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Biophysical controls on canopy transpiration in a black locust (*Robinia pseudoacacia*) plantation on the semi-arid Loess Plateau, China

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ABSTRACT

In the semi-arid Loess Plateau of China, black locust (*Robinia pseudoacacia*) was widely planted for soil conservation and afforestation purposes during the past three decades. Investigating biophysical controls on canopy transpiration (E_c) of the plantations is essential to understanding the effects of afforestation on watershed hydrology and regional water resources. In addition to monitoring of micrometeorology and soil water content, sap flux densities (F_d) of six representative trees in a 27-year stand were continuously measured using thermal dissipation probes during the growing seasons in 2013 and 2014. E_c was derived by multiplying stand total sapwood area (A_{ST}) with F_d. The daily mean E_c in the growing season was 0.14 and 0.23 mm day^{-1} in 2013 and 2014, respectively. The responses of daily E_c to R_s and vapour pressure deficit were explained with an exponential threshold model. The variability of monthly E_c was mainly explained by leaf area index (LAI) ($R^2 = 0.92$). The inter-annual variability of E_c was influenced by LAI that fluctuated dramatically during 2013 and 2014. We found that the status of soil water content at the beginning of the growing season had large impacts on LAI and E_c during the growing season. Contrary to common beliefs that the plantation uses a large amount of water, we found that the black locust plantation had rather low transpiration rates (5.3% of precipitation and 4.6% of ET_0). This study suggests that the black locust plantation has adapted to local soil water condition by reducing transpiration, and the major water loss from the plantation was not transpiration.

KEY WORDS sap flow; thermal dissipation probes; soil water budget; leaf area index; ET_0; afforestation

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INTRODUCTION

Transpiration is a physiological process that water diffuses from the plant tissue to the air through the plant stomata (Wullschleger *et al.*, 1998). It is considered as a main process in terrestrial ecosystem water cycling (Sun *et al.*, 2011; Schlesinger and Jasechko, 2014). Quantifying vegetation water use is important for understanding the interactions between afforestation-based ecological restoration and regional water resource (Wei and Sun, 2009).

Meteorological factors and soil water conditions exert strongly influences on canopy transpiration (E_c) (Oren *et al.*, 1996; Lundblad and Lindroth, 2002; Zeppel *et al.*, 2006; Small and McConnell, 2008; MacKay *et al.*, 2012), and this may affect ecosystem productivity by constraining plant photosynthesis. Stomatal responses to solar radiation (R_s) and vapour pressure deficit (VPD) are two key factors in terms of the trade-off between maximizing photosynthesis and minimizing transpiration (Granier *et al.*, 1996; Katul *et al.*, 2010; Ghimire *et al.*, 2014). The relationship between E_c and soil water condition was widely studied in various climatic regions (Oren *et al.*, 1996; Oren and Pataki, 2001; Bernier *et al.*, 2006; Manzoni *et al.*, 2011; Chang *et al.*, 2014a). However, inconsistent results have been reported. Some studies find that E_c was correlated with soil water content (SWC) in a polynomial or logistic fashion (Zhao and Liu, 2010; Chang *et al.*, 2014a). The studies that based on global eddy covariance measurements suggest that SWC or precipitation is not a good predictor for seasonal evapotranspiration (ET), especially for forests because of deeper roots access to deep soil water and major controls

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on ET from canopy structure and energy availability (Sun *et al.*, 2011; Fang *et al.*, 2015). Impacts of soil water condition on plants transpiration are complex, especially for the plants with deep roots (Li *et al.*, 2002; Kume *et al.*, 2007). Some studies suggest that clearer relationships between E_c and SWC can only be developed by separating the SWC regime such as separating the dry season and the wet season in analysis (David *et al.*, 2007; Kelley *et al.*, 2007; Brito *et al.*, 2015). Droughts that occur before and in the early growing season have strong effects on E_c by influencing vegetation development and growth (Noormets *et al.*, 2008; Limousin *et al.*, 2009; Dong *et al.*, 2011; MacKay *et al.*, 2012). How the SWC in pregrowing or initial growing season impacting on E_c was not clear, and there was no consistent conclusion.

For the semi-arid Loess Plateau, a series of revegetation projects have been implemented to control soil erosion since the late 1990s, during which large areas of farmlands on hillslope were converted to forest and grassland. Soil water is the main source of water for plant growth and has been regarded as one of the most limiting factor for the success of revegetation in this region. Black locust (*Robinia pseudoacacia*), an exotic species, was widely planted because it is a drought-tolerant and fast-growing species (Wang *et al.*, 2010b). Reforestation had positive effects on reducing soil erosion, increasing carbon sequestration and soil nutrient improvement (Feng *et al.*, 2013; Jiao *et al.*, 2013). A previous study showed that black locust is a species that can adapt in a prolonged water-stressed environment by reducing water loss through reducing both transpiration and leaf area (Mantovani *et al.*, 2014). Additionally, some debates arose on the hydrological effects of the plantations in the semi-arid Loess Plateau. For example, water yield was dramatically reduced as a result of large area afforestation in this region (Sun *et al.*, 2006). Some studies showed that the plantations excessively used soil water leading to soil desiccation, and the plantations usually degraded in early ages because of long-term water stress, which are obstacles to water cycling and sustainability of afforestation (Wang *et al.*, 2004a; Shangguan, 2007; Chen *et al.*, 2008). However, most of the previous studies are based on the observations of soil water changes; studies on the direct tree water use are lacking. Few existed studies only focused on the effects of climate factors on E_c (Chen *et al.*, 2014; Zhang *et al.*, 2015), the role of soil moisture in mediating E_c responses, and conversely, the potential effect of E_c on stand water balance was not clear, which are essential to understanding the effects of afforestation on watershed hydrology and regional water resources.

Therefore, sap flow, soil water condition and micrometeorology were simultaneously measured in a 27-year-old black locust plantation in the Yangjuangou catchment in the central of Loess Plateau. The objectives of this study were to (1) quantify the E_c of a 27-year-old black locust plantation in two continuous growing seasons; (2) examine the temporal dynamics of E_c at different time scales, i.e. daily, monthly and annual, and explore the mechanisms of dynamic water flux of the plantation; (3) evaluate proportion of E_c in precipitation and the potential influence of the tree transpiration on the stand water cycling in black locust plantation from the point of water balance.

MATERIALS AND METHODS

Research site characteristics

The study was carried out in the Yangjuangou catchment (36°42′N, 109°31′E), located in Yan'an city of Shaanxi province, China. The area of the catchment is 2.02 km^2 and the elevation ranges from 1050 to 1298 m. The gully density is 2.74 km km^{-2}. This region is a typical gully and hilly landscape in the Loess Plateau, which is notorious for soil erosion due to intensive vegetation destruction and cultivation. Black locust plantations were widely distributed in this catchment as a result of afforestation campaigns in the past 30 years.

