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# Final Response to the Reviews of MS No.: bg-2014-536

**Journal:** *Biogeosciences (BG)*
**Title:** *Responses of energy partitioning and surface resistance to drought in a poplar plantation in northern China*
**Author(s):** *M.C. Kang et al.*
**MS No.:** *bg-2014-536*
**MS Type:** *Research Article*

April 13, 2015

**Dear Editor-in-Chief, Prof. &, Dr. Michael Bahn,**

With our heartful thanks and appreciations, we have carefully read all the insightful reviews and comments by two anonymous reviewers for our paper submitted to your journal. We do think that all those review comments are addressable, therefore, we have revised the whole paper and answered all the questions raised accordingly. The most challenging question to us is how and in what way the sustainability of poplar plantation establishment can be assessed and measured. To our knowledge, there is no and it is hard to develop a quantitative metrics for sustainability of plantation establishment. Therefore, our argument for sustainability is rather general in terms of the forest ecosystem and environment interactions as the energy partitioning and surface resistance can provide insight to the mechanisms of adaptation and long term sustainability of plantations in water limited regions.

All our co-authors have contributed substantially to the revision of the paper and we believe that the revised paper meets the high quality requirement of your well-known journal. The reply to each comment and question is presented one by one following this cover letter.

Should you have any inquiries for the MS, please feel free to contact me at any time:

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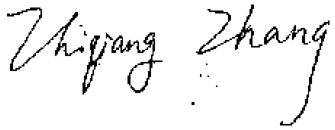
Best regards,
Yours sincerely



On behalf of all authors

See Reply on the next page.

**Referee #1 (C161):**

**General Comments**

In the introduction, write a review of sustainability index for ecosystem (or how to assess sustainability for ecosystem). And, introduce the sustainability index which you will use (or how will you assess the sustainability) in the paper.

*Reply: Thanks for your critical comments! To our knowledge, there is no and it is hard to develop a metrics for the sustainability of forest plantation, even though there are a couple of studies defining the sustainability of forest plantation by site and plantation productivity for commercial purpose only (e.g., (Richardson et al., 1999; Watt et al., 2005) other than in a broader sense of the plantation and environment interactions that were our focus in the current paper. However, we do think that the reviewer raised a great question directing our future exploration in semiarid regions in a holistic approach. We, thus, referred only a rather broad term here for sustainability in terms of ecosystem and environment interactions relating to the water availability and supply. For more clarification, we have revised the context in Revised MS from page 31, Line 16 to page 33, Line 4 as "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 may even 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 forests, clearly require large quantities of irrigation in water limited areas such as northern China. However, over the past 50 years, northern China has experienced the decline of the water table, land degradation, large increases in surface air temperature and severe droughts (Ding et al., 2007; Qiu et al., 2012; Wang et al., 2008; Zhang et al., 2014), while the wide-spread use of irrigation has been cited as one of possible causes for these impacts. Therefore, studying the drought response of poplars under water shortage is essential for effective management of water resource over this region and avoiding the use of water-intensive species in ecological restoration and reforestation efforts if the environmental resources are not sufficient. Whereas, most of previous and current studies are only concentrated on the water balance of forest ecosystem other than the interactions between forest ecosystem and environment, it is clear that exploring the energy partitioning and ecosystem response to drought is central important for understanding forest water and carbon cycling processes (Guo et al., 2010; Jamiyansharav et al., 2011; Sun et al., 2010; Takagi et al., 2009; Wu et al., 2007), and thus understanding the adaption and long term sustainability of plantation establish in water limited regions."*

In the methods, write how the indices (Rs, LE/LEeq, beta and Omega) are related to the ecosystem sustainability, or explain the sustainability index which is introduced in the introduction or the methodology which can assess the sustainability properly in this study case.

*Reply: Thanks for this suggestion. We have revised the content in Method in in Revised MS page 39, Line 2-*

*9 as "LE/LE$_{eq}$ characterizes the surface dryness of ecosystem. It, therefore, indicates whether soil water supply for evapotranspiration of an ecosystem is under limitation or not. An LE/LE$_{eq}$ of < 1 represents an ecosystem under water stress and, therefore, experiences reductions in evapotranspiration; whereas LE/LE$_{eq}$ of > 1.26 indicates an ecosystem of unrestricted water supply and only available energy limits evaporation (Arain et al., 2003)". Then, as we have stated in in Revised MS page 39, Line 5-7, LE/LEeq < 1 indicates that the poplar plantation needs water supply by pumping groundwater to supplement the insufficient precipitation, therefore, we could conclude that growing poplar plantation is not sustainable for the water limited regions.*

In the quantification of surface energy balance, the storage term is important, especially for forest ecosystems (e.g., Leuning et al., 2012). Estimate the storage term and add the result.

*Reply: Yes, the heat storage term is important for studying surface energy balance of forest ecosystem. Therefore, we have revised the content in Revised MS page 37, Line 8-16 as "*

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

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

*where S is the latent and sensible heat storage in the air-column below the EC system and is calculated in Eq. (4),*

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

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

*Also, we have added the results in Revised MS page 41, Line 12-14 "Moreover, the average value of daytime total S among four growing seasons were 0.46 MJ m-2, 0.49 MI m-2, 0.51 MJ m-2, 0.54 MJ m-2, respectively. S/Rn varied between 6.0% in 2007 and 6.8% in 2009 and showed no differences between the wet and dry years.", and revised "0.85" to "0.88" and "over 0.95" to "> 0.96" in Revised MS page 43, Line 20, and corrected the Figure 3 (Page 63-64 in revised MS) and Table 2 (Page 56 in revised MS).*

I recommend to analyze four components of radiation (i.e., incoming/outgoing shortwave/ longwave radiation), if the data from CNR1 is available. I think radiative energy balance is very important to assess surface energy balance. The authors only show net radiation (i.e., sum of the four components). The author can find the differences of radiative energy balance between the dry and wet years such that the outgoing longwave radiation is higher in the dry year than that in the wet year.

