Analysis on Water use Efficiency of Populus Euphratica Forest Ecosystem in Arid Area

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1 **Analysis on water use efficiency of *Populus euphratica* forest** 2 **ecosystem in arid area**

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9 **Abstract**

10 Water use efficiency (WUE, the ratio of gross primary productivity (GPP) to
11 evapotranspiration (ET)) reflects the coupled relationship between water loss and
12 carbon gain in the process of plant photosynthetic carbon assimilation. As a dominant
13 tree species in arid area, *Populus euphratica* plays an important ecological role in
14 slowing desertification. Here, continuous observations of carbon, water and energy
15 fluxes were carried out in *Populus euphratica* forest with eddy covariance (EC)
16 technique in 2018. We systematically explained the variation characteristics of energy
17 fluxes and WUE at different time scales, and explored the main controlling factors of
18 WUE in drought-stressed environment based on the synchronous meteorological data.
19 Results showed that the carbon exchange of the *Populus euphratica* forest ecosystem
20 occurred mainly during the growing seasons (April–October). During this period, the
21 entire ecosystem appeared as a carbon sink with the potential to sequester atmospheric
22 carbon dioxide. The average daily WUE was 2.2 g C/kg H₂O, which was lower than
23 other temperate forests (2.57–6.07 g C/kg H₂O) but higher than grassland, wetland
24 and cropland. We also concluded that an increase in carbon dioxide concentration
25 (CCO₂) and air relative humidity (RH) could promote the increase of WUE.
26 Nevertheless, WUE was negatively correlated with air temperature (Ta),

photosynthetically active radiation (PAR), and normalized difference vegetation index (NDVI). Additionally, WUE increased under moderate soil water content (SWC), but decreased due to the continuously rising SWC. WUE was more strongly affected by factors affecting water consumption than carbon uptake. Under the conditions of high temperature, strong radiation and low humidity in the summer, the growth rate of ET was much larger than that of GPP. This study not only contributes to our understanding of the carbon, water and energy dynamics of the *Populus euphratica* forest ecosystem but also provides an important reference for ecological conservation and ecological restoration in arid regions.

Keywords

Populus euphratica forest ecosystem; Eddy covariance; Water use efficiency; Gross primary productivity; Net ecosystem productivity; Evapotranspiration

1. Introduction

As global warming intensifies, climate change and its impact on terrestrial ecosystems is receiving increasing attention. Carbon and water cycles are key processes for maintaining nutritional state and energy balance of ecosystems, which are more deeply affected by climate change (Seddon et al., 2016). The development and maturity of eddy covariance (EC) technique enables long-term and continuous measurement of carbon, water and energy exchanges between land and atmosphere (Amiro et al., 2006; Yu et al., 2006). The global FLUXNET is conducting continuous observations of the carbon, water and energy exchange processes of terrestrial ecosystems. But there are fewer EC sites for arid area than the southern wet area (Kim et al., 2013). While water is the principal limiting factor in arid area, controlling plant growth and vegetation succession. Better insight into the relationship between limited water resources and ecosystem water use efficiency (WUE) would enhance our understanding of plantation-ecosystem processes, services and feedbacks to the regional climate system (Tong et al., 2014).

54 In the terrestrial ecosystem, carbon and water cycles closely couple because they
55 both exchange between biosphere and atmosphere via the same pathway, namely the
56 stomata (Yu et al., 2008). Plant photosynthesis absorbs CO₂ along with water loss to
57 regulate the carbon-water balance between ecosystems and the atmosphere
58 (Mammarella et al., 2015). In the same sense, WUE reflects the magnitude of fixed
59 CO₂ when plants consume unit mass of water, and reveals the exchange law of CO₂
60 and water vapor fluxes in ecosystems and their coupling cyclic relationship (Hui et al.,
61 2001). WUE refers to the ratio of ecosystem carbon flux to water vapor flux. This
62 concept has been extensively used in agronomy, plant physiology and ecology since
63 its introduction (Jin et al., 2017). Initially, studies of WUE were confined to the leaf
64 physiological or individual levels, with the aim of breeding good crops or directing
65 field management (Keenan et al., 2013). Later, ecologists explored the mechanism of
66 biological invasion and plant adaptation strategies to the environment by studying the
67 WUE (Xu et al., 2004). In recent years, as global climate change issues become more
68 prominent, more perspectives have been directed to native ecosystems such as
69 grasslands and forests. Research scales have also risen to canopy, ecosystems and
70 landscape levels (Zhao et al., 2007). Many scholars have carried out a large number of
71 WUE researches, involving different spatial scales such as tissues, populations,
72 communities, and regions (Jassal et al., 2009; Skubel et al., 2015; Oquist et al., 2017;
73 Stephens et al., 2018). These studies serve to reveal the interactions of water-carbon
74 cycles, to predict impacts of global change on ecosystem functions (Jin et al., 2017).
75 In the context of climate change, the response of the carbon cycle and water cycle in
76 the arid region of China has attracted special attention (Ma et al., 2019). Some studies
77 have found that drought can reduce WUE (Brümmer et al., 2012; Zhang et al., 2014),
78 while others have found that it can increase WUE (Ponton et al., 2006; Linderson et
79 al., 2012). However, these studies still lack a scientific understanding of the
80 physiological mechanism of the seasonal change of ecosystem WUE during drought
81 period. Studies have shown that the duration of drought also has different effects on

WUE (Hui et al., 2001). This is because the impact of drought on ET is long-term, including vegetation growth season and subsequent non-growth season (Yu et al., 2008; Govind et al., 2011). Obviously, the ecosystem WUE in arid areas needs more in-depth research.

In arid region, *Populus euphratica* plays an important role in the ecological protection of arid regions, which can prevent wind and immobilize sand effectively (Chen et al., 2017). In the world, 54% of *Populus euphratica* is distributed in China. While in China, more than 90% of *Populus euphratica* resources are concentrated in Xinjiang. Currently, the research of carbon and water cycles on *Populus euphratica* forest ecosystem mainly focuses on biomass or a certain component of *Populus euphratica*, such as forest soil, plant body or leaf. In addition, the observation time is short and discontinuous. Therefore, the process and mechanism of carbon, water and energy exchanges cannot be seriously studied. Based on the aforementioned scholars' research, we used the CO₂ flux (Fc) to directly estimate the respiration, and solved the problem that the respiration is difficult to be measured. In addition, we compared WUE in the major types of ecosystems around the world. This is an important reference for analyzing whether a *Populus euphratica* ecosystem is carbon source or a carbon sink, and predicting the impact of global changes and human disturbances on forest carbon budgets.

This study took the *Populus euphratica* community in the lower reaches of the Tarim River as the research object. Continuous observation of CO₂, water and energy exchanges was carried out using EC technique. The main objectives were (1) to clarify the daily and seasonal variations of carbon, water and energy fluxes caused by diurnal cycles and seasonal changes, (2) to study the carbon exchange process and carbon source/sink changes, (3) to determine the change law of ecosystem WUE, and analyze the influence mechanism of environmental factors on WUE by combining hydrometeorological elements.

