, 18(11), 2183-2186, 2004.

Ding, R. S., Kang, S. Z., Zhang, Y. Q., Du, T. S.: Multi-layer model of water vapor and heat fluxes over maize field in an arid inland region. ShuiLiXueBao, 45(1), 27-35, 2014 (in Chinese)

Dirmeyer, P. A., & Shukla, J.: Albedo as a modulator of climate response to tropical deforestation. Journal of Geophysical Research: Atmospheres, 99 (D10), 20863-20877, 1994.

Duchemin, B., Hadria, R., Erraki, S., Boulet, G.; Maisongrande, P.; Chehbouni, A.; Escadafal, R., Ezzahar, J.; Hoedjes, J.C.B., Kharrou, M.H.; et al. Monitoring wheat phenology and irrigation in Central Morocco: On the use of relationships between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. Agric. Water Manag. 79, 1–27, 2006.

Fabeiro, C. M. D. S. O. F., de Santa Olalla, F. M., De Juan, J. A.: Yield and size of deficit irrigated potatoes. Agricultural Water Management, 48(3), 255-266, 2001.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N. O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, H., Moors, E., Munger, J. W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K. and Wofsy, S.: Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology, 107, 71-77, 2001.

Fernández, O. A., Gil, M. E., Distel, R. A.: The challenge of rangeland degradation in a temperate semiarid region of Argentina: the Caldenal. Land Degradation & Development, 20(4), 431-440, 2009.

Feddema, J. J., Freire, S. C.: Soil degradation, global warming and climate impacts, 2001.

Feng, Q.. Preliminary study on the dry sand layer of sandy land in semi-humid region. Arid zone research, 11,1994 (in Chinese).

Fratini, G., Mauder, M.: Towards a consistent eddy-covariance processing: an intercomparison of EddyPro and TK3, Atmospheric measurement techniques, 7, 2273-2281, 2014.

Franssen, H. J., Stoeckli, R., Lehner, I., Rotenberg, E. and Seneviratne, S. I.: Energy balance closure of eddy-covariance data: A multisite analysis for European FLUXNET stations. Agricultural and forest meteorology, 150, 1553-1567, 2010.

Fernández, R.J.: Do humans create deserts? Trends Ecol. Evol. 17 (1), 6–7, 2002.

Fu. G. J.., Liao, C. Y., Sun, C. Z.: The effect of soil crust to water movement in maowusu sandland. Journal of northwest forestry university, 25: 7-10, 2010 (in Chinese)

Fulton, J. M.: Relationship of root extension to the soil moisture level required for maximum yield of potatoes, tomatoes and corn. Canadian Journal of Soil Science, 50, 92-94, 1970.

Gao, S., Pan, X., Cui, Q., Hu, Y., Ye, X., Dong, M.: Plant interactions with changes in coverage of biological soil crusts and water regime in Mu Us Sandland, china. PloS one, 9(1), e87713, 2014.

Ge, Q., Wang, H., Dai, J.: Phenological response to climate change in China: a meta‐analysis. Global change biology, 21(1), 265-274, 2015.

Glenn, E.; Huete, A.; Nagler, P.; Nelson, S. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors 2008, 8, 2136–2160.

Greene, E.M., Liston, G.E., Pielke, R.A.S.: Relationships between landscape, snowcover depletion, and regional weather and climate. Hydrological Processes 13, 2453–2466, 1999.

Gu, Y., Brown, J. F., Verdin, J. P., Wardlow, B.: A five‐year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States. Geophysical Research Letters,34(6), 2007.

Guo, K., Dong, X. J. and Liu, Z. M.: Characteristics of soil moisture content on sand dunes in mu us sandy grassland: why artemisia ordosica declines on old fixed sand dunes, Acta phytoecologica sinica, 24, 243-247, 2000 (in Chinese)

Gutman, G. and Ignatov, A.: The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models, International Journal of Remote Sensing, 19, 1533-1543, 1998.

Hatchett, B., Hogan, M., Grismer, M.: Mechanical mastication thins Lake Tahoe forest with few adverse impacts. California Agriculture, 60(2), 77-82, 2006.

Hoshino, A., Tamura, K., Fujimaki, H., Asano, M., Ose, K., Higashi, T.: Effects of crop abandonment and grazing exclusion on available soil water and other soil properties in a semi-arid Mongolian grassland. Soil and tillage research, 105(2), 228-235, 2009.

Hou, X.Y., F.X. Wang, J.J. Han, S.Z. Kang, S.Y. Feng.: Duration of plastic mulch for potato growth under drip irrigation in an arid region of Northwest China. Agricultural and Forest Meteorology, 150, 115–121, 2010.

