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9 **Response to the Correction of MS No. bg-2014-536:**

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18 **Dear Associate Editor, Prof. & Dr. Christopher A. Williams,**

19  
20 We really appreciate your suggestion and patience for ensuring the publication quality. As you  
21 suggested, we have replaced the citation ([Zhang et al., 2014](#)) across the whole paper (see in  
22 revised MS [P5 L23](#) and [P18 L21](#)), and revised the text “Earlier, we reported that...” to “[As we](#)  
23 [show in a forthcoming study.](#)” (see in revised MS [P18 L19](#)).

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26 Should you have any inquiries about this resubmission, please feel free to contact me at any  
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36  
37 Best regards,  
38 Yours sincerely

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1 **Energy partitioning and surface resistance of a poplar**  
2 **plantation in northern China**

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1 **Abstract**

2 Poplar (*Populus sp.*) plantations have been, on one hand, broadly used in northern China for  
3 urban greening, combating desertification, as well as for paper and wood production. On the  
4 other hand, such plantations have been questioned occasionally for their possible negative  
5 impacts on the water availability due to higher water use nature of poplar trees compared with  
6 other tree species in water limited dryland regions. To further understand the acclimation of  
7 poplar species to semiarid environment and evaluate the potential impacts of these plantations  
8 on the broader context of the region's water supply, we examine the variability of bulk  
9 resistance parameters and energy partitioning in a poplar (*Populus euramericana* CV. "74/76")  
10 plantation located in northern China over a four-year period encompassing both dry and wet  
11 conditions. The partitioning of available energy to latent heat flux (LE) decreased from 0.62 to  
12 0.53 under mediated meteorological drought by irrigation applications. A concomitant increase  
13 in sensible heat flux ( $H$ ) resulted in the increase of a Bowen ratio from 0.83 to 1.57. Partial  
14 correlation analysis indicated that surface resistance ( $R_s$ ) normalized by leaf area index (LAI)  
15 ( $R_s:LAI$ ) increased by 50% under drought conditions and was the dominant factor controlling  
16 the Bowen ratio. Furthermore,  $R_s$  was the main factor controlling LE during the growing season,  
17 even in wet years, as indicated by the decoupling coefficient ( $\Omega = 0.45$  and 0.39 in wet and dry  
18 years, respectively).  $R_s$  was also a major regulator of the  $LE/LE_{eq}$  ratio, which decreased from  
19 0.81 in wet years to 0.68 in dry years. All physiological and bioclimatological metrics indicated  
20 that the water demands of the poplar plantation were greater than the amount available through  
21 precipitation, highlighting the poor match of a water-intensive species like poplar for this water  
22 limited region.

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## 1 **1 Introduction**

2 Poplar (*Populus sp.*) plantations are the most dominant broadleaf forest ecosystems throughout  
3 northern and central China, due to their rapid growth rates, high productivity and wide  
4 adaptability ([Gielen and Ceulemans, 2001](#); [Wilske et al., 2009](#); [Zhang et al., 2011](#)). Since the  
5 late-1970s, with the implementation of the “Three-North Shelterbelt Program” (1978), the  
6 “Combating Desertification Project” (1991) and the “Grain for Grain Program” (1999) ([Wilske](#)  
7 [et al., 2009](#)), poplar plantations have been playing a vital role in timber production, bioenergy,  
8 urban greening, desertification control, and carbon sequestration ([Martín-García et al., 2011](#);  
9 [Zhou et al., 2013](#)). By 2007, China had the largest poplar plantation area in the world (over 7.0  
10 million ha, ([Fang, 2008](#)). However, indiscriminate use of poplar species beyond their native  
11 range and habitats may result in unanticipated consequences. For example, the use of poplars  
12 in water limited regions may increase the risk of environmental degradation, soil moisture  
13 deficit, hydrologic and vegetation changes ([Gao et al., 2014](#)).

14 Poplars require large quantities of water throughout the growing season, and may  
15 experience water limitation even on the mesic sites ([Kim et al., 2008](#); [Stanturf and Oosten,](#)  
16 [2014](#)). For example, poplar plantations could cause the transformation of wetlands into dry land  
17 due to the water-pumping effect on groundwater ([Li et al., 2014](#); [Migliavacca et al., 2009](#)). Thus,  
18 poplar plantations, which have higher productivity but also higher water use ([Zhou et al., 2013](#))  
19 than other tree species.

20 The intensive land use practices in northern China over the past 50 years, supported by  
21 irrigation, are thought to have triggered the decline in its water table, land degradation and  
22 increases in surface air temperature and severe droughts ([Ding et al., 2007](#); [Qiu et al., 2012](#);  
23 [Wang et al., 2008](#)) ~~[Zhang et al., 2014](#)~~). Therefore, understanding the contribution of current  
24 land cover, including the poplar plantations on the regional water resources is essential for long-  
25 term sustainability of ecosystem services and human wellbeing in this region. To date, most  
26 researches have concentrated primarily on the water balance of forest ecosystems, with less  
27 emphasis on the relationship of forest ecosystems to their environmental setting. Much can be  
28 learned from exploring the partitioning of available energy and ecosystem response to  
29 meteorological forcing such as droughts. Not only are these of central importance for  
30 understanding the water and carbon balance ([Guo et al., 2010](#); [Jamiyansharav et al., 2011](#); [Sun](#)  
31 [et al., 2010](#); [Takagi et al., 2009](#); [Wu et al., 2007](#)), but they also help elucidate the degree to

1 which forest water use is in balance with supply from precipitation, and hence the degree to  
2 which plantations located in water limited regions are sustainable in the long-term.

3 To investigate the variations of energy partitioning and associated evapotranspiration of  
4 poplar plantation under different climate conditions and highlight the management strategies  
5 for such plantation forests in water limited region, we evaluated energy partitioning at different  
6 water availabilities in a ten-year-old poplar (*Populus euramericana* CV. "74/76") plantation on  
7 sandy soil in northern China. We hypothesized that drought would trigger significant increase  
8 in the surface resistance and affect energy partitioning via increasing the Bowen ratio.  
9 Specifically, the objectives of this study were to: (1) quantify the seasonal and inter-annual  
10 variability of energy partitioning and bulk resistance parameters; (2) partition the control of  
11 energy partitioning to biological and climatological components; and (3) evaluate the long-term  
12 potential impact of poplar plantations on the availability of water for adjacent ecosystems and  
13 livelihoods in water-limited region.

## 14 **2 Materials and Methods**

### 15 **2.1. Study site**

16 The study was carried out in a managed poplar (*Populus euramericana* CV. "74/76")  
17 plantation at the Daxing Forest Farm, which is located in the southern suburbs of Beijing, China  
18 (116°15'07"E, 39°31'50"N, 30 m a.s.l.). The trees were planted in 1998 with 3 m × 2 m spacing,  
19 dead or low-vigor trees were replaced with new saplings in 2001 and 2003. The stand  
20 characteristics over the four years of study are provided in Table 1. At the end of 2009, the  
21 average height of the trees was 16.2±1.6 m (mean ± SD), and the diameter at breast height  
22 (DBH) was 14.1±1.6cm. The average leaf area index (LAI) of the stand increased over time.  
23 During the growing season, understory shrubs were kept at low density by manual removal.  
24 Perennial herbs included *Chenopodium glaucum* Linn., *Medicago sativa* L., *Melilotus*  
25 *officinalis* (L.) Lam., *Salsola collina* Pall., and *Tribulus terrestris* L.

26 The local climate is classified as sub-humid warm temperate zone, with a mean (1990–  
27 2009) annual temperature of 11.6°C; maximum and minimum temperature are 40.6 °C and -  
28 27.4 °C, respectively. The annual precipitation ranges from 262 mm to 1058 mm (1952–2000),  
29 with an average of 556 mm, of which 60%-70% falls from July to September (Daxing Weather  
30 Station, 116°19' 56" E, 39°43' 24" N). The annual frost-free period lasts 209 days, and the  
31 total sunshine-hour reaches 2772 h per year with 15.5 MJ m<sup>-2</sup> d<sup>-1</sup> of incoming solar radiation.

1 The average wind speed is  $2.6 \text{ m s}^{-1}$  and it mostly comes from the southeast (during the growing  
2 season) and the northwest (outside of the growing season).

3 The study area is on the alluvial plain of the Yongding River, and is flat with an average  
4 slope of  $< 5^\circ$ . The top two meters of the soil is mostly composed of well-drained fluvial sand  
5 with a bulk density of  $1.43\text{-}1.47 \text{ g}\cdot\text{cm}^{-3}$ , and a pH of  $8.25\text{-}8.39$ . The soil porosity is about 40%  
6 and capillary porosity is 32%. The mean groundwater depth over the past nine years (2001–  
7 2009) was  $16.5\pm 0.2 \text{ m}$ , and declined at an average rate of 0.6 m per year. The maximum pan  
8 evaporation occurs from May through June, exceeding precipitation for the same period. Severe  
9 drought during the beginning of the growing season (from April to June) in northern of China  
10 is common. The site was irrigated using pumped groundwater, and the amount of water supplied  
11 was estimated from the water meter records at the three adjacent wells on a weekly basis from  
12 2006 through 2009. Other management practices have included tilling and weeding since the  
13 establishment of the plantations.

## 14 **2.2. Eddy covariance system**

15 The micrometeorological and eddy flux measurements were conducted at a 32m tower in the  
16 center of the study site, which was established in June 2005. The foot-print of the eddy flux  
17 covariance system, was about  $1 \text{ km} \times 1 \text{ km}$  in size, with a fetch of at least 300 m in all directions.  
18 Fluxes of  $\text{CO}_2$ , sensible heat and latent heat were calculated based on the eddy-covariance (EC)  
19 principles. The sensors included a  $\text{CO}_2/\text{H}_2\text{O}$  infrared analyzer (Li-7500; LI-COR, Inc., Lincoln,  
20 NE, USA) and a three-dimensional sonic anemometer (CSAT-3; Campbell Scientific, Inc., CSI,  
21 UT, USA). The anemometer head was installed towards a predominant wind direction  
22 (southeast), and the IRGA was installed at a slight vertical angle tilted northward ( $< 20^\circ$ )  
23 between the sonic path and anemometer body. The IRGA was calibrated every year. The EC  
24 sensors were mounted initially at a height of 16 m in 2006. This was increased to about 18 m  
25 before the start of the growing season in 2007, and again to 20 m in February 2009 to ensure  
26 that the sensors remained well above the tree canopy.

