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Responses of energy partitioning and surface resistance to drought in a poplar plantation in northern China

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Abstract

Poplar (*Populus sp.*) plantations have been used broadly for combating desertification, urban greening, and paper and wood production in northern China. However, given the high water use by the species and the regional dry environment, the long-term sustainability of these plantations needs to be evaluated. Currently, the understanding of energy partitioning and canopy resistance to water vapor and CO_2 in poplar plantations is limited, impeding an accurate assessment of their true ecosystem functions. This study examined the variability of canopy bulk resistance parameters and energy partitioning over a four-year period encompassing both dry and wet conditions in a poplar (*Populus euramericana* CV. "74/76") plantation ecosystem located in northern China. Available energy (Net radiation R_n minus Soil Heat Flux, G) partitioning to latent (LE) and sensible (H) heat was responsive to climatological drought, with $\mathrm{LE}/(R_n - G)$ ranging from 62 % in wet years (e.g. 2007 and 2008) to 53 % in dry years (e.g. 2006 and 2009), and $H/(R_n - G)$ from 25 to 33 % between wet and dry years. Correspondingly, the Bowen ratio ($\beta = H/\mathrm{LE}$) were 0.83 and 1.57. Surface resistance (R_s) had the greatest response to drought (+43 %), but the aerodynamic and climatological resistances did not change significantly ($p > 0.05$). Partial correlation analysis indicated that R_s was the dominant factor in controlling the Bowen ratio. Furthermore, R_s was the major factor controlling LE during the growing season, even in wet years, as indicated by the decoupling coefficient ($\Omega = 0.45$ and 0.39 in wet and dry years, respectively), and the $\mathrm{LE}/\mathrm{LE}_{eq}$ ratio ranged from 0.81 and 0.68 in wet and dry years, respectively. In general, the dry surface conditions dominated in this poplar plantation ecosystem regardless of soil water availability suggesting that fast-growing and water use-intensive species like poplar plantations are poorly adapted for the water limited region.

1 Introduction

Poplar (*Populus sp.*) plantations are the most dominant broadleaf forest ecosystems throughout northern and central China, due to their rapid growth rates, high productivity and wide adaptability (Gielen and Ceulemans, 2001; Wilske et al., 2009; Zhang et al., 2011). Since the late-1970s, with the implementation of the "Three-North Shelterbelt Program" (1978), the "Combating Desertification Project" (1991) and the "Grain for Grain Program" (1999) (Wilske et al., 2009), poplar plantations have been playing a vital role in timber production, bioenergy, urban greening, desertification control, and carbon sequestration (Martín-García et al., 2011; Zhou et al., 2013). By 2007, China had the largest poplar plantation area in the world (i.e., more than 7.0 million ha, Fang, 2008). However, planting trees in regions with water scarcity may increase risk factors related to environmental degradation, potentially affecting soil moisture, hydrology and vegetation coverage (Gao et al., 2014).

Northern China is experiencing land degradation, a growing frequency of drought, and a rapid decline of the ground water table (Qiu et al., 2012; Wang et al., 2008) due to the pressures from rise of irrigation demand and climate change. In recent decades, there has been a rapid landscape-scale shift in ground cover along with the ecological restoration efforts (Liu et al., 2003; Wang et al., 2012). However, large-scale afforestation in those vulnerable arid and semi-arid regions could also intensify the severity of water shortages (Liu et al., 2010) due to rise of water use from forest plantations (Sun et al., 2006). Therefore, the long-term sustainability of planting poplar plantations, which typically have higher productivity but also higher water use (Zhou et al., 2013) than other forests, needs to be reevaluated for water limited areas such as northern China.

Over the past 50 years, northern China has experienced the largest increases in surface air temperature and severe droughts (Ding et al., 2007), which have led to a loss of river flow, and shrinkage of lakes (Qiu et al., 2012). In addition to climate variability and change, urbanization, agriculture, pasturing, deforestation, desertification and irrigation (Zhang et al., 2005a, b) have been cited as possible causes for these impacts. Therefore, studying the drought response of vegetation under the climate and land use change is essential for effective management of water resource over this region.

Drought impacts are universally reflected in lower canopy conductance as stomata close to prevent excessive loss of water and the onset of cavitation (Arango-Velez et al., 2011; Poggi et al., 2007; Vilagrosa et al., 2003). However, the extent of stomatal closure is determined by tradeoffs between plant water status and the thermal protections of leaf enzymes (Farooq et al., 2009). Plants can use a number of adaptive strategies to cope with drought stress (Chaves et al., 2002; Lens et al., 2013), which include a variety of physiological and biochemical responses at cellular and whole-organism levels, such as decreasing transpiration through stomatal closure, the timing of budburst, and the depth of root system (Zapater et al., 2013). Conversely, at an ecosystem level, the drought stress can be characterized either in hydrologic or physiological terms (Akinci and Lösel, 2012), and the drought response of an ecosystem is mainly reflected in energy partitioning leading to reduced evapotranspiration and water use efficiency (Wagle and Kakani, 2014). Depending on the physiological capacities of the vegetation these responses may diverge across different ecosystem types (Akinci and Lösel, 2012). Understanding of the energy partitioning and ecosystem response to drought is central to understanding forest water and carbon cycling processes under future environmental conditions (Guo et al., 2010; Jamiyansharav et al., 2011; Sun et al., 2010; Takagi et al., 2009; Wu et al., 2007).

The drought responses in energy partitioning in a ten-year old poplar (*Populus euramericana* CV. “74/76”) plantation in northern China was evaluated in this study. We hypothesized that the drought would trigger significant changes in the surface conductance, transpiration and energy partitioning in the water-demanding poplar species. Specifically, the objectives of this study were to: (1) quantify the seasonal and interannual variability of energy partitioning and bulk resistance parameters, (2) partition the control of energy partitioning to biological and climatological components; and (3)

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evaluate the long-term sustainability of poplar plantations in a water limiting region in northern China.

2 Materials and methods

2.1 Study site

The study was carried out in a managed poplar (*Populus euramericana* CV. “74/76”) plantation at the Daxing Forest Farm, which is located in the southern suburbs of Beijing, China (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, dead or low-vigor trees were removed and replanted in 2001 and 2003. The stand characteristics over the four years of study are given in Table 1. At the end of 2009, the average height of the trees were 16.2 ± 1.6 m, and the diameter at breast height (DBH) was 14.1 ± 1.6 cm. The average leaf area index (LAI) of the stand increased year by year. During the growing season, shrubs were present at low density under the canopy due to manual removal. Perennial herbs included *Chenopodium glaucum Linn.*, *Medicago sativa* L., *Melilotus officinalis* (L.) *Lam.*, *Salsola collina Pall.*, and *Tribulus terrestris* L.

The local climate is classified as sub-humid warm temperate zone. The mean annual temperature is 11.6 °C, and maximum and minimum extreme temperatures reaches 40.6 and −27.4 °C, respectively (1990–2009). Annual precipitation ranges from 262 to 1058 mm with a long-term (1952–2000) average of 556 mm, about 60–70 % of annual precipitation falls from July to September (Daxing Weather Station, 116°19′56″ E, 39°43′24″ N). The annual frost-free period lasts 209 days, and sunshine-hours reaches 2772 $\mathrm{h\,year^{-1}}$ with 15.5 $\mathrm{MJ\,m^{-2}\,d^{-1}}$ of incoming solar radiation. The average wind speed is 2.6 $\mathrm{m\,s^{-1}}$, mostly in the southern and northwest directions.