109 2. Methodology

110 2.1. Study site

111 The study site is located in Ruoqiang County (40°27'10.2"N, 87°54'02.9"E, 842m
112 above mean sea level, AMSL), Xinjiang, China. The EC station is located in the
113 *Populus euphratica* forest on the bank of the Tarim River (Fig. 1). The climate in this
114 region is temperate continental climate with annual precipitation between 27–58mm.
115 The annual potential evaporation amounts to 2671–2902mm. The temperature in
116 January and July is –14.9°C and 33.6°C, respectively. Annual sunshine hours are
117 3082.7–3121.3h (Wang and Guo, 2018). The water table is roughly between 2.8 and
118 4.5m. The soil is dominated by sand (0–100cm depth) and sandy loam soil
119 (100–200cm depth). The zonal vegetation in this area is temperate semi-arbor desert.
120 Due to the accumulation of river water and groundwater, the floodplain develops a
121 certain area of non-zonal meadow vegetation, forming arid riparian forest composed
122 of trees, shrubs and herbaceous plants. Trees and shrubs are distributed along the river,
123 and herbaceous plants are aggregated in the shrub community. Main dominant plants
124 are *Populus euphratica* (the only group of trees), *Tamarix*, *Karelinia caspica*,
125 *Halimodendron halodendron* and other shrubs. Average height of *Populus euphratica*
126 is 6–14m, and the average forest age is about 50a.

Fig. 1. Location of the study area and images of the observation instruments. (a) Geographical location of the study site (red triangle), (b) remote sensing image of the study site and (c) erection of experimental instruments.

2.2. Data collection and processing

Water vapor and CO₂ fluxes were measured at a height of 15 m above the ground surface by an eddy covariance (EC) system consisting of an open-path infrared gas analyzer (EC150) and a three-dimensional sonic anemometer (CSAT3). The EC system performed real-time monitoring for 24 h and automatically acquired raw data at a frequency of 10 Hz. It was further equipped with meteorological element monitoring sensors, including air temperature and humidity sensor (HMP155A), four-component radiometer (NR01), rain gauge (TE525MM), soil heat flux sensor (HFP01), photosynthetically active radiation sensor (LI190R) and soil moisture meter (SDI-12). The soil moisture meter (SDI-12) monitored the soil water content (SWC) at 20cm, 40cm and 60cm below the surface. We used SWC data at 20cm for calculation in this paper.

The datalogger (CR3000) collected horizontal wind speed (u , v), vertical wind speed (w), Supersonic temperature (T_s), H_2O concentration (q) and CO_2 concentration (CCO_2) at the sensor height. The final flux data, including CO_2 flux (F_c), net radiation (RN), latent heat flux (LE), sensible heat flux (H) and soil heat flux (G) were calculated and recorded by CR3000 at a frequency of 30 min. In the flux calculation process, double rotation, humidity correction and WPL density adjustment were performed (Foken et al., 2004). The stationary, integral turbulence characteristics of each 30 min flux data were calculated to filter out the periods of poor turbulent development (Zhao and Liu, 2018).

Due to the adverse weather, the flux data inevitably had outliers and missing values. Two methods were used to interpolate the missing and culled fluxes data: (1) Mean diurnal variation method for gaps less than 7 days: missing values can be replaced by the average of adjacent days in the same time. (2) Nonlinear regression method for gaps more than 7 days: the principle of this method is to establish a regression relationship between environmental factors and fluxes using observation data, and then use the regression function to estimate the missing data.

2.3. Energy balance closure

Energy balance closure is an indicator of flux data quality assessment (Meyers and Hollinger, 2004). Conventional methods for evaluating energy closure are: ordinary least squares (OLS) linear regression, reduced major axis (RMA) linear regression, energy balance ratio (EBR), and energy balance relative residual (Yang et al., 2018). Among them, the EBR is the most widely used method for analyzing the energy closure.

According to the first law of thermodynamics, the surface energy balance equation can be described by the following formula:

$$LE + H = RN - G - S - Q \quad (1)$$

where LE is the latent heat flux, H is the sensible heat flux, RN is the net radiation, G is the soil heat flux, S is the heat stored in the canopy, and Q is the sum of

additional energy source/sink. For bare land or ecosystems with low vegetation, the values of S and Q are usually small (Helbig et al., 2018). So, the energy balance equation can be simplified to:

$$LE + H = RN - G \quad (2)$$

In the above formula, left side of the equal sign is turbulent energy, and the right is available energy. When turbulent energy ($LE+H$) is equal to available energy ($RN-G$), it is called energy closure. This shows that the EC system can accurately observe the turbulent energy. Otherwise, the EC system overestimates or underestimates the turbulent energy. In this study, EBR was used to evaluate the energy closure condition, defined as:

$$EBR = \frac{\sum (LE + H)}{\sum (RN - G)} \quad (3)$$

2.4. Calculation of WUE

WUE (g C/kg H₂O) is the ratio of carbon flux to water vapor flux. That is, the ratio of the CO₂ fixation to the evapotranspiration (ET) in a certain period of time. We used the ratio of gross primary productivity (GPP) to ET to define ecosystem WUE, expressed as:

$$WUE = \frac{GPP}{ET} \quad (4)$$

GPP was calculated with the following formulas:

$$GPP = NEP + R_e = -NEE + R_e = -Fc + R_e \quad (5)$$

where NEP is net ecosystem productivity, which is equal to the negative value of the net ecosystem CO₂ exchange (NEE). CO₂ flux (Fc) measured by EC system is the net ecosystem CO₂ exchange; R_e is total respiration of the ecosystem.

R_e was calculated with the following formulas:

$$R_e = R_n + R_d \quad (6)$$

$$R_n = F_c(night) \quad (7)$$

$$R_e = R_{e,ref} \cdot \exp(B \cdot (T_a - T_{ref})) \quad (8)$$

196 where R_n is respiration at night. The net CO_2 exchange ($F_c(\text{night})$) can be
 197 considered as R_n of the ecosystem (Fei et al., 2018); R_d is respiration in daytime
 198 calculated by Vant's Hoff breathing equation (Eq. 9). Usually, fit the Vant's Hoff
 199 breathing equation by relationship between $F_c(\text{night})$ and air temperature (T_a). Then
 200 calculate R_d ; $R_{e,ref}$ is the respiration at the reference temperature, T_{ref} is the reference
 201 temperature and B is a constant. In this paper, $R_{e,ref}=0.73\text{umol}/(\text{m}^2\cdot\text{s})$, $T_{ref}=2.2^\circ\text{C}$,
 202 $B=0.044$. We found that the turbulence at night was weak, and the F_c data at 30min
 203 frequency was noisy. Therefore, we used the average value of F_c and T_a data at night
 204 to study the relationship between the two. As shown in Fig. 2, the correlation
 205 coefficient $R^2=0.61$.