27 Net radiation was measured with net radiometers (Q7.1, REBS, Seattle, WA, USA) and  
28 (CNR-1; Kipp and Zonen, Delft, Netherlands) at 26 m above the ground. Photosynthetically  
29 active radiation (PAR) was measured with a PAR quantum sensor (LI-190SB; LI-COR, Inc.)  
30 mounted at 20 m. The atmospheric pressure was measured by a barometric pressure sensor  
31 (CS105, CSI) at height of 21 m. Air temperatures and humidity were measured with a

1 temperature and relative humidity probe (HMP45C; Vaisala, Helsinki, Finland) at 5, 10, 15 and  
2 20 m above ground. Precipitation was measured with a tipping bucket rain gauge (TE525-L;  
3 Texas Electronics, USA) at 22.5m. Soil heat flux and soil temperatures, respectively, were  
4 measured with three soil heat transducers (HFT3, CSI) and three thermocouples (TCAV107;  
5 CSI) located at depths of 5, 10 and 20 cm below the soil surface. Soil water content was  
6 measured with TDR sensors (CS616; CSI) buried at 20 and 50cm.

7 With the exception of the rain gauge, all microclimatic data were recorded with a data-  
8 logger (CR23X; CSI) at 30 min intervals and the fluctuations in wind speed, sonic temperature  
9 and CO<sub>2</sub> and H<sub>2</sub>O concentrations were sampled at 10 Hz and recorded by a CR5000 data-logger  
10 (CSI).

### 11 **2.3. Data processing and QA/QC**

12 The 30-minute mean fluxes were calculated from raw 10 Hz data with an EC Processor software,  
13 version 2.3 ([Noormets et al., 2010](#)). The program is designed for reprocessing EC flux data and  
14 can calculate half-hour mean eddy covariance fluxes of carbon, water and energy. The wind  
15 coordinates were rotated using the planar fit method ([Paw U et al., 2000](#); [Wilczak et al., 2001](#)).  
16 Fluxes were corrected for additional sensor heating ([Burba et al., 2008](#)) and fluctuations in air  
17 density ([Webb et al., 1980](#)). The data quality controls included: screening of the 30-min mean  
18 eddy covariance fluxes based on instrument quality flag, integral turbulence characteristics  
19 ([Foken and Wichura, 1996](#)), flux stationarity, atmospheric stability, and adequate turbulent  
20 mixing([Goulden et al., 1996](#)). The threshold of friction velocity ( $\mu_*$ ) below which flux loss  
21 occurred was determined from the seasonal binned relationship between nighttime turbulent  
22 flux of CO<sub>2</sub> and friction velocity ( $\mu_*$ ) ([Schmid et al., 2003](#)). The threshold was consistent across  
23 different seasons, but differed slightly between years: 0.18 m s<sup>-1</sup> (2006), 0.12 m s<sup>-1</sup> (2007), 0.14  
24 m s<sup>-1</sup> (2008) and 0.13 m s<sup>-1</sup> (2009). Data gaps shorter than 2 hours were filled using linear  
25 regressions between the flux of interest and net radiation ( $R_n$ ), gaps between 2 hours and 7 days  
26 in length were filled using mean diurnal variation (MDV) method ([Falge et al., 2001](#)), and gaps  
27 longer than 7 days were not filled.

28 The four year study period was classified into “wet” and “dry” years distinctively. A dry  
29 year referred to a year with annual precipitation less than 85% of the 20-year average according  
30 to the National Standard of People's Republic of China (GB/T 20481-2006) ([China, 2006](#)) and  
31 “wet” when above it. Years 2007 and 2008 were classified as ‘wet’ while 2006 and 2009 were



1 ‘dry’ year, respectively. We focused on the growing season when the environmental forcing  
2 (e.g., solar radiation, and temperature) for energy and water fluxes, and the physiological  
3 response of vegetation were usually strong. In this study, the strongest forcing days occurred  
4 approximately between day 100 (mid-April) and day 300 (late October). The daytime was  
5 defined as the period between the sunrise and sunset with  $PAR > 4 \mu\text{molm}^{-2}\text{s}^{-1}$ . The regulation  
6 of surface energy and gas exchange are often different during nocturnal periods ([Mahrt, 1999](#)),  
7 with heat fluxes at night typically weaker and markedly less stationary than during the daytime  
8 ([Wilson et al., 2002b](#)). The midday was defined as the period from 10:00 to 15:00 LST when  
9 the coupling between vegetation and the atmosphere was the strongest.

## 10 **2.4. Biophysical characteristics**

11 The availability of relative extractable water (REW) content was calculated to analyze the  
12 ecosystem response on drought stress. According to [Granier et al. \(2007\)](#), soil water stress was  
13 assumed to occur when the REW dropped below the threshold of 0.4. Daily REW is calculated  
14 as,

$$15 \text{ REW} = \frac{\text{VWC} - \text{VWC}_{\min}}{\text{VWC}_{\max} - \text{VWC}_{\min}} \quad (1)$$

16 where  $\text{VWC}_{\min}$  and  $\text{VWC}_{\max}$  are the minimum and maximum soil volumetric water content  
17 across the four years, respectively.

18 The Bowen ratio ( $\beta$ ) reflects the influence of microclimate and the hydrological cycle on  
19 the energy partitioning and water use of the ecosystem ([Perez et al., 2008](#)). The midday  $\beta$  is  
20 calculated as Eq. (2),

$$21 \beta = \frac{H}{LE} \quad (2)$$

22 Based on the daytime half-hourly and daytime totals of turbulent energy fluxes, the energy  
23 balance ratio ( $E_{BR}$ ) is calculated as Eq. (3),

$$24 E_{BR} = \frac{\sum(H + LE)}{\sum(R_n - G - S)} \quad (3)$$

25 where  $S$  is the latent and sensible heat storage in the air-column below the EC system and is  
26 calculated as in Eq. (4) ([Dou et al., 2006](#)),

$$S = \int_0^{hc} \rho c_p \frac{\partial T}{\partial t} dz + \int_0^{hc} \frac{\rho c_p}{\gamma} \frac{\partial e}{\partial t} dz \quad (4)$$

where  $hc$  is the height of eddy flux system measurement (32 m),  $T$  is air temperature in the air-column below  $hc$ , and  $e$  is water vapor pressure.

During midday periods (10:00-15:00 LST), the *Penman-Monteith* approximation was inverted to calculate the surface resistance ( $R_s$ ) in Eq. (5) ([Kumagai et al., 2004](#)),

$$R_s = \frac{\rho c_p (\delta_e / LE)}{\gamma} + \left( \frac{\Delta}{\gamma} \beta - 1 \right) R_a \quad (5)$$

where  $R_s$  is the surface resistance to water vapor transport ( $s\ m^{-1}$ ), representing four components: bulk stomatal resistance of the canopy, bulk boundary layer resistance of the vegetation, bulk ground resistance, and bulk boundary layer resistance of the ground ([Admiral et al., 2006](#); [Cho et al., 2012](#); [Perez et al., 2008](#); [Wilson et al., 2002b](#)).

$R_i$  is the climatological resistance ( $s\ m^{-1}$ ) indicating the atmospheric demand ([Wilson et al., 2002b](#)) and is calculated as,

$$R_i = \frac{\rho c_p \delta_e}{\gamma A} \quad (6)$$

where  $A$  is the available energy ( $R_n - G$ );  $\rho$  is air density ( $kg\ m^{-3}$ ),  $c_p$  is the specific heat of the air ( $1005\ J\ kg^{-1}\ K^{-1}$ );  $\delta_e$  is the atmospheric vapor pressure deficit (Pa);  $LE$  is the latent heat flux;  $\Delta$  is the change of saturation vapor pressure with temperature ( $Pa\ K^{-1}$ );  $\gamma$  is the psychrometric constant ( $\approx 67\ Pa\ K^{-1}$ );  $\beta$  is the Bowen ratio.

$R_a$  is the aerodynamic resistance of the air layer between the canopy and the flux measurement height ( $s\ m^{-1}$ ), that reflects the aerodynamic properties of turbulent transport in the near surface boundary layer ([Holwerda et al., 2012](#); [Zhang et al., 2007](#)).  $R_a$  is calculated following [Hossen et al. \(2011\)](#) and [Migliavacca et al. \(2009\)](#),

$$R_a = r_{a,m} + r_b = \frac{\mu}{\mu_*^2} + 6.2\mu_*^{-2/3} \quad (7)$$

where  $r_{a,m}$  is the aerodynamic resistance for momentum transfer, and  $r_b$  is the quasi-laminar boundary-layer resistance,  $\mu$  is the wind speed, and  $\mu_*$  is the friction velocity.