Heish, C. I., Katul G. and Chi, T. W.: An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Advances in Water Resources, 23, 765-772, 2000.

Hu, H. H., Dai, M. Q., Yao, J. L., Xiao, B. Z., Li, X. H., Zhang, Q. F. and Xiong, L. Z.: Overexpressing a NAM, ATAF, and CUC (NAC) transcription factor enhances drought resistance and salt tolerance in rice, Proceedings of the National Academy of Sciences, 103, 12987-12992, 2006.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X. and Ferreira, L. G.: Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote sensing of environment, 83, 195-213, 2002.

Jarvis, P. G., Mansfield, T. A.. Stomatal phsilogy. 1981.

Jarvis P G, McNaughton K G. Stomatal control of transpiration: scaling up from leaf to region[J]. Advances in ecological research, 15, 1-49, 1986.

Jordan, D., Zitzer, S. F., Hendrey, G. R., Lewin, K. F., Nagy, J., Nowak, R. S., ... Seemann, J. R.: Biotic, abiotic and performance aspects of the Nevada Desert Free ‐ Air CO2 Enrichment (FACE) Facility. Global Change Biology, 5(6), 659-668, 1999.

Kalvelage, T., Willems, J.: Supporting users through integrated retrieval, processing, and distribution systems at the Land Processes Distributed Active Archive Center, Acta astronautica, 56, 681-687, 2005.

Kim, W., Kanae, S., Agata, Y., Oki, T.: Simulation of potential impacts of land use/cover changes on surface water fluxes in the Chaophraya river basin, Thailand, Journal of Geophysical Research: Atmospheres (1984-2012), 110, 2005.

Kondoh, A., Higuchi, A.: Relationship between satellite ‐ derived spectral brightness and evapotranspiration from a grassland. Hydrological processes, 15(10), 1761-1770, 2001

Lei, Z. D., Yang, S. X. and Xie, S. C.: Soil water dynamics, Tsing-Hua University Press, Beijing, 1988 (in Chinese).

Lettermaier, D. P. and Famiglietti, J. S.: Water from on high. Nature, 2006, 444, 562-563.

Liang, L., Lu, S. H. and Shang, L. Y.: Numerical simulation of effect of Loess Plateau vegetation change on local climate, Plateau Meteorol, 27, 293-300, 2008.

Leuning, R., Kelliher, F. M., Pury, D. D., SCHULZE, E. D.: Leaf nitrogen, photosynthesis, conductance and transpiration: scaling from leaves to canopies. Plant, Cell & Environment, 18(10), 1183-1200, 1995.

Li, P. F., Li, B. G.: Study on some characteristics of evaporation of sand dune and evapotranspiration of grassland in Mu Us desert. 3:23-28, 2000 (in Chinese).

Li, Z., Liu, W. Z., Zhang, X. C. and Zheng, F. L.: Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China, Journal of hydrology, 377, 35-42, 2009.

Li, X. L., Gao, J., Brierley, G., Qiao, Y. M., Zhang, J., Yang, Y. W.: Rangeland degradation on the Qinghai‐Tibet plateau: Implications for rehabilitation. Land Degradation & Development, 24(1), 72-80, 2013.

Li, S., Kang, S., Zhang, L., Du, T., Tong, L., Ding, R., ... Xiao, H.: Ecosystem water use efficiency for a sparse vineyard in arid northwest China. Agricultural Water Management, 148, 24-33, 2015.

Liu, C., Zhang, X., Zhang, Y.: Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agricultural and Forest Meteorology, 111(2), 109-120, 2002.

Liu, F.: Point pattern of Artemisia ordosica and the impact to soil crust thickness in Mu Us Sandland. Mater Thesis of Beijing Forestry University, 2012 (in Chinese)

Liu, X. P., Zhang, T. H., Zhao, H. L., He, Y. H., Yun, J. Y., Li, Y. Q.: Influences of dry sand bed thickness on soil moisture evaporation in mobile dune. Arid land geography, 29, 2006 (in Chinese)

Liu, J. S., Gao, Q., Guo, K., Liu, X. P., Shao, Z. Y., Zhang, Z. C.: Actual evaporation of bare sand dunes in maowusu, china and its response to precipitation pattern. Journal of plant ecology, 2008, 123-132, 2008

Liu, Z. D., Xiao, J. F., Yu, X. Q.: Effects of different soil moisture treatments on morphological index, water consumption and yield of potatoes. China Rural Water and Hydropower, 8, 1-7, 2010.