The study area belongs to the alluvial plain of Yongding River, and is flat with average slopes less than 5°. The upper two meter soil layer is mostly composed of well drained fluvial sand with bulk density of 1.43 ~ 1.47 $\mathrm{g\,cm^{-3}}$ and with a pH of 8.25 ~ 8.39. The soil porosity is about 40 % and capillary porosity is 32 %. The groundwater table has an average annual depth of 16.5 m below ground in the past nine years (2001 to 2009), and has declined at an average rate of 0.6 m year^{-1}. The maximum pan evaporation occurs from May to June, exceeding precipitation for the same period. Severe drought during the beginning of the growing season (from April to June) in northern of China is common. Thus, irrigation was periodically applied to meet the water deficit to the plantations at our study site. The amount of flood irrigation water was back calculated based on the records of the water meters from three wells on a weekly basis. Other management practices included tilling, weeding since the establishment of the plantations.

2.2 Eddy covariance system

The micrometeorological and eddy flux measurements were conducted at the 32 m central instrument tower in the center of the study site, established in June of 2005. The foot-print of the eddy flux covariance system, was about 1 km × 1 km in size. The observation site has a sufficiently wide fetch of at least 300 m in all directions. Fluxes of CO_2, water, sensible heat and latent heat were measured using the eddy-covariance technique. The eddy-covariance sensors included a CO_2/H_2O infrared analyzer (Li-7500; LI-COR, Inc., Lincoln, NE, USA) and a three-dimensional sonic anemometer (CSAT-3; Campbell Scientific, Inc., CSI, UT, USA). The CO_2/H_2O sensor head was installed downwind of the sonic anemometer in the predominant wind direction, and the analyzer was calibrated every year. The EC sensors were mounted initially at a height of 16 m in 2006. To ensure that the sensors remained well above the top of the growing tree canopy, the instrument height was increased before the start of the growing season in 2007, to about 18 m, and again to 20 m in February 2009.

Net radiation was measured with net radiometers (Q7.1, REBS, Seattle, WA, USA) and (CNR-1; Kipp and Zonen, Delft, Netherlands) at 26 m above the ground. Photosynthetically active radiation (PAR) was measured by a PAR quantum sensor (LI-190SB; LI-COR, Inc.) mounted at 20 m. The atmospheric pressure was measured by a barometric pressure sensor (CS105, CSI) at 21 m height. Air temperatures and humidity were measured with temperature and relative humidity probe (HMP45C; Vaisala, Helsinki, Finland) with sampling points at 5, 10, 15 and 20 m. Precipitation was measured with a tipping bucket rain gauge (TE525-L; Texas Electronics, USA) at 22.5 m above the ground. Soil heat flux was determined with three soil heat transducers (HFT3, CSI), and soil temperatures were measured with three thermocouples (TCAV107; CSI) located at depths of 5, 10 and 20 cm below the soil surface. Soil water content was measured with TDR sensors (CS616; CSI) buried at a 50 cm depth.

With the exception of the rain gauge, all microclimatic data were recorded with a data-logger (CR23X; CSI) at 30 min intervals and the fluctuations in wind speed, sonic temperature and CO_2 and H_2O concentrations were sampled at 10 Hz, and recorded by a CR5000 data-logger (CSI).

2.3 Data processing and QA/QC

Eddy covariance (EC) data have been processed with EC Processor, version 2.3 (Noormets et al., 2010). The program is designed for reprocessing eddy covariance flux data and can calculate half-hour mean eddy covariance fluxes of carbon, water and energy. The wind coordinates were rotated using planar fit method (Paw U et al., 2000; Wilczak et al., 2001). Fluxes were corrected for additional sensor heating (Burba et al., 2008) and fluctuations in air density (Webb et al., 1980). The data quality controls included: screening of 30 min mean eddy covariance fluxes based on instrument quality flag, integral turbulence characteristics (Foken and Wichura, 1996), flux stationarity, atmospheric stability, and adequate turbulent mixing (Goulden et al., 1996). Data gaps were filled using the MDV (mean diurnal variation) method (Falge et al., 2001). The threshold of friction velocity (μ_*) below which flux loss occurred was determined from the seasonal binned relationship between nighttime turbulent flux of CO_2 and friction velocity (μ_*) (Schmid et al., 2003). The threshold was consistent across different seasons, but differed slightly between years: 0.18 (2006), 0.12 (2007), 0.14 (2008) and 0.13 $m\,s^{-1}$ (2009). In this study, the MDV (mean diurnal variation) method (Falge et al., 2001) was used to fill the data gaps, the linear relationship between LE or H and net radiation (R_n) was used to gap-fill each flux when short period (< 2 h) flux data were missing. A ±7 day moving average was used to fill the each flux gaps for period between 2 h and 7 days. Gaps longer than 7 days were not filled.

The four-year measurement period was divided to "wet" and "dry" years, based on whether the annual precipitation exceeded the 20 year mean (1990–2009, mean annual precipitation 556 mm). Years 2007 and 2008 were classified as "wet", and 2006 and 2009 were "dry". We focused on the growing season when the driving forces (e.g., solar radiation, and temperature) for energy and water fluxes and the physiological response of vegetation were usually much stronger. In this study, the strongest forcing days occurred approximately between day 100 (mid-April) and day 300 (late October). The daytime was defined as the period between the sunrise and sunset with PAR > 4 umol m^{-2} s^{-1}, the controlling processes of surface exchange are often different during nocturnal periods (Mahrt, 1999) and heat fluxes at night are typically weaker and markedly less reliable than during the daytime (Wilson et al., 2002b). The midday was defined as the period from 10.00 a.m. to 15.00 p.m. at local standard time, when the interaction between vegetation and environment was usually the strongest.

2.4 Biophysical characteristics

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

$$\mathrm{REW} = \frac{\mathrm{VWC} - \mathrm{VWC_{min}}}{\mathrm{VWC_{max}} - \mathrm{VWC_{min}}} \tag{1}$$

where $\mathrm{VWC_{min}}$ and $\mathrm{VWC_{max}}$ are the minimum and maximum soil volumetric water content across the four years, respectively.

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As an indicator of water stress, the Bowen ratio (β) reflects the influence of microclimate and the hydrological cycle on the energy partitioning and water use of the ecosystem (Perez et al., 2008), the midday β is calculated as Eq. (2):

$$\beta = \frac{H}{\mathrm{LE}} \tag{2}$$

The energy balance ratio (E_{BR}) is calculated as Eq. (3) (Gu et al., 1999):

$$E_{\mathrm{BR}} = \frac{\sum(H + \mathrm{LE})}{\sum(R_{\mathrm{n}} - G)} \tag{3}$$

During midday periods (from 10:00 to 15:00 LST), the *Penman–Monteith* approximation was inverted to calculate the surface resistance (R_{s}) in Eq. (4) (Kumagai et al., 2004):

$$R_{\mathrm{s}} = \frac{\rho c_p(\delta_e/\mathrm{LE})}{\gamma} + \left(\frac{\Delta}{\gamma}\beta - 1\right) R_{\mathrm{a}} \tag{4}$$

where R_{s} is the surface resistance to water vapor transport ($\mathrm{s\,m^{-1}}$), 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, the climatological resistance ($\mathrm{s\,m^{-1}}$) indicates the atmospheric demand (Wilson et al., 2002b) and is calculated in Eq. (5):

$$R_i = \frac{\rho c_p \delta_e}{\gamma A} \tag{5}$$

where A is the available energy ($R_{\mathrm{n}} - G$); ρ is air density ($\mathrm{kg\,m^{-3}}$), c_p is the specific heat of the air ($1005\,\mathrm{J\,kg^{-1}\,K^{-1}}$); δ_e is the atmospheric vapor pressure deficit (Pa); LE is latent heat flux; Δ is the change of saturation vapor pressure with temperature ($\mathrm{Pa\,K^{-1}}$); γ is the psychrometric constant ($\approx 67\,\mathrm{Pa\,K^{-1}}$); β is the Bowen ratio.