The growing season is approximately from May to September for most deciduous plants. The mean annual air temperature is 9.8 (±0.8) °C and mean annual precipitation is 531.0 (±114.6) mm (from 1952 to 2012). The average precipitation in the growing season is 422 (±103) mm, accounted for 79% of annual precipitation. Because of more precipitation than other months, the period from July to September (accounting for 58.8% of annual precipitation) is defined as the rainy season. Therefore, we have further separated the growing season into pre-rainy season (May and June) and rainy season (July to September). The soil is derived mainly from loess, and the soil depth is approximately 50 ~ 200 m in the study area.

A 27-year-old black locust plantation plot was installed on a south slope in the Yangjuangou catchment (Table I). The plot was at middle slope position, and the slope floor was flat. Therefore, we assumed that there is no influence of micro topography on the plantation. The plot was selected for the reason that the plantation was planted in abandoned farmland and little disturbed by human activities. The age of the plantation was estimated based on the tree core rings sampled around the plot. The plot area is 10 × 10 m^2. The tree density was 1300 trees/ha. Understory vegetation consisted of a mosaic of patches of liana (*Periploca sepium*) and herb (*Artemisia sacrorum*). There is no shrub vegetation on the plantation floor.

Table I. Characteristics of the study plot for sap flow measurements.

Characteristics	South plot
Slope	25°
Elevation (m)	1179
Density (trees/ha)	1300
Overstory tree species	*Robinia pseudoacacia*
Overstory cover (%)	85
Average DBH (cm)	9.9 ± 4.2 (2013) 10.8 ± 4.3 (2014)
Average height (m)	7.4 ± 2.0 (2013) 8.8 ± 2.4 (2014)
Sapwood area (cm^2)	315.9 (2013) 359.5 (2014)
Understory species	*Artemisia sacrorum* and *Periploca sepium*
Understory cover (%)	35
Understory average height (m)	0.3
Bulk density (g cm^{-2}) 0–40 cm	1.2
Soil clay (%) 1–100 cm	3.6
Soil silt (%) 1–100 cm	66.8
Soil sand (%) 1–100 cm	29.3

DBH, diameter at breast height.

Micrometeorology and soil water content measurements

Micrometeorological variables were simultaneously monitored with sap flow measurements in the growing seasons of 2013 and 2014. Solar radiation (R_s, W m^{-2}) was measured by using a pyranometer (Li-200, Li-Cor, Lincoln, NE, USA), which measured 400 to 1100 nm wavelengths and was installed 2 m above ground in the open field adjacent to the plot. Air temperature (T_a, °C) and relative humidity (RH, %) were monitored by an HMP35C probe (Vaisala Co., Helsinki, Finland), which was installed 2 m above ground in the center of the plot. These data were sampled every 30 s and the averaged value of every 30 min were recorded on a CR10XTD data logger (Campbell Scientific, Logan, UT, USA). VPD (kPa) was calculated with T_a and RH data (Campbell and Norman, 1998). The volumetric soil water content (SWC, m^3 m^{-3}) was measured at 10, 20, 40, 60, 100, 120, 150 and 180 cm depths below the ground surface using EC-5 sensors (Decagon Devices Inc., Pullman, WA, USA). Data were recorded with a HOBO logger (H21, Onset Computer Corp., Bourne, MA, USA) at 30 min interval. Precipitation (P, mm) was measured using a tipping bucket rain gauge (TE525), and wind speed and wind direction were measured using a 03001 Wind Sentry set (Campbell Scientific, Logan, UT, USA), connecting to a weather station (Dynamax Inc., Houston, USA), which was about 500 m from the study plot.

The grass reference ET (ET_0, mm) that characterizes local meteorological and evaporative conditions was estimated by means of the FAO Penman–Monteith equation using the ET_0 Calculator software (http://www.fao.org/nr/water/eto.html) (Allen *et al.*, 1998). Data of T_a, RH, wind speed and sunshine hours were the required input parameters. Previous study estimated ET_0 used the software in Loess Plateau (Zhang *et al.*, 2013).

Sap flow measurements

E_c may be estimated by many methods such as scaling up measurements from large tree potometers (Olbrich, 1991), ventilated chambers (Denmead *et al.*, 1993), using more complex model parameterized by leaf scale physiological traits and three-dimensional tree architecture (Kumagai *et al.*, 2014) or sap flux density at given xylem depths (Granier, 1987; Granier *et al.*, 1996). We used sap flow technique as it has the advantage of not limiting by landform heterogeneity (Granier, 1987; Granier *et al.*, 1996; Kumagai *et al.*, 2008), and thus a suitable method in the study region (Wang *et al.*, 2010b; Du *et al.*, 2011; Chen *et al.*, 2014; Zhang *et al.*, 2015).

According to the distribution frequency of diameter at breast height (DBH) in the plot, six trees were selected for sap flow measurements. Sap flux density (F_d) was measured using the Granier-type thermal dissipation probes. A thermal dissipation probes sensor consists of a pair of probes with 10 mm long and 1.2 mm in diameter, a heated needle above and a reference needle below. The upper probe includes a heater, which was supplied with 0.15 W constant power. A copper–constantan thermocouple junction was enclosed in each probe. The thermocouple junction was located at 5 mm depth in the probe. After removal of the bark outside the sapwood, the sensor was inserted into the sapwood area vertically 40 mm apart at breast height. The temperature difference between the upper heated probe and the lower reference probe was measured every 30 s and recorded the averaged value every 30 min on a CR10XTD data logger (Campbell Scientific Inc., Logan, UT, USA). The sensors were installed in the north orientation of the stem. To prevent rainfall or water running down from the stem and touching the sensors, plastic putty was installed around the probes. To prevent the solar heating, reflective bubbles were wrapped the tree where the measurement was taken.

F_d (g m^{-2} s^{-1}) was calculated with the empirical model based on temperature difference between the two probes according to Granier (1987) as following:

$$F_d = 119\left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231} \quad (1)$$

where ΔT is the temperature difference between the upper heated probe and the lower reference probe and

ΔT_m is the maximum value of ΔT when F_d is zero at nighttime (Lu *et al.*, 2004).

If the sapwood thickness (T_s, cm) was smaller than probe length, F_d should be underestimated because of a portion of the probe was inserted into the nonconductive xylem. Calibration was conducted according to the following method (Clearwater *et al.*, 1999):

$$\Delta T_{sw} = \frac{\Delta T - b\Delta T_m}{a} \tag{2}$$

where a is the proportion of probe in sapwood, b is the proportion of probe in inactive xylem ($b = 1 - a$) and ΔT_{sw} is the temperature difference in sapwood. In formula 3, ΔT was replaced by ΔT_{sw}.

T_s of sampled trees was determined by regressions of bark thickness (T_b, cm) and sapwood area (A_s, cm^2) data on DBH (Zhang *et al.*, 2015). T_b of sampled tress was calculated with a linear regression between T_b and DBH. A_s of sampled trees was calculated by a power regression between A_s and DBH (Vertessy *et al.*, 1995). We found similar relationships between T_b and DBH and A_s and DBH in this study. The regression formulas were $T_b = 0.30 + 0.05 \times \text{DBH}$ ($R^2 = 0.74$, $n = 22$) and $A_s = 0.61 \times \text{DBH}^{1.55}$ ($R^2 = 0.94$, $n = 22$).