Loukas, A., Vasiliades, L., Domenikiotis, C. and Dalezios, N. R.: Basin-wide actual evapotranspiration estimation using NOAA/AVHRR satellite data, Physics and Chemistry of the Earth, 30, 69-79, 2005.

Lorup, J. K., Refsgaard, J. C., Mazvimavi, D.: Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: case studies from Zimbabwe. Journal of hydrology, 205(3), 147-163, 1998.

Lu, N., Chen, S., Wilske, B., Sun, G., Chen, J.: Evapotranspiration and soil water relationships in a range of disturbed and undisturbed ecosystems in the semi-arid Inner Mongolia, China. Journal of Plant Ecology,4(1-2), 49-60, 2011.

Lunetta, R.S., Knight, J. F., Ediriwickrema, J., Lyon, J. G., Worthy, L. D.: Land-cover change detection using multi-temporal MODIS NDVI data, Remote sensing of environment, 105, 142-154, 2006.

Lv, Y. Z., Hu, K. L., Li, B. G.: The spatio-temporal variability of soil water in sand dunes in maowusu desert. 43, 2006 (in Chinese).

Mackay, D. S., Ewers, B. E., Cook, B. D., Davis, K. J.: Environmental drivers of evapotranspiration in s shrub wetland and an upland forest in northern Wisconsin. Water resources research, 43, doi:10.1029/2006WR005149, 2007.

Maayar, M., & Chen, J. M.: Spatial scaling of evapotranspiration as affected by heterogeneities in vegetation, topography, and soil texture.Remote Sensing of Environment, 102(1), 33-51, 2006.

Maidment, D. R.: Handbook of hydrology, 1992.

Mao, D., Cherkauer, K. A.: Impacts of land-use change on hydrologic responses in the Great Lakes region. Journal of Hydrology, 374(1), 71-82, 2009.

Mo, X. G., Liu, S. X., Lin, Z. H. and Chen, D.: Simulating the water balance of the wuding river basin in the Loess Plateau with a distributed eco-hydrological model, Acta Geographica Sinica, 59, 341-347, 2004 (in Chinese)

Martens, S. N., D. D. Breshears, and C. W. Meyer.: Spatial distributions of understory light along the grassland/forest continuum: effects of cover, height, and spatialpattern of tree canopies. Ecological Modeling 126:79–93, 2000.

Nouri, H., Beecham, S., Anderson, S., Nagler, P.: High spatial resolution WorldView-2 imagery for mapping NDVI and its relationship to temporal urban landscape evapotranspiration factors. Remote sensing, 6(1), 580-602, 2014.

Ostwald, M., Chen, D.: Land-use change: Impacts of climate variations and policies among small-scale farmers in the Loess Plateau, China. Land Use Policy, 23(4), 361-371, 2006.

Pearcy, R. W., Schulze, E. D., Zimmermann, R.: Measurement of transpiration and leaf conductance. Plant physiological ecology. Springer Netherlands, 137-160, 1989.

Penman, H. L.: National evaporation from open water, bare soil and grass. Proc. R. Soc. London, A193, 120-145, 1948.

Penman, H. L.: Vegetation and hydrology, Tech. Comm. 53, Commenwealth Bureau of Soils, Harpenden, England, 1963.

Piao, S., Fang, J., Zhou, L., Ciais, P., Zhu, B.: Variations in satellite-derived phenology in China's temperate vegetation. Global Change Biol. 12, 672–685, 2006.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R.: Vesala, T. and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, 2006.

Panferov, O., Knyazikhin, Y., Myneni, R. B., Szarzynski, J., Engwald, S., Schnitzler, K. G., & Gravenhorst, G.: The role of canopy structure in the spectral variation of transmission and absorption of solar radiation in vegetation canopies. IEEE Transactions on Geoscience and Remote Sensing, 39, 2, 241-253, 2001.

Qin, S.H., L.L. Li, D. Wang, J.L. Zhang, Y.L. Pu.: Effects of limited supplemental irrigation with catchment rainfall on rain-fed potato in semi-arid areas on the Western Loess Plateau, China. American Journal of Potato Research, 90, pp. 33–42, 2013.

Qin, S., Zhang, J., Dai, H., Wang, D., Li, D.: Effect of ridge–furrow and plastic-mulching planting patterns on yield formation and water movement of potato in a semi-arid area. Agricultural Water Management, 131, 87-94, 2014.

Qiu, G. Y., Xie, F., Feng, Y. C., Tian, F.: Experimental studies on the effects of the "Conversion of Cropland to Grassland Program" on the water budget and evapotranspiration in a semi-arid steppe in Inner Mongolia, China.Journal of Hydrology, 411(1), 120-129, 2011.