The decoupling coefficient ( $\Omega$ ) explains the degree of coupling between the atmosphere and the vegetation, and describes the relative control of evapotranspiration by surface resistance

1 and net radiation ([Pereira, 2004](#)). The  $\Omega$  value ranges from 0 to 1, with values approaching zero  
2 indicating that LE is highly sensitive to surface resistance and ambient humidity deficit. The  $\Omega$   
3 value approaching 1 indicates that LE or evapotranspiration is mostly controlled by net  
4 radiation ([Jarvis and McNaughton, 1986](#)),

$$5 \quad \Omega = \frac{\Delta + \gamma}{\Delta + \gamma(1 + \frac{R_s}{R_a})} \quad (8)$$

6 The equilibrium evaporation ( $LE_{eq}$ ) is the climatologically determined evaporation  
7 (atmospheric demand) over an extensive wet surface and is dependent only on  $R_n$  and  
8 temperature. It is calculated as,

$$9 \quad LE_{eq} = \frac{\Delta(R_n - G)}{\Delta + \gamma} \quad (9)$$

10 The ratio  $LE/LE_{eq}$ , which is also known as the Priestley–Taylor  $\alpha$ , reflects the control of  
11 evaporation by atmospheric and physiological factors,  $LE/LE_{eq}$  characterizes the surface  
12 dryness of an ecosystem, indicating whether soil water supply for evapotranspiration of an  
13 ecosystem was under limited. An  $LE/LE_{eq}$  of  $< 1$  indicates water stress and suppressed  
14 evapotranspiration. Conversely,  $LE/LE_{eq} > 1.26$  indicates unrestricted water supply, and only  
15 available energy limits evapotranspiration ([Arain et al., 2003](#)). The  $LE/LE_{eq}$  is dependent of  
16 leaf area index (LAI), soil water content, meteorological conditions (e.g., wind speed, solar  
17 radiation, VPD, air stratification stability, convection, advection surface resistance), vegetation  
18 types, and altitude ([Guo et al., 2008](#)).

## 19 **2.5. Statistical analysis**

20 Repeated measurement ANOVA (SPSS) was used for quantifying the changes of all the  
21 biophysical variables, energy fluxes and bulk parameters across years. The  $t$  test was used to  
22 compare the differences of biophysical variables among different studies. The partial  
23 correlation analysis was used to distinguish the impacts of each of the three resistance  
24 parameters ( $R_s$ ,  $R_i$  and  $R_a$ ) on the Bowen ratios. All analyses were accessed at  $\alpha = 0.05$ .

25

## 1 **3 Results**

### 2 **3.1 Environmental conditions**

3 The annual precipitation rates in the four years of study differed from the long-term (i.e., 1990–  
4 2009) average (556 mm yr<sup>-1</sup>). Thus, years 2006 and 2009 were drier and 2007 and 2008 were  
5 wetter than the mean (Table 1). The interannual contrast was exaggerated by the seasonality of  
6 rainfall. Generally, over 90% precipitation of each year occurred in April–October, but with  
7 different timing and magnitude among the years. The study site was irrigated during the dry  
8 years of 2006 and 2009 to mitigate drought conditions (Fig.1). Seasonal drought stress (REW<  
9 0.4) occurred during periods in the late growing season of 2006 and 2009, the spring of 2007  
10 and 2009, but not at all in 2008 (Fig. 2a–d). In 2006, precipitation during the growing season  
11 reached 467 mm, of which 51% had occurred by July. The amount of irrigation was 35 mm in  
12 April, 21 mm in May and 30 mm in September. The two seasonal drought periods separately  
13 were #1\_06 (from DOY 164 to 192) and #2\_06 (from DOY 231 to 300). The total rainfall in  
14 2007 and 2008 was similar, but more evenly distributed throughout the year in 2008. In 2007,  
15 drought stress occurred during DOY 110-143 (#1\_07) and 151-200 (#2\_07). A single rain event  
16 in late May (57 mm) and a few large precipitation events (> 25 mm d<sup>-1</sup>) in July were recorded.  
17 The amount of rainfall in 2009 was the smallest among the four years, during which 195mm of  
18 irrigation was applied from March to September. There were several short and scattered  
19 droughts across the growing season in 2009 (Fig.2d). Despite the higher than normal rainfall in  
20 the two wet years, there was no flooding or overland runoff.

21 The growing season  $T_a$  in 2008 was significantly lower than that in 2007 and 2009 ( $dT=$   
22 1.3 ° C,  $p < 0.05$ , Fig.2 e-h). The years differed in the spring warm-up and the timing of peak  
23 temperature (by up to 35.9 ° C). The maximum air temperature occurred in June 2006 and 2009,  
24 and in July 2007 and 2008. The warmest month was June 2006 ( $27.1 \pm 2.4^\circ\text{C}$ ).

25 The daytime average VPD of the four growing seasons (Fig.2 e-h) was  $1.3 \pm 0.7$  kPa. The  
26 mean VPD in wet years (i.e., 2007 and 2008) was  $1.2 \pm 0.7$  kPa, which was significantly lower  
27 ( $F=6.093$ ,  $p < 0.01$ ) than that in dry years (i.e., 2006 and 2009,  $1.3 \pm 0.8$  kPa). The VPD of the  
28 growing seasons in 2008 (i.e.,  $1.1 \pm 0.5$  kPa) was lower than those in the other years ( $p < 0.05$ ).  
29 Higher  $T_a$  and lower precipitation in May 2007 led to higher VPD compared to the same period  
30 in 2006 and 2008 ( $p < 0.001$ ). Furthermore, the VPD was the highest in June 2009 (i.e.,  $2.3 \pm$   
31  $1.1$  kPa,  $p < 0.05$ ) and the lowest in 2008 (i.e.,  $1.0 \pm 0.5$  kPa,  $p < 0.01$ ).

### 1 3.2 Seasonal changes in energy partitioning and $\beta$

2 The energy partitioning trends of daytime total net radiation ( $R_n$ ) into latent, sensible heat fluxes  
3 (LE and  $H$ ), soil heat fluxes ( $G$ ) and heat storage of canopy ( $S$ ) for the year 2006-2009 were  
4 presented in Fig.3. Among these years,  $R_n$  varied with solar radiation ( $R > 0.95$ ,  $\alpha = 0.01$  level),  
5 reached the maximum in July, and gradually decreased until the late October (in dry years) or  
6 November (in wet years). During the growing season, there were no significant difference in  
7 average daytime total  $R_n$  between wet and dry years. The average of daytime total  $G$  during the  
8 growing season displayed great seasonal and annual differences among these years ( $p < 0.05$ ),  
9 with a lower value in wet years (2.1% in 2007) than in the dry years (4.9% in 2006;  $p < 0.001$ ).  
10 Moreover, the average value of daytime total  $S$  among the four growing seasons were 0.46 MJ  
11  $\text{m}^{-2}$ , 0.49 MJ  $\text{m}^{-2}$ , 0.51 MJ  $\text{m}^{-2}$ , 0.54 MJ  $\text{m}^{-2}$ , respectively.  $S/R_n$  varied from 6.0% in 2007 to 6.8%  
12 in 2009, showing no differences between the wet and dry years.

13 Partitioning of  $R_n$  into LE and  $H$  differed significantly between the wet and dry years  
14 (Table 3;  $F = 17.599$ ,  $p < 0.001$ ). The dominant turbulent energy flux during the early growing  
15 season was sensible heat flux ( $H$ ) with or without drought stress except in 2006 when the  
16 irrigation was applied (Table 3). Then LE was the dominant driver of energy partitioning during  
17 the middle and late growing seasons under drought stress. The average daytime total LE was  
18 about 20% greater in wet years (6.77 MJ  $\text{m}^{-2}$ ) than in dry years (5.72 MJ  $\text{m}^{-2}$ ,  $p < 0.01$ ). The  
19 timing of peak LE was weakly related to drought, peaking in July in 2006, 2008 and 2009, and  
20 in August in 2007. The peak value of daytime total LE was 16.61 MJ  $\text{m}^{-2}$ , 17.01 MJ  $\text{m}^{-2}$ , 19.72  
21 MJ  $\text{m}^{-2}$  and 16.27 MJ  $\text{m}^{-2}$ , in 2006–2009 respectively. The daily evaporative fraction (LE/( $R_n$ -  
22  $G$ )) was significantly higher in wet years (60.3% and 64.8% in 2007 and 2008, respectively)  
23 (64.8%) than in dry years (57.1% and 50.4% in 2006 and 2009, respectively;  $p < 0.05$ ).

24 The seasonal variation of the midday Bowen ratio ( $\beta$ ) displayed a rapid and significant  
25 trend across the growing season, especially at the beginning (April–June) and the end  
26 (September–October) of the growing season (Fig. 4). The Bowen ratios during the middle of  
27 the growing seasons were all smaller than 1, and approximately lasted from DOY 180–250 in  
28 the dry year and from DOY 180–290 in the wet years. The average midday  $\beta$  in the dry years  
29 was greater (1.57) than that in the wet years (0.83;  $F = 19.176$ ,  $p < 0.001$ ). The Bowen ratio  
30 showed differences in response to drought stress across the four growing seasons (Table 3);  
31 with much higher values ( $> 1$ ) during the drought periods in 2007 and 2009, but not in 2006.  
32 The Bowen ratio was smaller than 1 during drought stressed periods in 2008.

### 1 3.3 Biophysical controls of energy partitioning

2 The  $R_s$  varied widely at the beginning and the end of growing season, but changed steadily  
3 within a low range during the middle of growing season by comparison. Moreover, these lower  
4  $R_s$  in the dry year lasted a shorter period (DOY 190–250) than in the wet year (Fig. 5a). A  
5 significantly negative relationship was found between the  $R_s$  and LAI during the wet years  
6 (Fig.6). Overall, the seasonal average of  $R_s$  normalized by leaf area index (LAI) (i.e.,  $R_s$ :LAI)  
7 was lowest during the wettest year (2008, 54.1 s m<sup>-1</sup> leaf area;  $p < 0.05$ ). The  $R_s$ :LAI in the dry  
8 years (106.8 s m<sup>-1</sup> leaf area) was 50% higher than in the wet years (71.2 s m<sup>-1</sup> leaf area) ( $p <$   
9 0.001). The  $R_s$ :LAI in the seasonal drought stressed periods in 2006, 2007 and 2009 were much  
10 higher than those during unstressed periods ( $p < 0.001$ , Table 3).