R_a is the aerodynamic resistance of the air layer between the canopy and the flux measurement height ($\mathrm{s\,m^{-1}}$), which 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):

$$R_a = r_{a,\,m} + r_b = \frac{\mu}{\mu_*^2} + 6.2\mu_*^{-2/3} \tag{6}$$

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

The decoupling coefficient (Ω) explains the degree of coupling between the atmosphere and the vegetation, and describes the relative control of evapotranspiration by surface conductance and net radiation (Pereira, 2004). The Ω value ranges from 0 to 1, with value approaching zero indicating that LE is highly sensitive to surface resistance and ambient humidity deficit. The Ω value approaching to 1 indicates that LE or evapotranspiration is mostly controlled by net radiation (Jarvis and McNaughton, 1986):

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma(1 + \frac{R_s}{R_a})} \tag{7}$$

The Equilibrium evaporation ($\mathrm{LE_{eq}}$) is the climatologically determined evaporation (atmospheric demand) over an extensive wet surface and it is calculated as:

$$\mathrm{LE_{eq}} = \frac{\Delta(R_n - G)}{\Delta + \gamma} \tag{8}$$

The $\mathrm{LE_{eq}}$ is dependent only on R_n and temperature. Lower or higher values indicate that evaporation rates are lower or higher than the equilibrium rate, respectively (Wilson et al., 2002b).

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The ratio LE/LE_{eq}, which is also known as the Priestley–Taylor α, can denote the control of evaporation by atmospheric and physiological factors, and characterizes the surface dryness of ecosystem. An LE/$\text{LE}_{\text{eq}} < 1$ represents a dry ecosystem that undergoes limitations in water supply, and therefore experiences reductions in evapotranspiration, whereas LE/$\text{LE}_{\text{eq}} > 1.26$ signifies a wet ecosystems where the water supply is unrestricted and only available energy limits evaporation (Arain et al., 2003). The LE/LE_{eq} was generally related to leaf area index (LAI), soil water content, meteorological conditions (e.g., wind speed, solar radiation, VPD, air stratification stability, convection, advection surface resistance), vegetation types, and altitude (Guo et al., 2008).

2.5 Statistical analysis

Repeated measurement ANOVA (SPSS) was used to compare the environmental factors, the energy fluxes and bulk parameters among years. The *t* test was used to compare different studies. The partial correlation analysis was used to distinguish the impacts of each of the three resistance parameters (R_{s}, R_i and R_{a}) on the Bowen ratio values with the other two as the control variables. All analyses were accessed at $\alpha = 0.05$.

3 Results

3.1 Environmental conditions

The annual precipitation rates in the four study years differed from the long-term average (556 mm yr^{-1}) (1990–2009). Precipitation was 74 mm below this the long term mean in 2006 and 159 mm in 2009. Whereas in 2007 and 2008 rainfall exceeded the 20 year mean by over 100 mm. Generally, over 90 % precipitation of each year occurred in the growing season (i.e., April–October) but with different timing and magnitude among years. The study site was irrigated during the dry years of 2006 and 2009 to mitigate drought conditions (Fig. 1). Long-term drought stress ($\text{REW} < 0.4$) occurred during period in late growing season of 2006 and 2009, in spring in 2007 and 2009, but not at all in 2008 (Fig. 2a–d). In 2006, precipitation of growing season reached 467 mm, of which 51 % had occurred by July. The amount of irrigation was 35 mm in April, 21 mm in May and 30 mm in September. The two long-term drought periods separately were #1_06 (from DOY 164 to 192) and #2_06 (from DOY 231 to 300). The total rainfall in 2007 and 2008 was similar, but more evenly distributed in 2008. In 2007, drought stress occurred during the period from DOY 110 to 143 and from DOY 151 to 200. A single rain event in late May accounted for 57 mm of the total annual precipitation, and a few large precipitation events ($P > 25\,\text{mm}\,\text{d}^{-1}$) in July also presented a large portion of the total annual sum. The amount of rainfall in 2009 was smallest among the four years, and 195 mm of irrigation was applied from March to September, mostly in the early growing season, but there were several short and scattered drought periods across the growing season (Fig. 2d). Despite above-normal rainfall in two wet years, no flooding or overland runoff occurred even during intensive rain events because of the high infiltration capacity of the sandy soil.

The T_a in 2008 was significantly lower than that in 2007 and 2009 during growing season ($p < 0.05$, Fig. 2e–h). The years differed in the spring warm-up and the timing of peak temperature (by up to 35.9 °C). The maximum air temperature occurred in June in 2006 and 2009, and July in 2007 and 2008. The overall warmest month was June for 2006 (27.1 ± 2.4 °C).

The daytime average VPD of the four growing seasons (Fig. 2e–h) reached 1.3 ± 0.7 kPa. Mean VPD in wet years (i.e., 2007 and 2008) was 1.2 ± 0.7 kPa, which was significantly lower ($F = 6.093$, $p < 0.01$) than that in dry years (i.e., 2006 and 2009, 1.3 ± 0.8 kPa). The VPD of the growing seasons in 2008 (i.e., 1.1 ± 0.5 kPa) was lower than in the other years ($p < 0.05$). Higher T_a and lower precipitation in May 2007 led to higher VPD compared with the same period in 2006 and 2008 ($p < 0.001$). Further-

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more, the VPD of June 2009 was the highest (i.e., 2.3 ± 1.1 kPa,$p < 0.05$) and in 2008 was the lowest (i.e., 1. ± 0.5 kPa, $p < 0.01$).

3.2 Seasonal changes in energy partitioning and β

Seasonal and inter-annual energy partitioning trends of daytime total net radiation (R_n) among latent, sensible heat fluxes (LE and H) and soil heat fluxes (G) for the year 2006–2009 were presented in Fig. 3. Among these years, R_n varied with solar radiation (R > 0.95, at $\alpha = 0.01$ level) and reached the maximum in July, and then gradually decreased until the late October (in dry years) or November (in wet years). During growing season, there were no significant difference in average daytime total R_n between wet and dry years. On the other hand, even though the average of daytime total Gduring the growing season displayed great seasonal and annual differences between these years ($p < 0.05$), the value of wet years was lower than that of the dry years ($p < 0.001$). Also, G only accounted for a small proportion of R_n, which ranged from 2.1 (in 2007) to 4.9 % (in 2006).