206
 207 **Fig. 2.** The relationship between CO_2 flux at night ($F_c(\text{night})$) and air temperature (T_a). The downward shortwave
 208 radiation (DR) is used as an indicator to distinguish daytime and nighttime. It is generally considered that when
 209 $\text{DR}<1\text{W}/\text{m}^2$, the corresponding period is nighttime.

210 ET was calculated with the following formulas:

$$211 \quad ET = \frac{LE}{\lambda} \quad (9)$$

212 where LE is latent heat flux measured by EC system; λ is latent heat of vaporization
 213 with a fixed value of $2.454 \times 10^6 \text{W} \cdot \text{m}^{-2} \cdot \text{mm}^{-1}$.

3. Results

3.1. Dynamics of environmental factors

We used auxiliary sensors in EC system to measure the environmental factors. The changes of these environmental factors during the study period (2018.1.1–2018.12.31) were shown in Fig. 3. The seasonal variation characteristics of Ta (Fig. 3a), PAR (Fig. 3b) and SWC (Fig. 3c) were basically same, with the lowest in winter at -14.6°C , $95\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ and 6.7%, and the highest in summer at 34°C , $651\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ and 10.6%. PAR showed low values for a few days in July due to the effects of rainy days. The amount of soil water replenished by rainfall was expected to be very limited since precipitation in the study site was scarce. There were two reasons for the high SWC in summer. One was the incremental water from the upper reaches of the Tarim River. The second was ecological water supply (Xue et al., 2019).

Seasonal variation characteristics of CO_2 concentration (Fig. 3d) and RH (Fig. 3e) were similar, with the highest values of 326ppmv and 79% in winter and the lowest values of 271ppmv and 10% in summer. Photosynthesis was concentrated in summer, so the CO_2 concentration in the air was relatively low. Due to the high temperature in summer, the air in the study site was dry, which was contrary to the conclusion that RH was superior in the south of China. In general, the water resource in the arid region is limited and the actual evapotranspiration is small (Zhu et al., 2018).

Fig. 3. Seasonal variations in the daily mean environmental factors in 2018. (a) daily mean air temperature (T_a), (b) daily mean photosynthetically active radiation (PAR), (c) daily mean soil water content (SWC) at 20 cm, (d) daily mean CO_2 concentration, (e) daily mean air relative humidity (RH), (f) daily precipitation (P).

3.2. Evaluation results of EBR

The turbulent energy (LE+H) observed by the EC system usually cannot balance the available energy (RN-G). Wilson et al. (2002) analyzed the observation data from 22 stations in the Global Flux Network, indicating that 10%–30% fluxes unclosed in all stations. The energy fluxes obtained by the EC system were lower than that from the radiometer. Some scholars (Stoy et al., 2013) have therefore started to suspect CO_2 flux measurement result. The phenomenon of non-closing and its mechanism have also become a hot spot in the study of turbulent flux.

The half-hourly fluxes had mean EBR of 0.74 in this study (Fig. 4a), within the scope of international similar observations (0.55–0.99) (Wilson et al., 2002). Fig. 4b was an ordinary linear regression of turbulent energy and available energy. The

regression coefficient was 0.74, which was equal to the mean EBR. The EBR pattern presented a general decrease from 9:30 to 20:00 in every season (Fig. 4c). During the period of sufficient radiation (13:00–18:00), the EBR was very stable, close to 1.

However, compared with the available energy measured by the radiation system and the soil heat flux measuring instrument, LE and H were underestimated. This was primarily due to the weak turbulence at night. Moreover, the canopy heat storage term was not considered, and the source region of the EC system was different from the radiation observation system (Ding et al., 2010).

Fig. 4. (a) Daily mean EBR in 2018, (b) relationship between the turbulent flux (H+LE) and available energy (RN-G), (c) diurnal changes of EBR in different seasons. The EBR was not meaningful during the morning and evening transition periods when the mean value of RN-G is close to zero.

3.3. Seasonal and diurnal variations of energy fluxes

Fig. 5a showed the monthly variation of energy fluxes. RN, as the outward driving force of the soil-vegetation-atmosphere system, heats the atmospheric boundary layer mainly in the form of H and LE, and some energy in the form of G enters soil (Sánchez et al., 2009). The seasonal variation of LE, H and G was basically the same as

265 RN. After October, the air temperature decreased with RN. However, due to the
266 coverage of fallen leaves, the soil temperature did not decrease as rapidly as the air
267 temperature. The soil temperature was higher than the air temperature, indicating that
268 more heat stored in the soil, and the soil gradually released heat to the air. Since April,
269 with the rapid increase of RN, the heat stored in the soil became lower than that of air.
270 So, the atmosphere started to transmit heat to the soil. There were considerable
271 differences in seasonal variations of LE and H. LE was greater than H in
272 June–September and lower than H in other months. LE varied between 10–113 W/m²,
273 reaching its maximum in July and close to 10 W/m² in December, January and
274 February. LE characterizes the amount of surface ET, whose energy exchange is
275 linked to the phase transition of water. In summer, the temperature was high and the
276 ET was concentrated in the study area (Yan et al., 2006). There was a significant
277 seasonal variation in the ratio of every energy flux to RN, indicating that the
278 proportion of energy consumed by vegetation life activities increased during the
279 growing season, while the proportion of energy consumed in the physical
280 environment decreased (Chan et al., 2018).

281 From the perspective of diurnal variation in energy fluxes (Figs. 4b–e), each energy
282 flux showed a unimodal curve and peaked around 14:00. The positive and negative
283 changes in energy fluxes were linked to the sunrise and sunset. From January to
284 March, RN was positive within one day for 10.5h, with an average of 255W/m². From
285 April to June, RN was positive for 12.5h, with an average of 357W/m². From July to
286 September, RN was positive for 10h, with an average of 184W/m². From October to
287 December, RN was positive for 8h, with an average of 121W/m². LE and H had
288 similar daily trends with RN. The peak time was basically the same as RN. 1 h after
289 sunrise, the soil-vegetation system began to assimilate energy. LE was on the brink of
290 zero from October to March. This explained by the fact that the ground was mostly
291 frozen, and the water vapor transmission was very weak during this time. The peak
292 value of LE in July was 215W/m². From the perspective of H, it reached a peak

(254W/m²) in April. The positive and negative changes in G were not only affected by the sunrise time, but also by the soil. Owing to different soil physical and chemical properties in different seasons, soil thermal conductivity was different. Therefore, the delay time of soil heat absorption and heat dissipation was also altered. Negative value of G indicated that heat radiated from the soil to the atmosphere and the soil was the heat source. Conversely, the soil was heat sink (Sun et al., 2010).

Fig. 5. Variations of net radiation (RN), soil heat flux (G), latent heat flux (LE), and sensible heat flux (H) in 2018.