Rossato, L.; Alvala, R.C.S.; Ferreira, N.J.; Tomasella, J.: Evapotranspiration estimation in the Brazil using NDVI data. Proc. SPIE 2005, 5976, 377–385.

Snyman, H. A.: Water-use efficiency and infiltration under different rangeland conditions and cultivation in a semi-arid climate of South Africa. InProceedings of the XIX International Grassland Congress, Sao Paulo, Brazil (pp. 965-966), 2001.

Souza, D. C., Oyama, M. D.: Climatic consequences of gradual desertification in the semi-arid area of Northeast Brazil. Theoretical and Applied Climatology, 103(3-4), 345-357, 2011.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S. G., Vose, J. M.: Potential water yield reduction due to forestation across China. Journal of Hydrology, 328(3), 548-558, 2006.

Tian, H., Cao, C., Chen, W., Bao, S., Yang, B., Myneni, R. B.: Response of vegetation activity dynamic to climatic change and ecological restoration programs in Inner Mongolia from 2000 to 2012. Ecological Engineering, 82, 276-289, 2015.

Tong, X., Zhang, J., Meng, P., Li, J., Zheng, N.: Environmental controls of evapotranspiration in a mixed plantation in North China. International Journal of Biometeorology, 1-12, 2016.

Twine, T. E., Kucharik, C. J., Foley, J. A.: Effects of land cover change on the energy and water balance of the Mississippi River basin. Journal of Hydrometeorology, 5(4), 640-655, 2004.

Tucker, C. J.: Red and photographic infrared linear combinations for monitoring vegetation, Remote Sens. Environ.,8, 127–150, 1979.

Turrell, F. M.: Citrus leaf stomata: structure, composition, and pore size in relation to penetration of liquids. The University of Chicago Press108, 476-483, 1947.

Vanacker, V., Vanderschaeghe, M., Govers, G., Willems, E., Poesen, J., Deckers, J., De Bievre, B.: Linking hydrological, infinite slope stability and land-use change models through GIS for assessing the impact of deforestation on slope stability in high Andean watersheds.Geomorphology, 52(3), 299-315, 2003.

Vetter, S. H., Schaffrath, D., Bernhofer, C.: Spatial simulation of evapotranspiration of semi-arid Inner Mongolian grassland based on MODIS and eddy covariance data. Environmental Earth Sciences, 65(5), 1567-1574, 2012.

Wang, M. Y., Guan, S. H., Wang, Y.: Soil moisture regime and application for plants in Maowusu

Transition Zone from sandland to desert. 16 (2): 37-44, 2002.

Wang, Z., Wang, L., Liu, L. Y., Zheng, Q. H.: Preliminary study on soil moisture content in dried layer of sand dunes in the Mu Us sandland, 26, 2006 (in Chinese).

Wang, L., Wang, Q. J., Wei, S. P., Shao, M. A. and Yi, L.: Soil desiccation for Loess soils on natural and regrown areas, Forest Ecology and Management, 255, 2467-2477, 2008.

Wang, L., Wang Z., Liu, L.Y. and Hasi, E.: Field investigation on salix psammophila plant morphology and airflow structure, Front. For. China, 2, 136-141, 2006.

Wang, S., Wilkes, A., Zhang, Z., Chang, X., Lang, R., Wang, Y., Niu, H.: Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. Agriculture, Ecosystems & Environment,142(3), 329-340, 2011.

Wang, Y. Q., Shao, M. A., Zhu, Y. J. and Liu, Z. P.: Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China, Agricultural and Forest Meteorology, 151, 437-448, 2011.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B. E., Kowalski, A., Meyers, T., Moncrieff, J.,Monson, R., Oechel, W., Tenhunen, J., Valentini, R. and Verma, S.: Energy balance closure at FLUXNET sites, Agricultural and Forest Meteorology, 113, 223-243, 2002.

Wu, G. X.: Roots' distribution characteristics and fine root dynamics of Sabina vulgaris and Artemisia ordosica in Mu Us Sandland. Master thesis of Inner Mongolia Agricultural University, 2006.

Wu, B., Ci, L. J..: Landscape change and desertification development in the Mu Us Sandland, Northern China. Journal of Arid Environments, 50(3), 429-444, 2002.

Xiao, C.W., Zhou, G. S., Zhang, X. S., Zhao, J. Z. and Wu, G.: Responses of dominant desert species Artemisia ordosica and Salix psammophila to water stress, Photosynthetica, 43, 467-471, 2005.

Yang, Y. M., Yang, G. H., Feng, Y. Z.: Climatic variation and its effect on desertification in 45 recent years in Mu Us sandland. 35 (12): 87-92, 2007.