T_b and A_s were estimated based on tree core samples from 22 trees adjacent to the study plot. Samples were taken at DBH using an increment core borer. The tree DBH was measured at the beginning of each growing season in 2013 and 2014. T_b and A_s of all trees in the study plot were estimated based on the regression models. The total sapwood area of the stand (A_{ST}) was 315.85 cm^2 in 2013 and 359.48 cm^2 in 2014, respectively.

Estimation of E_c from sap flow measurements

E_c (mm day^{-1}) was calculated with the following formula:

$$E_c = \frac{J_s A_{ST}}{A_G} \tag{3}$$

where J$_s$ (kg m^{-2} day^{-1}) is stand sapflux density, A_{ST} is total sapwood area in study plot and A_G is the ground area.

J_s is calculated with the following formula:

$$J_s = \frac{\sum F_{di} A_{si}}{A_{ST}} \tag{4}$$

where F_{di} is the mean F_d of the ith DBH class and A_{si} is the total sapwood area of ith DBH class.

A_{ST} is calculated with the following formula:

$$A_{ST} = \sum A_{si} \tag{5}$$

where A_{si} is the total sapwood of trees in ith DBH class.

Estimation of E_c from leaf gas exchange measurements

To verify the estimates of E_c from sap flow methods, the gas exchange of an individual leaf was measured and scaled to E_c. The leaf transpiration rate (E_l) was measured with a portable infrared gas analyser system with a 2×3 cm^2 chamber (LI-6400, Li-Cor Inc., Lincoln, NE, USA) on three sunny days: 29 June, 30 August in 2013 and 14 July in 2014. Three sampled trees were selected and three leaves were measured in each tree. The sampled leaves were all at the middle position of the canopy in the south orientation, on the assumption that the leaf gas exchange traits at the measured position approximated the whole canopy. Measurements were conducted every hour from 6:00 in the morning to 18:00 in the afternoon.

E$_{c\text{-}l}$ (mm h^{-1}) was computed as a product of transpiration rate of individual leaves and leaf area:

$$E_{c\text{-}l} = LAI \times A_G \times \sum E_{li} \tag{6}$$

where LAI is leaf area index at the measurement period, A_G is the ground area of stand and E_{li} is leaf transpiration rate at i hour (kg m^{-2}ground area h^{-1}).

Overstory leaf area index

Overstory leaf area index was measured using a plant canopy analyser (LAI-2000, Li-Cor, Lincoln, NE, USA) twice a month at 10 or 15 days intervals from June to September in 2013 and from May to September in 2014. The measurement was taken at 1.3 m height above ground (not including understory layer). on cloudy days or at dusk. Each measurement represents the average of three samples on each date.

Stand water balance

The water balance for a stand and watershed during a long-term period (monthly or annual) can be described as

$$P = ET + Q + \Delta S \tag{7}$$

where, P, ET, Q and ΔS are precipitation, evapotranspiration, runoff and change of soil water storage (Sun *et al.*, 2006). Monthly ΔS (mm) in 0–180 cm profile was calculated according to initial and final SWC of each growing season (Wang *et al.*, 2012). ET and its components can be expressed as

$$ET = E_i + E_c + E_s \tag{8}$$

where E_i is canopy interception, E_c is canopy transpiration and E_s is soil evaporation (Sun *et al.*, 2014).

E_i was approximately estimated by the Gash analytical model (Gash, 1979). The model can be expressed as

$$E_{\mathrm{i}} = n(1 - \mathrm{p} - \mathrm{p_t})\mathrm{P}'_{\mathrm{G}} + \frac{\overline{E}}{R}\sum_{j=1}^{n}\left(P_{\mathrm{Gj}} - P'_{\mathrm{G}}\right) + (1 - p - p_{\mathrm{t}})\sum_{j=1}^{m}P_{\mathrm{Gj}} + qS_{\mathrm{t}} + p_{\mathrm{t}}\sum_{j=1}^{m+n-q}P_{\mathrm{Gj}} \tag{9}$$

where n is the numbers of the rainfalls that saturate the canopy; m is the numbers of rainfalls that would not saturate the canopy; q is the numbers of rainfalls that saturate the trunk; $\underline{p}$ is free throughfall coefficient; p_t is proportion of rain diverted to stemflow; $\bar{E}$ mean rate of evaporation from a saturated canopy (mm h^{-1}); $\overline{R}$ is mean rainfall rate (mm h^{-1}); S_t is trunk storage capacity (mm); P'_G is amount of rainfall to saturate the canopy (mm); and P_{Gj} is gross rainfall on the canopy (mm).

The parameter in the aforementioned model determined by Wang *et al.* (2013) was used in this study. Their study site was located in the Yangou catchment, nearly 30 km distance from our study site, under similar climatic condition. Additionally, the characteristics of their experimental plot were similar to those in this study, with 27 years old, 6.9 m mean height, 10.2 cm mean DBH and 900 trees/ha. During the growing seasons in 2013 and 2014, 53 and 55 individual rainfalls were recorded, respectively.

In this study, only the components of P, ΔS, E_c, E_i and ET_0 were quantified. We aimed to get a basic understanding of the role of trees in the stand water cycling but not to close the water balance.

Statistical analyses

T-test was performed to examine whether the micrometeorological factors were different between the two growing seasons.

To analyse the responses of E_c to VPD and R_s at daily scale, an exponential threshold model was used (Ewers *et al.*, 2002):

$$E_{\mathrm{c}} = a\left(1 - e^{-bx}\right) \tag{10}$$

where a and b are fitting parameters, E_c is daily canopy transpiration (mm day^{-1}) and x is corresponding meteorological variables.

Stepwise regression analysis was used to examine the main factors controlling E_c at monthly scales (the independent variables included ET_0, R_s, VPD, RH, T_a, SWC and LAI), respectively. A combination of forward and backward selections was used in the regression. All statistical analyses were performed with SPSS 16.0 software package (SPSS Inc., Chicago, IL, USA).

RESULTS

Micrometeorology

Mean daily R_s was not significantly different between the two growing seasons ($p > 0.05$) and showed similar seasonal trends (Figure 1). Mean R_s in the entire growing season was 160 W m^{-2} in 2013 and 179 W m^{-2} in 2014, respectively. Daily R_s showed a declining trend from May to September. Maximum monthly R_s was recorded in May and the minimum value in September. Daily daytime VPD in the growing season of 2013 was significantly higher than that in 2014 ($p < 0.01$), being 1.07 kPa in 2013 and 0.84 kPa in 2014, respectively. Maximum monthly daytime VPD was observed in May in 2013 and in June in 2014. Mean daily T_a between the two growing season was similar ($p > 0.05$). The highest daily T_a was recorded at the end of June in 2013 and at the end of July in 2014. Decrease of R_s, VPD and T_a in the rainy season was probably related to increasing cloudy and rainy days in this time period.