(a) Monthly variations in energy fluxes, (b)–(m) diurnal variations in energy fluxes in different seasons.

3.4. Seasonal and diurnal variations of GPP, NEP and Re

Carbon flux data was used to calculate the gross primary productivity (GPP), net ecosystem productivity (NEP) and respiration (Re) of the *Populus euphratica* in 2018. The seasonal variation characteristics were shown in Fig. 6a. GPP was generally larger during the growing season (from April to October). During this period, the photosynthesis and respiration of the ecosystem were relatively active. During the non-growth season from November to March of the following year, the temperature drop caused the vegetation to dry up, and the respiration of the entire ecosystem was much greater than photosynthesis. GPP of the *Populus euphratica* ecosystem was 877g C/m²/yr and the maximum rate was 3.40 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which appeared in June. The minimum production rate of GPP was 0.192 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which appeared in December.

NEP was positive from May to September, indicating that photosynthesis in the ecosystem was greater than respiration during this period, and the entire ecosystem behaved as a carbon sink. NEP of the *Populus euphratica* ecosystem was 345g C/m²/yr. The maximum production rate of NEP was 1.28 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which appeared in June. The minimum production rate of NEP was -0.68 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which appeared in March. The average production rate of NEP is 0.086 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$.

The respiration intensity of *Populus euphratica* ecosystem was 532 g C/m²/yr, accounting for 61% of GPP. The respiration intensity of ecosystem was greater than NEP. The seasonal change of respiration showed a single peak curve, which increased from February to August. The maximum rate of respiration rate was 2.51 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which occurred in August, and the minimum value was 0.04 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$, which occurred in February. The average respiration rate of *Populus euphratica* ecosystem was 0.97 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$.

The diurnal variation characteristics of GPP, NEP and Re were shown in Figs. 6b–m. Similar to the diurnal variation of energy flux (Figs. 5b–m), their variations also showed a single-peak curve. During January–March, April–June, July–September

330 and October–December, GPP and NEP from 12:00 to 19:00, 9:30 to 20:30, 10:30 to
 331 21:00 and 10: 30 to 18:30 was a positive value. It indicated that the ecosystems
 332 absorbed carbon and the duration was 7, 11, 10.5 and 8.5h, respectively. However, the
 333 peak time (15:00) was about an hour later than the energy flux (14:00).

Figure 6. Variations of gross primary productivity (GPP), net ecosystem productivity (NEP), and total respiration (Re) in 2018. (a) Monthly variations, (b)–(m) diurnal variations.

3.5. Seasonal and diurnal variations of WUE

In the *Populus euphratica* ecosystem, ET was close to zero in winter (Fig. 7), so

only the WUE of the growing seasons was calculated. During this period, the mean WUE was 2.2g C/kg H₂O and the maximum WUE was 5.5g C/kg H₂O. Due to the combined effects of photosynthesis and evapotranspiration, WUE didn't peak when GPP and ET reached their highest values. WUE was opposite to the trend of photosynthetic and evapotranspiration. This showed that WUE of the *Populus euphratica* ecosystem was not necessarily high when GPP and ET were high. Under the conditions of high temperature, strong radiation and low humidity in summer, the growth rate of ET was much larger than that of GPP.

Figure 7. Daily gross primary productivity (GPP), evapotranspiration (ET) and water use efficiency (WUE) during the growing seasons (April–October) in 2018.

The instantaneous WUE in daytime (8:30–20:00) was calculated using fluxes data at a frequency of 30 min (Fig. 8). We eliminated the data from 20:30 to 8:00 because WUE in night was of little significance, and the change rate of WUE was larger when the illumination was low. The daily variation of WUE in each month of the growing season was basically the same. WUE gradually increased with the enhancement of radiation (Fig. 5), reached a maximum at 14:00, and then gradually decreased.

Figure 8. Diurnal water use efficiency (WUE) during the growing seasons (April–October) in 2018.

3.6. Effects of climatic variables on WUE

Various environmental factors influenced WUE by controlling vegetation photosynthetic and transpiration (Kuglitsch et al., 2008). Both photosynthesis and evapotranspiration will increase with temperature. However, the growth rate is different, and the value of the ecosystem WUE determined by the two is also different (Wolf et al., 2013; Wu et al., 2017). In *Populus euphratica* forest, WUE became smaller as T_a increased (Fig. 9a). This is because ET increased greater than photosynthesis with increasing temperature.

It can be seen from Fig. 9b that WUE decreased as PAR increased. Solar radiation first affects the stomatal conductance of vegetation leaves, and then photosynthesis and transpiration change accordingly. Although PAR is the source of photosynthesis, the impact on transpiration is different. Plant photosynthesis only takes place within a certain range of radiation. Photosynthesis is limited with the increase of PAR, and there will be light saturation phenomenon. However, there is no upper limit for transpiration. Under sufficient water conditions, light will cause the temperature to

rise, and transpiration will continue to strengthen.

The water for vegetation growth in *Populus euphratica* forest ecosystem mainly comes from soil water. Therefore, soil water is an important factor influencing WUE. Fig. 9c showed that WUE increased as SWC decreased. The study area is in an arid area, so the vegetation often closes the leaf stomata due to lacking water. As a result, evapotranspiration decreased, and WUE increased accordingly. Moderate drought is beneficial to improve WUE (Krishnan et al., 2006; Yang et al., 2016), but if the drought continues to increase, the intensity of photosynthesis will decrease (Zhao et al., 2007). It is another matter to reduce or continue to maintain WUE under this result.

The increase of CO₂ concentration promoted the increase of WUE (Fig. 9d). There are two reasons. For one thing, increased CO₂ concentration will directly promote vegetation photosynthesis. For another, increased CO₂ concentration will cause the vegetation leaf stomata to close, and the water consumption will decrease. Thus vegetation can convert more water into productivity (Forner et al., 2018).

RH was the main environmental factor affecting WUE (Figure 9e). Most studies have found a linear positive correlation between RH and WUE, but some studies have reached the opposite conclusion (Li et al., 2008). The reasons for the two diametrically opposite research results may be related to the soil water content.

Fig. 9f showed that WUE decreased sharply with the increase of P and then slowly decreased. Although the increase in precipitation could improve the GPP of the ecosystem, ET increased faster.

Figure 9. Relationship between water use efficiency (WUE) and (a) air temperature (Ta), (b) photosynthetically active radiation (PAR), (c) soil water content (SWC), (d) carbon dioxide concentration (CO₂), (e) air relative humidity (RH), (f) precipitation (P) during the growing seasons (April–October).

3.7 Evapotranspiration characteristics at different time scales

The main form of LE is water phase change, so the variation of ET is similar to the LE (Fig. 5a). The annual ET of the *Populus euphratica* ecosystem was about 345mm.