Yang, Y., Bu, C., Mu, X., Zhang, K.: Effects of differing coverage of moss‐dominated soil crusts on hydrological processes and implications for disturbance in the Mu Us Sandland, China. Hydrological Processes, 29(14), 3112-3123, 2015.

Yang, L., Wei, W., Chen, L., Chen, W., Wang, J.: Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China. Catena, 115, 123-133, 2014.

Yuan, P. F., Ding, G. D., Wang, W. W., Wang, X. Y., Shi, H. S.: Characteristics of rainwater infiltration and evaporation in Mu Us Sandland. Science of Soil and Water Conservation, 4, 004, 2008.

Zeng, N., Yoon, J.: Expansion of the world's deserts due to vegetation‐albedo feedback under global warming. Geophysical Research Letters, 36(17), 2009.

Zeng B, Yang T-B.: Impacts of climate warming on vegetation in Qaidam area from 1990 to 2003. Environmental Monitoring and Assessment, 144: 403–417, 2008.

Zeng, X. B., and Coauthors.: Coupling of the common land model to the NCAR community climate model. J. Climate, 15, 1832–1854, 2002.

Zhang, Y., Munkhtsetesg, E., Kadota, T. and Ohata, T.: An observational study of ecohydrology of a sparse grassland at the edge of the Eurasian cryosphere in Mongolia, Journal of Geophysical Research: Atmospheres (1984-2012), 110, doi:10.1029/2004JD005474, 2005.

Zhang, Z. P.: Vegetation pattern changes in Mu Us desert and the analysis of water income and

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

expenses: a case study in Mu Us county. Master thesis of Inner Mongolia University, 2006.

Zhang, Z. P.: Vegetation pattern changes in Mu Us desert and the analysis of water income and expenses: a case study in wushen county. Mater thesis of Inner Mongolia University, 2006 (in Chinese)

Zhang, Z. S., Wang, X. P., Li, X. R., Zhang, J. G.: Soil evaporation in artificially revegetated desert area. Journal of desert research, 25, 243-248, 2005 (in Chinese)

Zhang, Y. Y., Zhou, Z. F., Cheng, J. H., Dang, H. Z., Li, W.: Soil moisture characteristics of several types of shrubs in different anchored dune positions in maowusu sandy land. 42, 73-78, 2010 (in Chinese).

Figure and table captions

Fig. 1. Location of the Loess Plateau and the map of study site (LP: the Loess Plateau; black triangle: flux tower; white triangle: Yulin meteorological station; ①: Tu River; ②: Yuxi River; ③: Yellow River).

Fig. 2. Land use/cover conditions of the study site over the Loess Plateau: (a) the natural land use/cover condition of shrubland (photo was taken at 6th August 2011); (b) the natural land use/cover condition of grassland (photo was taken at 7th September 2011); (c) the undisturbed zone (natural vegetation) and the disturbed zone (bare soil) in the land degradation process (photo was taken at 26th April 2013); (d) the undisturbed zone (natural vegetation) and the disturbed zone (grassland) in the vegetation rehabilitation process (photo was taken at 16th August 2014).

Fig. 3. Diagrams of wind rose and footprint (a) wind rose of study site by using half-hourly wind speed and wind direction data; (b) simulated footprint by ellipse (the long axis is 1682m, and the short axis is 1263m; zone A is the source area that have not encountered any land use/cover change, while zone B is the source area that have experienced land use/cover change by human activities; white triangle is the flux tower).

Fig. 4. Seasonal characteristics of monthly (a) sunshine duration (D_S); (b) temperature (T_a); (c) relative humidity (R_H); (d) total precipitation (P) of four periods at the study site and climatological normal (1954-2014 climatological normal in Yulin meteorological station).

Fig. 5. Seasonal and inter-annual characteristics of daily (a) evapotranspiration (E_T, mm); (b) potential evapotranspiration (E_{TP}, mm); (c) NDVI in zone A and zone B within the footprint; (d) precipitation (P, mm); (e) soil water stress of root zone (f_s) during 1st July 2011 to 30th June 2015.

Fig. 6. The correlations between daily evapotranspiration (E_T, mm) and its controlling factors: (a) daily potential evapotranspiration (E_{TP}, mm); (b) daily weight-averaged NDVI within footprint (NDVI_w); (c) daily soil water stress of root zone (f_s) in Period I excluding the data in rainy days (r: Pearson's correlation significance; T: T-test significance).