The growing season P was 624 mm in 2013 and 444 mm in 2014, indicating that 2013 was a wet year and 2014 was a normal year in compared with the long-term mean. A total of 413 mm of rainfall occurred in July 2013 from

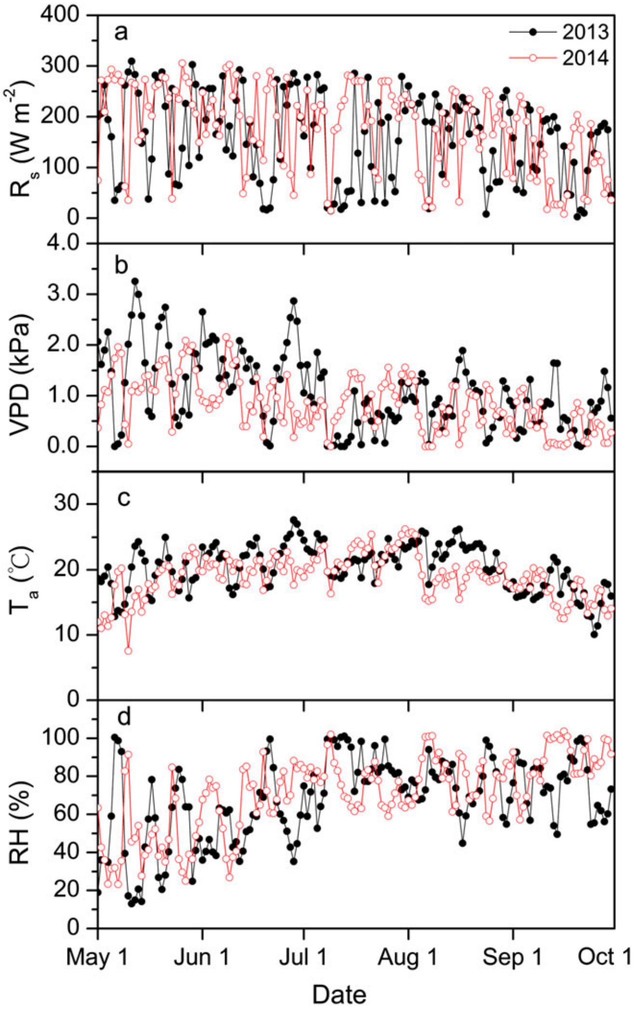

Figure 1. Variations in (a) daily solar radiation (R_s), (b) mean daytime vapor pressure deficit (VPD), (c) mean air temperature (T_a) and (d) mean relative humidity (RH) of the study plot during the growing seasons in 2013 and 2014.

several extreme rainfall events. Overall, the mean SWC of 0–180 cm in 2013 was higher than that in 2014 ($p < 0.01$). However, it was noted that SWC at the beginning of the growing season in 2014 was higher than that in 2013 ($p < 0.01$), with a mean value of 0.14 $m^3 m^{-3}$ and 0.09 $m^3 m^{-3}$, respectively (Figure 2). The SWC profile (10 to 180 cm depth) varied dramatically over time in the two growing seasons as a result of periodical rainfalls and water loss through ET and soil moisture redistribution within the soils (Figure 3).

Temporal dynamics of E_c and the impacting factors

The daily E_c ranged from 0.03 to 0.23 mm day^{-1} in 2013 and from 0.04 to 0.45 mm day^{-1} in 2014. The E_c rates peaked in pre-rainy season, in 29 May 2013 and in 26 June 2014. The dynamic patterns of daily E_c were similar in both growing seasons in 2013 and 2014 (Figure 2). At the monthly scale, the maximum E_c occurred in May in 2013 (5.4 mm $month^{-1}$) and June in 2014 (9.0 mm $month^{-1}$). Monthly E_c tended to decrease from July to September (Figure 2). Lowest monthly E_c was 2.55 and 4.25 mm $month^{-1}$ in September 2013 and 2014, respectively (Table II). At the annual scale, the mean daily E_c of the growing season was 0.14 mm day^{-1} in 2013 and 0.23 mm day^{-1} in 2014. Overall, cumulative E_c in the plantation during the growing season was 21 mm in 2013 and 36 mm in 2014.

Daily E_c increased sharply with R_s and VPD and tended to level off at higher values of R_s and VPD in both growing seasons. Including R_s and VPD as the independent variables, the exponential threshold models for daily E_c were as follows (Figure 4):

2013:

$$E_c = 0.18 \times \left(1 - e^{-0.01 \times R_s}\right),\ R^2 = 0.60,\ P < 0.001 \quad (11)$$

$$E_c = 0.19 \times \left(1 - e^{-1.73 \times VPD}\right),\ R^2 = 0.58,\ P < 0.001 \quad (12)$$

2014:

$$E_c = 0.29 \times \left(1 - e^{-0.01 \times R_s}\right),\ R^2 = 0.45,\ P < 0.001 \quad (13)$$

$$E_c = 0.27 \times \left(1 - e^{-4.01 \times VPD}\right),\ R^2 = 0.40,\ P < 0.001 \quad (14)$$

In both growing seasons, R_s explained more variability of daily E_c than *VPD*.

Overall, LAI in 2014 was much higher than that in 2013 (Figure 5), although the seasonal trends were similar. Stepwise regression analysis of monthly E_c resulted in a

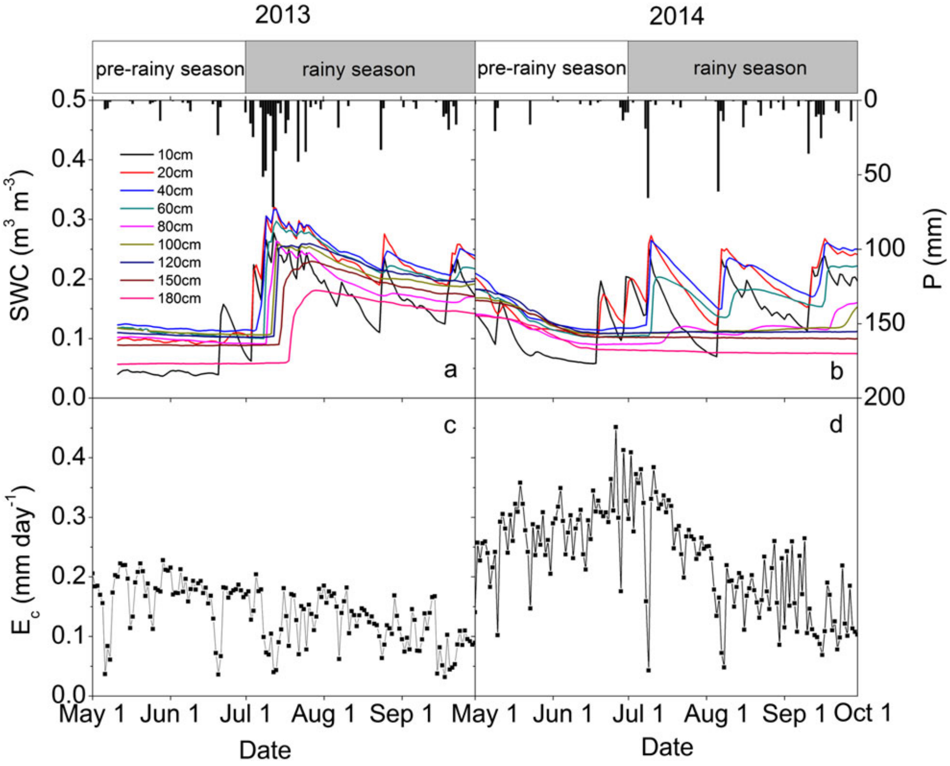

Figure 2. Daily canopy transpiration (E_c), precipitation (P) and volumetric soil water content (SWC) in 0–180 cm depth in study plot during 2013 and 2014 growing seasons. The growing season was separated into pre-rainy season and rainy season.