The evapotranspiration process mainly occurred from May to October at 286mm, accounting for 93% of the annual evapotranspiration, indicating that the ET in this area was relatively concentrated. Vegetation of the *Populus euphratica* ecosystem has grown rapidly since April. As the temperature rises, the melting snow at the source of the Tarim River supplements the amount of water in the channel. In addition, summer rainfall is relatively high. River water and groundwater are abundant. These conditions are conducive to the growth of vegetation while also accelerating the evaporation and transpiration of the ecosystem.

The daily evapotranspiration of the *Populus euphratica* ecosystem was basically close to zero from November to March (Figs. 10b–m). At the same time as the temperature decreased, it became difficult for vegetation to grow, and the water consumption of the ecosystem also decreased sharply. The maximum value of daily evapotranspiration occurred in July at 3.82mm. The daily changes of evapotranspiration in July and August were basically similar, and both reached their maximum around 14:30 pm. Evapotranspiration lasts from 11:30 to 19:30 at a high value.

Figure 10. Variations of evapotranspiration (ET) in 2018. (a) Monthly variations, (b) –(m) diurnal variations.

4. Discussion

4.1 Comparison of WUE with other ecosystems

The daily average WUE (2.2g C/kg H₂O) of the *Populus euphratica* ecosystem was lower than other temperate forest ecosystems (2.57–6.07g C/kg H₂O) (Tan et al., 2015). When compared with forests of the same latitude, WUE of *Populus euphratica* forest was not as high as other forests in non-arid regions, but higher than grassland, wetland and crop land (Fig. 11), because long-term drought enhanced the ecosystem's

resistance and resilience to water scarcity in order to mitigate the effects of water loss (Gang et al., 2016).

In addition, we found that the WUE of *Populus euphratica* was relatively low, which was closely related to the local climatic conditions. During the growing season, although the ecosystem had the highest GPP, intense ET led to more water consumption while absorbing the same amount of carbon.

4.2 Latitudinal trends of WUE in different vegetation types

It is widely known that the vegetation types, stand structure, soil type, stand age, and geological evolution of terrestrial ecosystems vary widely. WUE had a clear zonal change trend (Fig. 10). As the latitude increased from tropical to high latitudes in the north, the average WUE of different ecosystems for many years has shown an upward trend, peaking at about 51 ° N, and then tending to decline at high latitudes. Although the WUE of different plant type ecosystems was different, all the peaks occurred within approximately the same latitude range (45 ° N–55 ° N). This indicated that there was a key zone of differentiation driven by radiation and moisture. In fact, latitude itself is not a driving variable, but a complex proxy factor under the combined action of abiotic and biological factors, which determines the main ecological zone (Tang et al., 2014).

However, in the case of the same latitude range, there were also differences in the size of WUE among different vegetation groups (Fig. 10). The WUE of evergreen forests was higher than that of deciduous vegetation at the same latitude. Broad-leaved forests had higher WUE than coniferous forests. The overall WUE of the forest ecosystem was higher than that of grasslands, wetlands and crop land. Except for the wetland ecosystem, WUE of crop land was the lowest, which might be affected by the unproductive stage, and the soil evaporation was higher than that of permanent vegetation.

Figure 11. Latitudinal trends in multiyear mean annual WUE for different plant functional types. ENF, EBF, DBF, MF, GRA, WET and CRO represent evergreen needleleaf forest, evergreen broadleaved forest, deciduous broadleaved forest, mixed forest, grassland, wetland and cropland, respectively. References: Beer et al. [2009], Tang et al. [2014], Tan et al. [2014], Kwon et al. [2018], Quansah et al. [2015], Gang et al. [2016], Chatterjee et al. [2018], Zanutelli et al. [2013].

5. Conclusions

Patterns in ecosystem carbon, water, energy fluxes and WUE of *Populus euphratica* forest in northwest China were studied in light of combined influences of environmental variables and plant biological processes. The main conclusions are as follows:

(1) The energy fluxes of the *Populus euphratica* ecosystem were not closed. The average EBR was 0.74, which was within the range of international comparable observations (0.55–0.99).

(2) Seasonal variations of RN, G, LE and H all showed a unimodal curve. With the exception of H, each energy flux reached its maximum in summer. From the perspective of the diurnal variations, each energy flux also showed a unimodal curve based on RN, reaching a peak around 14:00.

(3) The carbon exchange in the *Populus euphratica* ecosystem mainly occurred

from April to October, and the whole ecosystem showed a strong carbon sink. From December to February, the ecosystem became a carbon source. Annual GPP, NPP and Re were 877, 345, 532g C/m², respectively. The daily maximum ET appeared in July (3.82 mm) and the annual evaporation was about 345 mm.

(4) During the growing seasons, the mean and maximum daily WUE was 2.2 and 5.5g C/kg H₂O. WUE decreased with increasing Ta, PAR, and NDVI. CCO₂ and RH could promote the growth of WUE. WUE increased under moderate SWC condition. Under the conditions of high temperature, strong radiation and low humidity in summer, the growth rate of ET was much larger than that of GPP, causing WUE to drop to the lowest point.

(5) WUE of the *Populus euphratica* ecosystem was lower than other temperate forest ecosystems, but higher than grassland, wetland and crop land. By comparing WUE of various types of terrestrial ecosystems, we found that WUE exhibited significant spatial variability with geographical location and climate, but the peaks of different plant functional types occurred within approximately the same latitude range (45°N–55°N).

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author's Contribution

Fangbing Fu: Writing - original draft, Methodology, Software, Data curation.

498 **Lianqing Xue:** Methodology, Supervision, Writing - review & editing, Project
499 administration, Funding acquisition. **Xinfang Chen:** Supervision, Review. **Yuanhong**
500 **Liu:** Software, Data curation. **Qiang Han:** Resources. **Shumin Liao:** Writing,
501 Software. **Qing Wei:** Investigation.

502 Availability of data and material

503 All data generated or analysed during this study are included in this article.

504 Code availability

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506 Ethics approval

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508 Consent to participate

509 All the authors read and approved the final version of the manuscript. The authors
510 agree to publish the article.

511 Consent for publication

512 The authors confirm that the work described has not been published before, and it
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514 References

- 515 Amiro, B.D., Barr, A.G., Black, T.A., Iwashita, H., Kljun, N., McCaughey, J.H.,
516 Morgenstern, K., Murayama, S., Nesic, Z., Orchansky, A.L., Saigusa, N., 2006.
517 Carbon, energy and water fluxes at mature and disturbed forest sites,
518 Saskatchewan, Canada. *Agricultural and Forest Meteorology*, 136, 237–251.
- 519 Beer, C., Ciais, P., Reichstein, M., Baldocchi, D., Law, B.E., Papale, D., Soussana,
520 J.F., Ammann, C., Buchmann, N., Frank, D., Gianelle, D., Janssens, I.A., Knohl,
521 A., Kostner, B., Moors, E., Rouspard, O., Verbeeck, H., Vesala, T., Williams, C.A.,

522 Wohlfahrt, G., 2009. Temporal and among-site variability of inherent water use
 523 efficiency at the ecosystem level. *Global Biogeochemical Cycles*, 23, GB2018.