11 The average midday  $R_i$  peaked in June and decreased in July/August before reaching a  
12 second peak in October (Fig. 5b). The seasonal average  $R_i$  during the growing season ranged  
13 from 68.3 s m<sup>-1</sup> to 77.9 s m<sup>-1</sup>, with a mean value of 74.4 s m<sup>-1</sup>, and showed no difference among  
14 the four growing seasons ( $p > 0.05$ ). Figure 5c presents the seasonal and annual variations of  
15 midday  $R_a$ . The average  $R_a$  for the four growing seasons was 23.2±8.5 s m<sup>-1</sup>, ranging from 10.6  
16 to 43.5 s m<sup>-1</sup>, 9.7 to 52.5 s m<sup>-1</sup>, 6.5 to 43.1 s m<sup>-1</sup>, and 9.7 to 74.5 s m<sup>-1</sup>, from 2006 to 2009,  
17 respectively.  $R_a$  in 2007 was significantly higher than in the dry years ( $p < 0.01$ ), while  $R_a$  in  
18 2008 was smaller than in the dry years ( $p < 0.001$ ). However, there were no significant  
19 differences between dry and wet years  $R_a$  ( $p > 0.05$ ).

20 The seasonal changes of LE/LE<sub>eq</sub> value varied between 0.4 and 1.0 during most of the  
21 growing seasons (Fig. 5d). The average LE/LE<sub>eq</sub> of the four years were 0.76, 0.73, 0.89 and  
22 0.63, respectively. The mean LE/LE<sub>eq</sub> of the dry years (0.68) was lower than that of wet years  
23 (0.81;  $p < 0.001$ ). Specifically, the value of LE/LE<sub>eq</sub> in drought periods of 2007 and 2009 were  
24 much smaller. A significantly exponential relationship existed between the LE/LE<sub>eq</sub> and  $R_s$   
25 during the growing season (Fig.7).

26 The decoupling coefficient ( $\Omega$ ) across the growing season peaked in mid-July in 2008 and  
27 in early August in the other years (Fig. 5e). The mean  $\Omega$  for the four years was 0.41, 0.46, 0.43  
28 and 0.39 (Table 3), respectively, and was significantly higher in wet year (0.45) than that in dry  
29 year (0.40;  $F=9.460$ ,  $p < 0.01$ ). Compared to the value during unstressed periods, the  
30 decoupling coefficient during the seasonal drought periods (#1\_06, #2\_06; #1\_07, #2\_07 and  
31 #1\_09, #2\_09, #3\_09) was much lower in value.

32

## 1 **4 Discussion**

### 2 **4.1 Energy partitioning and Bowen ratio**

3 The energy balance ratio ( $E_{BR}$ ) at the current study was 0.88 based on daytime 30-minute fluxes  
4 and  $> 0.96$  based on daytime totals (Table 2). The annual mean  $E_{BR}$  at our site was similar to the  
5 values of eight ChinaFlux sites, which averaged 0.83 and ranged from 0.58 to 1.00 ([Li et al.,](#)  
6 [2005](#)). The energy budget is also consistent with the 50 site-years of flux data from 22 in  
7 FLUXNET sites, which had energy closure of 0.34–1.69 (Mean = 0.84, ([Wilson et al., 2002a](#))).  
8 A recent analysis of 173 FLUXNET sites also found an average closure of 0.84 ([Stoy et al.,](#)  
9 [2013](#)), although the authors also detected consistent differences among the biomes and based  
10 on metrics of landscape heterogeneity. In addition to the known reasons for decreasing energy  
11 balance closure ([Hernandez-Ramirez et al., 2010](#); [Li et al., 2005](#); [Nakai et al., 2006](#); [Stoy et al.,](#)  
12 [2013](#)), management operations at our site (e.g., irrigation, tilling and partial felling) may also  
13 affect the energy balance. Although the causes of surface energy balance closure continues to  
14 be debated ([Stoy et al., 2013](#)) and will not be conclusively answered in the current study, the  
15 results reported here are similar to other FLUXNET sites.

16 The surface energy partitioning to sensible and latent heat depends on water potential  
17 gradient and surface resistance ([Arain et al., 2003](#); [Baldocchi et al., 2000](#); [Chen et al., 2009](#)).  
18 Canopy development ([Guo et al., 2010](#)), rainfall dynamics and irrigation ([Ozdogan et al., 2010](#))  
19 affect these properties to some extent and could directly lead to a change in soil moisture and  
20 the evaporation component of LE, thereby impacting energy partitioning and  $\beta$  ([Chen et al.,](#)  
21 [2009](#); [Ozdogan et al., 2010](#)). However, the impact of precipitation on the Bowen ratio may vary  
22 by even at any site ([Tang et al., 2014](#)). In our study, detectable responses of  $LE/(R_n-G)$  and the  
23 Bowen ratio to drought stress and non-stress periods were observed in response to soil water  
24 supply (Table 3) with a 50 mm threshold on average (Fig 8). The variability of energy  
25 partitioning during the growing season was highly sensitive to water availability from  
26 precipitation and irrigation. On an annual scale, the Bowen ratio appeared linearly related to  
27 the total growing season precipitation ( $R^2=0.89$ ,  $p < 0.05$ ). Thus, the Bowen ratio is very  
28 responsive to the site water supply; a similar finding was reported in [Grünwald and Bernhofer](#)  
29 [\(2007\)](#) in a temperate spruce forest.

30 By contrast,  $\beta$  varied from 0.18 to 0.71, with a mean of  $0.35 \pm 0.15$  during most of the  
31 growing season in 2008 and in the non-stressed periods of the other 3 years. This variation was

1 close to 0.42 for deciduous forests ([Wilson et al., 2002b](#)) and 0.55 in a temperate Douglas-fir  
2 ([Humphreys et al., 2003](#)), which is also similar to the variations in a ponderosa pine forest in  
3 the western United States ([Goldstein et al., 2000](#)) and a deciduous broadleaved forest in the  
4 southern United States ([Wilson and Baldocchi, 2000](#)). Seasonal drought stress had a discernible  
5 impact on the Bowen ratio of this poplar plantation. However, compared to the reported  $\beta$  values  
6 such as 0.74 in a temperate mixed forest ([Wu et al., 2007](#)), 0.81 in a boreal Scots pine forest  
7 ([Launiainen, 2010](#)) and 0.89 in a loblolly pine plantation ([Sun et al., 2010](#)), the average  $\beta$  in wet  
8 years were close to the above values.  $\beta$  was higher in seasonal drought periods and dry years  
9 than most temperate coniferous forests (Mean = 1.07, ([Wilson et al., 2002b](#)), which typically  
10 had higher  $\beta$  values. The high  $\beta$  value in this study reflects the semi-arid conditions, and  
11 suggests a low tree water supply which might be resulted from the combination of low rainfall,  
12 the sandy soil's low water holding capacity and the high plant and atmospheric water demand.  
13 It has been suggested that the large-scale establishment of poplar plantation in sandy semi-arid  
14 regions of northern China could have an adverse impact on the region's groundwater reserves  
15 ([Li et al., 2014](#); [Petzold et al., 2011](#)). Our findings corroborate the hypothesis that drought  
16 would trigger significant changes in the energy partitioning of water-demanding poplar species  
17 in a water-stressed region.

## 18 **4.2 Biophysical control on Bowen ratio**

19 The Bowen ratio is dependent on the interactions of climatic and biological factors ([Perez et al.,](#)  
20 [2008](#); [Wilson and Baldocchi, 2000](#)).  $R_i$  quantifies the climatic control on energy partitioning  
21 and tends to decrease the Bowen ratio. A higher  $R_i$  implies a warm and dry climate in continental  
22 regions ([Raupach, 2000](#); [Wilson et al., 2002b](#)).  $R_s$  reflects the physiological control on surface  
23 energy exchange of an ecosystem ([Costa et al., 2010](#); [Launiainen, 2010](#); [Zhou et al., 2010](#)) and  
24 generally increases the Bowen ratio.

25 In this study,  $R_s$  similarly varied seasonally with plant phenology and showed similar  
26 seasonal characteristics to other deciduous forests during the course of the growing season  
27 ([Cabral et al., 2010](#); [Kutsch et al., 2008](#); [Li et al., 2012](#)). As reported by [Tchebakova et al.](#)  
28 [\(2002\)](#),  $R_s$  in seasonal drought stressed periods was much higher than that in non-stressed  
29 periods. It has been shown that drought stress during the canopy development affects leaf area  
30 and may have lasting effects on canopy gas exchange through the entire growing season, even  
31 after the moisture limitation is removed ([Noormets et al., 2008](#)), which may explain significant  
32 difference in  $R_s$  between wet year 2007 and 2008 (Fig.9). Compared with the  $R_s$  in other studies,



1 the  $R_s$ :LAI in dry years in the current study was close to that of the Euphrates Poplar (*Populus*  
2 *euphratica* Oliv.) (130.2 s m<sup>-1</sup> LAI<sup>-1</sup>) and smaller than that of the Gansu Poplar (*Populus*  
3 *gansuensis* Wang et Yang) (189.4 s m<sup>-1</sup> LAI<sup>-1</sup>) in semiarid regions (Chen et al., 2004). In wet  
4 years it was similar to that of poplar (58.6 s m<sup>-1</sup> LAI<sup>-1</sup>) (Wilson et al., 2002b) and boreal aspen  
5 during the full-leaf period (51.8 s m<sup>-1</sup> LAI<sup>-1</sup>) (Blanken et al., 1997) in mesic temperate regions.  
6  $R_s$  is primarily driven by solar radiation, moisture availability and VPD (Fernández et al., 2009;  
7 Li et al., 2012) and modulated by leaf area and stomatal resistance, which in turn changes as a  
8 function of the above factors (Wilson and Baldocchi, 2000). Compared to the strong correlation  
9 between  $R_s$  and LAI in wet years, the increased scatter in the  $R_s$ -LAI relationship during dry  
10 years (Fig.6) suggests that  $R_s$  in dry years was also influenced by other physiological and non-  
11 physiological (e.g., soil evaporation, canopy structure and turbulence) factors (Wilson et al.,  
12 2002b). The mean  $R_i$  in the current study was higher than the mean  $R_i$  reported for temperate  
13 forests in Wilson et al. (2002b) ( $t=5.91$ ,  $df=741$ ,  $p < 0.001$ ), but was ~ 50% lower than the value  
14 reported by Li et al. (2009) in a vineyard in Gansu Province in China ( $t= -29.87$ ,  $df=741$ ,  $p <$   
15  $0.001$ ), as might be expected given the predominant climatic conditions.