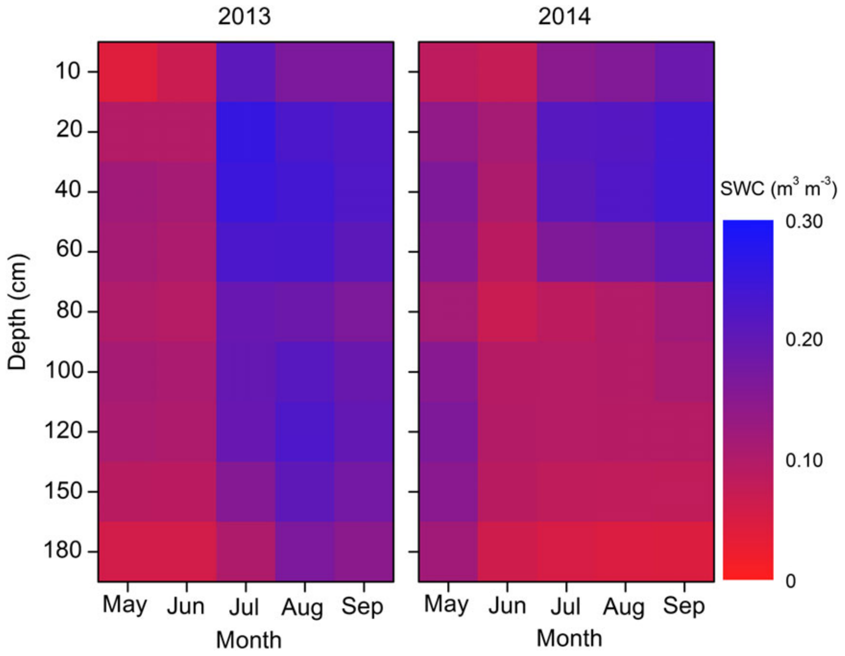

Figure 3. Vertical distribution and monthly variations in soil water content (SWC) in the 0–180 cm profile during growing seasons in 2013 and 2014.

Table II. Monthly canopy transpiration (E_c), change in soil water storage in the 0–180 profile (ΔS), precipitation (P), E_c/P ratio, E_c/ET_0 ratio during May to September in 2013 and 2014.

Month	E_c (mm)	ΔS[a] (mm)	E_i (mm)	P (mm)	E_c/P (%)	E_i/P (%)	ET_0 (mm)	E_c/ET_0 (%)
May	5.4(4.1[c])	−4.3[b]		33.8	15.6		137.7	3.8
Jun	5.0	4.7		42.2	11.8		148.8	3.3
Jul	4.0	230.9		412.5	1.0		128.8	3.1
Aug	4.1	−60.5		62.2	6.6		127.8	3.2
Sep	2.8	−8.3		73.4	3.5		80.0	3.2
Growing season	21.3	162.5	65.7	624.1	3.4	10.5	623.1	3.4
May	7.9	−95.8		44.7	17.9		132.2	6.1
Jun	9.0	11.0		36.6	24.7		139.3	6.3
Jul	8.9	−1.2		106.5	8.4		140.7	6.5
Aug	5.5	25.8		122.7	4.4		114.5	4.7
Sep	4.3	56.1		133.9	2.7		77.78	4.7
Growing season	35.6	−4.1	50.9	444.4	8.0	11.5	604.48	5.9

[a] Negative ΔS value represents soil water loss and positive ΔS value represents soil water recharge.
[b] Data for 11 to 31 May.
[c] Data for 11 to 31 May.

model with LAI as the only variable determining E_c. The regression was (Figure 6)

$$E_c = -4.4 + 4.5 \times LAI, R^2 = 0.92 \qquad (15)$$

During the two continuous growing seasons, LAI was positive correlated with monthly E_c. Most of the variability of monthly E_c was explained by LAI.

E_c *and the stand water budget*

E_c of the black locust plantation was a small proportion in the stand water budget. Monthly E_c/P ratio was rather low in both growing seasons. However, monthly E_c/P ratio in pre-rainy season was significantly higher than that in rainy season. The maximum ratio was 16% in May 2013 and 25% in June 2014. Total E_i in growing season was 65.7 mm in 2013 and 50.9 mm in 2014, accounting for 10.5% and 11.5% of P, respectively (Table II). ΔS varied dramatically by month because of the dynamics of soil water recharge from rainfall and water loss from E_c and E_s. It was noted that E_c was similar to the change in ΔS during the period without rainfall from 11 May to 31 May in 2013. E_c/ET_0 ratios in different months were similar during the growing season in 2013, ranging from 3.10% to 3.90%. However, the ratio ranged from 3.78% to 6.48% in 2014.

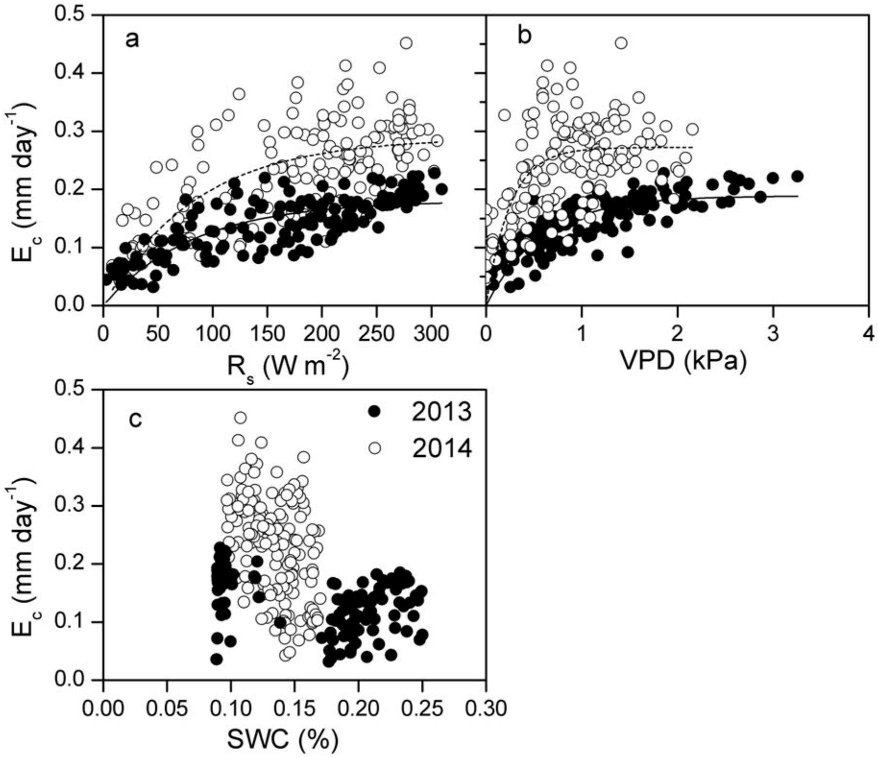

Figure 4. Relationships between daily E_c and (a) daily solar radiation (R_s), (b) daily daytime vapor pressure deficit (VPD), (c) daily soil water content (SWC) during growing seasons in 2013 and 2014.

