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Evapotranspiration over artificially planted shrub communities in the shifting sand dune area of the Tengger Desert, north central China

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ABSTRACT

Revegetation is a common method to combat desertification in arid and semi-arid areas worldwide. The objective of this study was to characterize the evapotranspiration (ET) of a 20-year-old revegetated area of the Tengger Desert. During the measurement period from 2009 to 2012, ET was measured by the eddy covariance technique. The result showed that the values for mean daily ET were 0.43, 0.39, 0.43 and 0.59 mm d^{-1} in 2009–2012, respectively. In the non-growing season, the diurnal ET variation showed a normal distribution with a maximum value occurring at noon, while it showed multimodal distribution trend occurred in a dry day and a unimodal trend in a wet day with a maximum value occurring at noon in the growing season. During the 4-year measurements, despite the large inter-annual variation of precipitation (annual mean precipitation of 164.4 ± 33.5 mm), the water loss through ET (667.5 mm) was almost equal to rainfall (657.8 mm), and the mean of ET/P was 1.01.The annual ET amounts were 153.6, 143.3, 156.2 and 214.4 mm y^{-1} in 2009–2012, respectively, with corresponding ratio between accumulated ET and precipitation (ET/P) of 1.03, 1.14, 0.82 and 1.12. This indicated that the annual ET amounts can be modified by the soil water storage, which led to water loss through ET exceeding the water input by precipitation in a drier year, and soil water can be replenished in a wetter year. Thus, the vegetation protection system using plantations of xerophyte shrubs in the present study area is a success with a trade-off of acceptable hydrological consequences that deserve to be popularized.

KEY WORDS evapotranspiration; revegetated area; eddy covariance; arid desert ecosystem

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INTRODUCTION

Water scarcity and vegetation vulnerability are common characteristics of desert ecosystems, where the relationships between the vegetation and water are much investigated because of the tight coupling between the water, energy and biogeochemical budgets (Wang *et al*., 2009; Tietjen *et al*., 2010, Wang *et al*., 2012). In these water-controlled systems, the hydrologic cycle largely determines the shaping processes of main plant communities. Water availability has both direct and indirect effects on the ecological processes by both the water distribution between various parts of topographical structure (such as topsoil, root zone, groundwater and steam) and the division of water loss though different pathways versus water available to plants (Yaseef *et al*., 2010). Estimating the components of the water budget will contribute to understanding and modelling capacities of vegetation responses to variations in environmental conditions (Huxman *et al*., 2005; Kurk and Small, 2007; Yaseef *et al*., 2010).

Evapotranspiration (ET) dominates water losses in arid and semi-arid area, often accounting for over 90% of annual precipitation (Zhang *et al*., 2001; Huxman *et al*., 2005; Li *et al*., 2013). For a given rain-fed ecosystem, total annual ET is highly correlated with amount of annual rainfall (Reynolds *et al*., 2000; Wang *et al*., 2004). Vegetation change is unlikely to lead to significant consequences for regional hydrology because precipitation in such environments is usually completely exhausted, despite variations in vegetative structure or species composition (Dugas *et al*., 1996). However, the process of ET in a desert ecosystem is influenced by environmental conditions and controlled by water distribution within the soil profile of the root zone (Wang *et al*., 2011). Vegetation change may make important modifications to the magnitude and dynamics of ET, as well as its relative importance in the local water balance (Gerten *et al*., 2004; Li *et al*., 2013). The pathway of water returning to the atmosphere that is determined partly by the duration and depth of soil wetting is quite different between the

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vegetation types, i.e. deep-rooted shrubs and shallow-rooted grass (Snyder and Maxwell, 2005). Evaluation of the ecohydrological consequences of woody-plant encroachments into grassland indicates an increasing trend of the ET losses with increasing woody-plant dominance (Scott *et al.*, 2006). Quantitative knowledge of ET losses in desert communities is particularly important to various water management agencies, especially in areas where vegetation is vulnerable to both climate change and anthropic activities (Sammis, 1981; Wang *et al.*, 2004).

In arid and semi-arid areas human-induced vegetation change is also a global phenomenon with important ecohydrological consequences. For example, plantations of woody species have been widely accepted as an effective method for reversing deforestation, degradation and desertification (Cao, 2008). Because of the significant variations of climatic and topographic backgrounds and economic characteristics, plantation activities differ between regions. As one of the most seriously desertified regions in the world, where water is the most crucial variable for ecosystem function, north China has also experienced extensive plantation activities over the past century-during which several ecological engineering projects were established to control desertification and prevent dust storms. Despite the great benefits to the environment, there were some negative outcomes from the costly projects because of reduced water availabilities, such as groundwater level decline (Bell *et al.*, 1990) and increasing runoff (Maestre and Cortina, 2004). Inappropriate plantations consume too much water because of increased ET, and thus undermine the natural water balance (Wilske *et al.*, 2009). These unintended problems can be alleviated by selecting water-saving species and suitable planting techniques (Cao, 2008). In the severely arid area of north China with precipitation < 200 mm, water-saving xerophytic shrubs were usually experimentally selected as useful species to stabilize the shifting sand dunes to protect infrastructure or traffic lines from encroachment in arid deserts. Among them, the Shapotou vegetation protective system is considered as one of the most successful revegetation models and has protected the Baotou–Lanzhou railway line since the 1950s where it crosses the sand dune area on the southeast fringe of the Tengger Desert (Zhao, 1991; Xiao *et al.*, 2003). Xerophytic shrubs, such as *Caragana korshinskii* and *Artemisia Ordosica* are the dominant species introduced in the revegetated area following the stabilization of shifting sand dune by straw checkerborder. In the present study, the eddy covariance method was used to measure the ET dynamics of the Shapotou revegetation system. The results may provide useful information for revegetation and ecosystem management agencies in desert areas, given the increasing shortage of water resources.