LE was the dominant turbulent flux with changes of R_n, and started to rapidly increase in mid-April and reached a maximum in July for all 3 years (i.e., in 2006, 2008 and 2009), except in August for the year of 2007. The peak value of daytime total LE was 16.61, 17.01, 19.72 and 16.27 MJ m^{-2}, in 2006 to 2009 respectively. H was the dominant factor controlling the growing season R_n (in October for dry years and in November for wet years). Among four years, LE/($R_n - G$) was significantly higher in 2008 (64.8 %) than in 2006 (57.1 %), 2007 (60.3 %) and 2009 (50.4 %) ($p < 0.05$). LE/($R_n - G$) was much lower in 2009 than in the other 3 years ($p < 0.01$). Partitioning of R_n into LE and H differed significantly between the wet and dry years (Table 3). The average daytime total LE in wet years was greater (6.77 MJ m^{-2}) than that of dry years (5.72 MJ m^{-2}, $p < 0.01$). The dominant part in energy partitioning during the early growing season was sensible heat flux (H) with or without drought stress, except in 2006 during which the irrigation were applied (Table 3). Then LE was the dominate driver

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of energy partitioning during the middle and late growing season even under drought stress.

The seasonal variation of the midday Bowen ratio (β) displayed rapid and significant trend across growing season, especially at the beginning (from April to June) and end (from September to October) of the growing season (Fig. 4). The Bowen ratios during the middle of growing seasons were all smaller than 1, and approximately lasted from DOY 180 to 250 in the dry year and from DOY 180 to 290 in the wet year, separately. The average midday β of dry year was greater (1.57) than that of wet year (0.83; $F = 19.176$, $p < 0.001$). The Bowen ratio showed differences in response to drought stress across four growing seasons (Table 3), and had much higher values (> 1) during long-term drought periods in 2007 and 2009, but not in 2006. The Bowen ratio were all smaller than 1 during short drought stressed periods in 2008.

3.3 Biophysical controls of energy partitioning

The R_s varied widely at the beginning and the end of growing season, but changed steadily within a low range during the middle of growing season by comparison. Moreover, these lower R_s in the dry year lasted a shorter period (DOY: from 190 to 250) than in the wet year (Fig. 5a). Overall, the seasonal average R_s in 2008 was lowest among four year (i.e., $p < 0.05$, Table 3). The R_s in the dry year ($240.3\,\mathrm{s\,m^{-1}}$) was 50 % higher than in the wet year ($153.1\,\mathrm{s\,m^{-1}}$) ($p < 0.001$). The R_s in the long-term drought stressed periods of 2006, 2007 and 2009 were greatly higher than in the no stressed periods ($p < 0.001$). In addition, significantly negative relationship was found between the R_s and LAI during the wet year (Fig. 6).

The average midday R_i peaked in June, and decreased in July and August, before reaching a second peak in October (Fig. 5b). The seasonal average R_i during growing season ranged from 68.3 to $77.9\,\mathrm{s\,m^{-1}}$, with mean value of $74.4\,\mathrm{s\,m^{-1}}$, and showed no difference between four growing seasons ($p > 0.05$). Figure 5c depicts the seasonal and annual variations of midday R_a. The average R_a for the four growing seasons was

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$23.2 \pm 8.5\,\mathrm{s\,m^{-1}}$, ranging from 10.6 to $43.5\,\mathrm{s\,m^{-1}}$, 9.7 to $52.5\,\mathrm{s\,m^{-1}}$, 6.5 to $43.1\,\mathrm{s\,m^{-1}}$, 9.7 to $74.5\,\mathrm{s\,m^{-1}}$, from 2006 to 2009, respectively. R_a in 2007 was significantly higher than during the dry years ($p < 0.01$), while R_a in 2008 was smaller than in dry years ($p < 0.001$). However, there were no significant difference between dry and wet year R_a ($p > 0.05$).

In this study, the seasonal changes of $\mathrm{LE/LE_{eq}}$ value were generally below 1 and > 0.4 during most of the growing seasons (Fig. 5d). The average $\mathrm{LE/LE_{eq}}$ of four years were 0.76, 0.73, 0.89, and 0.63, respectively. The mean $\mathrm{LE/LE_{eq}}$ of the dry years (0.68) was lower than that of wet years (0.81; $p < 0.001$). Specifically, the value of $\mathrm{LE/LE_{eq}}$ in drought periods of 2007 and 2009 was much smaller. A significantly exponential relationship was observed between the $\mathrm{LE/LE_{eq}}$ and R_s during the growing season (Fig. 7).

The decoupling coefficient (Ω) across the growing season peaked in mid-July in 2008 and in early August in the other years (Fig. 5e). The mean Ω for the studied years were 0.41, 0.46, 0.43 and 0.39 (Table 3), respectively, and was significantly higher in wet year (0.45) than in dry year ($p < 0.01$). Compared to the value during non-stressed periods, the decoupling coefficient during the long-term drought periods (#1, #2 in 2006; #1, #2 in 2007 and #1, #2, #3 in 2009) showed dramatic lower values.

4 Discussion

4.1 Energy partitioning and Bowen ratio

The energy balance ratio (E_BR) is one way of evaluating scalar flux estimates from eddy covariance (Chen et al., 2009). In this study, the closure of the energy budget was 0.85 based on daytime 30 min fluxes, and over 0.95 based on daily totals (Table 2). The annual mean E_BR at our site was similar to the value of eight ChinaFlux sites, which averaged 0.83 and ranged from 0.58 to 1.00 (Li et al., 2005). The energy budget is also consistent with 50 site-year of flux data from 22 in FLUXNET sites, which had energy

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closure of 0.34–1.69 (Mean = 0.84) (Wilson et al., 2002a). It should be noted that the mean closure has not changed in over decade of additional measurements. A recent analysis of 173 FLUXNET sites also found an average closure of 0.84 (Stoy et al., 2013), although the authors also detected consistent differences between biomes, and based on metrics of landscape heterogeneity. At our site, in addition to reasons known to decrease energy balance closure (Hernandez-Ramirez et al., 2010; Li et al., 2005; Nakai et al., 2006; Stoy et al., 2013), management operations on the plantation site, such as irrigation, tilling and partial felling, may also affect the energy balance. Although the causes of surface energy balance closure continues to be debated (Stoy et al., 2013) and will not be conclusively answered in the current study, to the extent that the closure represents the quality of turbulent flux data, the results reported here are similar to other FLUXNET sites.

The surface energy partitioning depends on water potential gradient and surface conductance (Arain et al., 2003; Baldocchi et al., 2000; Chen et al., 2009). To the extent that canopy development (Guo et al., 2010), rainfall dynamics and irrigation (Ozdogan et al., 2010) affect these properties, and they could directly lead to a change in soil moisture and the evaporation component of LE, therefore impact energy partitioning and β (Chen et al., 2009; Ozdogan et al., 2010). However, the impact of precipitation on the Bowen ratio may vary even at specific forest site (Tang et al., 2014). In our study, a detectable response of $\mathrm{LE}/(R_\mathrm{n}-G)$ and Bowen ratio to drought stress and non-stress periods was observed in response to soil water supply (Table 3) with a 50 mm threshold on average (Fig. 8). The variability of energy partitioning during the growing season was highly sensitive to water avaiability from precipitation and irrigation. On an annual timescale, the Bowen ratio was linearly related to the total precipitation amount of growing season ($R^2 = 0.89$, $p < 0.05$). Thus, the Bowen ratio is very responsive to the site water supply, similar finding was reported in Grünwald and Bernhofer (2007) in a temperate spruce forest.

