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

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Abstract

Poplar (*Populus sp.*) plantations have been, on one hand, broadly used in northern China for urban greening, combating desertification, as well as for paper and wood production. On the other hand, such plantations have been questioned occasionally for their possible negative impacts on the water availability due to higher water use nature of poplar trees compared with other tree species in water limited dryland regions. To further understand the acclimation of poplar species to semiarid environment and evaluate the potential impacts of these plantations on the broader context of the region's water supply, we examine the variability of bulk resistance parameters and energy partitioning in a poplar (*Populus euramericana* CV. "74/76") plantation located in northern China over a four-year period encompassing both dry and wet conditions. The partitioning of available energy to latent heat flux (LE) decreased from 0.62 to 0.53 under mediated meteorological drought by irrigation applications. A concomitant increase in sensible heat flux (*H*) resulted in the increase of a Bowen ratio from 0.83 to 1.57. Partial correlation analysis indicated that surface resistance (R_s) normalized by leaf area index (LAI) (R_s:LAI) increased by 50% under drought conditions and was the dominant factor controlling the Bowen ratio. Furthermore, R_s was the main factor controlling LE during the growing season, even in wet years, as indicated by the decoupling coefficient (Ω =0.45 and 0.39 in wet and dry years, respectively). R_s was also a major regulator of the LE/LE$_{eq}$ ratio, which decreased from 0.81 in wet years to 0.68 in dry years. All physiological and bioclimatological metrics indicated that the water demands of the poplar plantation were greater than the amount available through precipitation, highlighting the poor match of a water-intensive species like poplar for this 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 (over 7.0 million ha, Fang, 2008). However, indiscriminate use of poplar species beyond their native range and habitats may result in unanticipated consequences. For example, the use of poplars in water limited regions may increase the risk of environmental degradation, soil moisture deficit, hydrologic and vegetation changes (Gao et al., 2014).

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

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

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

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 replaced with new saplings in 2001 and 2003. The stand characteristics over the four years of study are provided in Table 1. At the end of 2009, the average height of the trees was 16.2±1.6 m (mean ± SD), and the diameter at breast height (DBH) was 14.1±1.6cm. The average leaf area index (LAI) of the stand increased over time. During the growing season, understory shrubs were kept at low density by 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, with a mean (1990–2009) annual temperature of 11.6°C; maximum and minimum temperature are 40.6 °C and -27.4 °C, respectively. The annual precipitation ranges from 262 mm to 1058 mm (1952–2000), with an average of 556 mm, of which 60%-70% 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 the total sunshine-hour reaches 2772 h per year with 15.5 MJ m^{-2} d^{-1} of incoming solar radiation.

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

The study area is on the alluvial plain of the Yongding River, and is flat with an average slope of < 5 °. The top two meters of the soil is mostly composed of well-drained fluvial sand with a bulk density of 1.43-1.47 g·cm^{-3}, and a pH of 8.25-8.39. The soil porosity is about 40% and capillary porosity is 32%. The mean groundwater depth over the past nine years (2001–2009) was 16.5±0.2 m, and declined at an average rate of 0.6 m per year. The maximum pan evaporation occurs from May through 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. The site was irrigated using pumped groundwater, and the amount of water supplied was estimated from the water meter records at the three adjacent wells on a weekly basis from 2006 through 2009. Other management practices have included tilling and weeding since the establishment of the plantations.

2.2. Eddy covariance system

The micrometeorological and eddy flux measurements were conducted at a 32m tower in the center of the study site, which was established in June 2005. The foot-print of the eddy flux covariance system, was about 1 km x 1 km in size, with a fetch of at least 300 m in all directions. Fluxes of CO_2, sensible heat and latent heat were calculated based on the eddy-covariance (EC) principles. The 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 anemometer head was installed towards a predominant wind direction (southeast), and the IRGA was installed at a slight vertical angle tilted northward (< 20 degree) between the sonic path and anemometer body. The IRGA was calibrated every year. The EC sensors were mounted initially at a height of 16 m in 2006. This was increased to about 18 m before the start of the growing season in 2007, and again to 20 m in February 2009 to ensure that the sensors remained well above the tree canopy.

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 with 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 height of 21 m. Air temperatures and humidity were measured with a temperature and relative humidity probe (HMP45C; Vaisala, Helsinki, Finland) at 5, 10, 15 and 20 m above ground. Precipitation was measured with a tipping bucket rain gauge (TE525-L; Texas Electronics, USA) at 22.5m. Soil heat flux and soil temperatures, respectively, were measured with three soil heat transducers (HFT3, CSI) and 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 20 and 50cm.

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

The 30-minute mean fluxes were calculated from raw 10 Hz data with an EC Processor software, version 2.3 (Noormets et al., 2010). The program is designed for reprocessing EC flux data and can calculate half-hour mean eddy covariance fluxes of carbon, water and energy. The wind coordinates were rotated using the 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 the 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). 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 m s^{-1} (2006), 0.12 m s^{-1} (2007), 0.14 m s^{-1} (2008) and 0.13 m s^{-1} (2009). Data gaps shorter than 2 hours were filled using linear regressions between the flux of interest and net radiation (R_n), gaps between 2 hours and 7 days in length were filled using mean diurnal variation (MDV) method (Falge et al., 2001), and gaps longer than 7 days were not filled.