*Reply: Yes, this is a great point for in-depth analysis. The current paper focused on the energy balance, surface resistance, coupling of canopy and atmosphere as a whole. We will further conduct the detailed* *radiative energy balance analysis to explore the responses of poplar plantation under different climate conditions.*

The authors have LAI data. I recommend normalizing Rs using LAI (i.e., Rs per unit leaf area). It guarantees to evaluate more clear response of Rs to drought.

*Reply: Great, the normalized $R_s$ by LAI allows a more straightforward comparison between years. We have revised the context in Revised MS page 42, Line 13-18 as "Overall, the seasonal average of LAI-normalized $R_s$ (i.e., $R_s$:LAI) in 2008 (54.1 s $m^{-1}$ leaf area)was lowest among four years(i.e., $p < 0.05$). The $R_s$:LAI in the dry year (106.8 s $m^{-1}$ leaf area) was 50% higher than in the wet year (71.2 s $m^{-1}$ leaf area) ($p < 0.001$). The $R_s$:LAI in the seasonal drought…"; Moreover, we also have revised the content in Revised MS page 45, Line 26 – page 46, Line3 as "Compared with the $R_s$ in other researches, the $R_s$:LAI in dry years of this poplar plantation was close to that of Euphrates Poplar (Populus euphratica Oliv.) (130.2 s $m^{-1}$ leaf area) and smaller than that of Gansu Poplar (Populus gansuensis Wang et Yang) (189.4 s $m^{-1}$ leaf area) in northwest China (Chen et al., 2004), but in wet years it was similar to that of poplar (58.6 s $m^{-1}$ leaf area)in Iceland (Wilson et al., 2002b) and boreal aspen during the full-leaf period (51.8 s $m^{-1}$ leaf area)in Canada (Blanken et al., 1997)."*

In the discussion, explain which ecosystem is sustainable ecosystem. For example, an ecosystem which water loss equal to water supply is sustainable or an ecosystem which vegetation can survive in drought is sustainable or an ecosystem which surface resistance is not sensitive to drought is sustainable. And, explain why the authors argue that. Currently, it is hard to know how the authors assess the ecosystem sustainability. I guess the authors may argue that the higher Rs, beta and Omega is the less sustainability. It is hard to be acceptable without additional explanation.

*Reply: As we have replied in the earlier comments, the broad sense of the sustainability of poplar plantation in water limited region was assessed in terms of plantation and environment interactions relating to water availability and supply. Therefore, thanks for this constructive suggestion. We have added the discussion of sustainability in Revised MS page 47, Line 12-31 as "[4.3 Implication for poplar plantation establishment]To our knowledge, there is no and it is hard to develop a metrics for the sustainability of forest plantation, even though there are a couple of studies defining the sustainability of forest plantation by site and plantation productivity for commercial purpose only (e.g. (Richardson et al., 1999; Watt et al., 2005)) other than in a broader sense of the plantation and environment interactions that were our focus in the current paper. Our previous study indicated that annual water use of the plantation was even higher than the annual precipitation (Zhang et al., 2014) and thus the irrigation was applied in dry years by pumping groundwater (Table 1). Such water abstraction for irrigating plantation and agriculture crops led to the dramatic water table decline in the last 30 years (Zhang et al., 2014). Energy partitioning to latent and sensible heat and* *surface resistance was dramatically responsive to meteorological drought, and as indicated by low $LE/LE_{eq}$ (< 1) and low values of decoupling coefficient ( $\Omega$) (Zhu et al., 2014), the dry climate dominated the poplar plantation no matter in wet or dry years, which led to the shortage of water use in poplar plantation. In other words, the poplar plantation would consume much water which comes from precipitation or groundwater to maintain its ecological services,* while *the required irrigation for sustaining these forests may present a threat to the adjacent ecosystems because of their role in reducing ground water table, and may compromise long-term sustainability and livelihoods in the region. Therefore, from the viewpoint of hydrologic balance as well as interactions with atmosphere, growing poplar trees in a water-stressed region is not sustainable."*

Everyone knows that Rs, beta and Omega for an ecosystem under water stress is higher than that under normal condition. But, the authors compare Rs, beta and Omega between the study site and the others, without explanation of water stress status of the sites. I recommend to find the reported Rs, beta and Omega for ecosystems in (semi) arid region, and compare those with the indices for the study site.

*Reply: Thanks for your suggestion, as suggested in general comment 5, we compared the LAI normalized Rs (Rs:LAI) with other studies, can be seen in Revised MS page 45, Line 26 – page 46,Line 3.*

**Specific Comments**

Line 12, page 350: present –> presented

*Reply: Thanks for your careful reading. Revised. (see in Revised MS page 33, Line 25).*

Line 18, page 352: The correction method of Burba et al. (2008) can be applied to the case a sensor LI-7500 is installed perpendicularly. Write how the sensor is installed.

*Reply: Thanks for this review comment. The sensor Li-7500 was installed towards predominant wind direction (southeast) with a slight tilt (< 20 degree). Therefore, we have revised the statement in Revised MS from page 34, Line 29 – page 35, Line 2 as "The $CO_2/H_2O$ sensor head was installed towards a predominant wind direction (southeast) with a slightly vertical angle (< 20 degree) and downwind of the sonic anemometer in the predominant wind direction; The".*

Line 24, page 352: The friction velocity threshold method is also applied to the latent/ sensible heat flux? If not, eliminate the explanation of friction velocity correction for CO2 flux during nighttime.

*Reply: Thanks for your comments and we are sorry for the confusions. The friction velocity threshold was applied to process the EC data for screening and gap-filling $CO_2$ fluxes and the latent heat fluxes, but not* *for the sensible heat fluxes.*

Line 19-21, page 355: The sentence, "Lower or higher…" should move to the next paragraph.