16 On the seasonal scale, the Bowen ratio and  $R_s$  of this poplar plantation were correlated and  
17 consistent with Wilson et al. (2002b) and Li et al. (2009), but differed in wet and dry years (Fig  
18 10). The water limitation during the dry years manifested in disproportional increase in  $R_s$  than  
19 the Bowen ratio; this response may serve as an indicator when water reserves are being  
20 depleted. At the extremes, the relationship converges, but as water becomes limiting, stomatal  
21 closure and increased  $R_s$  do not appear to be able to affect the seasonal dynamics of the Bowen  
22 ratio. The partial correlation analysis indicated that  $R_s$  and  $R_i$  had strong positive and negative  
23 effects, respectively, on  $\beta$  in both wet and dry years (Table 4), which could not be detected  
24 through correlation analysis (e.g., the impact of  $R_i$  and  $R_a$  on  $\beta$ ). Furthermore, the regulation of  
25 the Bowen ratio by  $R_s$  and  $R_i$  seemed stronger in dry than in wet years.  $R_a$  had a significant  
26 negative impact on the Bowen ratio in wet years, but not in dry years.

27 The average LE/LE<sub>eq</sub> in the growing season was 0.74 at our site, which is similar to  
28 deciduous forests (0.72) (Wilson et al., 2002b), but smaller than at a temperate broad-leaved  
29 forest (0.82) (Komatsu, 2005). The average  $\Omega$  value of  $0.42 \pm 0.22$  (0.39-0.46) was close to the  
30 other forests (0.26-0.4, Wilson and Baldocchi (2000); 0.25-0.43, Motzer et al. (2005)). As  
31 essentially implied by the Penman-Monteith equation, LE/LE<sub>eq</sub> exponentially related to  $R_s$   
32 during the growing season (Fig.7), which is equivalent to the logarithmic relationship between

1 LE/LE<sub>eq</sub> and  $G_s$  (surface conductance) reported by other studies ([Chen et al., 2009](#); [Hossen et](#)  
2 [al., 2011](#); [Zhu et al., 2014](#)). The asymptotic value of LE/LE<sub>eq</sub> in dry years (0.89) and wet years  
3 (0.96) were both lower than the 1.1–1.4 range typical in temperate deciduous forest reported by  
4 [Monteith \(1995\)](#), indicating that our study site was drier than these reference sites during both  
5 dry and wet years. The low LE/LE<sub>eq</sub> values under dry surface conditions of the ecosystem in  
6 this study may also be related to the high porosity of the sandy soil and the low ground water  
7 table ([Zhao et al., 2013](#)). Overall, as indicated by the lower  $\Omega$  values and the significant  
8 correlation coefficients between LE/LE<sub>eq</sub> and  $R_s$ , the  $R_s$  was the major factor controlling the LE  
9 during the growing season, which was consistent with the relations between  $R_s$  and the Bowen  
10 ratio. In addition, LE was more coupled to the atmosphere during the dry years and seasonal  
11 drought periods across the growing season, as reported in other studies ([Bagayoko et al., 2007](#);  
12 [Bracho et al., 2008](#); [Zha et al., 2013](#)).

### 13 **4.3 Implications for poplar plantation establishments**

14 As forestry is a long-term endeavor, with the economic payback decades from stand  
15 establishment, the availability of resources for the stand to prosper should come naturally to  
16 natural resource managers. Supplementing limiting resources directly (fertilization, irrigation)  
17 or indirectly (competition control, site preparation, thinning) is commonplace in commercial  
18 forestry, but it has to be sustainable in the broader context of the region's ecosystems and  
19 livelihoods. ~~As we show in a forthcoming study, Earlier, we reported that~~ the water needs of  
20 poplar plantation exceed the annual precipitation in the region and plant survival during dry  
21 years depends on irrigation from groundwater ~~(Zhang et al., 2014)~~. In the current study, energy  
22 partitioning to latent and sensible heat and surface resistance was sensitive to climatological  
23 drought—even under the irrigation—as indicated by low LE/LE<sub>eq</sub> ( $< 1$ ) and low values of the  
24 decoupling coefficient ( $\Omega$ ) ([Zhu et al., 2014](#)); the dry surface conditions dominated the poplar  
25 plantation in both wet and dry years. In wet years, the plantation itself is in hydrologic balance  
26 with the water that arrives as precipitation, with evapotranspiration consuming nearly all of the  
27 precipitation. The same is true in dry years, but irrigation increases  $ET$  even further by depleting  
28 groundwater. Even if the plantations were in hydrologic balance with water delivered as  
29 precipitation, their existence and operation could be a threat to adjacent ecosystems and  
30 livelihoods if those rely on runoff or groundwater recharge from the areas where the plantation  
31 has been sited. In the absence of the plantations it is likely that groundwater recharge would  
32 increase, especially given the sandy textured soil that tends to allow rapid infiltration and

1 percolation as well as limits moisture delivery to the atmosphere directly from the soil surface  
2 itself. While poplar plantation growth in this water-limited location might be sustained by the  
3 modest precipitation in the region, it could still be unsustainable for the broader context of the  
4 region's ecosystems and livelihoods. However, further study to truly access these effects is  
5 needed by comparing the surface water balance and /or spatial and temporal variations of  
6 groundwater levels at an adjacent, similar site without a plantation.

7

## 8 **5 Conclusions**

9 The seasonal drought stress affected the dynamics of individual turbulent energy fluxes and the  
10 surface resistances in the poplar plantation during the growing seasons. Partitioning of available  
11 energy into latent (LE) and sensible heat ( $H$ ) flux responded to meteorological drought and  
12 resulted in higher  $\beta$  in dry years (1.57) than that in wet years (0.83). Similar to the response of  
13 the Bowen ratio on drought conditions, the LAI normalized surface resistance ( $R_s:LAI$ ) was 33%  
14 higher in dry than in wet years. Correspondingly, the contrasting effects of  $R_s$  and  $R_i$  on the  
15 Bowen ratio were stronger in dry years than in wet years, while the effect of  $R_a$  was stronger in  
16 wet years.  $R_s$  was the major factor in controlling energy partitioning during the growing season,  
17 as indicated by the relatively low decoupling coefficient ( $\Omega$ ) values. Furthermore, the low  
18  $LE/LE_{eq}$  ( $< 1$ ) of poplar plantations indicated that the permanent limitation of plant water use  
19 and surface energy partitioning by water availability. Even at mean long-term precipitation, the  
20 water demand of poplar plantation may consume nearly all of it and leave little for run-off and  
21 groundwater recharge in this semi-arid region, potentially compromising the region's  
22 ecosystems and livelihoods.

23

24

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3

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Table 1. The stand characteristics of four years from 2006 to 2009, including the minimum, maximum and mean temperature (T), the annual precipitation (P), evapotranspiration (ET), irrigation (I), canopy height (H), breast height diameter (DBH), leaf area index (LAI). The error estimates are standard deviation (SD).

	Tmin	Tmax	Tmean	P	ET	I	H	DBH	LAI
	(°C)			(mm)	( mm)	(mm)	(m)	(cm)	( m <sup>2</sup> m <sup>-2</sup> )
2006	-10.6	29.7	12.5±0.73	482	599	86	11.5±1.1	10.8±1.5	1.6±0.3
2007	-9.8	29.5	13.0±0.55	667	560	-	13.0±1.3	12.2±1.8	2.1±0.4
2008	-7.4	28.8	13.3±0.54	662	653	-	14.8±1.2	13.8±1.8	2.2±0.7
2009	-10.2	30.5	12.5±0.60	428	511	195	16.2±1.6	14.5±1.6	2.9±0.4

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Table 2. Energy balance closure statistics using half-hourly and daytime totals during growing season from 2006 to 2009

	daytime				Daytime sum			
	2006	2007	2008	2009	2006	2007	2008	2009
Slope	0.92	0.87	0.92	0.82	1.07	0.91	1.04	0.84
Intercept	20.50	17.24	10.72	13.08	-0.63	-0.09	-0.79	-0.30
$R^2$	0.81	0.80	0.81	0.82	0.88	0.81	0.92	0.82

Daytime was defined as the period between the sunrise and sunset with  $PAR > 4 \text{ umol m}^{-2} \text{ s}^{-1}$ ;  
The unit of Intercept for Half-hourly value and Daytime sum value were  $\text{W} \cdot \text{m}^{-2}$  and  $\text{MJ} \cdot \text{m}^{-2}$ , respectively.