By contrast, β during the most of growing season in 2008 and non-stressed periods in other 3 years varied from 0.18 to 0.71, with a mean of 0.35 ± 0.15, which was close to 0.42 in deciduous forests (Wilson et al., 2002b) and 0.55 in a temperate Douglas-fir (Humphreys et al., 2003). Similar to the variations of Bowen ratio in a ponderosa pine forest in the western United States (Goldstein et al., 2000) and in a deciduous broadleaved forest in the southern United States (Wilson and Baldocchi, 2000), long-term drought stress had a discernible impact on the Bowen ratio of this poplar plantation. However, compared to the reported β values such as, 0.74 in a temperate mixed forest (Wu et al., 2007), 0.81 in a boreal Scots pine forest (Launiainen, 2010), 0.89 in a Loblolly pine plantation (Sun et al., 2010), the average β in wet years were close to the above values. β was higher in long-term drought periods and dry years than most temperate coniferous forests (Mean = 1.07, Wilson et al., 2002b), which typically had a higher β values. The high β value in this study reflects the semi-arid conditions, and suggests a low tree water supply which resulted from the combination of low rainfall, low water holding capacity of the sandy soil, and high plant and atmospheric water demand. It has been suggested that the large-scale establishment of poplar plantation in sandy semi-arid regions of northern China could have an adverse impact on the region's groundwater reserves (Li et al., 2014; Petzold et al., 2011). Our current findings corroborate that hypothesis. Growing poplar trees by irrigation in a water stress region is not sustainable, and the productivity of the plantation was water-limited even during the wetter years, as indicated by the resistance terms.

4.2 Biophysical control on Bowen ratio

The Bowen ratio is dependent on the interactions of climatic and biological factors (Perez et al., 2008; Wilson and Baldocchi, 2000). R_i qualifies the climatic control on energy partitioning and tends to decrease the Bowen ratio. A higher R_i implies a warm and dry climate in continental regions (Raupach, 2000; Wilson et al., 2002b). R_s reflects the physiological control on surface energy exchange of ecosystem (Costa et al., 2010; Launiainen, 2010; Zhou et al., 2010), and generally increases the Bowen ratio. Wilson et al. (2002b) reported that R_s was the dominant factor in controlling the variability of the Bowen ratio of forests in temperate regions. A linear relation was also found

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between the Bowen ratio and R_s normalized by aerodynamic (R_a) and climatological resistance (R_i) parameters (Cho et al., 2012).

In this study, similar to Kutsch et al. (2008), R_s varied seasonally with plant phenology, and showed similar seasonal characteristics with the other deciduous forests during the course of the growing season (Cabral et al., 2010; Li et al., 2012). As reported by Tchebakova et al. (2002), R_s in the long-term drought stressed periods were much higher than in non-stressed periods. The drought stress during the canopy development in 2007 led to lower leaf area and higher canopy resistance (Noormets et al., 2008), which may explain significant difference in R_s between wet year 2007 and 2008 (Fig. 9). Compared with the mean R_s illustrated by Wilson et al. (2002b), the R_s of this poplar plantation (especially in dry years) was significantly greater than that of poplar and other deciduous forests (Mean = $72\,\mathrm{s\,m^{-1}}$). The R_s was over 60 % higher than the R_s of boreal aspen during the full-leaf period (Blanken et al., 1997). R_s is primarily driven by solar radiation, moisture availability and VPD (Fernández et al., 2009; Li et al., 2012), and modulated by leaf area and stomatal resistance, which in turn changes as a function of the above factors (Wilson and Baldocchi, 2000). Drought is also an expected source of interannual variation in R_s (Wilson et al., 2002b). The strong correlation between R_s and LAI in wet years (Fig. 6) suggested that R_s in dry years was impacted by other physiological and non-physiological (soil evaporation, canopy structure and turbulence) factors (Wilson et al., 2002b). The mean R_i in this study area was higher than mean R_i across site-year for forests in Wilson et al. (2002b) ($t = 5.91$, df = 741, $p < 0.001$), but over 50 % lower than the value reported by Li et al. (2009) for a vineyard in Gansu Province in China ($t = -29.87$, df = 741, $p < 0.001$), due to the warm-dry climate of the northern region in China.

On the seasonal timescale, the Bowen ratio and R_s of this poplar plantation were correlated, and consistent with Wilson et al. (2002b) and Li et al. (2009), but differed in wet and dry years. The Bowen ratio and R_s were linearly related in wet years ($R^2 = 0.98$, $p < 0.001$), and correlated exponentially in dry years ($R^2 = 0.93$, $p < 0.001$, Fig. 10). The partial correlation analysis indicated that R_s and R_i, respectively, had strong pos-

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itive and negative effects on β in both wet and dry years (Table 4), which could not detected through correlation analysis (such as the impact of R_i and R_a on β). Furthermore, both controlling factors of R_s and R_i on the Bowen ratio in dry years were greater than in wet years. Finally, R_a had a significant negative impact on the Bowen ratio in wet years, but no impact in dry years, which was not mentioned in earlier studies.

The average $\mathrm{LE}/\mathrm{LE}_\mathrm{eq}$ in the growing season was 0.74 in this site, similar to deciduous forests (0.72) (Wilson et al., 2002b), but smaller than at a temperate broad-leaved forest (0.82) (Komatsu, 2005) which ranged from 0.58 to 1.06. The average Ω value of 0.42 ± 0.22 (ranging from 0.39 to 0.46) was close to the other forests (0.26–0.4, Wilson and Baldocchi, 2000; 0.25–0.43, Motzer et al., 2005). Similar to Baldocchi (1994), $\mathrm{LE}/\mathrm{LE}_\mathrm{eq}$ declined with increasing R_s during the growing season (Fig. 7), which is equivalent to the logarithmic relationship between $\mathrm{LE}/\mathrm{LE}_\mathrm{eq}$ and G_s (surface conductance) reported by other studies (Chen et al., 2009; Hossen et al., 2011; Zhu et al., 2014). The asymptotic value of $\mathrm{LE}/\mathrm{LE}_\mathrm{eq}$ in dry years (0.89) and wet years(0.96) were both lower than the universal 1.1–1.4 range reported by Monteith (1995), indicating that our study site was characterized by drier surface conditions than average for the deciduous forest biome during both dry and wet years. The low $\mathrm{LE}/\mathrm{LE}_\mathrm{eq}$ values under dry surface conditions of the ecosystem in this study may also be related to the high porosity of sandy soil and a low ground water table (Zhao et al., 2013). Overall, as indicated by the lower Ω values and the significant correlation coefficient between $\mathrm{LE}/\mathrm{LE}_\mathrm{eq}$ and R_s, the R_s was the major factor controlling the LE during growing season, which was consistent with the relations between R_s and the Bowen ratio. In addition, LE was more coupled to the atmosphere during the dry years and long-term drought periods across growing season, which were reported in other studies (Bagayoko et al., 2007; Bracho et al., 2008; Zha et al., 2013).