*Reply: Thanks for your careful reading. We have removed the sentence "Lower or higher values indicate that evaporation rates are lower or higher than the equilibrium rate, respectively (Wilson et al., 2002b)." (see in Revised MS page 38, Line 24-26).*

Line 8, page 363: (Noormets et al., 2008) –> (e.g., Noormets et al., 2008)

*Reply: Corrected. See in Revised MS page 45, Line 24-25.*

Figure 2, 3, 4, and 5: Unify the ranges of x axis (DOY). Use running mean average for time series data. After applying running mean, it will be easier to distinguish the differences of seasonalities of time series.

*Reply: Thanks for your suggestion. We have revised the Figure 2, 3, 4, 5 based on the comments, see as follow: (see Page 61, 64, 65, 67 in Revised MS)*

----------------------------------------------The-----End----Line----------------------------------------------------------

**Referee #2 (C298):**

**General Comments**

1. The researchers investigated an important topic related to the exacerbation of drought conditions due to large-scale afforestation of high water-use hybrid poplar in China. Four years (2006-2009) of continuous eddy-covariance flux and climate measurements were made above and within the Daxing Forest Farm located in Beijing, China. This appears to be a valuable dataset with fluxes achieving high energy balance closure. The climatic controls on surface resistance, calculated from the inverted Penman-Monteith equation, and the subsequent partitioning of net radiation into turbulent energy fluxes (latent and sensible heat) were discussed.

2. The authors need to justify using the term "drought" when there was one year with below-average precipitation followed by two years with above average precipitation and a final year with below-average precipitation. Perhaps it should be described as four years with seasonal dry periods.

*Reply: Yes, there were seasonal dry periods within the four years. As we have already reported the effects of timing of drought occurrence on the carbon exchange throughout growing season for the plantation from 2006 to 2009 (Zhou et al., 2013), therefore, we focused on the contrasting of energy balance and surface resistance between the dry and wet year for accessing the suitability of poplar plantation in water-limited regions. As we stated in Revised MS page 36, Line 10-13, we classified four studied years into "dry" and "wet" years. The dry year referred to the meteorological drought when yearly precipitation less than 75% of the multi-year average according to the National Standard of People's Republic of China (GB/T 20481-2006). Therefore, we have revised the content in Revised MS page 36, Line 10-16 as "Four year study period was classified as "wet" or "dry" year distinctively. The dry year referred to the meteorological drought when yearly precipitation less than 75% of the 20-year average according to the National Standard of People's Republic of China (GB/T 20481-2006) (China, 2006). Years 2007 and 2008 were classified as "wet" while 2006 and 2009 were "dry" year, respectively."*

3. A further concern is that adding irrigation of 86 and 195 mm in the first and fourth years brings all four years above the long-term mean precipitation. Was this irrigation scheduling part of regular stand management? If so make it clear. Considering these amounts of irrigation water that were applied, distinguishing between "dry" and "wet" years becomes very difficult. The question arises: if the hybrid poplar had not been irrigated in 2006 and 2009 (the years with low precipitation) how would that have affected the conclusions?

*Reply: Thanks for raising these questions. The plantation was designated as "ecological forest" other than "commercial forest" after 2004, therefore, the application of irrigation and other management practices were nonscheduled and not well documented. We have revised the text in Material and methods section (see in Revised MS page 34, Line 16-19 as "The amount of flood irrigation was applied by pumping groundwater and back calculated based on records of water meters from three wells on a weekly basis from 2006 through 2009."*

*It surely becomes difficult to distinguish the "dry" and "wet" years when irrigation water was applied. However, the dry year really referred to the meteorological drought according to the national standard. Our result indicated that the drought triggered physiological stress (higher surface resistance) in the dry years even with the irrigation applied. It is a pity that we could not compare the situation without irrigation due to our study was not a controlled one. Comparison with irrigation and without irrigation would have drawn more insights on the effects of meteorological drought and seasonal drought on energy partitioning and resistance parameters.*

4. It was found that the latent heat flux accounted for 62% and 53% of the available energy flux in the wet and dry years, respectively. The authors also report this in terms of the ratio of LE to LEeq (0.81 and 0.68, respectively). Certainly the fraction for the wet years is higher than for

the dry years but it is not a large difference. Unfortunately it is not known how much lower the values in the dry years would have been with no irrigation. Could the same irrigation totals have been applied in different amounts at different times during the year resulting higher latent heat flux totals and presumably higher growth rates? This is an important question since the soil is coarse textured with limited water holding capacity. These issues need to be addressed in the introduction to the paper when addressing the objectives and the experimental design.

*Reply: Yes, unfortunately, we could not calculate the values in the dry years if irrigation would not have been applied. Given that this was not a controlled experiment, the carbon and water exchanges of the plantation with the atmosphere have been studied under different soil moisture conditions (Zhou et al., 2013). Due to the coarse textured sandy soil and flood irrigation applied, we assumed that timing and amount of irrigation would have shorter time scale effects on the energy partitioning and surface resistance. Therefore, we have revised the content in Revised MS page 32, Line 5-11 as "The goal of the current study was to examine how forest water and energy balances vary under different climatic conditions and how to best manage the plantation forests to maximize ecological benefits in water limited region. Therefore, we evaluated drought responses in energy partitioning 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 changes in the surface resistance and energy partitioning in the water-demanding poplar species."*

5. The conclusions need to be made clearer. For example, the authors concluded that "partitioning of available energy to latent and sensible heat differed significantly between wet and dry years" but also concluded that "overall low LE/LEeq and high surface resistance values in all years indicated that the study area was under water stress even in the wetter years". The implications of these somewhat different statements need to be explained. The final concluding statement (repeated in the Abstract) needs to be rewritten. It states "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". I suggest that the authors make it very clear what is meant by "dry surface conditions". Are they referring to surface resistance or surface soil moisture content? What criterion is being used in determining that conditions are dry? How do these conditions lead to the conclusion that "fast-growing and water use-intensive species like poplar plantations are poorly adapted for the water limited region"? If less water is used (low LE), and the trees remain healthy (or are the trees dying?), doesn't this suggest they quite well adapted?