1 Table 3. The value of the soil water supply (WS), energy partitioning ratios and biophysical variables in the different periods of the growing  
 2 season during 2006-2009

Year	Periods(DOY)	WS (mm)	LE/(R <sub>n</sub> -G)(%)	H/(R <sub>n</sub> -G)(%)	$\beta$	R <sub>s</sub> (s m <sup>-1</sup> )	R <sub>i</sub> (s m <sup>-1</sup> )	R <sub>a</sub> (s m <sup>-1</sup> )	$\alpha$	$\Omega$
2006	100-163	76.2+56	50.5(23.4)	45.9(19.7)	3.48(6.37)	418.7(528.7)	87.8(30.2)	20.0(6.3)	0.64(0.35)	0.25(0.13)
	164-192 <sup>d</sup>	127.8	68.0(13.3)	33.2(11.1)	0.66(0.35)	184.0(94.7)	94.9(45.2)	23.8(5.1)	0.79(0.19)	0.42(0.14)
	193-230	219.6	77.7(11.9)	13.8(6.7)	0.19(0.13)	50.4(29.9)	51.5(16.4)	27.8(8.6)	1.01(0.24)	0.70(0.12)
	231-300 <sup>d</sup>	43	51.9(12.7)	31.7(11.6)	0.94(0.52)	178.5(68.8)	77.4(27.5)	25.6(6.8)	0.69(0.23)	0.36(0.14)
2007	100-143 <sup>d</sup>	61.8	35.2(6.4)	57.8(8.3)	2.37(0.66)	426.9(148.8)	96.1(29.4)	18.1(5.4)	0.41(0.13)	0.16(0.07)
	151-200 <sup>d</sup>	146.8	49.5(18.2)	37.0(17.7)	1.41(1.06)	314.1(225.6)	91.7(42.8)	25.3(7.1)	0.58(0.23)	0.35(0.16)
	200-300	396.8	66.0(16.3)	15.5(8.5)	0.35(0.32)	74.1(27.3)	61.1(22.7)	30.4(9.2)	0.87(0.20)	0.60(0.15)
2008	100-117	53.4	16.3(14.1)	71.8(9.7)	1.86(1.12)	206.9(102.0)	60.7(22.9)	13.6(4.1)	0.59(0.35)	0.21(0.14)
	118-155 <sup>d</sup>	15.6	58.8(12.3)	39.5(10.7)	0.71(0.36)	130.8(48.6)	81.1(32.3)	14.7(4.2)	0.81(0.23)	0.31(0.11)
	156-188	212.7	68.1(14.6)	33.3(10.7)	0.35(0.23)	70.2(33.4)	56.1(20.6)	19.3(5.9)	0.94(0.23)	0.53(0.14)
	189-212 <sup>d</sup>	26	73.5(12.7)	20.4(7.5)	0.18(0.15)	59.3(27.1)	67.4(41.1)	27.8(6.8)	1.07(0.25)	0.68(0.11)
	213-239	173.4	74.8(11.9)	11.8(6.2)	0.24(0.16)	61.5(23.7)	55.8(14.3)	19.3(5.2)	0.92(0.14)	0.57(0.10)
	240-251 <sup>d</sup>	19.2	60.4(12.6)	23.4(9.9)	0.42(0.22)	88.7(34.6)	60.4(15.3)	18.0(4.1)	0.87(0.21)	0.46(0.10)
	252-300	116.2	47.2(5.7)	39.2(3.6)	0.41(0.22)	72.1(17.8)	57.3(28.9)	18.4(4.4)	0.85(0.23)	0.48(0.10)
2009	100-158 <sup>d</sup>	37.6+52	36.0(16.5)	48.8(13.4)	1.90(0.83)	298.9(150.8)	84.2(39.3)	18.2(3.8)	0.43(0.19)	0.21(0.08)

	165-186 <sup>d</sup>	1.2	47.8(15.6)	38.1(14.8)	1.32(0.78)	360.5(139.8)	137.4(43.8)	21.2(5.9)	0.53(0.28)	0.24(0.10)
	187-235	265+32	65.9(12.8)	12.4(6.7)	0.28(0.18)	61.2(30.9)	53.0(22.8)	27.4(6.6)	0.82(0.18)	0.66(0.13)
	236-300 <sup>d</sup>	20.4+20	50.4(20.5)	33.1(18.4)	1.28(1.31)	208.3(194.3)	72.3(26.5)	26.9(10.7)	0.64(0.28)	0.39(0.21)
2006	Growing season	466+86	59.1(18.9)	31.8(16.4)	1.60(3.94)	231.4(338.3)	77.9(33.6)	24.0(7.4)	0.76(0.30)	0.41(0.21)
2007	Growing season	630	56.6(19.5)	28.7(19.6)	0.93(0.98)	192.2(190.7)	75.4(34.0)	26.9(9.3)	0.73(0.44)	0.46(0.22)
2008	Growing season	630	66.1(15.2)	22.1(13.4)	0.73(1.04)	118.1(115.3)	68.3(44.9)	18.5(6.3)	0.89(0.59)	0.43(0.19)
2009	Growing season	400+195	48.5(21.9)	34.6(18.5)	1.54(2.19)	248.9(273.3)	77.1(39.1)	23.8(8.5)	0.63(0.38)	0.39(0.24)
dry years										
(2006, 2009)	Growing season	-	52.6(22.3)	33.0(18.4)	1.57(3.17)	240.3(306.9)	77.5(36.5)	23.9(8.0)	0.68(0.31)	0.40(0.22)
wet years										
(2007, 2008)	Growing season	-	61.5(18.1)	25.1(17.0)	0.83(1.01)	153.1(159.7)	71.6(40.3)	22.5(8.9)	0.81(0.29)	0.45(0.20)

WS: soil water supply of period (sum of precipitation and irrigation);  $\beta$ : Bowen ratio;  $R_s$ , the surface resistance;  $R_i$ , the climatological resistance;  $R_a$ , the aerodynamic resistance;  $\alpha$ , the Priestley-Taylor coefficient;  $\Omega$ , the decoupling coefficient;

<sup>d</sup> indicate the drought stressed periods.

The value in table represents Mean (SD), the superscript uppercase letters (A, B, C) and lowercase letters (a, b, c) respectively indicate the significance at the 0.01 level and the 0.05 level.

Table 4. The correlation analysis between the Bowen ratio ( $\beta$ ) and  $R_s$ ,  $R_i$  and  $R_a$ .

		Partial correlation analysis*			Correlation analysis		
		<i>SOCC</i>	<i>p</i>	df	Pearson	<i>p</i>	df
dry year	$\beta$ & $R_s$	0.965	<0.001		0.939	<0.001	
	$\beta$ & $R_i$	-0.667	<0.001	347	-0.042	=0.436	349
	$\beta$ & $R_a$	0.037	=0.496		-0.221	<0.001	
wet year	$\beta$ & $R_s$	0.905	<0.001		0.85	<0.001	
	$\beta$ & $R_i$	-0.614	<0.001	383	0.64	=0.006	385
	$\beta$ & $R_a$	-0.217	<0.001		-0.286	<0.001	

\*Partial correlation analysis was proceeded between Bowen ratio and each of three resistance parameters ( $R_s$ ,  $R_i$  and  $R_a$ ) with the other two as controlling variables.

*SOCC*: The abbreviation of *Second-order correlation coefficient*.

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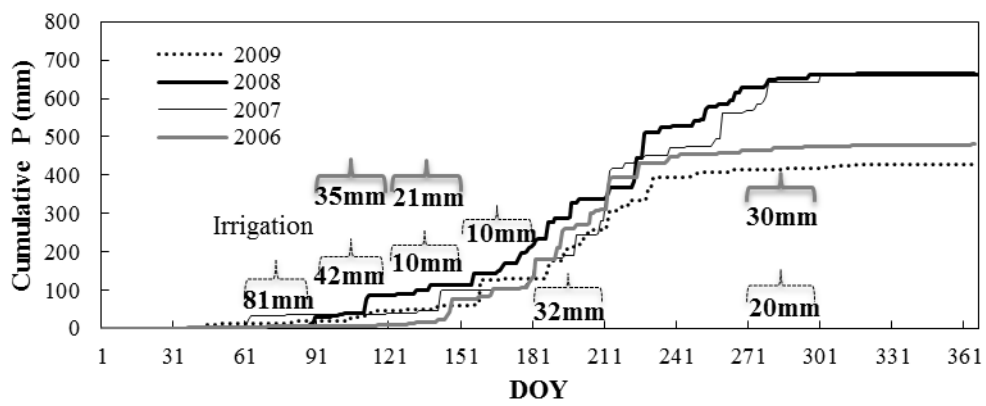


Figure 1. The cumulative precipitation (P) and periodic irrigation during 2006-2009, irrigation in 2006 and 2009 were separately represented by the solid and dotted brackets, respectively.

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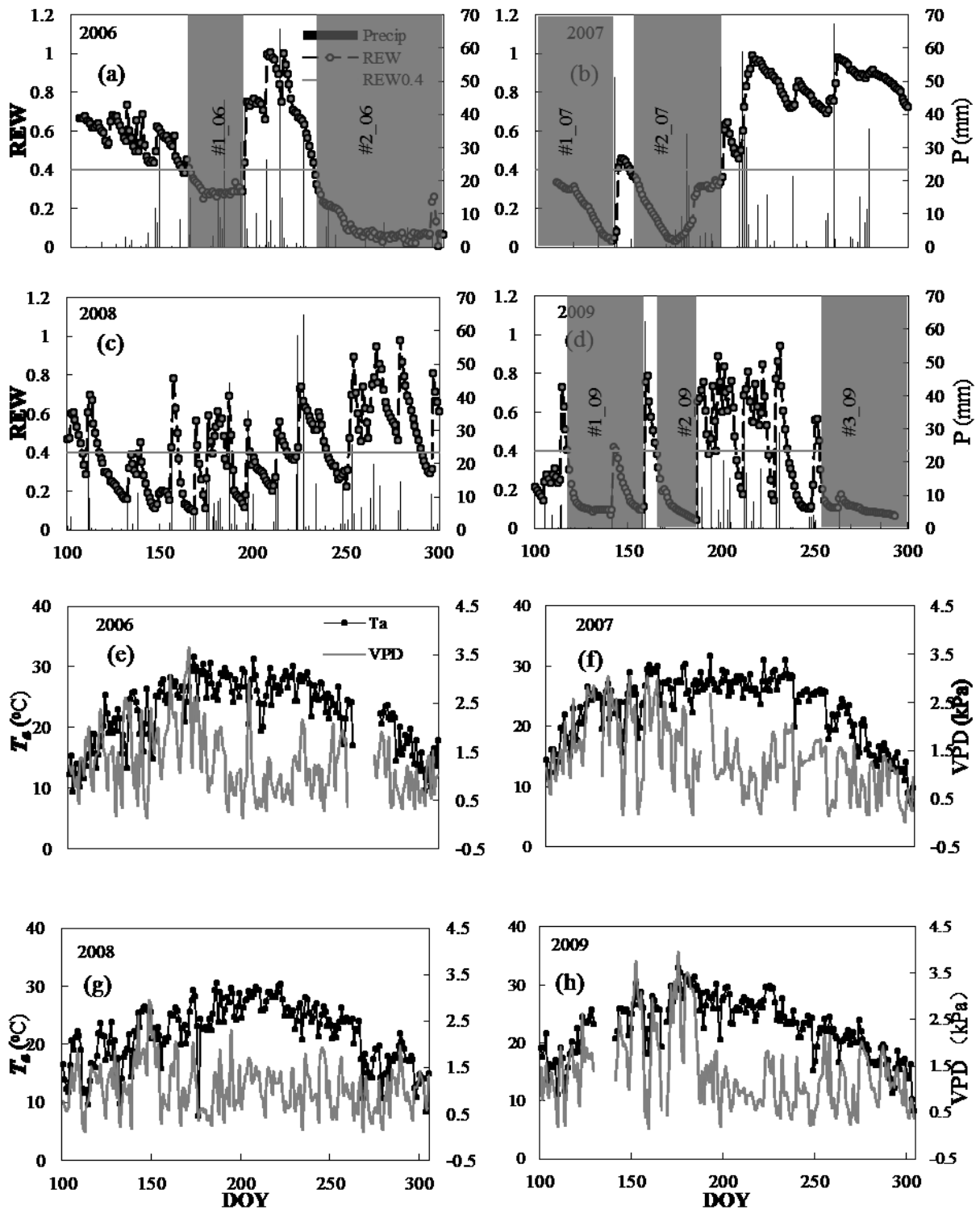