The four year study period was classified into “wet” and “dry” years distinctively. A dry year referred to a year with annual precipitation less than 85% of the 20-year average according to the National Standard of People's Republic of China (GB/T 20481-2006) (China, 2006) and “wet” when above it. Years 2007 and 2008 were classified as ‘wet’ while 2006 and 2009 were ‘dry’ year, respectively. We focused on the growing season when the environmental forcing (e.g., solar radiation, and temperature) for energy and water fluxes, and the physiological response of vegetation were usually strong. 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 μmolm^{-2}s^{-1}. The regulation of surface energy and gas exchange are often different during nocturnal periods (Mahrt, 1999), with heat fluxes at night typically weaker and markedly less stationary than during the daytime (Wilson et al., 2002b). The midday was defined as the period from 10:00 to 15:00 LST when the coupling between vegetation and the atmosphere was 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,

$$\mathrm{REW} = \frac{\mathrm{VWC} - \mathrm{VWC_{min}}}{\mathrm{VWC_{max}} - \mathrm{VWC_{min}}} \qquad (1)$$

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

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),

$$\beta = \frac{H}{\mathrm{LE}} \qquad (2)$$

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

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

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

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

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),

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

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,

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

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

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

where $r_{a,m}$ is the aerodynamic resistance for momentum transfer, and r_b is 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 resistance and net radiation (Pereira, 2004). The Ω value ranges from 0 to 1, with values approaching zero indicating that LE is highly sensitive to surface resistance and ambient humidity deficit. The Ω value approaching 1 indicates that LE or evapotranspiration is mostly controlled by net radiation (Jarvis and McNaughton, 1986),

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

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

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

The ratio LE/LE_{eq}, which is also known as the Priestley–Taylor α, reflects the control of evaporation by atmospheric and physiological factors, LE/LE_{eq} characterizes the surface dryness of an ecosystem, indicating whether soil water supply for evapotranspiration of an ecosystem was under limited. An LE/LE_{eq} of < 1 indicates water stress and suppressed evapotranspiration. Conversely, $LE/LE_{eq} > 1.26$ indicates unrestricted water supply, and only available energy limits evapotranspiration (Arain et al., 2003). The LE/LE_{eq} is dependent of 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 for quantifying the changes of all the biophysical variables, energy fluxes and bulk parameters across years. The *t* test was used to compare the differences of biophysical variables among 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 ratios. All analyses were accessed at $\alpha = 0.05$.

3 Results

3.1 Environmental conditions

The annual precipitation rates in the four years of study differed from the long-term (i.e., 1990–2009) average (556 mm yr^{-1}). Thus, years 2006 and 2009 were drier and 2007 and 2008 were wetter than the mean (Table 1). The interannual contrast was exaggerated by the seasonality of rainfall. Generally, over 90% precipitation of each year occurred in April–October, but with different timing and magnitude among the years. The study site was irrigated during the dry years of 2006 and 2009 to mitigate drought conditions (Fig.1). Seasonal drought stress (REW< 0.4) occurred during periods in the late growing season of 2006 and 2009, the spring of 2007 and 2009, but not at all in 2008 (Fig. 2a–d). In 2006, precipitation during the 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 seasonal 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 throughout the year in 2008. In 2007, drought stress occurred during DOY 110-143 (#1_07) and 151-200 (#2_07). A single rain event in late May (57 mm) and a few large precipitation events (> 25 mm d^{-1}) in July were recorded. The amount of rainfall in 2009 was the smallest among the four years, during which 195mm of irrigation was applied from March to September. There were several short and scattered droughts across the growing season in 2009 (Fig.2d). Despite the higher than normal rainfall in the two wet years, there was no flooding or overland runoff.

The growing season T_a in 2008 was significantly lower than that in 2007 and 2009 (dT= 1.3 °C, $p < 0.05$, Fig.2 e-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 2006 and 2009, and in July 2007 and 2008. The warmest month was June 2006 (27.1 ± 2.4 °C).

The daytime average VPD of the four growing seasons (Fig.2 e-h) was 1.3 ± 0.7 kPa. The 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 those in the other years ($p < 0.05$). Higher T_a and lower precipitation in May 2007 led to higher VPD compared to the same period in 2006 and 2008 ($p < 0.001$). Furthermore, the VPD was the highest in June 2009 (i.e., 2.3 ± 1.1 kPa, $p < 0.05$) and the lowest in 2008 (i.e., 1.0 ± 0.5 kPa, $p < 0.01$).

3.2 Seasonal changes in energy partitioning and β

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

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

The seasonal variation of the midday Bowen ratio (β) displayed a rapid and significant trend across the growing season, especially at the beginning (April–June) and the end (September–October) of the growing season (Fig. 4). The Bowen ratios during the middle of the growing seasons were all smaller than 1, and approximately lasted from DOY 180–250 in the dry year and from DOY 180–290 in the wet years. The average midday β in the dry years was greater (1.57) than that in the wet years (0.83; F=19.176, $p < 0.001$). The Bowen ratio showed differences in response to drought stress across the four growing seasons (Table 3); with much higher values (> 1) during the drought periods in 2007 and 2009, but not in 2006. The Bowen ratio was smaller than 1 during 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 190–250) than in the wet year (Fig. 5a). A significantly negative relationship was found between the R_s and LAI during the wet years (Fig.6). Overall, the seasonal average of R_s normalized by leaf area index (LAI) (i.e., R_s:LAI) was lowest during the wettest year (2008, 54.1 s m^{-1} leaf area; $p < 0.05$). The R_s:LAI in the dry years (106.8 s m^{-1} leaf area) was 50% higher than in the wet years (71.2 s m^{-1} leaf area) ($p < 0.001$). The R_s:LAI in the seasonal drought stressed periods in 2006, 2007 and 2009 were much higher than those during unstressed periods ($p < 0.001$, Table 3).