*Reply: Thanks for your suggestion and sorry for not clarifying the statement. LE/LEeq less than 1 and higher surface resistance even in the wet year indicated that the low LE of poplar plantation was actually caused* *by the soil water deficit and drought stress rather than low water demand. Therefore, irrigation was needed to maintain the poplar plantation by extracting groundwater in the water limited region. We could then conclude that "fast-growing and water use-intensive species like poplar plantations are poorly suited for the water limited region".*

*We have revised the* ***conclusion*** *in Revised MS page 48, Line 2-32 as "The seasonal drought stress affected the dynamics of individual turbulent energy fluxes and the surface resistances in the poplar plantation during growing seasons. Partitioning of available energy into latent (LE) and sensible heat (H) flux responded to meteorological drought and correspondingly displayed 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) in dry years was 33% higher than that in wet years. Accordingly, the contrasting impact 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 overall low LE/LEeq (< 1) of poplar plantations indicated that dry climate dominated in this water limited region, which suggested that the fast-growing and water-intensive species like poplar plantation are poorly adapted for the water limited regions."*

6. There is considerable poor grammar and composition which should be corrected by the native English-speaking co-authors.

*Reply: Thanks for your suggestion for ensuring the publication quality. The native English speaking co-authors have edited the paper for language. Revised content can be seen in authors' changes in manuscript.*

7. After addressing the above concerns and the specific points below, the paper would make a valuable contribution to ongoing international hybrid poplar water use research.

**Specific Comments**

1. Page 347, Lines 6 and 8: In line 6 you refer to "canopy resistance" and then to "bulk canopy resistance" in line 8. Throughout the paper and within equations you refer to "surface resistance". I think you should change both resistances mentioned in lines 6 and 8 to surface resistance to remain consistent.

*Reply: Thanks for careful reading and sorry for the confusions. Corrected ( see in Revised MS page 30, Line 6, 9).*

2. Page 347, Line 6: Insert "fluxes" after CO2.

*Reply: Thanks for careful reading. Corrected (see in Revised MS page 30, Line 7).*

3. Page 347, Line 7: What is meant by “true” ecosystem functions? Make this clearer.

*Reply: Sorry for inappropriate expression. We have revised the expression (see in Revised MS page 30, Line 8);*

4. Page 347, Line 11: I suggest using ", calculated as net radiation (Rn) minus soil heat flux (G), was partitioned into" rather than "(Net radiation Rn minus Soil Heat Flux, G).

*Reply: Thanks for your suggestion. We have revised the content in Revised MS page 30, Line 11-14 as “The partitioning of available energy (Net radiation Rn minus Soil Heat Flux, G) partitioning to latent heat (LE) decreased from 0.62 to 0.53 under meteorological drought. A concomitant increase in sensible heat (H) resulted in the increase of a Bowen ratio from 0.83 to 1.57.”.*

5. Page 347, Line 12: Define what is meant by climatological drought.

*Reply: Sorry for the confusion. We have revised “climatological drought” to “meteorological drought” (see in Revised MS page 30, Line 13), which was defined based on whether the precipitation in a period exceed the average precipitation over the same period during years (China, 2006).*

6. Page 347, Line 13: 62%. I’d suggest this be written as 0.62 to be consistent with other ratios you’ve reported.

*Reply: Thanks a lot. Corrected (see in Revised MS page 30, Line 12, 14);*

7. Page 347, Line 21: Start a new sentence “The LE/LEeq…”.

*Reply: Sorry for the confusions, the statement “and the LE/LEeq ratio ranged from 0.81 and 0.68 in wet and dry years, respectively.” is juxtaposed with “the decoupling coefficient ($\Omega$ = 0.45 and 0.39 in wet and dry years, respectively),”, so we have revised the statement as “as indicated by the decoupling coefficient ($\Omega$ = 0.45 and 0.39 in wet and dry years, respectively) and the $LE/LE_{eq}$ ratio ranging from 0.81 and 0.68 in wet and dry years, respectively.” (see in Revised MS page 30, Line 22-24).*

8. Page 347, Line 21-24: This last sentence is not clear enough (dry surface conditions vs soil water availability...?); should be rephrased to make it clearer.

*Reply: Thanks for this review comment. We have revised the statement as “In general, the dry climate dominated the poplar plantation ecosystem regardless of soil water availability suggesting that fast-growing and water use-intensive species like poplar plantations are poorly suited for the water limited region” (see in Revised MS page 30, Line 24-27).*

9. Page 348, Line 14: I suggest using "increased" rather than "a growing".

*Reply: Corrected. (see in Revised MS page 32, Line 4);*

10. Page 349, Line 24-25: I suggest using "resistance" throughout the paper rather than "conductance" to keep consistent with equations and maintain clarity. An advantage of conductance is that tends to be proportional to LE, whereas resistance is very nonlinear with LE, e.g., you get a wide range of high Rs values that correspond to low values of LE.

*Reply: Thanks a lot, corrected parts as followed:*

*Line 21, Page 32 in Revised MS;*

*Line 10, Page 33 in Revised MS;*

*Line 15, Page 38 in Revised MS;*

*Line 5, Page44 in Revised MS;*

11. Page 350, Line 23: Is the wind coming from OR going toward "the southern and northwest directions". Usually wind is described in terms of which direction it is coming from.

*Reply: Sorry for the inappropriate expression. We have revised the statement as "and it mostly comes from southeast (during growing season) and northwest (during non-growing season)." (see in Revised MS page 34, Line 5-7);*

12. Page 352, Lines 7-8: It should be indicated at which depths the CS616 probes are placed. Were they all placed at 50 cm?