MATERIAL AND METHODS

Experiment site

The study area is located on the southeast fringe of the Tengger Desert, north central China (37°32′N, 105°02′E) (Figure 1). Meteorological records from the Shapotou weather station show that the annual mean temperature is 9.6 °C with a historical extreme minimum of -25.1 °C in January and maximum 38.1 °C in July, during the last 50 years. The annual mean precipitation is about 180 mm with a large inter-annual variability. The maximum annual precipitation was 495.8 mm in 1987, versus the minimum of 88.3 mm in 1957. More than 80% of rainfall events occur during the growing season of May–October when warm temperatures benefit plant growth. The mean annual pan potential evaporation is around 3000 mm (observed by an evaporation pan of type E-601). The average wind velocity is $3.5\,\mathrm{m\,s^{-1}}$, with northwest being the dominant wind direction and 122 d involve dust events (Liu *et al.*, 2006).

Before revegetation, the natural landscape was dominated by large and dense reticulate barchan chains of sand dunes with relative height of 15–20 m, and only the fragmentary and sand-mobility-resistant shrubs of *Hedysarum scoparium* were scattered sparsely. In the growing season, some annual herbaceous plants, such as *Agriophyllum squarrosum* and *Eragrostis poaeoides*, complete their life cycle during the short period in some lowland among dunes when rainfall is available. The total vegetation cover by visual estimation should be quite less than 1%. Precipitation is the sole source of soil moisture and groundwater is unavailable for plant growth.

The Shapotou vegetation protective system was designed to ensure the unimpeded passage of the Baotou–Lanzhou railway line by shifting sand dunes in the Shapotou area. The combination of windbreaks, straw checkerboards and plantations of xerophytic shrubs is believed to react comprehensively and lead to a successful revegetation (Zhao, 1991; Xiao *et al.*, 2003). (1) Windbreaks in the project are made of dead willow branches or bamboo planted on the north border of the revegetation area. This functions as a barrier to prevent sand dune invasion through filtering of aeolian sand. This now forms as a high protruding ridge because of sand accumulation between the revegetation area and shifting dunes. (2) The straw checkerboard is a method in which straw is inserted into soil along grid lines with 10–15 cm protruding above the soil surface to fix shifting sand through an increase in roughness height. (3) Xerophytic shrubs, such as *C. korshinskii* and *A. ordosica* planted inside the straw checkerboards, constitute the protective revegetation system. The leaf area indices of *C. korshinskii* and *A. ordosica* were approximately 0.6 and 0.4 $\mathrm{m^2\,m^{-2}}$ (Huang *et al.*, 2014), and average plant heights were 1.2 and 0.6 m (Gao *et al.*, 2012),