524 Brümmer, C., Black, T.A., Jassal, R.S., Grant, N.J., Spittlehouse, D.L., Chen, B.,
 525 Nesic, Z., Amiro, B.D., Arain, A.F., 2012. How climate and vegetation type
 526 influence evapotranspiration and water use efficiency in Canadian forest, peatland
 527 and grassland ecosystems. *Agricultural and Forest Meteorology*, 153, 14–30.

528 Chan, F.C.C., Arain, M.A., Khomik, M., Brodeur, J.J., Peichl, M., Restrepo-Coupe, N.,
 529 Thorne, R., Beamesderfer, E., McKenzie, S., Xu, B., Croft, H., Pejam, M., Trant,
 530 J., Kula, M., Skubel, R., 2018. Carbon, water and energy exchange dynamics of a
 531 young pine plantation forest during the initial fourteen years of growth. *Forest
 532 Ecology and Management*, 410, 12–26.

533 Chatterjee, D., Tripathi, R., Chatterjee, S., Debnath, M., Shahid, M., Bhattacharyya, P.,
 534 Swain, C.K., Tripathy, R., Bhattacharya, B.K., Nayak, A.K., 2018.
 535 Characterization of land surface energy fluxes in a tropical lowland rice paddy.
 536 *Theoretical and Applied Climatology*, 136, 157–168.

537 Sánchez, J.M., Caselles, V., Nicolòs, R., Coll, C., Kustas, W.P., 2009. Estimating
 538 energy balance fluxes above a boreal forest from radiometric temperature
 539 observations. *Agricultural and Forest Meteorology*, 149, 1037–1049.

540 Ding, R.S., Kang, S.Z., Li, F.S., Zhang, Y.Q., Tong, L., Sun, Q.Y., 2010. Evaluating
 541 eddy covariance method by large-scale weighing lysimeter in a maize field of
 542 northwest China. *Agricultural Water Management*, 98(1), 87–95.

543 Fei, D.Y., Guo, J.M., Liu, J.W., W, Q., 2018. Light use efficiency estimation of rice
 544 using eddy covariance flux data. *Journal of the Meteorological Sciences*, 38(1),
 545 76–88.

546 Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B.D., Munger, J.W., 2004.
 547 Postfield data quality control. In: Lee, X., Massman, W.J., Law, B. (Eds.),
 548 *Handbook of Micrometeorology: A Guide for Surface Flux Measurement and
 549 Analysis*. Kluwer, Dordrecht, pp. 181–208.

550 Forner, A., Valladares, F., Bonal, D., Granier, A., Grossiord, C., Aranda, I., 2018.
 551 Extreme droughts affecting Mediterranean tree species' growth and water-use
 552 efficiency: the importance of timing. *Tree Physiology*, 38 (8), 1127–1137.
 553 Gang, C.C., Wang, Z.Q., Chen, Y.Z., Yang, Y., Li, J.L., Cheng, J.M., Qi, J.G., Odeh, I.,
 554 2016. Drought-induced dynamics of carbon and water use efficiency of global
 555 grasslands from 2000 to 2011. *Ecological Indicators*, 67, 788–797.
 556 Govind, A., Chen, J.M., McDonnell, J., Kumari, J., Sonnentag, O., 2011. Effects of
 557 lateral hydrological processes on photosynthesis and evapotranspiration in a
 558 boreal ecosystem. *Ecohydrology*, 4(3), 394–410.
 559 Hui, D.F., Luo, Y.Q., Cheng, W.X., Coleman, J.S., Johnson, D.W., Sims, D.A., 2001.
 560 Canopy radiation- and water-use efficiencies as affected by elevated [CO₂].
 561 *Global Change Biology*, 7, 75–91.
 562 Jassal, R.S., Black, T.A., Spittlehouse, D.L., Brümmer, C., Nesic, Z., 2009.
 563 Evapotranspiration and water use efficiency in different-aged Pacific Northwest
 564 Douglas-fir stands. *Agricultural and Forest Meteorology*, 149, 1168–1178.
 565 Jin, J.X., Zhan, W.F., Wang, Y., Gu, B.J., Wang, W.F., Jiang, H., Lu, X.H., Zhang,
 566 X.Y., 2017. Water use efficiency in response to interannual variations in
 567 flux-based photosynthetic onset in temperate deciduous broadleaf forests.
 568 *Ecological Indicators*, 79, 122–127.
 569 Kim, J., Hirano, T., Yu, G.R., Li, S.G., Tamai, K., 2013. Lessons learned from
 570 CarboEastAsia: carbon and water cycles in East Asian terrestrial ecosystems.
 571 *Journal of Forest Research*, 18, 1–3.
 572 Kominami, Y., Jomura, M., Dannoura, M., Goto, Y., Tamai, K., Miyama, T., Miyama,
 573 T., Kanazawa, Y., Kaneko, S., Okumura, M., Misawa, N., Hamada, S., Sasaki, T.,
 574 Kimura, H., Ohtani, Y., 2008. Biometric and eddy-covariance-based estimates of
 575 carbon balance for a warm-temperate mixed forest in Japan. *Agricultural and*
 576 *Forest Meteorology*, 148(5), 723–737.
 577 Krishnan, P., Black, T.A., Grant, N.J., Barr, A.G., Hogg, E.H., Jassal, R.S.,

578 Morgenstern, K., 2006. Impact of changing soil moisture distribution on net
579 ecosystem productivity of a boreal aspen forest during and following drought.
580 *Agricultural and Forest Meteorology*, 139, 208–223.

581 Kuglitsch, F.G., Reichstein, M., Beer, C., Carrara, A., Ceulemans, R., Granier, A.,
582 Janssens, I.A., Koestner, B., Lindroth, A., Loustau, D., Matteucci, G., Montagnani,
583 L., Moors, E.J., Papale, D., Pilegaard, K., Rambal, S., Rebmann, C., Schulze, E.D.,
584 Seufert, G., Verbeeck, H., Vesala, T., Aubinet, M., Bernhofer, C., Foken, T.,
585 Grünwald, T., Heinesch, B., Kutsch, W., Laurila, T., Longdoz, B., Miglietta, F.,
586 Sanz, M.J., Valentini, R., 2008. Characterisation of ecosystem water-use
587 efficiency of European forests from eddy covariance measurement.
588 *Biogeosciences Discuss*, 5, 4481–4519.

589 Kwon, H., Creason, W., Law, B.E., Still, C.J., Hanson, C., 2018. Influence of
590 concurrence of extreme drought and heat events on carbon and energy fluxes in
591 dominant ecosystems in the Pacific Northwest region, *Biogeosciences Discuss*,
592 297, 1–31.