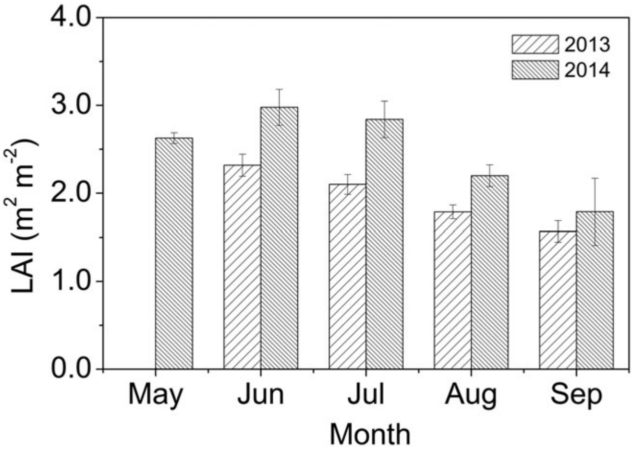

Figure 5. Variation in monthly leaf area index (LAI) of the black locust plantation during growing seasons in 2013 and 2014. Error bars represent standard deviations.

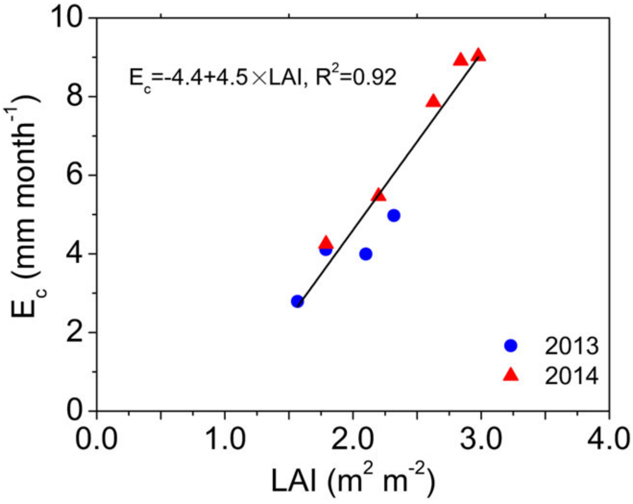

Figure 6. Relation between monthly leaf area index(LAI) and E_c in two growing seasons.

DISCUSSION

Comparing E_c estimated by the thermal dissipation probes method and porometers

To test the magnitude of E_c estimated by sap flow method in this study, we conducted gas exchange measurements with a porometer on individual leaves. There are many uncertainties in scaling such measurements to the canopy scale (Jarvis and Mcnaughton, 1986), as both leaf characteristics and environmental conditions, such as light and temperature, have high spatial variability within a canopy (Kupper *et al*., 2006). The leaf E_c value could be overestimated as the measurements were taken only on the leaves facing south (Figure 7). On the other hand, E_c values could be underestimated because of radial variations in F_d, which introduced 33 ~ 44% error in estimating E_c in black locust plantation (Kume *et al*., 2012). Although the leaf E_c

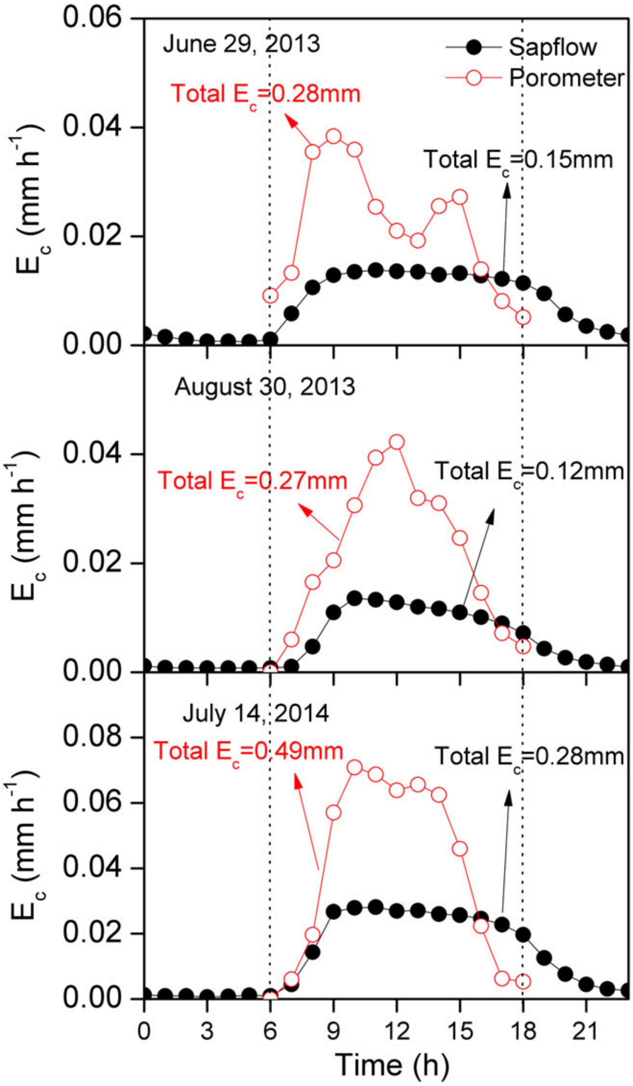

Figure 7. A comparison of E_c estimated by the sapflow method and by leaf gas exchange method. Cumulative E_c was also showed.

and sapflow measurements approximately represented canopy E_c because of methodological limitations, they verified the general magnitude of canopy E_c.