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5 Conclusions

It is central important to explore the energy partitioning and surface resistance to drought for understanding the adaption and thus long term sustainability of plantation establish in water limited regions. The drought conditions affected the seasonal dynamics of individual energy fluxes and the surface resistances in the poplar plantation during long-term drought periods. Partitioning of available energy to latent (LE) and sensible (H) heat differed significantly between wet and dry years ($\beta = 0.83$ and 1.57), with high proportional sensible heat fluxes even during the wet years, indicating a soil moisture limitation. Surface resistance (R_s) of this poplar plantation was significantly higher than reported for other deciduous forests, during both in wet and dry years. The contrasting impact of R_s (the second-order correlation coefficient, SOCC > 0.9) and R_i (SOCC < -0.6) on the Bowen ratio were stronger in dry years, while the effect of R_a(SOCC $= -0.22$) was stronger in wet years. Furthermore, the overall low LE/LE$_{eq}$ and high R_s values in all years indicated that the study area was under water stress even in the wetter years. With averaged Ω value of 0.45 ± 0.21 and 0.39 ± 0.22 in wet and dry years, vegetation canopy was strongly coupled with the atmospheric boundary layer, the R_s was the major factor in controlling LE during growing season, especially in dry years. In conclusion, the dry surface conditions dominated in this poplar plantation ecosystem regardless of soil water availability suggesting that fast-growing and water use-intensive species like poplar plantations are poorly adapted for the water limited region.

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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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 SD.

	Tmin	Tmax (°C)	Tmean	P (mm)	ET (mm)	I (mm)	H (m)	DBH (cm)	LAI ($m^2 m^{-2}$)
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

Table 2. Energy balance closure statistic 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	0.87	0.86	0.89	0.79	0.99	0.91	0.96	0.79
Intercept	15.50	0	0	8.78	−0.76	0.65	0.87	−0.41
R^2	0.82	0.81	0.83	0.83	0.92	0.93	0.94	0.85

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

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

Year	Periods(DOY)	WS (mm)	LE/(R_n-G) (%)	H/(R_n-G) (%)	β	R_s (sm^{-1})	R_i (sm^{-1})	R_a (sm^{-1})	α	Ω
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^{d}	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^{d}	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^{d}	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^{d}	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^{d}	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^{d}	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^{d}	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^{d}	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^{d}	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^{d}	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); β: Bowen ratio; R_s, the surface resistance; R_i, the climatological resistance; R_a, the aerodynamic resistance; α, the Priestley–Taylor coefficient; Ω, the decoupling coefficient.

^{d} indicate the drought stressed periods.

The value in table represents Mean (SD).

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

		Partial correlation analysis*			Correlation analysis		
		SOCC	*p*	df	Pearson	*p*	df
dry year	β and R_s	0.965	< 0.001	347	0.939	< 0.001	349
	β and R_i	−0.667	< 0.001		−0.042	$= 0.436$	
	β and R_a	0.037	$= 0.496$		−0.221	< 0.001	
wet year	β and R_s	0.905	< 0.001	383	0.85	< 0.001	385
	β and R_i	−0.614	< 0.001		0.64	$= 0.006$	
	β and 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.

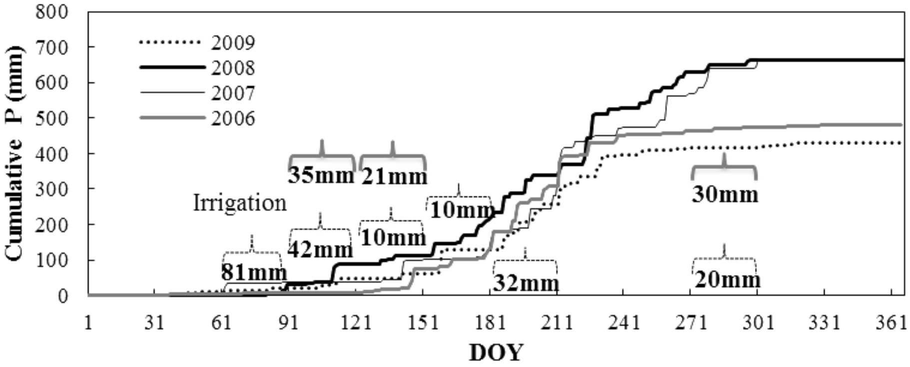

Figure 1. The cumulative precipitation (*P*) and periodic irrigation during 2006–2009, irrigation in 2006 and 2009 were separately represented by the solid and dotted brace.

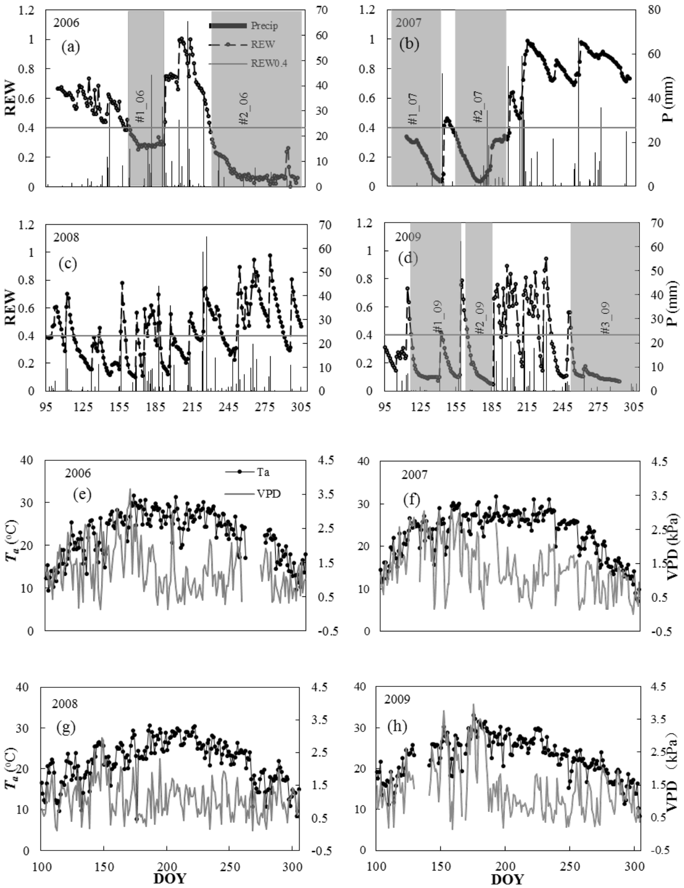

Figure 2. The seasonal variation of environmental conditions during 2006–2009, **(a–d)** include: the relative extractable water (REW) (The drought periods longer than 20 days across 4 year were marked by grey shade in figures **(a–d)**), daily sum of precipitation (*P*); **(e–h)** include: daytime mean air temperature (T_a), daytime mean air vapor deficit (VPD).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