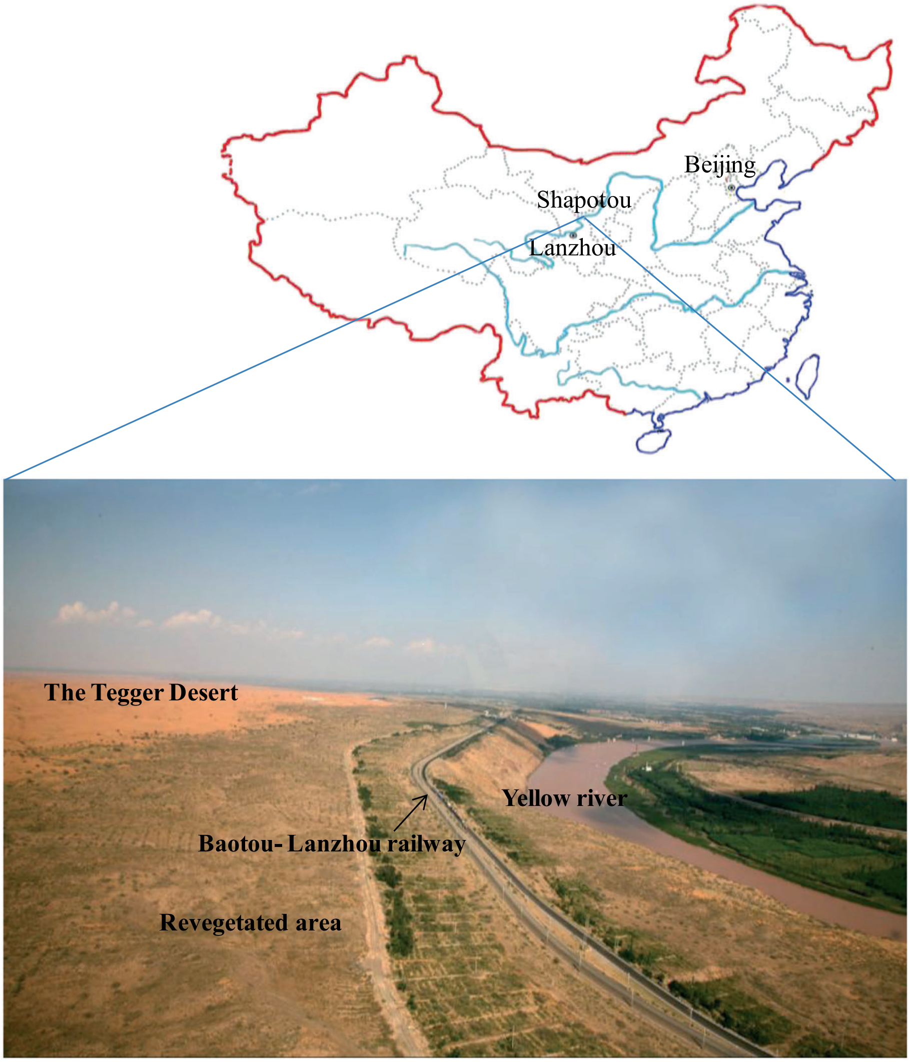

Figure 1. The study site of the revegetated area at the Shapotou region, bordering the Tengger Desert, northwest China.

respectively. The revegetation activities commenced in 1956 and expanded several times in last decades. This now forms a 16-km green corridor along the railway with width of 700 m in the north and 500 m in the south (Figure 1).

Methods and data

An open-path eddy covariance system was set up in the 20-year-old revegetated area (established in 1989) on 19 May 2008. Three-dimensional wind vector was measured using a sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA). An open-path infrared gas analyser (LI-7500, LiCor, Lincoln, NE, USA) was used to capture the concentrations of water vapour and CO_2. The Li-7500 was calibrated at regular intervals for CO_2 and water vapour using calibration gases and a dew point generator supported by the China Land-Atmosphere Coordinated Observation System, CLACOS. The flux instruments were installed 4 m above the soil surface and orientated in the direction of prevailing winds (northwest). A data logger (CR3000, Campbell Scientific, Logan) was used to record 10-Hz raw data.

Parallel to the eddy covariance measurements, meteorological conditions were also measured. Air temperature, relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland) and net radiation (Rn) (CNR-1, Kipp & Zonen, The Netherlands) were measured at 4, 4 and 3 m above the soil surface, respectively, and above *C. korshinskii* that stood about 1.2 m high and *A. ordosica* which was about 0.6 m in height. Two self-calibrating soil heat flux sensors (HFP01) were installed 0.05 m below the soil surface. Average soil temperature (TCAV) was placed at a depth of 0.20 m. Soil temperature and volumetric soil moisture content were measured using five soil temperature sensors (109-L, Campbell Scientific Ltd., Edmonton, Alberta, Canada) and five volumetric soil moisture probes (EnviroSMART, Campbell Scientific Ltd., Edmonton) placed at depths of 0.05, 0.10, 0.15, 0.20, 0.40 m and 0.20, 0.40, 0.60, 1.0, 2.0 m. Precipitation was measured at 0.5 m above ground level at 10 m away from the eddy covariance system using a rain gauge (TE525MM, Texas Electronics Inc., Dallas, TX, USA).

The post-processing software Edire (University of Edinburgh's eddy covariance system, Scotland) was used to process the 10-Hz raw data. Based on the data processing method of Lee *et al.* (2004) and Gao *et al.* (2012), we calculated the net ecosystem exchange of CO_2 and latent and sensible heat. Moreover, the eddy covariance method with open-path CO_2 analysers may heat up the environment and introduce uncertainties into the data, especially in cold climates (Burba *et al.*, 2008). To avoid this, we recalculated the half-hour flux data using the method proposed by Burba *et al.* (2008).

Data was initially filtered using a rejection criteria of anomalous value for three-dimensional wind velocities or scalar, as well as for rain events, and U_* (friction velocity) $<0.1\,\mathrm{m\,s^{-1}}$. Short periods of <2 h were filled by linear regression, while longer periods were dealt with using mean diurnal variation with a 7-d window (Falge *et al.*, 2001).

Energy balance (EB) closure can serve as a valuable tool to further refine the ET measurement and is considered an important method in evaluating eddy covariance (Twine *et al.*, 2000; Wilson *et al.*, 2002), which can be expressed as Equation (1):

$$\lambda ET + H = a(Rn\text{–}G\text{–}\Delta S) + b \qquad (1)$$

where λET is the latent heat flux (the energy equivalent of ET) ($\mathrm{W\,m^{-2}}$), H is the sensible heat flux ($\mathrm{W\,m^{-2}}$), Rn is the net radiation ($\mathrm{W\,m^{-2}}$), G is soil heat flux ($\mathrm{W\,m^{-2}}$), ΔS is rate of change of heat storage in biomass (neglected because of shrubs were quite sparse), a is slope and b is intercept.

The data collected during 2009–2012 were used to analyse the EB enclosure. The linear regression between the total daily turbulent energy (λET + H) and available energy (Rn-G) is shown in Figure 2. The EB enclosure was 79%, which reached moderate level (Wilson *et al.*, 2002; Li *et al.*, 2005).