*Reply: Thanks for raising this question. The CS616 probes were placed at 20cm and 50cm depth. We have corrected the statement in Revised MS page 35, Line 16-17as "Soil water content was measured with TDR sensors (CS616; CSI) buried at 20 and 50 cm.";*

13. Page 354, Line 6: Gu et al. (1999) does not present the energy balance ratio in summation notation as you do in Eq (3). If the summation notation is kept, the interval over which the summation is calculated should be specified. 24 hr, half-hourly, etc.

*Reply: You are right that the paper of Gu et al. (1999) that did not make this statement and we are sorry for this mistake. We have revised Equation (3) and corrected the content in Revised MS page 37, Line 8-10 as "Based on the daytime half-hourly and daytime totals of turbulent energy fluxes, the energy balance ratio ($E_{BR}$) is calculated as Eq. (3),";*

14. Page 355, Line 16: "Equilibrium" should not be capitalized.

*Reply: Corrected. (see in Revised MS page 38, Line 20).*

15. Page 357, Lines 2-4: “Long-term drought stress (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).” would read better as “Long-term 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).

*Reply: Thanks a lot. We have revised this sentence to “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).” (see in Revised MS from page 39, Line 29 to page 40, Line 2);*

16. Page 357, Line 9: The drought stress periods for 2007 should be introduced in a consistent manner, formatted as they were in on Page: 357 Line: 7 for 2006 (#2_06).

*Reply: Thanks for this review comment. We have corrected the statement as “drought stress occurred during DOY 110-143 (#1_07) and DOY 151-200 (#2_07).” (see in Revised MS page 40, Line 7-8);*

17. Page 358, Line 18-19: I don’t think H can be a dominant factor controlling Rn. Explain.

*Reply: You’re right. We are sorry for inappropriate expression. We have corrected the text as “H became the main consumer of the growing season $R_n$ in October for dry years and in November for the wet years.” (see in Revised MS page 41, Line 19-22);*

18. Page 358, Line 21-22: “LE/(Rn - G) was significantly higher in 2008 (64.8 %) than in 2006 (57.1 %), 2007 (60.3 %) and 2009 (50.4 %)”. These aren’t really large differences.

*Reply: Yes, the magnitudes of these seasonal average LE/(Rn-G) look similar to each other. On the basis of ANOVA, LE/(Rn-G) in 2006 was not significantly lower than that in 2007 and 2008 ($p > 0.254$), LE/(Rn-G) in 2008 was significantly higher than that in 2007 and 2009 ($p < 0.031$), LE/(Rn-G) in 2009 was smallest among four years ($p < 0.001$); but there was a significant difference between dry and wet year, with $F=17.599$, $p < 0.001$. We have revised the text as “Partitioning of Rn into LE and H differed significantly between the wet and dry years ($F = 17.599$, $p < 0.001$).” (see in Revised MS page 41, Line 24-25).*

19. Page 358, Lines 25-27: “The dominant part in energy partitioning” should be changed to “The dominant turbulent energy flux” throughout the paper.

*Reply: Thanks for this comment. Changed. (see in Revised MS page 41, Line 27)*

20. Page 358, Line 27: “dominate” should be “dominant”.

*Reply: Sorry for the mistake. Corrected. (see in Revised MS page 41, Line 29-30)*

21. Page 360, Line 4: "Difference" should be "differences" and "year" should be "years".

*Reply: Thanks for your careful reading. Corrected. (see in Revised MS page 42, Line 32);*

22. Page 360, Line 14: "dramatic" should be "dramatically".

*Reply: Thanks for your patience for ensuring the publication quality. We assume that the referee means the "dramatic" in Line 18, Page 360. Correct it to "much". (see in Revised MS page 43, Line 14);*

23. Page 360, Line 4: The sentence "Drought is also an expected source of interannual variation in Rs (Wilson et al., 2002b)." seems redundant and should probably be removed given you make this apparent in previous sentences.

*Reply: Thanks for your suggestion. We think that the referee refers to Page 363, Line 16-17. We have deleted the text "Drought is also an expected source of interannual variation in $R_s$ (Wilson et al., 2002b)."(see in Revised MS page 46, Line 5-6);*

24. Page 360, Line 14: "The mean $\Omega$ for the studied years were 0.41, 0.46, 0.43 and 0.39". The magnitudes of these numbers are very similar.

*Reply: Thanks a lot. Yes, the magnitudes of these seasonal mean decoupling coefficient ( $\Omega$) look similar to each other. But on the basis of ANOVA, the significant differences were only showed between 2007 (0.46) and 2009 (0.39) among four years ($p < 0.01$), but there was a significant difference between dry and wet year, with $F=9.460$, $p=0.002$. We have revised "($p < 0.01$)" (in BGD Page 360, Line 16) as "($F=9.460$, $p < 0.01$)". (see in Revised MS page 43, Line 11);*

25. Page 360, Line 17-18: The drought periods within the brackets (#1, #2, etc.) should be consistent with the format in which they were introduced on page 357.

*Reply: Thanks for your patience. We have corrected the expression as "(#1_06, #2_06; #1_07, #2_07 and #1_09, #2_09, #3_09)". (see in Revised MS page 43, Line 12-13);*

26. Line 362, Line 16-19: "Our current findings corroborate that hypothesis." But you report you observed low rates of evapotranspiration (LE) on Page 364, Line 17. Regarding the statement "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." What is your evidence of that productivity was limited by water supply? Why would there be an adverse regional region's groundwater reserves if evapotranspiration is

low?