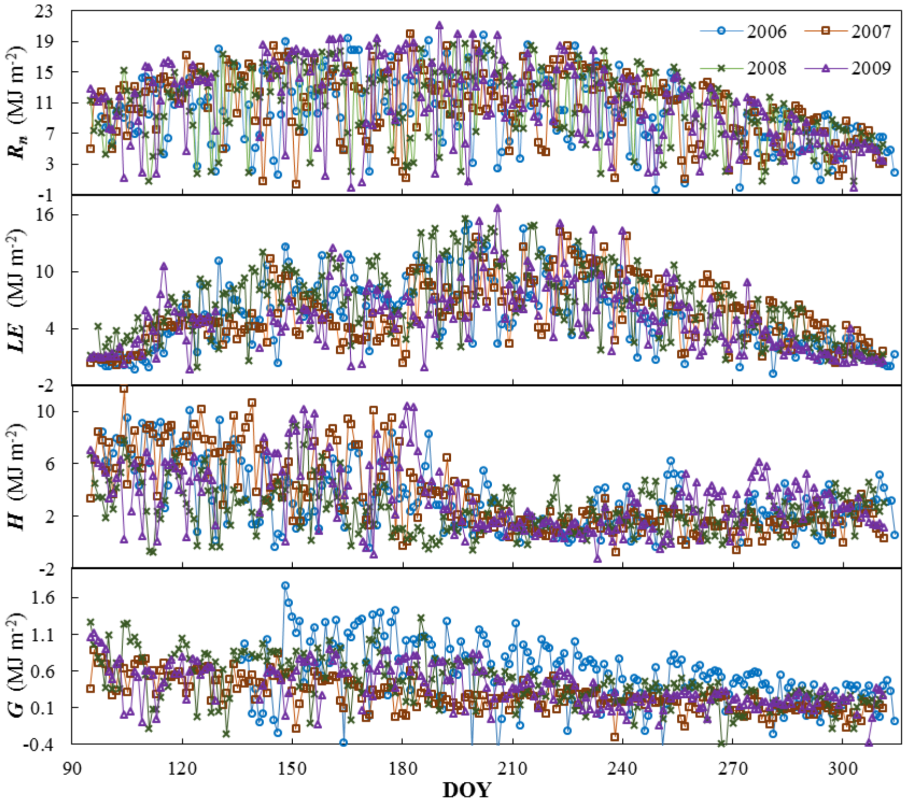

Figure 3. Seasonal patterns of daytime energy components during the growing season from 2006 to 2009, including net radiation (R_n), latent heat (LE), sensible heat (H) and soil heat flux (G).

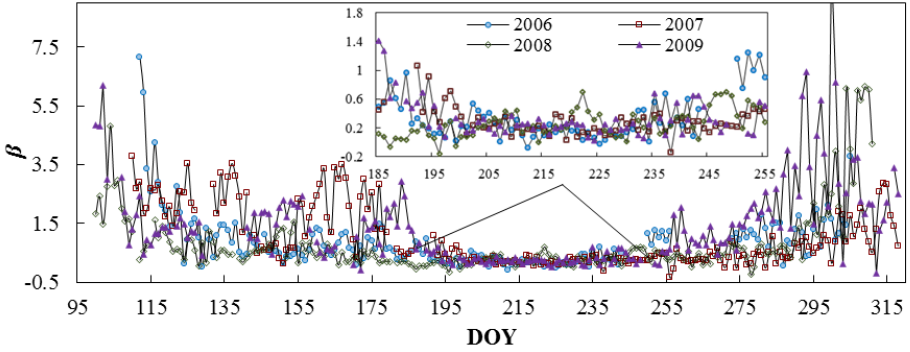

Figure 4. Seasonal and inter-annual variability of the midday mean Bowen ratio (β) across the growing season, with detailed β between DOY 185 and 255 representing in small pane; Midday means the time course from 10.00 a.m. to 15.00 p.m. at local standard time.

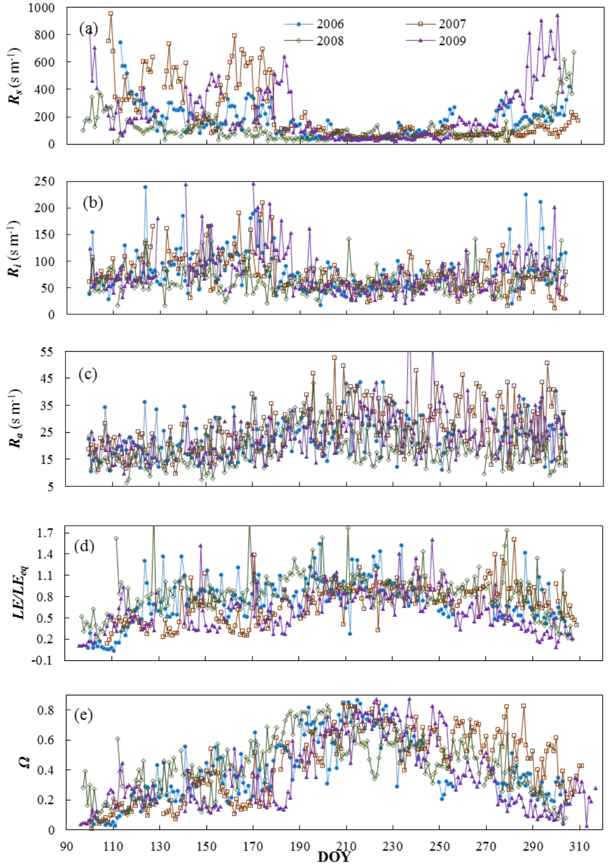

Figure 5. Seasonal dynamics of the midday mean surface resistance (R_s), climatological resistance (R_i), aerodynamic resistance (R_a), LE/LE$_{eq}$ and decoupling coefficient (Ω) across the growing season from 2006 to 2009. Midday means the time course from 10.00 a.m. to 15.00 p.m. LST.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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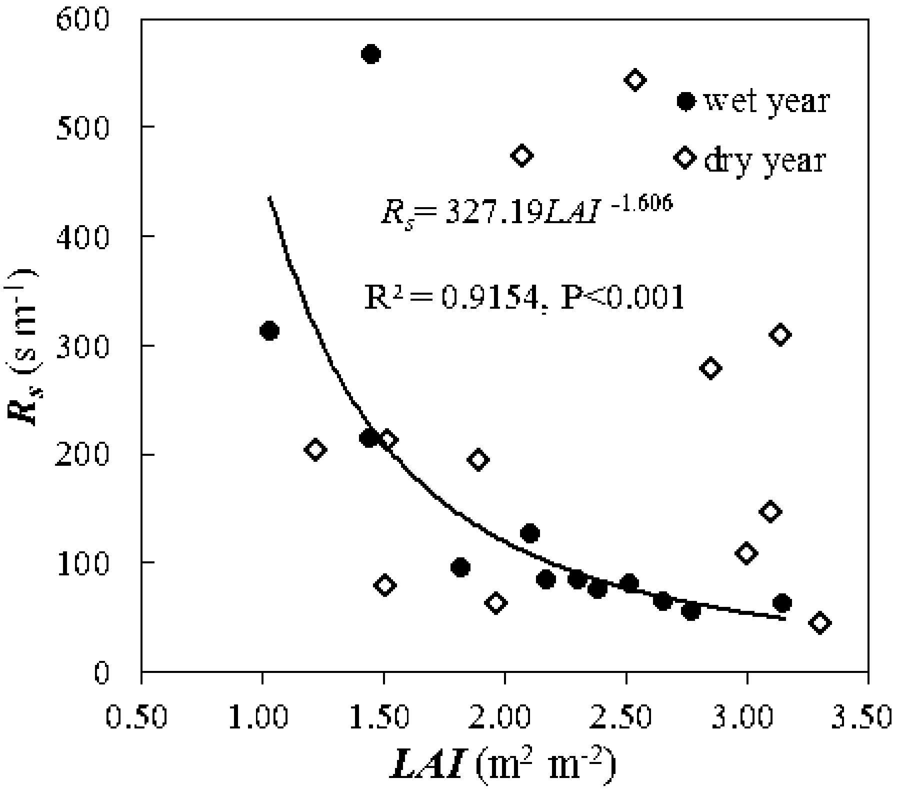

Figure 6. The relationship between leaf area index (LAI) and surface resistance (R_s) during growing season of the wet and dry year.