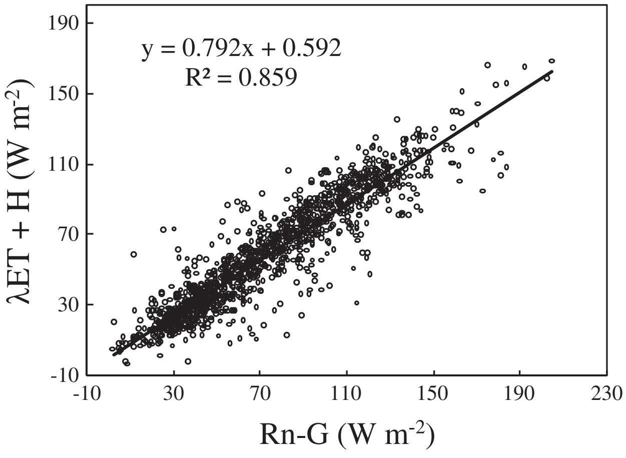

Figure 2. Daily energy balance ratios in the revegetated area from 2009 to 2012.

The reference evapotranspiration (ET_o) of the plant canopy was calculated following the FAO Penman–Monteith equation according to standard FAO procedure (Allen *et al.*, 1998), which can be expressed as Equation (2):

$$ET_o = \frac{0.408\Delta(Rn - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

where ET_o is the reference ET ($\mathrm{mm\,d^{-1}}$), Rn is the net radiation at the crop surface ($\mathrm{MJ\,m^{-2}\,d^{-1}}$), G is the soil heat flux density ($\mathrm{MJ\,m^{-2}\,d^{-1}}$), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height ($\mathrm{m\,s^{-1}}$), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (VPD, kPa), Δ is the slope vapour pressure curve (kPa $°C^{-1}$) and γ is the psychrometric constant (kPa $°C^{-1}$).

RESULTS

Environmental conditions during measurement

The annual parameters of precipitation, net radiation, vapour pressure deficit (VPD), ET, ET/P and ET/ET_o were shown in Table I. Daily environmental condition time series during the study period are shown in Figure 3. The annual precipitation in 2009 and 2010 was 147.6 and 125.4 mm, respectively, both of which were much lower than the average record of 180 mm (Table I). However, 2011 and 2012 were relatively wet with rainfall of 191.5 and 193.3 mm, respectively (Table I). During the measurement

Table I. Annual parameters of precipitation, net radiation, VPD, ET, ET/P and ET/ET_o.

Year	Precipitation ($\mathrm{mm\,y^{-1}}$)	Net radiation ($\mathrm{W\,m^{-2}}$)	VPD (kPa)	ET ($\mathrm{mm\,y^{-1}}$)	ET_o ($\mathrm{mm\,y^{-1}}$)	ET/P	ET/ET_o
2009	147.6	69.3	0.82	153.6	988	1.04	0.15
2010	125.4	72.1	0.79	143.3	1015	1.14	0.14
2011	191.5	76.4	0.78	156.2	1002	0.82	0.16
2012	193.3	77.4	0.77	214.4	1013	1.11	0.21

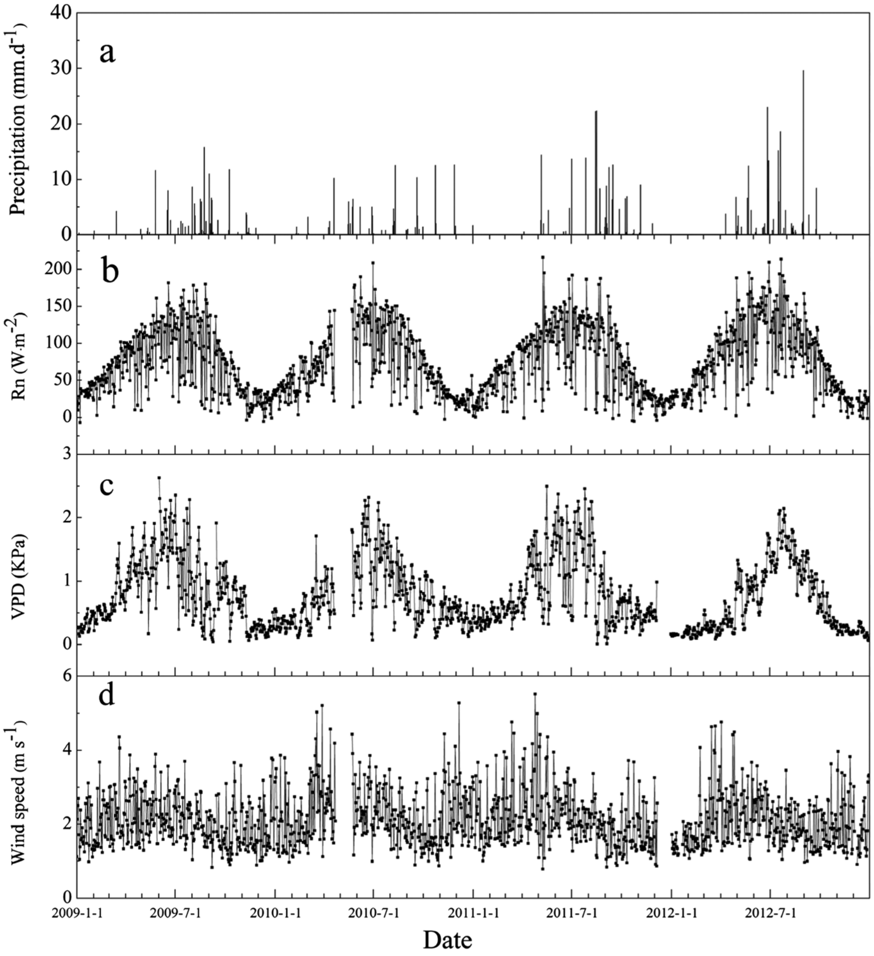

Figure 3. Mean daily precipitation (a), net radiation (b), vapour pressure deficit (c) and wind speed (d) in the revegetated area.