*Reply: Sorry for the confusions. We agree that we could not reach this conclusion based on the results from energy partitioning, therefore, we have revised the text in Revised MS page 45, Line 3-8 as "Our current findings corroborate the hypothesis that drought would trigger significant changes in energy partitioning of water-demanding poplar species in a water-stressed region.";*

"Why would there be an adverse regional region's groundwater reserves if evapotranspiration is low?"---- *To maintain the ecological function of poplar plantation, the low evapotranspiration due to soil water limitation lead to irrigation in this water shortage region by pumping groundwater, which would intensify the water shortage in the water limited regions.*

27. Page 362, Line 22: quantifies?

*Reply: Thanks for careful reading and sorry for the mistake. Corrected "qualifies" to "quantifies". (see in Revised MS page 45, Line 11);*

28. Page 365, Lines 2-4: Delete sentence. It is unnecessary.

*Reply: Thanks for your suggestion. Corrected (see in Revised MS page 48, Line 15-18);*

29. Page 365, Line 6: I think they are really seasonal drought periods rather than long-term drought periods.

*Reply: Thanks for this revise comment. We have revised the statement "long-term drought periods" as "seasonal drought periods" throughout the manuscript. See corrections in the following sentences in BGD,*

*Page 357, Line 2, 6 (see Line 29, page 11 and Line 4, page 40 in Revised MS);*

*Page 359, Line 11, change "long term drought" to "the drought" (see Line 8, page 42 in Revised MS);*

*Page 359, Line 19 (see Line 18, page 42 in Revised MS);*

*Page 360, Line 17 (see Line 12, page 43 in Revised MS);*

*Page 362, Line 5, 9 (see Line 24, 29, page 44 in Revised MS);*

*Page 363, Line 6 (see Line 22, page 45 in Revised MS);*

*Page 364, Line 23 (see Line 9, page 47 in Revised MS);*

*Page 365, Line 6 (see Line 3, page 48 in Revised MS);*

30. Page 365, Lines 18-21: See General Comment 5.

*Reply: See reply for General comment 5(see text from page 9, Line 34 to page 10, Line 16 of this file);*

31. Page 379, Fig. 1: Insert "respectively" after "brace".

*Reply: Corrected (see in Revised MS page 60, Line 13);*

32. Page 380, Fig. 2: Were the soil moisture sensors installed at a location that received all irrigations? I see only a small effect of the 30 mm irrigation on DOY 290 in 2006. Is that because the moisture sensors are so deep?

*Reply: Thanks for raising this question. As we stated earlier in Reply of General Comment 3(Referee #2), the management operations were not well documented, the irrigation of the plantation was applied by workers in Daxing Forest Farm according to their personal experience, and the irrigation was only applied for young plantation, and some of young plantation was apart from the location of soil moisture sensors. Therefore, the small effect of the 30 mm irrigation on DOY 290 in 2006 may be caused by the irrigation for the young plantation which was relatively close to the sensors location.*

33. Page 381, Fig. 3: Plotting 5-day running means or weekly numbers will likely show clear distinctions among years by reducing crowding.

*Reply: revised the Figure 3 and corrected the caption to "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)." (see in Revised MS page 64);*

34. Page 382, Fig. 4: Renumber the y axis with the inclusion of "0". I'd suggest -2, 0, 2, 4, 6, and 8.

*Reply: revised the Figure 4 and corrected the caption to "Figure 4. Seasonal and inter-annual variability of the midday mean Bowen ratio (β) (5-day running average) across the growing season, with detailed β during DOY 185-255 representing in small pane; Midday means the time course from 10:00 a.m. to 15:00 p.m. at local standard time" (see in Revised MS page 65);*

35. Page 383, Fig. 5: 5-day means or running means would make the 4 years more distinguishable from each other.

*Reply: revised the Figure 5, and correct the caption to "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) (5-day running average) across the growing season from 2006 to 2009. Midday means the time course from 10:00 a.m. to 15:00 p.m. LST." (see in Revised MS page 67);*

36. Page 384, Fig. 6: This figure is virtually the same as Fig. 9b. Delete Fig. 6 or Fig. 9b.

*Reply: Thanks for this comment, we have revised the Figure 9, and correct the caption to "Figure 9. Seasonal variations of monthly average LAI and $R_s$ during the growing season in wet year 2007 and 2008." (see in Revised MS page 71);*

37. Page 386, Fig. 8: Unexpected values for the Bowen ratio and LE/(Rn – G) for WS < 50 mm. Specify for what depth of the root zone does the 50 mm apply (1 m depth?). How is WS calculated when the sensors are all at 50 cm depth?

*Reply: Thanks for raising this question and sorry for the confusion. As we displayed at Table 3(see in Revised MS page 57), the amount of water supply (WS) during each drought stressed and non-stressed periods was calculated as the sum of precipitation and irrigation. The 50mm of WS was not related to the depth of sensors location.*

38. Page 388, Fig. 10: It can be shown that the data can be separated (stratified) into increasing values of Ri with higher values for dry years.

*Reply: Thanks for suggestion. We are not sure that we really follow the referee's advices. Accordingly, we have added the content in Revised MS page 46, Line 17-18, as "during which the sensitivity of Bowen ratio on $R_s$ increased with the growing $R_s$."*

----------------------------------------------The-----End----Line---------------------------------------------------------

# Additional changes:

## Highlighted by green in Revised MS (page 29-72)

1. Page 347, in BGD: revised "S. McNulty" to "S. G. McNulty" (*see in Revised MS page 29, Line 4*); and corrected "Eastern Forest Environmental Threat Center" to "Eastern Forest Environmental Threat Assessment Center" (*see in Revised MS page 29, Line 12*);