593 Li, S., Eugster, W., Asanuma, J., Kotani, A., Davaa, G., Oyunbaatar, D., Sugita, M.,
594 2008. Response of gross ecosystem productivity, light use efficiency, and water
595 use efficiency of Mongolian steppe to seasonal variations in soil moisture. *Journal*
596 *of Geophysical Research*, 113, G01019.

597 Linderson, M.L., Mikkelsen, T.N., Ibrom, A., Lindroth, A., Ro-Poulsen, H., Pilegaard,
598 K., 2012. Up-scaling of water use efficiency from leaf to canopy as based on leaf
599 gas exchange relationships and the modelled in-canopy light distribution.
600 *Agricultural and Forest Meteorology*, 152, 201–211.

601 Keenan, T.F., Hollinger, D.Y., Bohrer, G., Dragoni, D., Munger, J.W., Schmid, H.P.,
602 Richardson, A.D., 2013. Increase in forest water-use efficiency as atmospheric
603 carbon dioxide concentrations rise. *Nature*, 499, 324–327.

604 Ma, J.Y., Jia, X., Zha, T.S., Bourque, C.P.-A., Tian, Y., Bai, Y.J., Liu, P., Yang, R.Z., Li,
605 C., Li, C.Y., Xie, J., Yu, H.Q., Zhang, F., Zhou, C.X., 2019. Ecosystem water use

606 efficiency in a young plantation in Northern China and its relationship to drought.
 607 Agricultural and Forest Meteorology, 275, 1–10.

608 Chen, Y.N., Li, W.H., Zhou, H.H., Chen, Y.P., Hao, X.M., Fu, A.H., Ma, J.X., 2017.
 609 Experimental study on water transport observations of desert riparian forests in
 610 the lower reaches of the Tarim River in China. Int. J. Biometeorol., 61,
 611 1055–1062.

612 Mammarella, I., Nordbo, A., Rannik, U., Haapanala, S., Levula, J., Laakso, H., Ojala,
 613 A., Peltola, O., Heiskanen, J., Pumpanen, J., Vesala, T., 2015. Carbon dioxide and
 614 energy fluxes over a small boreal lake in Southern Finland. Journal of
 615 Geophysical Research: Biogeosciences, 120(7), 1296–1314.

616 Meyers, T.P., Hollinger, S.E. 2004. An assessment of storage terms in the surface
 617 energy balance of maize and soybean. Agricultural and Forest Meteorology, 125,
 618 105–115.

619 Öquist, M.G., Erhagen, B., Haei, M., Sparrman, T., Ilstedt, U., Schleucher, J., Nilsson,
 620 M.B., 2017. The effect of temperature and substrate quality on the carbon use
 621 efficiency of saprotrophic decomposition, Plant and Soil, 414, 113–125.

622 Ponton, S., Flanagan, L.B., Alstad, K.P., Johnson, B.G., Morgenstern, K., Kljun, N.,
 623 Black, T.A., Barr, A.G., 2006. Comparison of ecosystem water-use efficiency
 624 among douglas fir forest, aspen forest and grassland using eddy covariance and
 625 carbon isotope techniques. Global Change Biology, 12, 294–310.

626 Quansah, E., Mauder, M., Balogun, A.A., Amekudzi, L.K., Hingerl, L., Bliefernicht,
 627 J., Kunstmann, H., 2015. Carbon dioxide fluxes from contrasting ecosystems in
 628 the Sudanian savanna in west Africa. Carbon Balance and Management, 10(1),
 629 1–17.

630 Seddon, A.W.R., Macias-Fauria, M., Long, P.R., Benz, D., Willis, K.J., 2016.
 631 Sensitivity of global terrestrial ecosystems to climate variability. Nature, 531,
 632 229–232.

633 Skubel, R., Arain, M.A., Peichl, M., Brodeur, J.J., Khomik, M., Thorne, R., Trant, J.,

634 Kula, M., 2015. Age effects on the water-use efficiency and water-use dynamics
635 of temperate pine plantation forests. *Hydrological Processes*, 29, 4100–4113.

636 Stephens, J.J., Black, T.A., Jassal, R.S., Nesic, Z., Grant, N.J., Barr, A.G., Helgason,
637 W.D., Richardson A.D., Johnson M.A., Christen A., 2018. Effects of forest tent
638 caterpillar defoliation on carbon and water fluxes in a boreal aspen stand.
639 *Agricultural and Forest Meteorology*, 253–254, 176–189.

640 Stoy, P.C., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M.A.,
641 Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle,
642 D., Gorsel, E.V., Kiely, G., Knohl, A., Margolis, H., McCaughey, H., Merbold, L.,
643 Montagnani, L., Papale, D., Reichstein, M., Saunders, M., Serrano-Ortiz, P.,
644 Sottocornola, M., Spano, D., Vaccari, F., Varlagin, A., 2013. A data-driven analysis
645 of energy balance closure across FLUXNET research sites: The role of landscape
646 scale heterogeneity, *Agricultural and Forest Meteorology*, 171–172, 137–152.

647 Tan, Z.H., Zhang, Y.P., Deng, X.B., Song, Q.H., Liu, W.J., Deng, Y., Tang, J.W., Liao,
648 Z.Y., Zhao, J.F., Song, L., Yang, L.Y., 2015. Interannual and seasonal variability of
649 water use efficiency in a tropical rainforest: results from a 9 year eddy flux time
650 series. *Journal of Geophysical Research: Atmospheres*, 120, 464–479.

651 Tang, X.G., Li, H.P., Desai, A.R., Nagy, Z., Luo, J.H., Kolb, T.E., Olioso, A., Xu, X.B.,
652 Yao, L., Kutsch, W., Pilegaard, K., Kostner, B., Ammann, C., 2014. How is
653 water-use efficiency of terrestrial ecosystems distributed and changing on earth?.
654 *Scientific Reports*, 4, 7483.

655 Tong, X.J., Zhang, J.S., Meng, P., Li, J., Zheng, N., 2014. Ecosystem water use
656 efficiency in a warm-temperate mixed plantation in the North China. *Journal of*
657 *Hydrology*, 512, 221–228.

658 Wang, W.J., Cui, S., Liu, W., Zu, Y.G., Sun, W., Wang, H.M., 2008. Seasonal variation
659 of soil heat conduction in a larch plantation and its relations to environmental
660 factors. *Chinese Journal of Applied Ecology*, 19(10), 2125–2131.

661 Wang, Y.J., Guo, Y.H., 2018. Characteristics of Oasis before and after the ecology

662 water transportation in lower reaches of the Tarim River. *Desert and Oasis*
663 *Meteorology*, 68(2), 41–46.

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

669 Wolf, S., Eugster, W., Ammann, C., Häni, M., Zielis, S., Hiller, R., Stieger, J., Imer, D.,
670 Merbold, L., Buchmann, N., 2013. Contrasting response of grassland versus forest
671 carbon and water fluxes to spring drought in Switzerland. *Environmental*
672 *Research Letters*, 8 (3), 035007.