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

The seasonal changes of LE/LE$_{eq}$ value varied between 0.4 and 1.0 during most of the growing seasons (Fig. 5d). The average LE/LE$_{eq}$ of the four years were 0.76, 0.73, 0.89 and 0.63, respectively. The mean 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 LE/LE$_{eq}$ in drought periods of 2007 and 2009 were much smaller. A significantly exponential relationship existed between the 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 four years was 0.41, 0.46, 0.43 and 0.39 (Table 3), respectively, and was significantly higher in wet year (0.45) than that in dry year (0.40; $F=9.460$, $p < 0.01$). Compared to the value during unstressed periods, the decoupling coefficient during the seasonal drought periods (#1_06, #2_06; #1_07, #2_07 and #1_09, #2_09, #3_09) was much lower in value.

4 Discussion

4.1 Energy partitioning and Bowen ratio

. The energy balance ratio (E_{BR}) at the current study was 0.88 based on daytime 30-minute fluxes and > 0.96 based on daytime totals (Table 2). The annual mean E_{BR} at our site was similar to the values 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 the 50 site-years of flux data from 22 in FLUXNET sites, which had energy closure of 0.34–1.69 (Mean = 0.84, Wilson et al., 2002a). 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 among the biomes and based on metrics of landscape heterogeneity. In addition to the known reasons for decreasing energy balance closure (Hernandez-Ramirez et al., 2010; Li et al., 2005; Nakai et al., 2006; Stoy et al., 2013), management operations at our site (e.g., 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, the results reported here are similar to other FLUXNET sites.

The surface energy partitioning to sensible and latent heat depends on water potential gradient and surface resistance (Arain et al., 2003; Baldocchi et al., 2000; Chen et al., 2009). Canopy development (Guo et al., 2010), rainfall dynamics and irrigation (Ozdogan et al., 2010) affect these properties to some extent and could directly lead to a change in soil moisture and the evaporation component of LE, thereby impacting energy partitioning and β (Chen et al., 2009; Ozdogan et al., 2010). However, the impact of precipitation on the Bowen ratio may vary by even at any site (Tang et al., 2014). In our study, detectable responses of LE/(R_n-G) and the Bowen ratio to drought stress and non-stress periods were 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 availability from precipitation and irrigation. On an annual scale, the Bowen ratio appeared linearly related to the total growing season precipitation (R^2=0.89, $p < 0.05$). Thus, the Bowen ratio is very responsive to the site water supply; a similar finding was reported in Grünwald and Bernhofer (2007) in a temperate spruce forest.

By contrast, β varied from 0.18 to 0.71, with a mean of 0.35 ± 0.15 during most of the growing season in 2008 and in the non-stressed periods of the other 3 years. This variation was close to 0.42 for deciduous forests (Wilson et al., 2002b) and 0.55 in a temperate Douglas-fir (Humphreys et al., 2003), which is also similar to the variations in a ponderosa pine forest in the western United States (Goldstein et al., 2000) and a deciduous broadleaved forest in the southern United States (Wilson and Baldocchi, 2000). Seasonal 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) and 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 seasonal drought periods and dry years than most temperate coniferous forests (Mean = 1.07, (Wilson et al., 2002b), which typically had higher β values. The high β value in this study reflects the semi-arid conditions, and suggests a low tree water supply which might be resulted from the combination of low rainfall, the sandy soil's low water holding capacity and the 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 findings corroborate the hypothesis that drought would trigger significant changes in the energy partitioning of water-demanding poplar species in a water-stressed region.

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 quantifies 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 an ecosystem (Costa et al., 2010; Launiainen, 2010; Zhou et al., 2010) and generally increases the Bowen ratio.

In this study, R_s similarly varied seasonally with plant phenology and showed similar seasonal characteristics to other deciduous forests during the course of the growing season (Cabral et al., 2010; Kutsch et al., 2008; Li et al., 2012). As reported by Tchebakova et al. (2002), R_s in seasonal drought stressed periods was much higher than that in non-stressed periods. It has been shown that drought stress during the canopy development affects leaf area and may have lasting effects on canopy gas exchange through the entire growing season, even after the moisture limitation is removed (Noormets et al., 2008), which may explain significant difference in R_s between wet year 2007 and 2008 (Fig.9). Compared with the R_s in other studies, the R_s:LAI in dry years in the current study was close to that of the Euphrates Poplar (*Populus euphratica Oliv*.) (130.2 s m^{-1} LAI^{-1}) and smaller than that of the Gansu Poplar (*Populus gansuensis Wang et Yang*) (189.4 s m^{-1} LAI^{-1}) in semiarid regions(Chen et al., 2004). In wet years it was similar to that of poplar (58.6 s m^{-1} LAI^{-1}) (Wilson et al., 2002b) and boreal aspen during the full-leaf period (51.8 s m^{-1} LAI^{-1}) (Blanken et al., 1997) in mesic temperate regions. 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). Compared to the strong correlation between R_s and LAI in wet years, the increased scatter in the R_s-LAI relationship during dry years (Fig.6) suggests that R_s in dry years was also influenced by other physiological and non-physiological (e.g., soil evaporation, canopy structure and turbulence) factors (Wilson et al., 2002b). The mean R_i in the current study was higher than the mean R_i reported for temperate forests in Wilson et al. (2002b) (t=5.91, df=741, $p < 0.001$), but was ~ 50% lower than the value reported by Li et al. (2009) in a vineyard in Gansu Province in China (t= -29.87, df=741, $p < 0.001$), as might be expected given the predominant climatic conditions.