2. Page 347, Line 1-24 in BGD: the **Abstract** has been revised **(***see in Revised MS page 30, Line 2-29*) as "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 climate, the sustainability of these plantations needs to be evaluated. Currently, the understanding of the acclimation of the species to the semiarid environment is limited, impeding assessments of their long-term success and impact on the environment. In this study we examine the variability of 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 located in northern China. The partitioning of available energy to latent heat (LE) decreased from 0.62 to 0.53 under meteorological drought. A concomitant increase in sensible heat (*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) (i.e., $R_s$:LAI) increased by 50% and became the dominant factor 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 LE/$LE_{eq}$ ratio ranging from 0.81 and 0.68 in wet and dry years, respectively. In general, the dry climate dominated the poplar plantation ecosystem regardless of soil water availability suggesting that fast-growing and water use-intensive species like poplar plantations are poorly suited for the water limited region. The required irrigation for sustaining these forests also presents a thread to the adjacent ecosystems because of their role in reducing ground water table, and may compromise long-term sustainability and livelihoods in the region.";

3. Page 348, Line 11-13 in BGD: revised the content as "However, indiscriminate use of the same species beyond its 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" *(see in Revised MS page 31, Line 10-15).*

Page 350 in BGD,

Line 8 and 9: change "removed and replanted" to "replaced with new saplings", and change "given" to "provided" (*see in Revised MS page 33, Line 21-22*);

Line 11-13: change the sentence to "The average leaf area (LAI) of the stand increased over time. During the growing season, shrubs as the understory layer were low at density due to manual removal." (*see in Revised MS page 33, Line 24-26*);

Line 16-21: change sentences to "The local climate is classified as sub-humid warm temperate zone, with a mean (1990–2009) annual temperature of 11.6 ℃, and maximum and minimum temperature are 40.6 ℃ and -27.4 ℃, respectively. The annual precipitation ranges from 262 mm to 1058 mm (1952-2000), with an average of 556 mm, of which 60%-70%..." (*see in Revised MS from page 33, Line 29 to page 34, Line 2*);

Line 24-26: change "belong to" to "is on", add "the" before "Yongding River", remove "with" (*see in Revised MS page 34, Line 8-10*);

10. Page 351 in BGD,

Line 2: change “average annual depth of 16.5 m below ground” to “annual average of 16.5 m below the ground” (*see in Revised MS page 34, Line 12*);

Line 4: correct “from May to June” to “from May through June” (*see in Revised MS page 34, Line 14*);

Line 12 to 13: change “at the 32 m central instrument tower” to “at a 32 m tower” (*see in Revised MS page 34, Line 22-23*);

Line 13: add “which was” before “established” (*see in Revised MS page 34, Line 23*)

Line 16: change “measured using the eddy-covariance” to “calculated based on the eddy-covariance (EC) principles” (*see in Revised MS page 34, Line 26-27*);

Line 17: delete “eddy-covariance” (*see in Revised MS page 34, Line 27*);

Line 22 to 24: revise sentences “To sure that …in February.” to “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” (*see in Revised MS page 35, Line 3-6*);

10. Page 352 in BGD,

Line 3: remove “with sampling points” (*see in Revised MS page 35, Line 12*);

Line 5: remove “above the ground” (*see in Revised MS page 35, Line 14*);

Line 14: revise the sentence to “The raw 10Hz data were processed with an EC Processor,” (*see in Revised MS page 35, Line 23*);

Line 15: correct “eddy covariance” to “EC” (*see in Revised MS page 35, Line 24-25*);

Line 17: add “the” before “planar fit method” (*see in Revised MS page 35, Line 26*);

Line 22-23: Delete sentence “Data gaps were filled using the MDV (mean diurnal variation) method (Falge et al., 2001).”, which duplicated with Page 352, Line 28 in BGD (*see in Revised MS from page 35, Line 31 to page 36, Line 1*);

11. Page 353 in BGD,

Line 3: remove “the” (*see in Revised MS page 36, Line 8*);

Line 10: revise “much stonger” to “strong” (*see in Revised MS page 36, Line 18*);

Line 13: revise “PAR > 4 umol $m^{-2}$ $s^{-1}$, the controlling processes” to “PAR > 4 μmol $m^{-2}$ $s^{-1}$. The regulations” (*see in Revised MS page 36, Line 20-21*);

Line 14: correct “and” to “, with”; and delete “are” (*see in Revised MS page 36, Line 22*);

Line 15: change “reliable than” to “station than those” (*see in Revised MS page 36, Line 23*);

Line 22: change “:” to “,” (*see in Revised MS page 36, Line 30);*

12. Page 354 in BGD,

Line 1: revise “As an indicator of water stress, the…” to “The…” (*see in Revised MS page 37, Line 4*);

Line 3: change “the midday” to “. The midday” (*see in Revised MS page 37, Line 6*);

Line 6-7: add the equation for calculating the heat storage term as Eq. (4) (*see in Revised MS page 37, Line 11-16);*

Line 8: change “Eq (4):” to “Eq (5),” (*see in Revised MS page 37, Line 18*);

Line 9: change “(4)” to “(5)” (*see in Revised MS page 37, Line 19*);

Line 14: revise “$R_i$, the climatological resistance (s $m^{-1}$) indicates” to “$R_i$ is the climatological resistance (s $m^{-1}$) indicating” (*see in Revised MS page 37, Line 24*);

Line 15: change “in Eq. (5):” to “as,” (*see in Revised MS page 37, Line 25*);

Line 16: change “(5)” to “(6)” (*see in Revised MS page 38, Line 1*);

13. Page 355 in BGD,

Line 4: change “:” to “,” (*see in Revised MS page 38, Line 9*);

Line 5: change “(6)” to “(7)” (*see in Revised MS page 38, Line 10*);

Line 6: revise “transfer and $r_b$” to “transfer, and $r_b$ is” (*see in Revised MS page 38, Line 11*);

Line 7: add “,” after “wind speed” (*see in Revised MS page 38, Line 12*);

Line 11: change “value” to “values” (*see in Revised MS page 38, Line 16);*

Line 14: change “:” to “,” (*see in Revised MS page 38, Line 18*);