period, 70% of rainy days had rainfall amounts < 5 mm, with the largest daily amounts of 15.8, 14.6, 22.4 and 29.6 mm in 2009–2012, respectively (Figure 3a).

Average monthly Rn on an annual basis was similar in all 4 years (Figure 3b). Average annual Rn was 69.3, 72.1, 76.4 and 77.4 W m^{-2} in 2009–2012, respectively (Table I). The 4-year mean monthly Rn is 30.9 W m^{-2} in January and 93.9 W m^{-2} in July, respectively.

Average annual VPD was 0.82, 0.79, 0.78 and 0.77 kPa, for 2009–2012, respectively (Table I, Figure 3c). Wind speed in winter was less than in the growing season. The mean of annual wind speed was 2.04, 2.23, 2.4 and 2.04 m s^{-1} in 2009–2012, respectively (Figure 3d).

Annual ET$_o$ was 988, 1015, 1002 and 1013 mm y^{-1} for 2009–2012, respectively (Table I). And the ET/ET$_o$ was 0.15, 0.14, 0.16 and 0.21 in 2009–2012, respectively.

Seasonal variation of ET

The seasonal variations of ET are shown in Figure 4. The seasonal dynamics of ET was similar throughout 2009–2012. ET began to increase at the end of April and maintained high values until October with two peaks in 2009–2011 (one in May, and another in August in 2009 and 2010 or September in 2011); however, there were three peaks in 2012 (the first in May, the second in July and the third in September). The values for mean daily ET were 0.43, 0.39, 0.43 and 0.59 mm d^{-1} in 2009–2012, respectively. For each year, the largest daily ET amounts were 2.76, 2.33, 3.44 and 3.76 mm d^{-1} in 26 August 2009, 26 May 2010, 10 May 2011 and 22 July 2012, respectively.

In 2009 and 2010, the cumulative of ET was always higher than precipitation. In 2011, cumulative of ET was higher than precipitation before July and lower than precipitation after July; however, in 2012, cumulative of ET was lower than precipitation before July and higher than precipitation after July (Figure 5). The annual total ET amounts were 153.6, 143.3, 156.2 and 214.4 mm y^{-1} in 2009–2012, respectively, with corresponding ratio between accumulated ET and precipitation (ET/P) of 1.03, 1.14, 0.82 and 1.12. However, despite inter-annual variation, cumulative ET (667.5 mm) was almost equal to total precipitation amount (657.8 mm) in all 4 years with ET/P 1.01. ET in the growing season

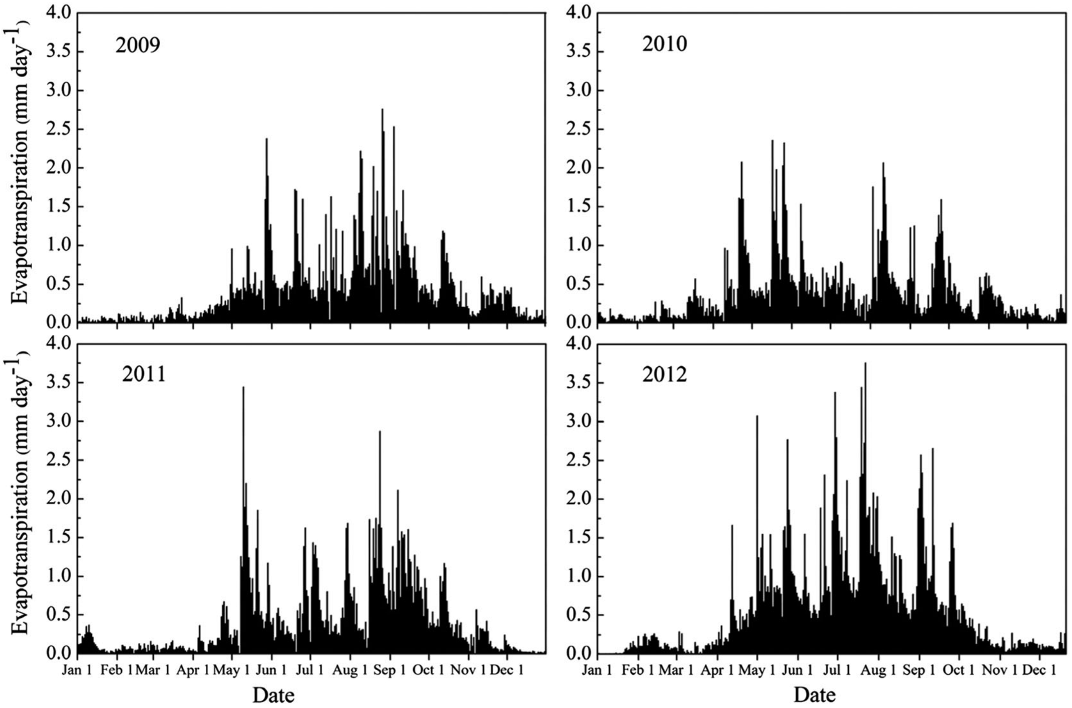

Figure 4. Seasonal variation of evapotranspiration in the revegetated area from 2009 to 2012.