Low E_c

The E_c rates in our study were rather low compared with the means of temperate forests (Fang *et al.*, 2015), but the values were comparable with the findings from other studies in the semi-arid area of the Loess Plateau (Table III). There are at least four possible reasons for the low E_c. Firstly, the relatively lower E_c value in our study may be due to the lower tree density and A_{ST} as the values of F_d were in similar ranges compared with other plantations, including black locust and other studies (e.g. oak and eucalyptus) (Wang *et al.*, 2010b). The daily mean and peak J_s in each month were showed in Table IV. Secondly, plants may have undergone structural and developmental changes to adapt to long-term water stress in the study area (Shan *et al.*, 2003; Wang *et al.*, 2004b; Wang *et al.*, 2010b). A study showed that black locust can survive under prolonged water stress by reducing water loss through reducing both transpiration and leaf area (Mantovani *et al.*, 2014). In this study, reduction in LAI for 2013 could be related to drought at beginning of growing season. Larger LAI for 2014 was due to higher SWC at beginning of growing season. Thirdly, as found in some other studies, these trees may have strictly regulated their transpiration in response to short-term water stress during periods of high VPD and low soil moisture (Chen *et al.*, 2014). In this study, the trees transpired more water in June compared with other months and tapped water from deeper soil layer under higher VPD and lower SWC during same period. Furthermore, determination of total F_d in the sapwood by a single point measurement could be a large error for estimating tree and canopy transpiration due to radial variation in F_d in the sapwood (Nadezhdina *et al.*, 2002; Ford *et al.*, 2004). On one hand, radial variation in F_d in the trunk was widely observed in various forest tree, which were different among species (Delzon *et al.*, 2004; Cohen *et al.*, 2007; Kumagai *et al.*, 2007; Chang *et al.*, 2014a). For the black locust in Loess Plateau, F_d decreased from the outmost xylem to the inner xylem, and the F_d at the depth of >10 mm was almost zero, which was conducted in August because of ideal environmental conditions (i.e. sufficient soil water, appreciable diurnal variations in radiation, temperature and humidity) at that time (Kume *et al.*, 2012). Kume *et al.* (2012) also suggested that omitting radial variation in F_d could be 33~44% of the error for estimating E_c of the black locust plantations. On the other hand, the radial profile of F_d changed under varied soil water, VPD and radiation conditions, which correlated to changes of hydraulic conductivity in the trunk (Lu *et al.*, 2000; Nadezhdina *et al.*, 2002; Delzon *et al.*, 2004; Ford *et al.*, 2004; del Campo *et al.*, 2014). Taken together, the measurement at a point in 5 mm depth in the probe probably introduced a potential error for estimating total F_d in whole sapwood and upscaling E_c. Finally, circumferential variations in F_d in the stems from measurement of individual trees (Clearwater *et al.*, 1999; Lu *et al.*, 2000; Lu *et al.*, 2004; Kume *et al.*, 2012; Chang *et al.*, 2014a) and errors from the scaling process (i.e. classification in DBH distribution) can be sources of errors for E_c estimates. Sap flow measurement was conducted only in the north orientation in this study. Data was not available to indicate circumferential variations in F_d and to access the potential error for estimating E_c. However, Kume *et al.* (2012) suggested that omitting circumferential variation in F_d affected E_c estimate by 16~21% errors in the black locust plantation in Loess Plateau.

Table III. A comparison of *Robinia pseudoacacia* stand canopy transpiration (E_c) between this study and reported results measured with thermal dissipation probes method in the Loess Plateau, China.

Species	Study area	Location	Understory vegetation	MAT (°C)	MAP (mm)	Study period	LAI	Density (trees/ha)	A_s/A_G (m^2 ha^{-1})	E_c (mm day^{-1})	Source
Robinia pseudoacacia	Mt. Gonglushan, Yan'an	36°25′24″N 109°31′32″E	Grasses and a few scattered shrub	10.6	498	Apr 24 to Oct 21, 2008	0.96 ~ 2.89	3100	5.10	0.41	Wang *et al.* (2010b)
	Mt. Gonglushan, Yan'an	36°25′24″N 109° 31′32″E	Grasses and a few scattered shrub	10.6	498	April to October, 2008	0.96 ~ 2.89	3100	5.09	0.49	Zhang *et al.* (2015)
						April to October, 2009	0.98 ~ 2.73		5.13	0.33	
						April to October, 2010	1.42 ~ 3.14		5.35	0.32	
	Caijiachuan catchment, Ji County	36°14′27″ ~ 36°18′23″N 110°39′45″ ~ 110°47′45″ E		10.0	579	Jul 11 to Oct 19, 2008		850[a]	1.57	<0.2	Chen *et al.* (2014)
						Jun 25 to Oct 19, 2009				<0.2	
						Jun 11 to Oct 12, 2010				<0.2	
	Yangjuangou catchement, Yan'an	36°42′N, 109°31′E	Patches of liana (*Artemisia sacrorum*) and herb (*Periploca sepium*)	9.8	531	May 1 to Sep 30, 2013	1.57 ~ 2.32	1300	3.16	0.14	This study
						May 1 to Sep 30, 2014	1.79 ~ 2.98		3.59	0.23	

[a] The study plot is composed of *Pinus tabulaeformis* and *Robinia pseudoacacia*. The density of *Robinia pseudoacacia* is 850 trees/ha.
MAT, mean annual air temperature; MAP, mean annual precipitation.

Table IV. Monthly mean and peak stand sap flux density (J_s, kg m^{-2} day^{-1}) during May to September in 2013 and 2014.

Year	Month	Mean J_s (kg m^{-2} day^{-1})	Peak J_s (kg m^{-2} day^{-1})
2013	May	541.5 ± 154.1	728.0
	Jun	529.92 ± 128.4	688.0
	Jul	397.8 ± 141.0	652.2
	Aug	407.8 ± 141.0	591.4
	Sep	277.4 ± 99.9	464.7
2014	May	665.9 ± 140.7	978.9
	Jun	823.9 ± 160.0	1273.9
	Jul	801.3 ± 194.1	1166.2
	Aug	507.7 ± 146.0	732.1
	Sep	402.6 ± 160.9	735.0

Factors affecting on E_c

It is well known that at a given stand E_c is mainly controlled not only by climatic variables but also by the soil water available in the root zone (Granier *et al.*, 2000a, 2000b; Ewers *et al.*, 2002; Kumagai *et al.*, 2008; Ghimire *et al.*, 2014; Chang *et al.*, 2014b). Previous studies focused on relationships between E_c and the independent environmental factor, such as R_s and VPD, and threshold responses wer+e observed in individual tree and canopy transpiration to R_s and VPD (Granier *et al.*, 1996; Kumagai *et al.*, 2008; Ghimire *et al.*, 2014; Chang *et al.*, 2014b). Ewers *et al.* (2002) developed an exponential saturation to describe the threshold relationship between E_c and environmental factors, which was widely used to examine the regulation of environmental factors on E_c (Ewers *et al.*, 2007; Du *et al.*, 2011; Zhang *et al.*, 2015). For example, the model with VPD and R_s can explain 77 ~ 78% and 50 ~ 57% variations in daily stand transpiration rate in Japanese cedar forests, respectively (Kumagai *et al.*, 2008). Regulations of VPD on daily tree transpiration of different species in northern Wisconsin were moderately verified by the model (Ewers *et al.*, 2007). Ghimire *et al.* (2014) showed that E_c exhibited a threshold relationship with VPD and R_s in a natural broad-leaved forest and planted coniferous forest in the Lesser Himalaya of Central Nepal, with threshold values of 0.4 kPa for VPD and 200 W m^{-2} for R_s. In this study, daily E_c increased sharply with increasing VPD and a VPD threshold was showed, with approximately 1.5 in 2013 and 1.0 kPa in 2014. Similarly, E_c reasonably increased with increasing R_s and levelled off at a threshold value of around 250 W m^{-2} in both growing seasons. Ewers' model including R_s or VPD can explain the variability of daily E_c. R_s could explain 60% and 45% variability of E_c in 2013 and 2014, respectively, compared with VPD explaining 58% and 40% variability of E_c. However, a clear relationship between daily E_c and SWC was not found (Figure 4c). Some studies showed that plants have the ability to tap water from deeper soil layers in semi-arid environment (Li *et al.*, 2002; David *et al.*, 2007; Xu *et al.*, 2007). A likely reason for this is that black locust taps water from deeper soil layers, especially when top soil moisture is exhausted (Kumagai *et al.*, 2008; Brito *et al.*, 2015).