On the seasonal scale, 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 (Fig 10). The water limitation during the dry years manifested in disproportional increase in R_s than the Bowen ration; this response may serve as an indicator when water reserves are being depleted. At the extremes, the relationship converges, but as water becomes limiting, stomatal closure and increased R_s do not appear to be able to affect the seasonal dynamics of the Bowen ratio. The partial correlation analysis indicated that R_s and R_i had strong positive and negative effects, respectively, on β in both wet and dry years (Table 4), which could not be detected through correlation analysis (e.g., the impact of R_i and R_a on β). Furthermore, the regulation of the Bowen ratio by R_s and R_i seemed stronger in dry than in wet years. R_a had a significant negative impact on the Bowen ratio in wet years, but not in dry years.

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

LE/LE$_{eq}$ 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 LE/LE$_{eq}$ in dry years (0.89) and wet years (0.96) were both lower than the 1.1–1.4 range typical in temperate deciduous forest reported by Monteith (1995), indicating that our study site was drier than these reference sites during both dry and wet years. The low LE/LE$_{eq}$ values under dry surface conditions of the ecosystem in this study may also be related to the high porosity of the sandy soil and the low ground water table (Zhao et al., 2013). Overall, as indicated by the lower Ω values and the significant correlation coefficients between LE/LE$_{eq}$ and R_s, the R_s was the major factor controlling the LE during the 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 seasonal drought periods across the growing season, as reported in other studies (Bagayoko et al., 2007; Bracho et al., 2008; Zha et al., 2013).

4.3 Implications for poplar plantation establishments

As forestry is a long-term endeavor, with the economic payback decades from stand establishment, the availability of resources for the stand to prosper should come naturally to natural resource managers. Supplementing limiting resources directly (fertilization, irrigation) or indirectly (competition control, site preparation, thinning) is commonplace in commercial forestry, but it has to be sustainable in the broader context of the region's ecosystems and livelihoods. Earlier, we reported that the water needs of poplar plantation exceed the annual precipitation in the region and plant survival during dry years depends on irrigation from groundwater (Zhang et al., 2014). In the current study, energy partitioning to latent and sensible heat and surface resistance was sensitive to climatological drought—even under the irrigation—as indicated by low LE/LE$_{eq}$ (< 1) and low values of the decoupling coefficient (Ω) (Zhu et al., 2014); the dry surface conditions dominated the poplar plantation in both wet and dry years. In wet years, the plantation itself is in hydrologic balance with the water that arrives as precipitation, with evapotranspiration consuming nearly all of the precipitation. The same is true in dry years, but irrigation increases *ET* even further by depleting groundwater. Even if the plantations were in hydrologic balance with water delivered as precipitation, their existence and operation could be a threat to adjacent ecosystems and livelihoods if those rely on runoff or groundwater recharge from the areas where the plantation has been sited. In the absence of the plantations it is likely that groundwater recharge would increase, especially given the sandy textured soil that tends to allow rapid infiltration and percolation as well as limits moisture delivery to the atmosphere directly from the soil surface itself. While poplar plantation growth in this water-limited location might be sustained by the modest precipitation in the region, it could still be unsustainable for the broader context of the region's ecosystems and livelihoods. However, further study to truly access these effects is needed by comparing the surface water balance and /or spatial and temporal variations of groundwater levels at an adjacent, similar site without a plantation.

5 Conclusions

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

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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 (°C)	Tmean	P (mm)	ET (mm)	I (mm)	H (m)	DBH (cm)	LAI (m^2m^{-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 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 umol m^{-2} s^{-1};

The unit of Intercept for Half-hourly value and Daytime sum value were W • m^{-2} and MJ • 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/$(R_n$-$G)$(%)	$H/(Rn$-$G)$(%)	β	R_s(s m^{-1})	R_i (s m^{-1})	R_a(s m^{-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), 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 (β) and R_s, R_i and R_a.

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

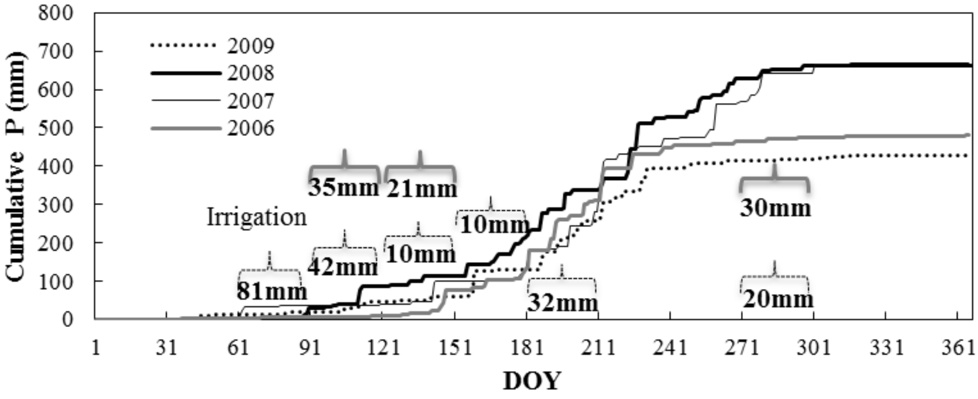

Figure 1.The cumulative precipitation (P) and periodic irrigation during 2006-2009, irrigation in 2006 and 2009 were separately represented by the solid and dotted brackets, respectively.