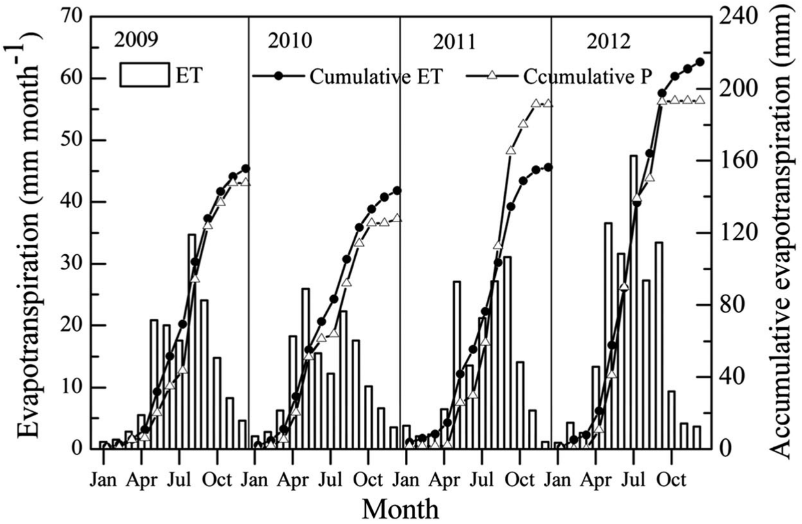

Figure 5. Monthly total evapotranspiration (open bars), cumulative evapotranspiration (closed circles) and accumulative precipitation (open triangles) in the revegetated area from 2009 to 2012.

accounted for 85, 85, 86 and 94% of the annual total ET amounts in 2009–2012, respectively.

Diurnal variation of ET

The daily ET for January (from 1 January to 31 January) and July (from 1 July to 31 July) was selected to compare the diurnal dynamics between non-growing and growing seasons (Figure 6). In the non-growing season (January), diurnal ET showed strong regular variations, with increases from 10:00 and a peak at about 12:00–14:00, followed by a gradual decrease. After 17:00, the ET was as low as about 0 mm. Cumulative ET during whole days was 0.03, 0.06, 0.12 and 0.05 mm d^{-1} on January of 2009–2012, respectively.

In the growing seasons of 2009–2011, the ET increased from the early morning (08:00) and reached its first peak about 11:00, and then gradually decreased; there was a

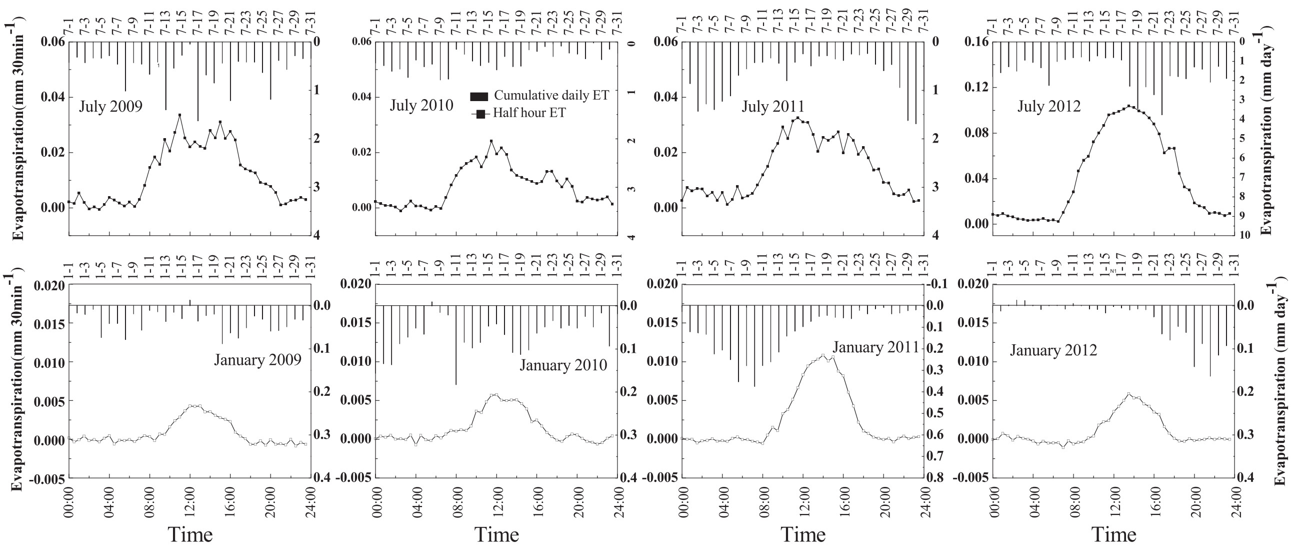

Figure 6. Diurnal trends in evapotranspiration (ET) using 1/2 hourly data and cumulative daily ET for the months of July and January for 2009 to 2012.