At the monthly scale, the stepwise regression analysis implied that the variations in LAI determined the magnitudes and patterns of E_c in this study. Some other studies also concluded that LAI was a major proxy to estimate ET or E_c at a monthly scale. Zhang *et al.* (2015) found that LAI was one of the major factors that tightly correlated with monthly E_c in the black locust plantation in Mt. Gonglushan, 30 km from our study site. Similarly, a study on oak forest by Xie *et al.* (2014) suggested LAI explained 78% of the monthly total ET measured by the eddy covariance method over a 7-year study period. The global syntheses by Sun *et al.* (2011) and Fang *et al.* (2015) also indicate that LAI is a major predictor of ET at the ecosystem level.

The relationship between E_c and SWC was analysed by separating the SWC regime as the pre-rainy season and rainy season. Contrary to June of the pre-rainy season, SWC significantly increased in July of the rainy season because of more P replenishing (Figure 3). However, E_c in July have not increased but declined compared with that in June (4.0 mm to 5.0 mm in 2013 and 8.9 mm to 9.0 mm in 2014). In the rainy season in 2014, SWC dramatically improved and exhibited an increased trend from July to September, while E_c declined from 8.9 to 4.3 mm month^{-1} (Table II). The transpiration rate in the pre-rainy season was higher than that in the rainy season, and monthly E_c peaked in June when the drought was exacerbated in both growing seasons (Figure 3). Additionally, although SWC and P in the whole growing season of 2013 were higher than in 2014, E_c in 2013 was lower in 2014 because of lower LAI in 2013 (Figure 5). Previous findings showed that SWC at the beginning of the growing season exerts a crucial influence on stand development (e.g. LAI and DBH increment) and consequently affected gas exchange of the ecosystem (Kwon *et al.*, 2008; Noormets *et al.*, 2008; Dong *et al.*, 2011). It is noted that SWC in May and June 2013 was significantly lower than that in same period of 2014.

LAI in 2013 was lower than that in 2014. It is implied that variation in LAI in the two growing seasons was possibly related to SWC at the beginning of growing season, resulting in variations in annual E_c in this study. Therefore, our 2-year study indicated that SWC mediated annual E_c by modifying LAI.

Implication for regional water resource and restoration management

In this study, E_c accounted for a small proportion in stand water balance during the two growing seasons (only 3.4% of P in 2013 and 8.0% of in 2014). Although we did not measure all the water budget components, a closer examination of the fluxes offered some insights of the relative magnitude of total water use by the plantations. For example, E_i and E_s possibly accounted for a larger proportion of ET in the black locust plantation according to the formula 8. A study showed that E_s was nearly twofolds to threefolds of E_c both in natural and irrigated black locust plantations in this region (Hou *et al.*, 2003). With SWC increased, more water would evaporate from the soil under similar climatic conditions (Zhang *et al.*, 2007). It is implied that the magnitude of E_s was larger than that of E_c. Moreover, E_i during the growing season estimated by the Gash analytical model was 65.7 mm in 2013 and 50.9 mm in 2014. Although the values are approximately estimated, it is suggested that E_i is higher than E_c in the black locust plantation. In June 2013, assuming no surface runoff occurred because of the low P and dry soil in this period, ET was estimated to be 32.5 mm according to formula 7. Therefore, E_c accounted for 15.4% of monthly ET in June 2013. For the wet periods in 2013, Q should be considered on the hillslopes to construct the water balance of the black locust plantation. For example, Q probably increased as a consequence of extreme rainfall events in July 2013. Relatively, a large amount of Q was observed in nearby experimental runoff plots covered with grass, shrub and orchard located in the Yangjuangou catchment.

Previous studies showed that soil desiccation in deep soil layers was developed and soil water scarcity was aggravated in vegetation rehabilitation areas, especially in black locust plantations (Wang *et al.*, 2010a; Wang *et al.*, 2011). It was generally believed that one of the possible reasons for soil desiccation was that artificial vegetation (i.e. black locust) consumed more water than native vegetation in semi-arid Loess Plateau (Wang *et al.*, 2004b; Chen *et al.*, 2008). Soil water excessive depletion resulted in potential negative impact on water resources and decreased tree growth (Wang *et al.*, 2004a, 2004b) Therefore, the sustainability of black locust plantations in this region was widely studied in recent years (Shan *et al.*, 2003; Wang *et al.*, 2004a; Jin *et al.*, 2011). Our finding indicated that the transpiration of the black locust plantation was remarkably lower than previously believed. We argue that the black locust plantation might have adapted to the local soil water condition in the semi-arid environment on the Loess Plateau.

E_c values estimated by sap flow could be moderately underestimated because of potential error in estimation in E_c due to radial variation in F_d across the sapwood area in this study. Nonetheless, E_c values estimated by sapflow could approximated represent general magnitude of E_c. A future study should take radial variation in F_d into consideration to derive the accurate E_c estimates.

We found considerable variability of water use at daily, seasonal and inter-annual scales in this 2-year study. It appears that soil water conditions at the beginning of the growing season had a great influence on tree development, leaf area and water use in the next few months. Future studies should further examine the linkages of non-growing season soil water conditions with tree growth in both previous and current years.

CONCLUSION

Black locust was widely planted for revegetation in the semi-arid Loess Plateau. In contrary to the wide perception that black locust plantations use a large amount of soil water, we found that E_c of the plantation was low and was not a major component of the stand water balance even though possible limitation of E_c estimates because of radial variations in F_d in sapwood area. A further study should investigate the full water budget of the plantation to offer useful information for managing the forest covers in the study region.

Our study also found that responses of daily E_c to R_s and VPD were well explained by an exponential saturation model. Whereas, LAI was the dominate factor controlling E_c at monthly and annual scales. Accurate LAI data (e.g. from monitoring and remote sensing products) are necessary to estimate accurate monthly E_c in this region. Variation in soil water at the beginning of growing season possibly induced variation in annual LAI, resulting in variation in annual E_c. The potential influences of soil water availability in pregrowing or initial growing season on E_c and vegetation development in the following growing season should be further studied in the future.

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