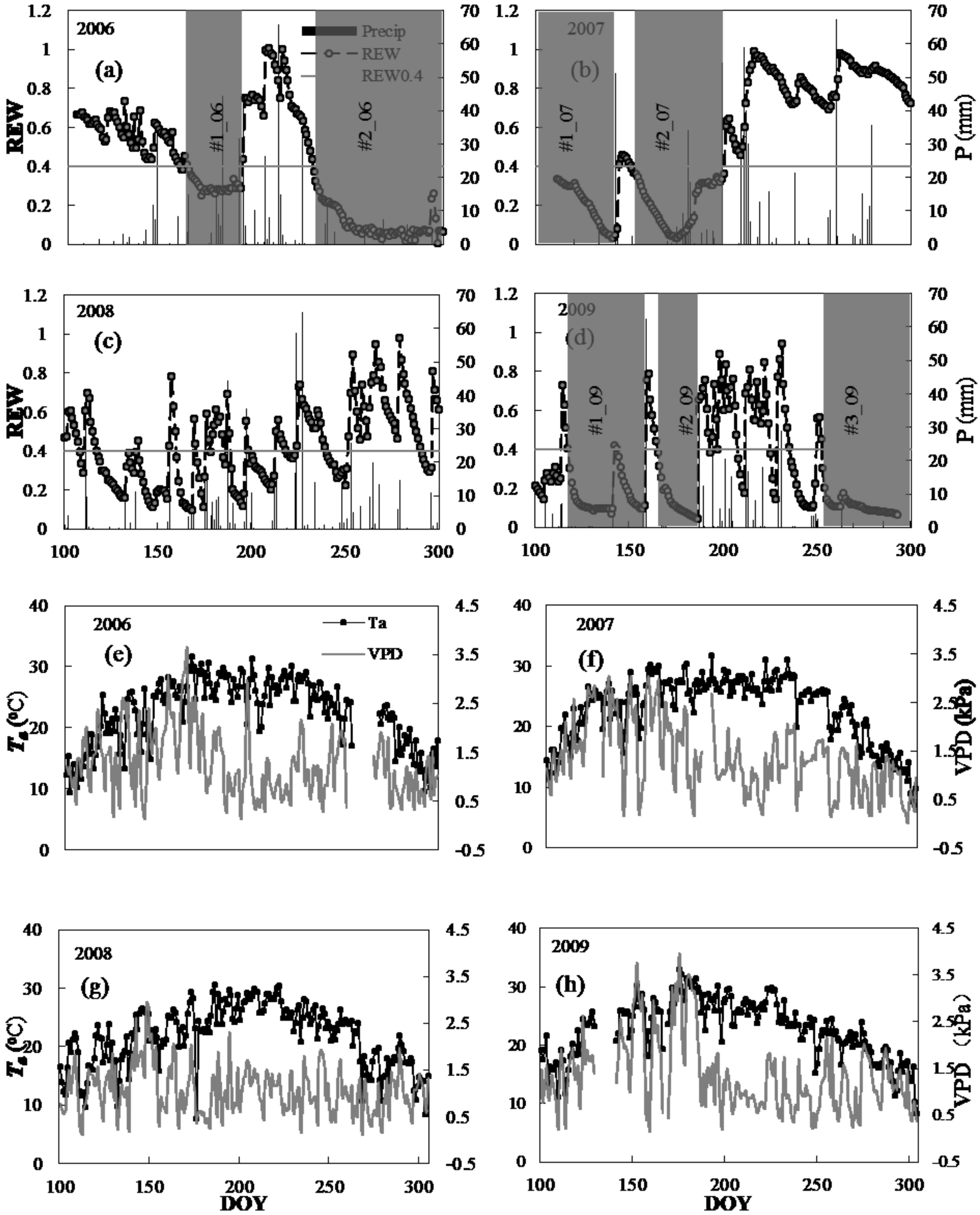

Figure 2. The seasonal variation of environmental conditions during 2006-2009, a-d: the relative extractable water (REW) (drought periods longer than 20 days are shaded), daily sum of precipitation (P); e-h: daytime mean air temperature (T_a), daytime mean air vapor deficit (VPD).