Fig. 7. Quantitative analysis between (a) vegetation phenological change (NDVI_w) and daily normalized E_T ($f_v = E_T/(E_{TP} \times f_s)$) in Period I (exclude the data in rainy days and frozen days); (b) the indicator of land use/cover change (D_{lu}) and total normalized E_T ($f_v = E_T/(E_{TP} \times f_s)$) of the growing season in each period.

Table 1. Daily air temperature (Ta, °C), relatively humidity (R_H, %), sunshine duration (Ds, h), soil water content of the root zone (θ_r, m^3 m^{-3}), the groundwater level (GWL, m) and precipitation (P, mm) in 1954-2014 and in the growing season of each period (Because there were some missing data in Period IV (from 12th September 2014 to 23th November 2014 and from 13th March 2015 to 22th April 2015), we got rid of data in

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

these two time range of Period I~III and 1954-2014)

Items	1954-2014	I	II	III	IV
Ta (℃)	19.8	19.6	20.4	19.9	19.3
R_H (%)	57.7	57.3	54.9	53.4	52
Ds (h)	213.3	220.7	215.8	218.2	220.7
P (mm)	329.8	357.1	384.1	330.2	199.8
θ_r (m^3 m^{-3})	_	0.077	0.077	0.076	0.064
GWL (m)	_	-3.8	-3.6	-3.0	-3.5

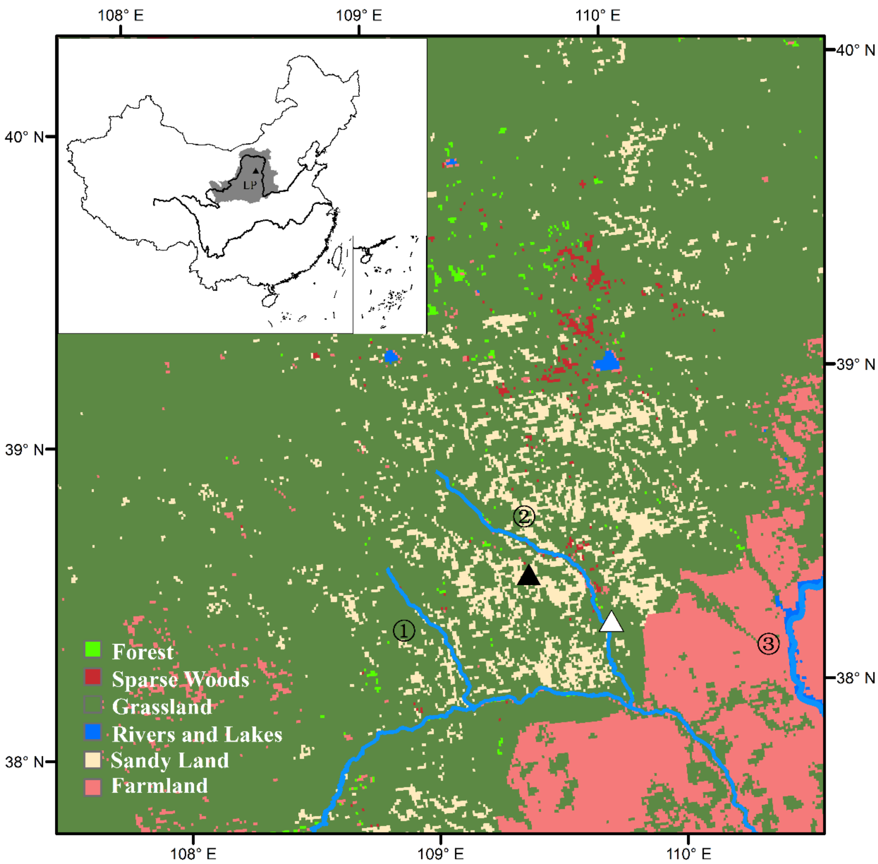
Table 2. Typical values of total evapotranspiration (E_T, mm), total potential evapotranspiration (E_{TP}, mm), indicator of land use/cover change (D_{lu}), soil water stress of root zone (f_s) and normalized E_T (i.e., f_v $(= E_T/(E_{TP} \times f_s))$) in the growing season of each period. (Because there were some missing data in Period IV (from 12th September 2014 to 23th November 2014 and from 13th March 2015 to 22th April 2015), we removed the values of E_T, E_{TP} and f_s of these two time ranges in Period I~III).