673 Wu, X., Liu, H., Li, X., Ciais, P., Babst, F., Guo, W., Zhang, C., Magliulo, V., Pavelka,
674 M., Liu, S., Huang, Y., Wang, P., Shi, C., Ma, Y., 2017. Differentiating drought
675 legacy effects on vegetation growth over the temperate northern hemisphere.
676 *Global Change Biology*, 24 (1), 504–516.

677 Xu, L.K., Hsiao, T.C., 2004. Predicted versus measured photosynthetic water-use
678 efficiency of crop stands under dynamically changing field environments. *Journal*
679 *of Experimental Botany*, 55(407), 2395–2411.

680 Xue, L.Q., Wang, J., Zhang, L.C., Wei, G.H., Zhu, B.L., 2019. Spatiotemporal
681 analysis of ecological vulnerability and management in the Tarim River Basin,
682 China. *Science of the Total Environment*, 649, 876–888.

683 Yan, W., Zhang, X.Z., Shi, P.L., Yang, Z.L., He, Y.T., Xu, L.L., 2006. Carbon dioxide
684 exchange and water use efficiency of alpine meadow ecosystems on the Tibetan
685 Plateau. *Journal of Natural Resources*, 21(5), 756–767.

686 Yang, B., Zuo, H.C., Dong, L.X., Yang, H.L., Chen, B.L., Dai, L.D., 2018. Impact of
687 observation error of desert underlying surface energy flux on energy closure in
688 arid area. *Arid Zone Research*, 35(2), 452–460.

689 Yang, S.H., Xu, J.Z., Liu, X.Y., Zhang, J.G., Wang, Y.J., 2016. Variations of carbon

690 dioxide exchange in paddy field ecosystem under water-saving irrigation in
691 Southeast China. *Agricultural Water Management*, 166, 42–52.

692 Yu, G.R., Fu, Y.L., Sun, X.M., Wen, X.F., Zhang, L.M., 2006. Recent progress and
693 future directions of ChinaFLUX. *Science in China Series D: Earth Sciences*, 49(2
694 Supplement), 1–23.

695 Yu, G.R., Song, X., Wang, Q.F., Liu, Y., Guan, D., Yan, J., Sun, X.M., Zhang, L.M.,
696 Wen, X. F., 2008. Water-use efficiency of forest ecosystems in eastern China and
697 its relations to climatic variables. *New phytologist*, 177, 927–937.

698 Sun, G., Noormets, A., Gavazzi, M.J., McNulty, S.G., Chen, J., Domec, J.C., King, J.S.,
699 Amatya, D.M., Skaggs, R.W., 2010. Energy and water balance of two contrasting
700 loblolly pine plantations on the lower coastal plain of North Carolina, USA. *Forest*
701 *Ecol. Manag.*, 259, 1299–1310.

702 Zanutelli, D., Montagnani, L., Manca, G., Tagliavini, M., 2013. Net primary
703 productivity, allocation pattern and carbon use efficiency in an apple orchard
704 assessed by integrating eddy covariance, biometric and continuous soil chamber
705 measurements, *Biogeosciences*, 10, 3089–3108.

706 Zhang, F.M., Ju, W.M., Shen, S.H., Wang, S.Q., Yu, G.R., Han, S.J., 2014. How recent
707 climate change influence water use efficiency in East Asia. *Theoretical and*
708 *Applied Climatology*, 116, 359–370.

709 Zhao, F.H., Yu, G.R., Li, S.G., Ren, C.Y., Sun, X.M., Mi, N., Li, J., Zhu, O.Y., 2007.
710 Canopy water use efficiency of winter wheat in the North China Plain.
711 *Agricultural Water Management*, 93(3), 99–108.

712 Zhao, X.S., Liu, Y.B., 2018. Variability of surface heat fluxes and its driving forces at
713 different time scales over a large ephemeral lake in China. *Journal of Geophysical*
714 *Research: Atmospheres*, 123, 4939–4957.

715 Zhu, B.L., Xue, L.Q., Wei, G.H., Zhang, L.C., Chen, X.F., 2018. CMIP5 projected
716 changes in temperature and precipitation in arid and humid basins. *Theoretical and*
717 *Applied Climatology*, 136, 1133–1144.

Figures

Figure 1

Location of the study area and images of the observation instruments. (a) Geographical location of the study site (red triangle), (b) remote sensing image of the study site and (c) erection of experimental instruments. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The relationship between CO₂ flux at night ($F_c(\text{night})$) and air temperature (T_a). The downward shortwave radiation (DR) is used as an indicator to distinguish daytime and nighttime. It is generally considered that when $DR < 1 \text{ W}/\text{m}^2$, the corresponding period is nighttime.

Figure 3

Seasonal variations in the daily mean environmental factors in 2018. (a) daily mean air temperature (T_a), (b) daily mean photosynthetically active radiation (PAR), (c) daily mean soil water content (SWC) at 20 cm, (d) daily mean CO_2 concentration, (e) daily mean air relative humidity (RH), (f) daily precipitation (P).

Figure 4

(a) Daily mean EBR in 2018, (b) relationship between the turbulent flux (H+LE) and available energy (RN-G), (c) diurnal changes of EBR in different seasons. The EBR was not meaningful during the morning and evening transition periods when the mean value of RN-G is close to zero.

Figure 5

Variations of net radiation (RN), soil heat flux (G), latent heat flux (LE), and sensible heat flux (H) in 2018. (a) Monthly variations in energy fluxes, (b)-(m) diurnal variations in energy fluxes in different seasons.

Figure 6

Variations of gross primary productivity (GPP), net ecosystem productivity (NEP), and total respiration (Re) in 2018. (a) Monthly variations, (b)-(m) diurnal variations.

Figure 7

Daily mean gross primary productivity (GPP), evapotranspiration (ET) and water use efficiency (WUE) during the growing seasons (April-October) in 2018.

Figure 8

Diurnal water use efficiency (WUE) during the growing seasons (April-October) in 2018.

Figure 9

Relationship between water use efficiency (WUE) and (a) air temperature (T_a), (b) photosynthetically active radiation (PAR), (c) soil water content (SWC), (d) carbon dioxide concentration (CO_2), (e) air relative humidity (RH), (f) precipitation (P) during the growing seasons (April–October).

Figure 10

Variations of evapotranspiration (ET) in 2018. (a) Monthly variations, (b)-(m) diurnal variations.

Figure 11

Latitudinal trends in multiyear mean annual WUE for different plant functional types. ENF, EBF, DBF, MF, GRA, WET and CRO represent evergreen needleleaf forest, evergreen broadleaved forest, deciduous broadleaved forest, mixed forest, grassland, wetland and cropland ,respectively. References: Beer et al. [2009], Tang et al. [2014], Tan et al. [2014], Kwon et al. [2018], Quansah et al. [2015], Gang et al. [2016], Chatterjee et al. [2018] , Zanutelli et al. [2013].