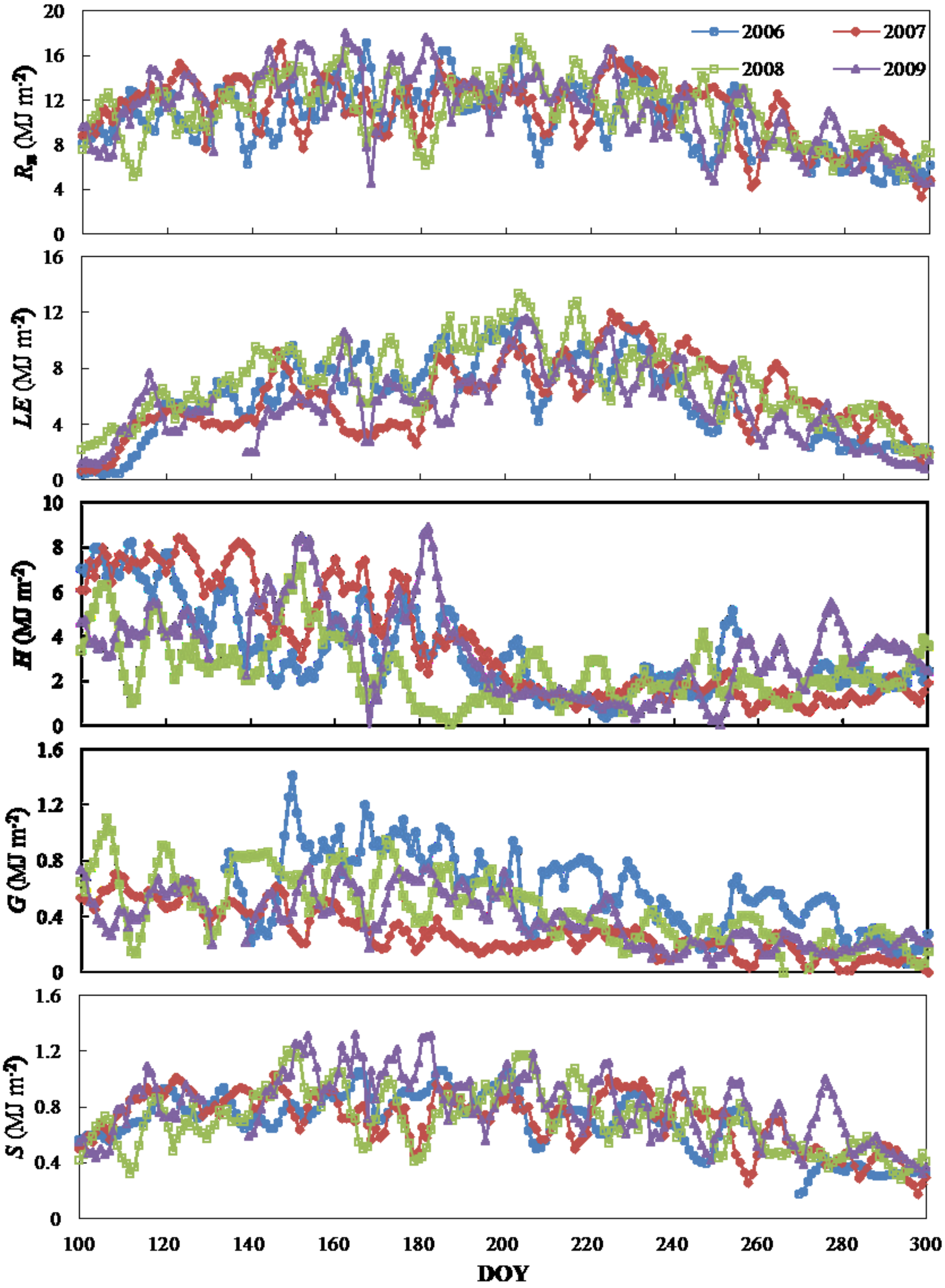

Figure 3. Seasonal patterns of daytime energy components (5-day running average) during the growing season from 2006 to 2009, including net radiation (R_n), latent heat (LE), sensible heat (H) and soil heat flux (G) and heat storage term (S).

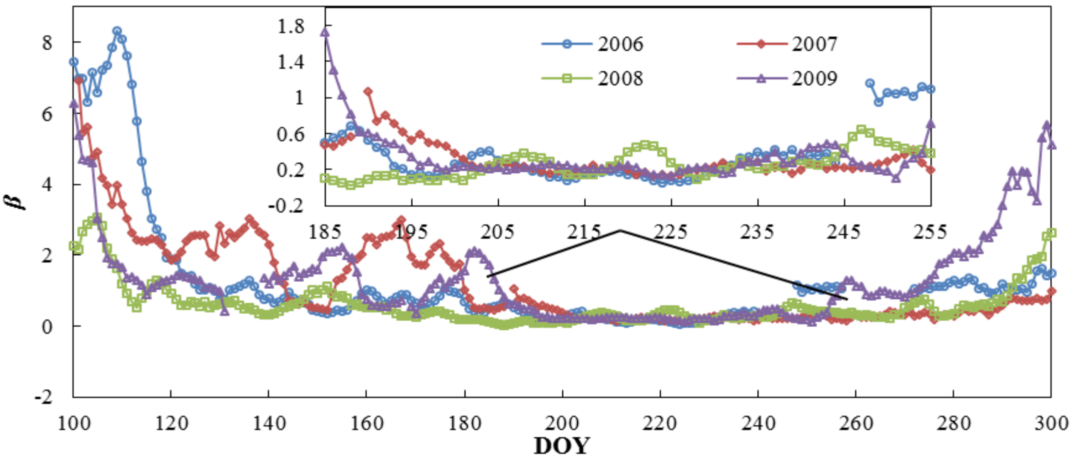

Figure 4. Seasonal and inter-annual variability of the midday (10:00-15:00 LST) mean Bowen ratio (β) (5-day running average) across the growing season, with detailed β during DOY 185-255 representing in small pane.