Figure 2. The seasonal variation of environmental conditions during 2006-2009, a-d: the relative extractable water (REW) (drought periods longer than 20 days are shaded), daily sum of precipitation (P); e-h: daytime mean air temperature ( $T_a$ ), daytime mean air vapor deficit (VPD).

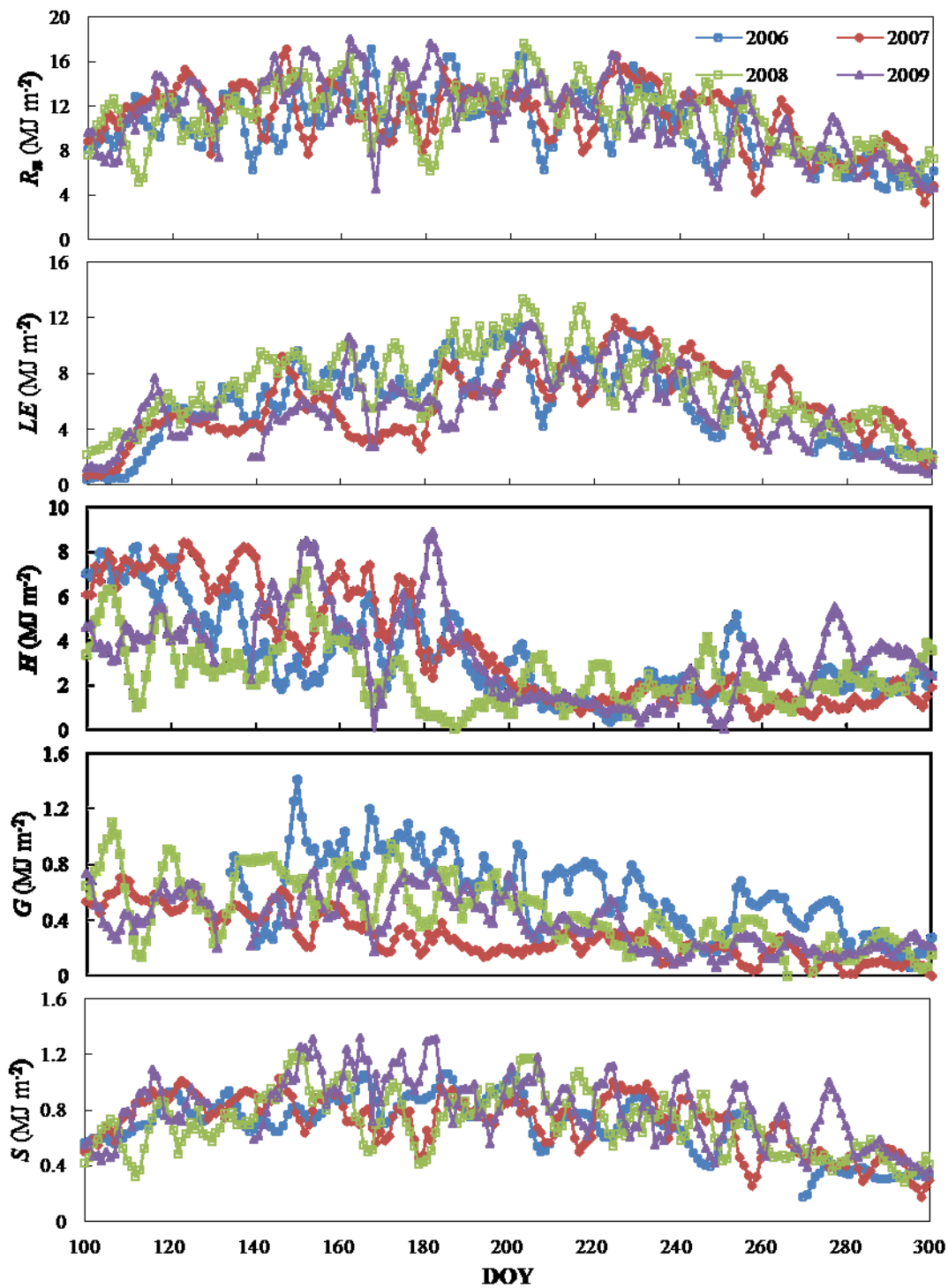


Figure 3. Seasonal patterns of daytime energy components (5-day running average) during the growing season from 2006 to 2009, including net radiation ( $R_n$ ), latent heat (LE), sensible heat (H) and soil heat flux (G) and heat storage term (S).



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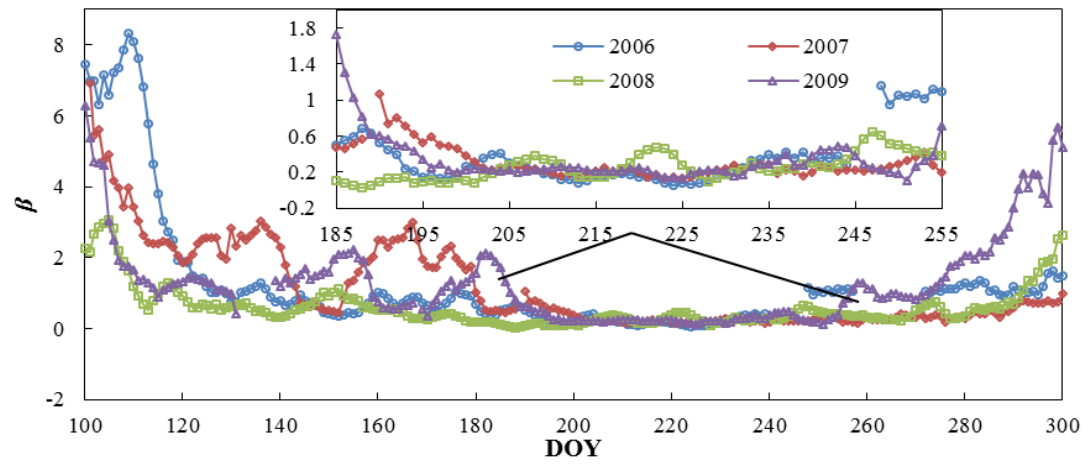


Figure 4. Seasonal and inter-annual variability of the midday (10:00-15:00 LST) mean Bowen ratio ( $\beta$ ) (5-day running average) across the growing season, with detailed  $\beta$  during DOY 185-255 representing in small pane.

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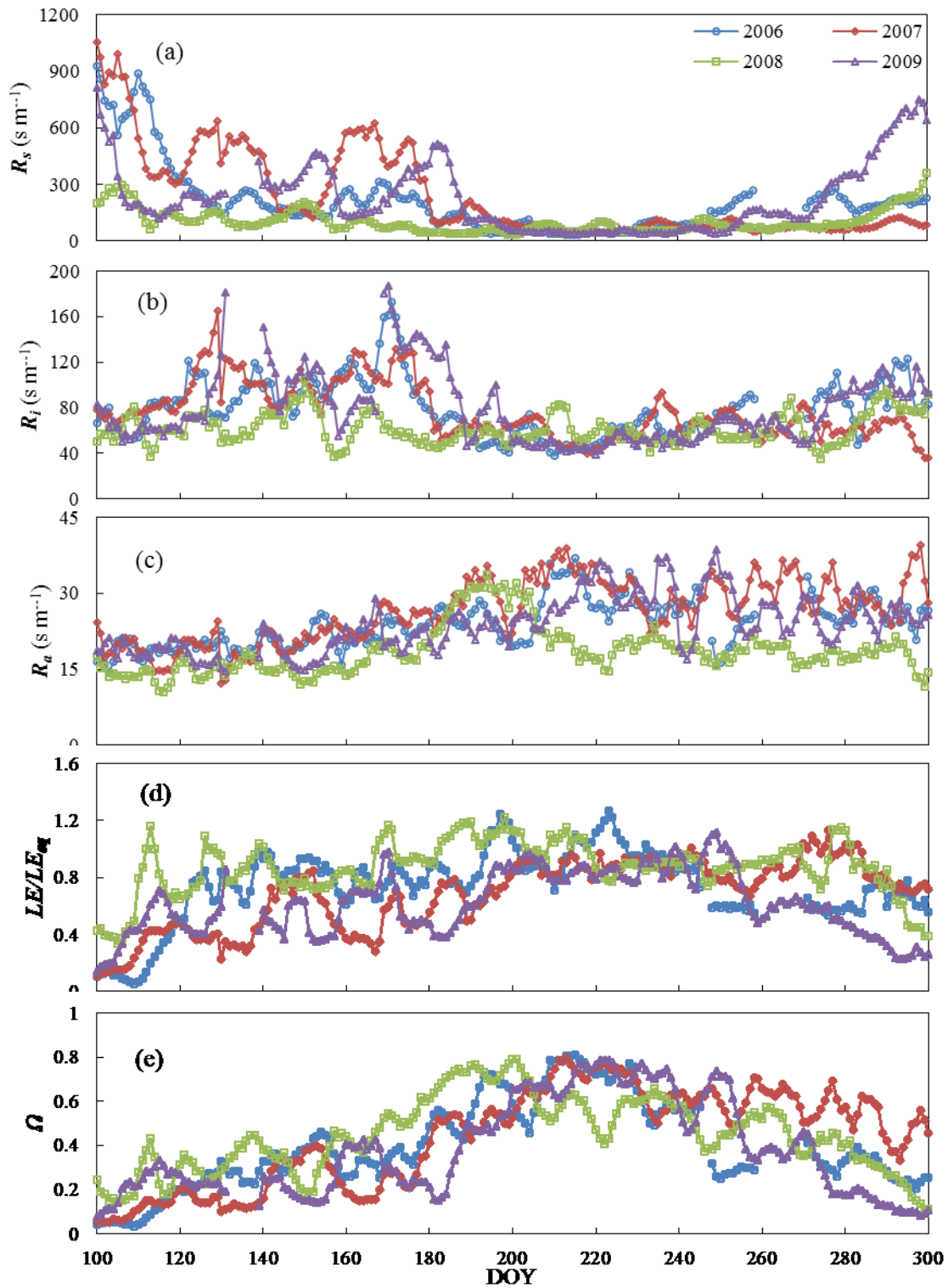