	Items / Periods	E_T (mm)	E_{TP} (mm)	D_{lu} (%)	f_s (dimensionless)	f_v (dimensionless)
Growing season	I	238.4	876.1	-0.2	0.62	78.1
	II	236.5	870.7	4.6	0.63	79.9
	III	292.1	956	10.4	0.59	86.3
	IV	332.2	937	6	0.37	111.9

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

Hydrology and Earth System Sciences
Open Access
Discussions

Fig.1



Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

Hydrology and Earth System Sciences
Discussions
Open Access

Fig.2

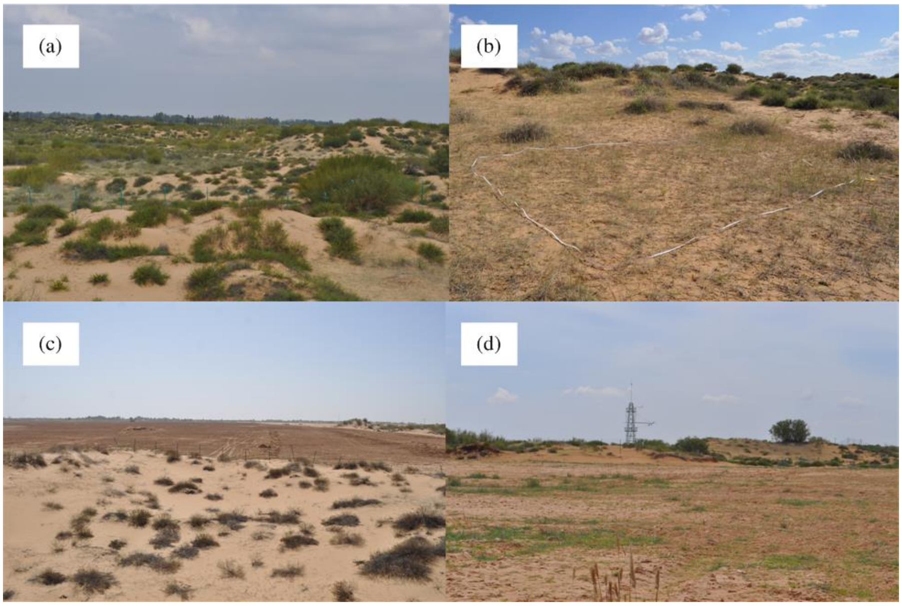
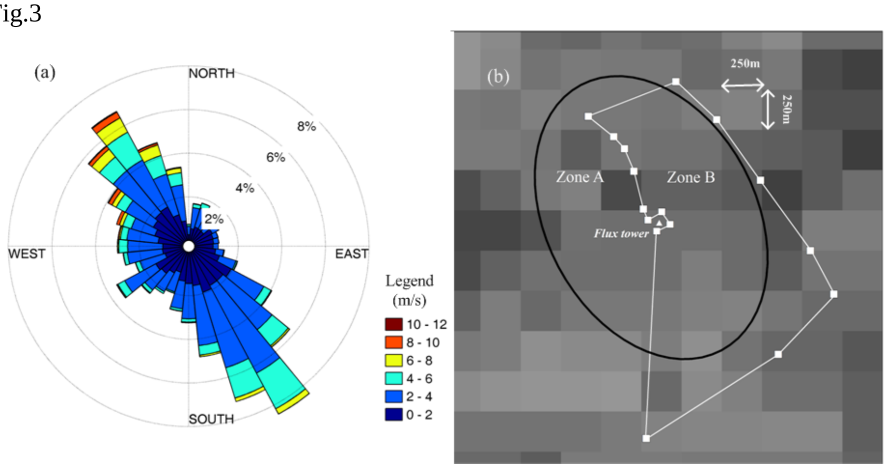