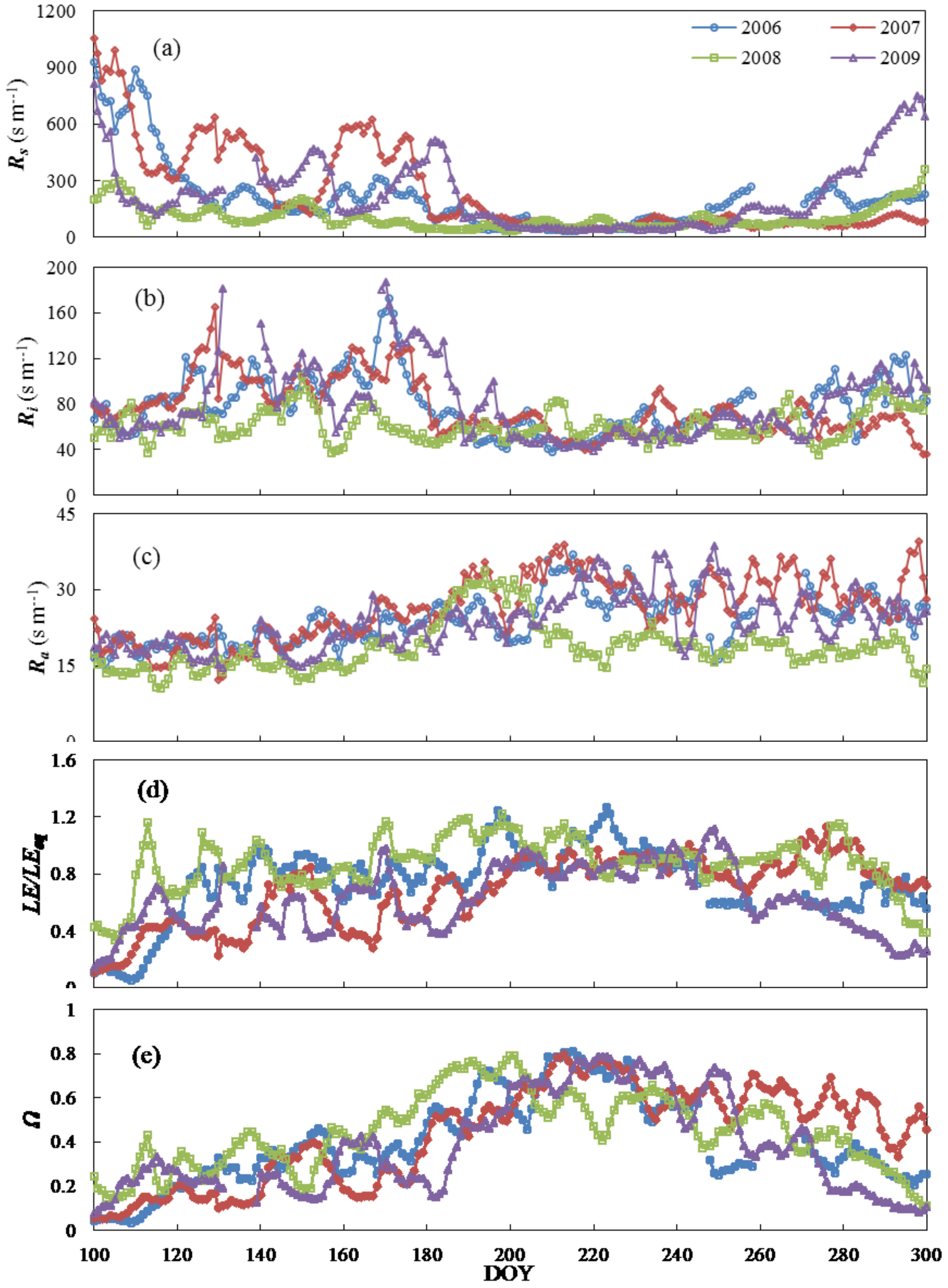

Figure 5. Seasonal dynamics of the midday (10:00-15:00 LST) mean surface resistance (R_s), climatological resistance (R_i), aerodynamic resistance (R_a), LE/LE$_{eq}$ and decoupling coefficient (Ω) (5-day running average) across the growing season from 2006 to 2009.

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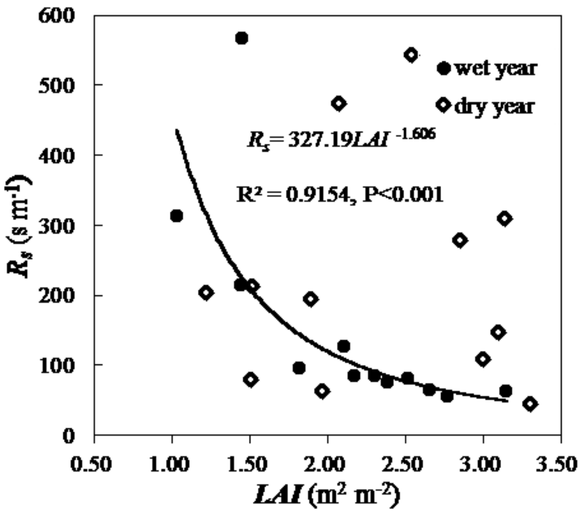

Figure 6. The relationship between leaf area index (LAI) and surface resistance (R_s) during growing season of the wet and dry year.