Figure 5. Seasonal dynamics of the midday (10:00-15:00 LST) mean surface resistance ( $R_s$ ), climatological resistance ( $R_i$ ), aerodynamic resistance ( $R_a$ ),  $LE/LE_{eq}$  and decoupling coefficient ( $\Omega$ ) (5-day running average) across the growing season from 2006 to 2009.

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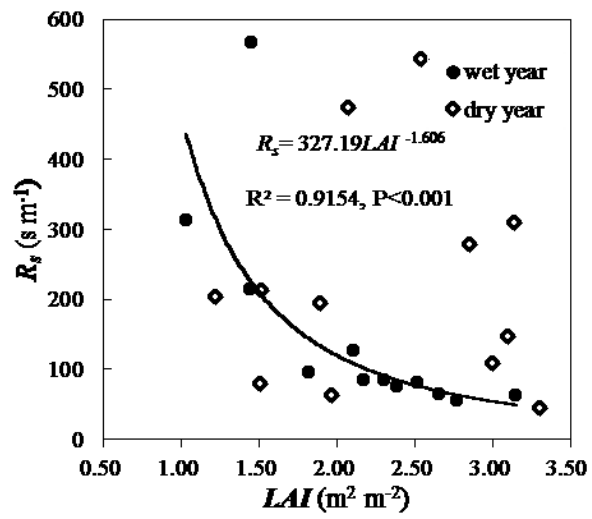


Figure 6. The relationship between leaf area index (LAI) and surface resistance ( $R_s$ ) during growing season of the wet and dry year.

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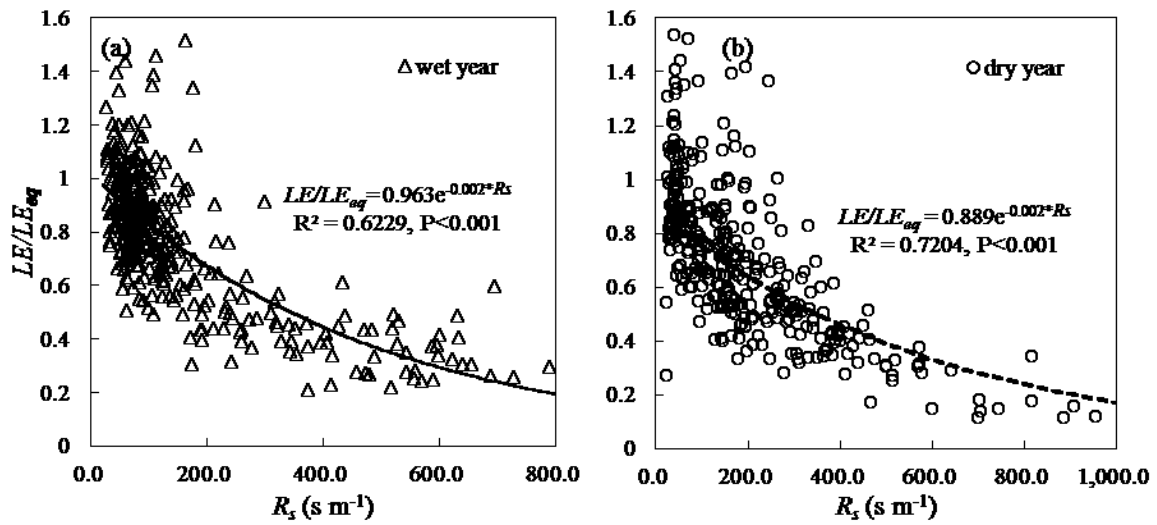
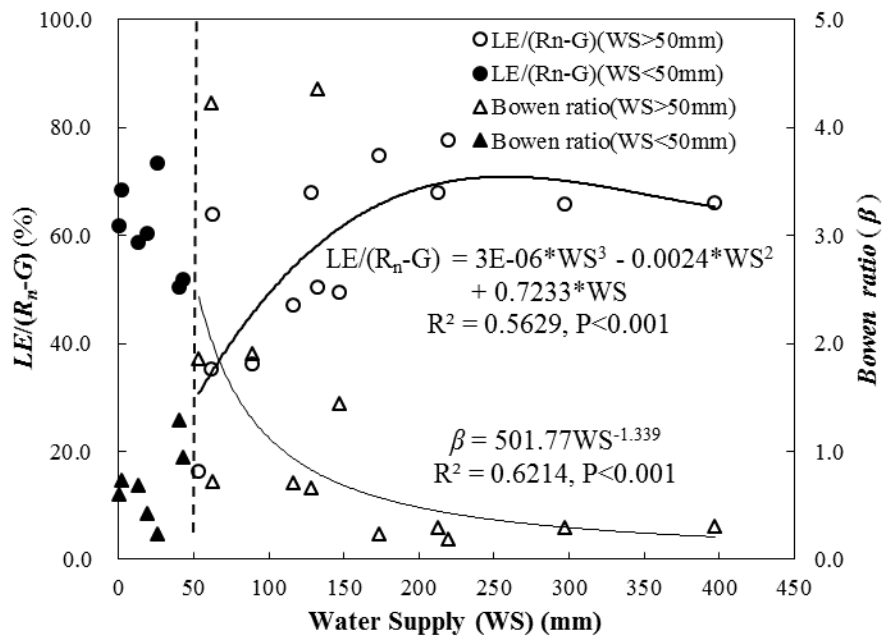


Figure 7. The relationships between surface resistance ( $R_s$ ) and  $LE/LE_{eq}$  (Priestley-Taylor coefficient) during growing season of the wet (a) and dry (b) year.

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Figure 8. The response of Bowen ratio and  $LE/(R_n-G)$  on Water Supply (WS) (including precipitation (P) and irrigation (I) during individual period) of the different periods across the four growing seasons.

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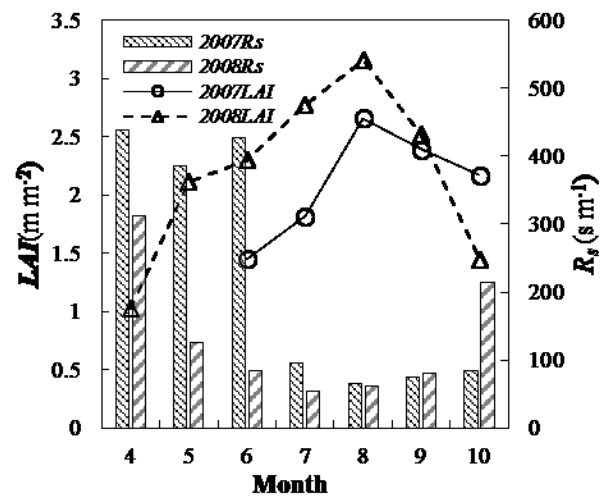


Figure 9. Seasonal variations of monthly average LAI and  $R_s$  during the growing season in wet year 2007 and 2008.

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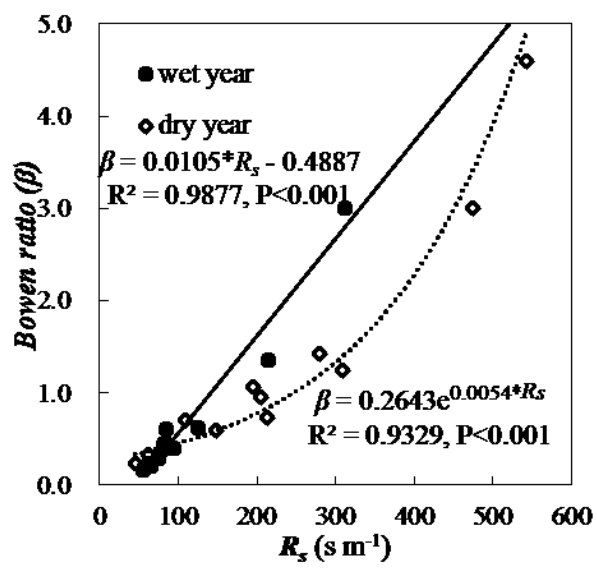


Figure 10. Response of monthly average Bowen ratio ( $\beta$ ) on surface resistance ( $R_s$ ) in the wet and dry year.