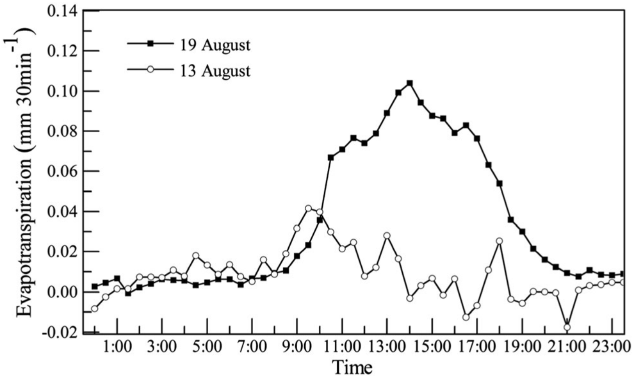

Figure 7. Diurnal variation patterns of evapotranspiration of the revegetated area during a wet day (19 August 2011) and a dry day (13 August 2011).

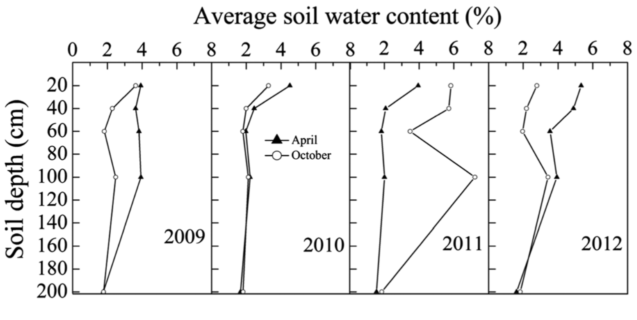

Figure 8. Vertical distributions of soil water content in the 20–200 cm soil profile in April and October during 4 years.

second peak at about 15:00 (in 2009 and 2011) or 17:00 (in 2010), and then decreased gradually until 20:00 with ET of nearly zero. Differing to the other year, diurnal variation of ET in 2012 had only one peak at 13:30. The cumulative average daily ET for the month of July in four years were 0.57, 0.38, 0.68 and 1.99 mm d^{-1} for 2009-2012, respectively, and corresponding half-hour ET in July were in the ranges of 0–0.033, 0–0.024, 0.001–0.033 and 0.002–0.104 mm.

To understand the response of ET to available water, two days of measurements from before and after a rain event in 2011 were selected to compare the diurnal variation of ET (15–16 August 2011, with a total rainfall of 18.9 mm). The result indicated that diurnal variation of ET before rain (13 August 2011, with no rain events in the 15 d before and mean of daily soil moisture of 3.10%) showed a multimodal trend (Figure 7). The half-hour ET amount at night (21:00–07:00) was as low as 0.01 mm, and showed an increasing trend during 09:00–10:00, following by decrease with a very low ET rate (equal to zero or immeasurable) at early afternoon (13:00–15:00) when Rn was at a daily maximum. The diurnal variation of ET after the rain (19 August 2011, mean of daily soil moisture is 9.71%) showed a similar trend to Rn. The half-hour ET amounts increased from 9:00 and reached a peak at 14:00, and then decreased until 21:00 and the remained at a very low value throughout the night. The total daily ET amount was 1.62 mm on 19 August 2011 which was 4 times the value (0.39 mm d^{-1}) of 13 August 2011.

DISCUSSION AND CONCLUSIONS

The hydrological consequences of plantations are a common issue in current research (Dye and Versfeld, 2007; Chirino *et al*., 2006;Farley *et al*., 2005). Different types of planted vegetation (e.g. plantation tree, shrub or grass) have significant impacts on local hydrological processes. Large-scale afforestation or reforestation may use more water than grass or shrubs in semi-arid areas (Bell *et al*., 1990; Farley *et al*., 2005). In our research area, xerophytic shrubs such as *C. korshinski* and *A. ordosica* planted on the southeastern fringe of the Tengger Desert have changed the water balance (Wang *et al*., 2004; Li *et al*., 2013), change in the rainfall interception and redistribution (Wang *et al*., 2005a; Zhang *et al*., 2005), evapotranspiration, canopy transpiration (Wang *et al*., 2004), rainfall infiltration (Li, 2012).