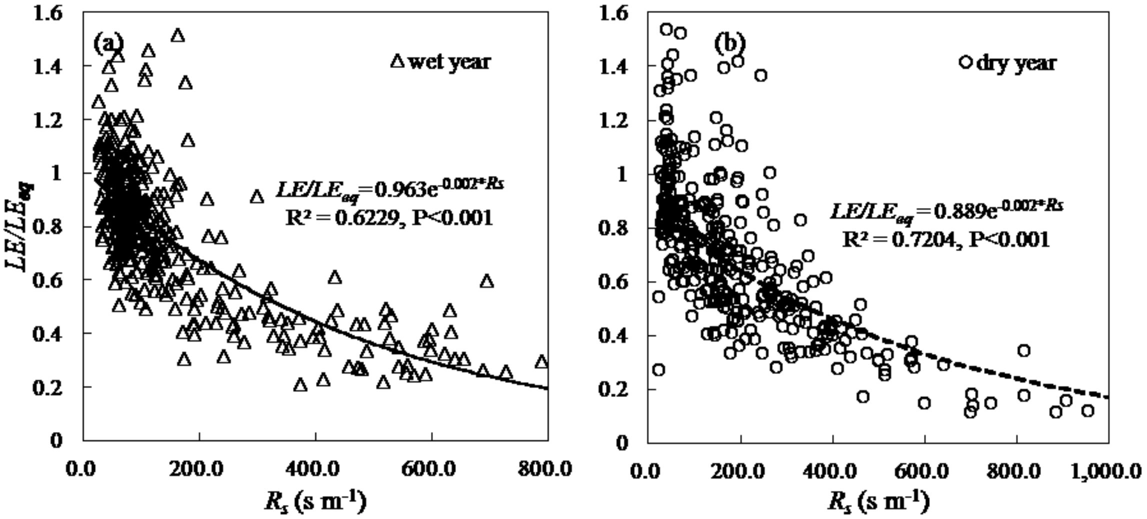

Figure 7. The relationships between surface resistance (R_s) and LE/LE$_{eq}$ (Priestley-Taylor coefficient) during growing season of the wet (a) and dry (b) year.

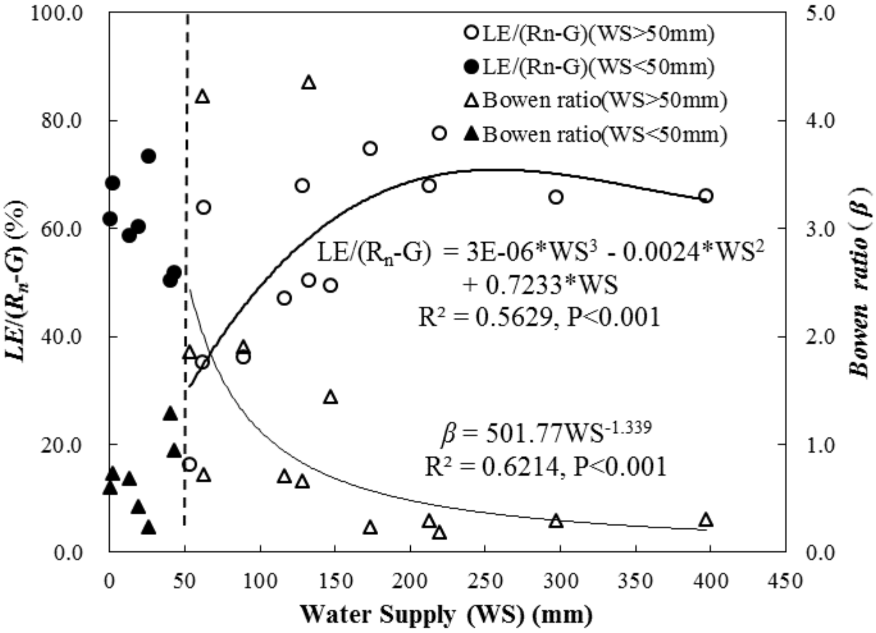

Figure 8. The response of Bowen ratio and LE/(R_n-G) on Water Supply (WS) (including precipitation (P) and irrigation (I) during individual period) of the different periods across the four growing seasons.

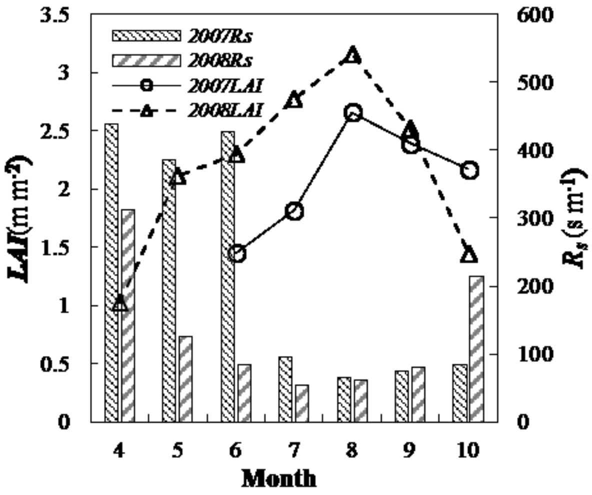

Figure 9. Seasonal variations of monthly average LAI and R_s during the growing season in wet year 2007 and 2008.

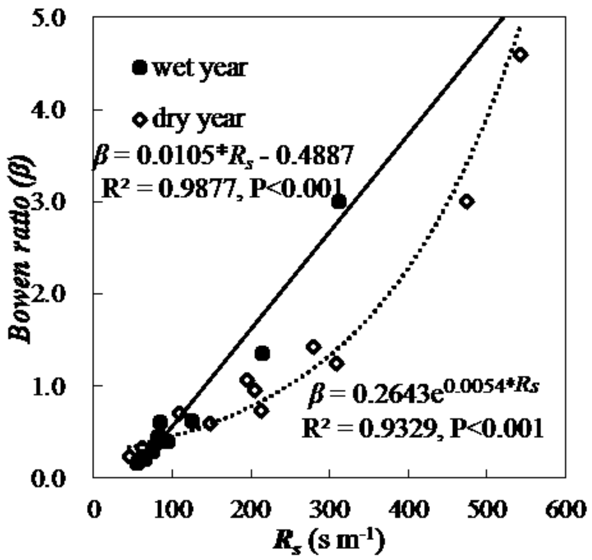

Figure 10. Response of monthly average Bowen ratio (*β*) on surface resistance (R_s) in the wet and dry year.

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