Fig.3



Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

Fig.4

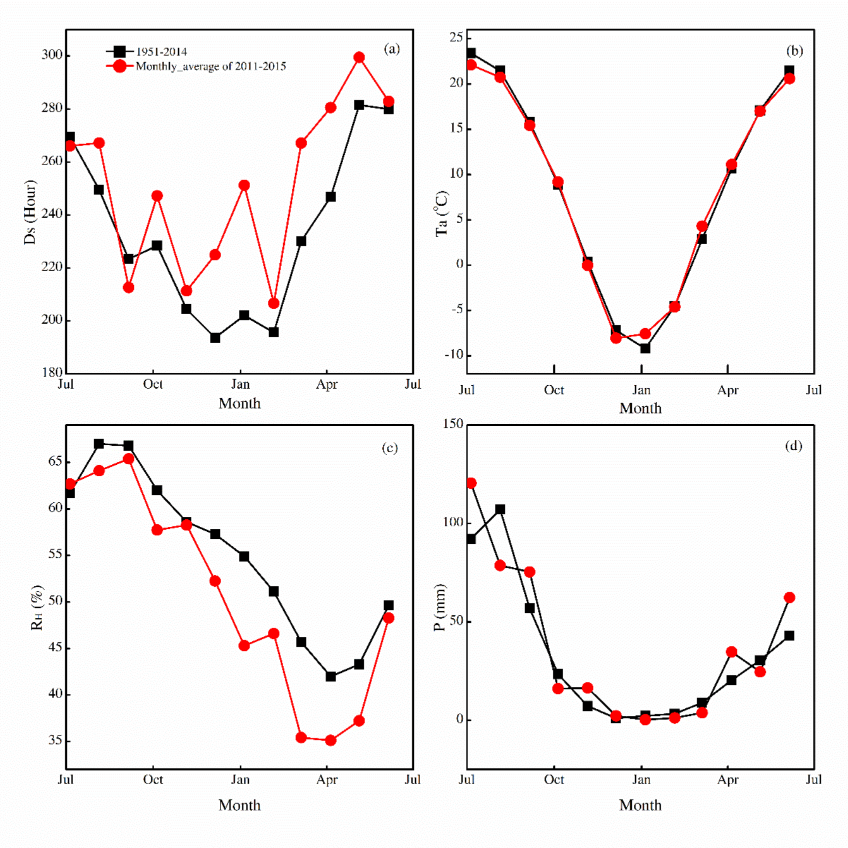


Fig.5

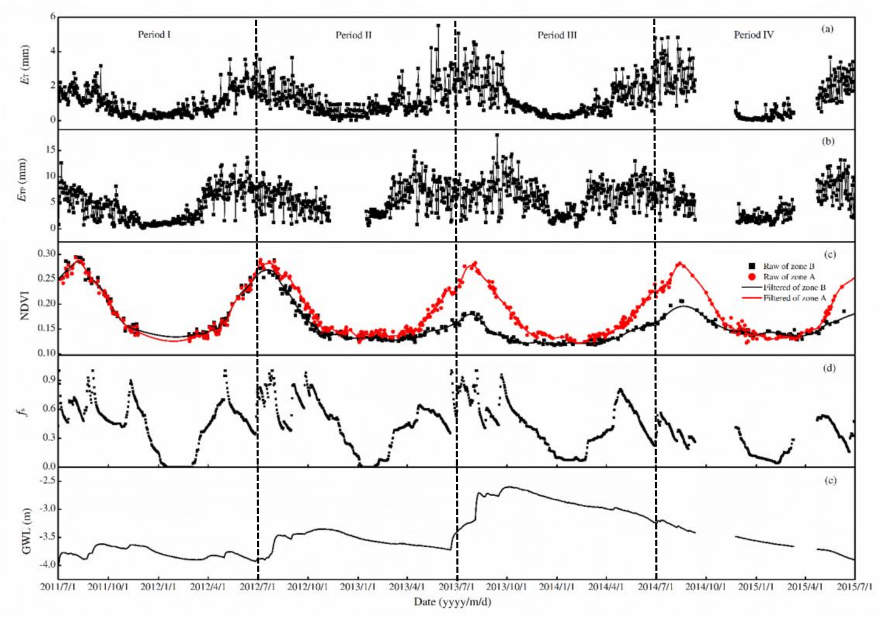
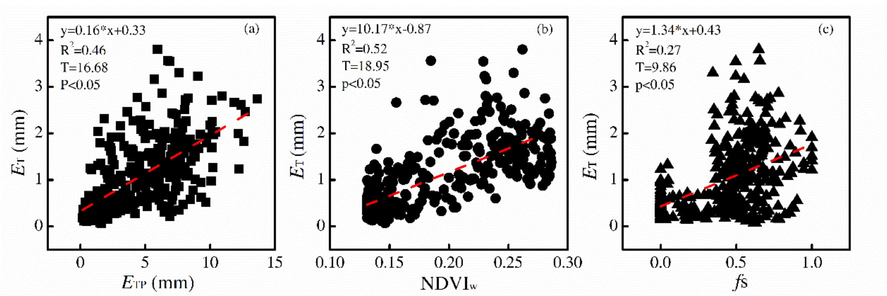

Period I
Period II
Period III
Period IV
(a)
(b)
(c)
(d)
(e)
NDVI
Raw of zone B
Raw of zone A
Filtered of zone B
Filtered of zone A
GWL (m)
Date (yyyy/m/d)

Fig.6


y=0.16*x+0.33
R2=0.46
T=16.68
P<0.05
(a)
y=10.17*x-0.87
R2=0.52
T=18.95
p<0.05
(b)
y=1.34*x+0.43
R2=0.27
T=9.86
p<0.05
(c)
ET (mm)
ETP (mm)
NDVIw
fs

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-490, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 30 September 2016

Fig.7