The meteorological records of the Shapotou weather station showed that, on average, >80% of precipitation was during the growing season of May–October, and this characteristic of rain and warmer temperature during the same period may enhance the water use efficiency and contribute to the success of plantations in this severely dry desert. In the revegetated area in Shapotou, our measurements showed that cumulative ET in 2009–2011 was 153.6, 143.3 and 156.2 mm y^{-1}, respectively. Cumulative ET in 2012, at 214.4 mm y^{-1}, was higher than for the other three years. Precipitation in 2009 and 2010 was 147.6 and 125.4 mm, respectively, which was less than the average annual precipitation (180 mm), and precipitation events > 10 mm occurred only four times. Drought stress decreased canopy transpiration and for that matter ET, and increased precipitation loss because of soil evaporation, which in turn led to a large decrease in available water for plant growth (Li *et al*., 2007, 2013). Furthermore, as plant succession proceeded in the revegetated area, biological soil crusts (BSCs) formed on the surface of sand dunes, which may significantly alter rainfall infiltration and soil evaporation (Li *et al*., 2013). BSCs reduced evaporation in topsoil after small rainfall events (when the precipitation volumes were <7.5 mm and <5 mm for moss and algal crusts, respectively). However, during large precipitation events (>10 mm), the situation was reversed (Li *et al*., 2013). Although precipitation was 191.5 mm in 2011, >70% of precipitation was after mid August, and a continuing drought before August may have affected plant growth and decreased transpiration and evaporation, and so ET was still low in 2011. Furthermore, in 2009 and 2010, the soil water content in soil layers within 20–100 cm depth at the end (October) was lower than that at the beginning of the growing season (April), which indicates the excessive water consumption in the relatively drier years (Figure 8). In the wetter year of 2011, its replenishment was indicated by the increase in soil water content at the end of growing season (October) of compared to the beginning of the growing season (April). This may imply that ET can be modified by soil water storage, which led to water loss through ET exceeding the water input by precipitation (i.e. a larger ET/P) in the drier year. Thus water deficit in the drier year was replenished in the wetter year. Because of replenishment of soil water at the end of the rain season in 2011, and more rainfall in 2012 (193.3 mm), the cumulative ET in 2012 was higher than for the other three years. A similar phenomenon was also observed in North Carolina (Amatya and Skaggs, 2011).

The ET/P was 1.03, 1.07, 0.82 and 1.11 in 2009–2012, respectively. During the four years of measurements, despite the large inter-annual variation of precipitation (annual mean precipitation of 164.4 ± 33.5 mm), the water loss through ET (667.5 mm) was almost equal to rainfall (657.8 mm), and the mean of ET/P was 1.01. Wilske *et al.* (2009) researched the ET of a 3-year-old poplar plantation and nearly shrubland in the Hubuqi Desert. Their results showed that, growing season ET was 227.8 and 223.1 mm for poplar plantation and shrubland, respectively; however, corresponding ET/P was 1.5 and 1.0. The ET/P in natural vegetation of the Tennger Desert was 1.18 (Li *et al.* 2014). In a desert halophyte community in western China, Liu *et al.* (2012) found that annual ET was 155 mm with the ET/P of 1.20 in a dry year (precipitation of 129 mm) and annual ET was 259 mm with the ET/P of 1.22 in a wet year (precipitation of 213 mm). In a Chihuahua Desert grassland, long-term measurements showed that average annual ET was 299 mm and precipitation was 272 mm, with the ET/P was 1.09 (Mielnick *et al*., 2005). Compared with other desert areas, ET was lower in the present study, and the ET/P was in the range of 0.82–1.11 with mean for the 4 years of 1.01, close to that of the nature desert area.

A large body of evidences indicates that water balance should be considered carefully before the woody plants are introduced into a water-limited area (Cao, 2008). In our study area, revegetation has led to an increase of the vegetation cover from <1% to >20%, which has also significantly modified process of the water budget (Wang *et al*., 2004; Li *et al*., 2013). In the revegetated area at Shapotou, where precipitation is the sole water source for the planted shrubs, water loss through ET during the 4 years of this study was almost equal to total precipitation. Consequently, there was no water recharge of soil below 2 m (the soil water content at 2-m depth was nearly the same for all four years, Figure 8). In the shifting sand dune area without plantations, evaporation was nearly 70.5% of total precipitation, and water recharge in the deep layers amounted to 12.6% of the total precipitation (Li *et al*., 2014). However, such infiltration would disappear within several years of plantation establishment (Wang *et al*., 2005b), meaning that the presence of the shrubs leads to more water being consumed through transpiration and no water replenishment to deep soil. Thus, the vegetation protection system using plantations of xerophyte shrubs in the present study area is a success with a trade-off of acceptable hydrological consequences that deserve to be popularized.

In the non-growing season, the diurnal ET variation showed a regular unimodal trend with a maximum value occurring at noon. Meanwhile, a multimodal distribution occurred in a typical dry day of the growing season, and the ET showed only small fluctuations around noon when experiencing the strongest radiation of the day. However, the ET showed a similar trend in variation to that for Rn when water was available following a rainfall event and the maximum was at about 14:00. In general, ET is controlled by many factors including LAI, water availability, temperature, VPD, Rn and plant stomatal conductance (Li *et al*., 2000; Giambelluca *et al*., 2009; Guo and Sun, 2012). The relationships among these variables are very complicated, and their importance can shift with the environment conditions. In water-limited area, water availability greatly determines the water loss of ET. In arid areas where the ecosystem frequently suffers from the drought and high-temperature stress, water loss can be reduced by regulation of stomata. In the present study, diurnal ET variation showed a 'U'-shaped curve in the dry seasons with two peaks before and after noon when the strongest radiation and highest temperatures occurred. This is consistent with different previous measurements in the Shapotou area that indicated that stomatal conductance of *C. korshinskii* and *A. ordosica* also displayed a two-peak diurnal pattern and the peaks of stomatal conductance measured at 9:00 and 16:00 were 2.8 and $1.8\,\mathrm{cm\,s^{-1}}$ of *C. korshinskii* and 4.0 and $2.8\,\mathrm{cm\,s^{-1}}$ of *A. ordosica*, respectively (Zhang *et al*., 1998). That led to lower ET values at noon on a dry and sunny day.

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