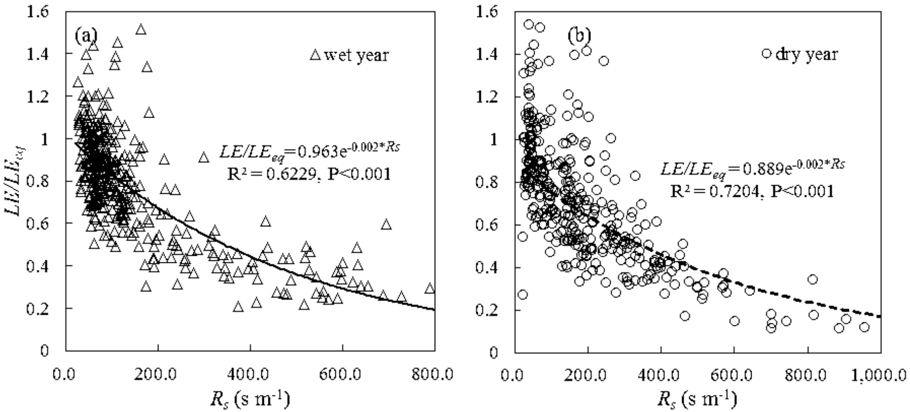

Figure 7. The relationships between surface resistance (R_s) and $\mathrm{LE}/\mathrm{LE}_{\mathrm{eq}}$ (Priestley–Taylor coefficient) during growing season of the wet **(a)** and dry **(b)** year.

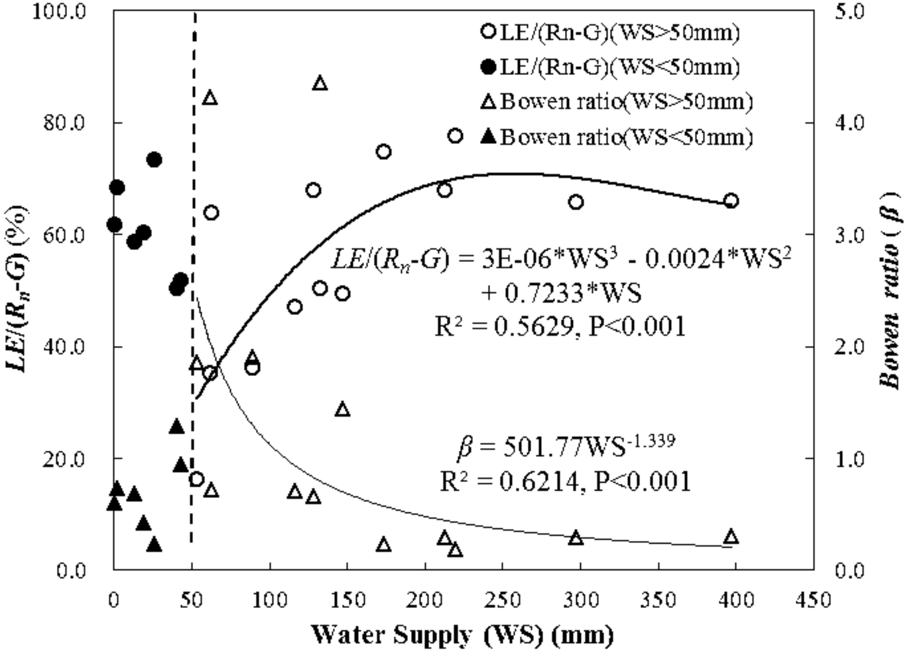

Figure 8. The response of Bowen ratio and LE/$(R_n - G)$ on Water Supply (WS) (including precipitation (P) and irrigation (I) during individual period) of the different periods across four growing seasons.

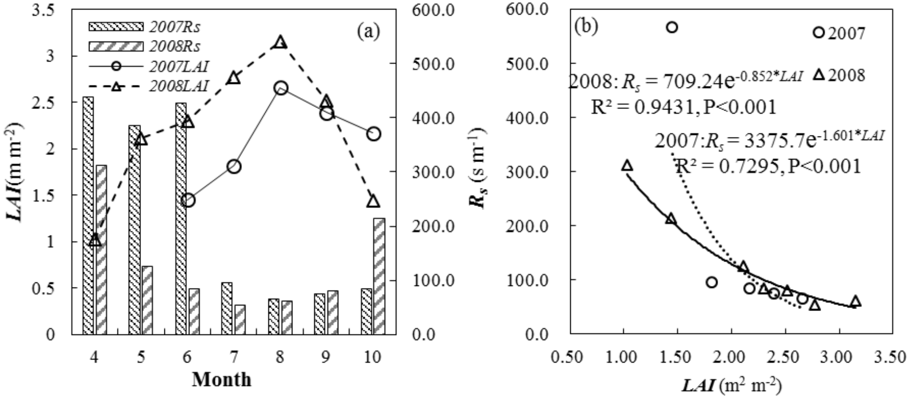

Figure 9. Seasonal variations of monthly average LAI and R_s **(a)**, and the response of R_s on LAI **(b)** during the growing season in wet year 2007 and 2008.

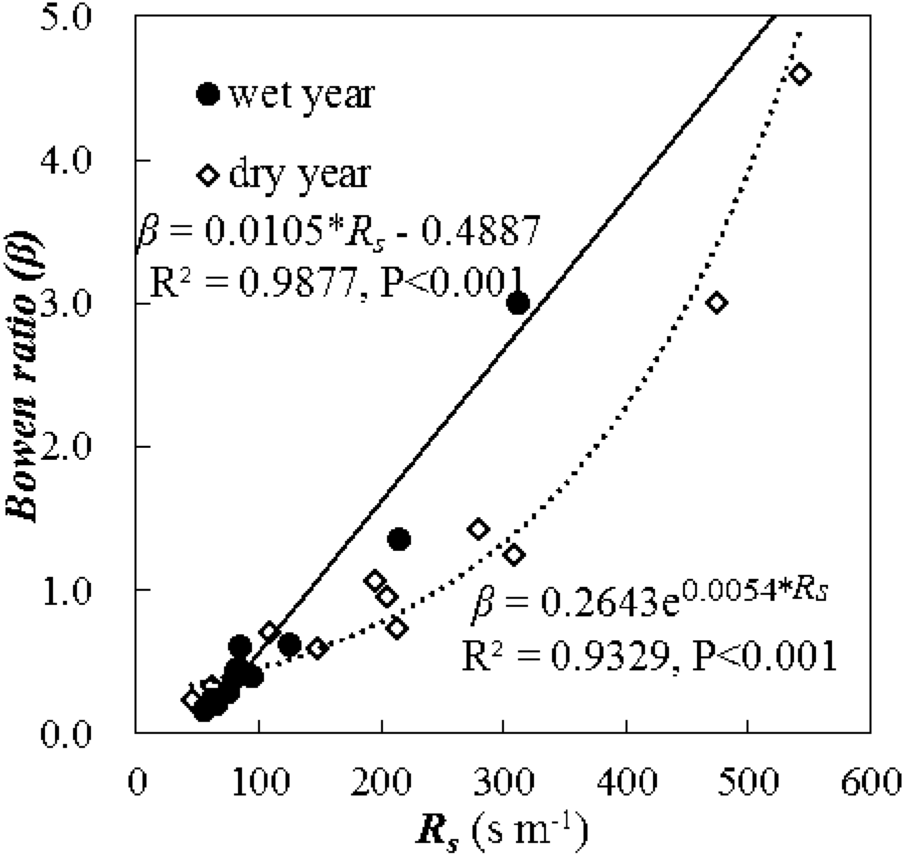

Figure 10. Response of monthly average Bowen ratio (β) on surface resistance (R_s) in the wet and dry year.