Line 15: change “(7)” to “(8)” (*see in Revised MS page 38, Line 19*);

Line 17: revise “it is calculated as:” to “is dependent only on Rn and temperature. It is calculated as,” (*see in Revised MS page 38, Line 21-22*);

Line 19-21: delete the sentences “The LEeq is dependent only on …, respectively (Wilson et al., 2002b)” (*see in Revised MS page 38, Line 24);*

14. Page 356 in BGD,

Line 1: revise “can denote” to “reflects” (*see in Revised MS page 39, Line 1*);

Line 3-7: revise to “An $LE/LE_{eq}$ of < 1 represents an ecosystem under water stress and, therefore, experiences reductions in evapotranspiration; whereas $LE/LE_{eq}$ of > 1.26 indicates an ecosystem of unrestricted water supply and only available energy limits evaporation (Arain et al., 2003). The $LE/LE_{eq}$ is dependent of" (*see in Revised MS page 39, Line 5-9*);

Line 12-13: revise "to compare the environmental factors, the energy fluxes and" to "for quantifying the changes of all biophysical variables, energy fluxes, and" (*see in Revised MS page 39, Line 14-15*);

Line 14: change "different studies" to "the differences of biophysical variables among different studies." (*see in Revised MS page 39, Line 16-17*);

Line 15-16: revise "Bowen ratio values with the other two as the control variables" to "Bowen ratios" (*see in Revised MS page 39, Line 18-19*);

Line 21: delete "the" (*see in Revised MS page 39, Line 24*);

Line 22-23: revise the sentence "Whereas in 2007 and 2008 rainfall exceeded the 20 year mean by over 100 mm" to "Whereas rainfall exceeded the 20-year mean by over 100 mm in 2007 and 2008." (*see in Revised MS page 3, Line 25-26*);

Line 24: revise "the growing season (i.e., April-October)" to "April-October," (*see in Revised MS page 39, Line 26-27*);

15. Page 357 in BGD,

Line 1: change "among years" to "among the years" (*see in Revised MS page 39, Line 27*);

Line 8: add "throughout the year" after "distributed" (*see in Revised MS page 40, Line 6*);

Line 10: correct "accounted for 57 mm of the total annual precipitation" to "(57 mm)" (*see in Revised MS page 40, Line 9*);

Line 11-12: revise "(P > 25 mm $d^{-1}$) in July also presented a large portion of the total annual sum." to "(i.e., > 25 mm $d^{-1}$) in July were recorded." (*see in Revised MS page 40, Line 10-11*);

Line 13: correct "and" to "during which" (*see in Revised MS page 40, Line 12*);

Line 13-17: revise the sentences ", mostly … of the sandy soil" to ". There were several short droughts across the growing season of 2009 (Fig. 2d). Despite the higher-than normal rainfall in the two wet years, there was no flooding or overland runoff." (*see in Revised MS page 40, Line 12-13*);

Line 18: correct "The $T_a$" to "The growing season $T_a$", and delete "during growing season" (*see in Revised MS page 40, Line 17-18*);

Line 21: delete "overall" (*see in Revised MS page 40, Line 20*);

Line 23: change "reached" to "was" (*see in Revised MS page 40, Line 22*);

Line 24: revise "Mean" to "The mean" (*see in Revised MS page 40, Line 23*);

Line 27: add "those" behind "than" (*see in Revised MS page 40, Line 25*);

16. Page 358 in BGD,

Line 1-2: revise the sentence "the VPD of … (i.e., $p < 0.01$)." to "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, $p < 0.01$)." (*see in Revised MS page 40, Line 27-29*);

Line 4: change "Seasonal and inter-annual" to "The" (*see in Revised MS page 41, Line 1*);

Line 5: change "among" to "into" (*see in Revised MS page 41, Line 3*);

Line 5: add "heat storage of canopy (*S*)" (*see in Revised MS page 41, Line 3-4*);

Line 7: delete "at", revise "and" to ", ", and remove "then" (*see in Revised MS page 41, Line 5*);

Line 10: revise "On the other hand, even though the" to "The" (*see in Revised MS page 41, Line 8*);

Line 11: change "between" to "among" (*see in Revised MS page 41, Line 9*);

Line 12: revise "the value of wet years was lower than" to "with a lower value in wet years" (*see in Revised MS page 41, Line 10*);

Line 13: change "Also" to "Additionally" (*see in Revised MS page 41, Line 11*);

Line 13-14: revise "which ranged from 2.1 (in 2007) to 4.9% (in 2006)" to "which ranged from 2.1 in 2007 to 4.9% in 2006" (*see in Revised MS page 41, Line 11-12*);

Line 17: correct "except in August for the year of" to "but August for" (*see in Revised MS page 41, Line 18*);

Line 20: add "the" before "four years" (*see in Revised MS page 41, Line 22*);

Line 21: add "those" before "in 2006" (*see in Revised MS page 41, Line 23*);

Line 22: revise "in the other" to "those in other" (*see in Revised MS page 41, Line 24*);

Line 27: correct "during which" to "when" (*see in Revised MS page 41, Line 29*);

17. Page 359 in BGD,

Line 1: delete "even" (*see in Revised MS page 41, Line 30*);

Line 4-5: revise "(from April to June) and end (from September to October)" to "(April-June) and end (September-October)" (*see in Revised MS from page 41, Line 32 to page 42, Line 3*);

Line 7: revise "DOY 180 to 250" to "DOY 180-250", and change "DOY 180 to 290" to "DOY 180-290" (*see in Revised MS page 42, Line 4-5*);

Line 8: change "wet year" to "the wet year" (*see in Revised MS page 42, Line 6*);

Line 9: add “the” before “four growing season” (*see in Revised MS page 42, Line 7*);

Line 11-12: revise “The Bowen ratio … in 2008” to “The Bowen ratio was smaller than 1 during drought stressed periods in 2008” (*see in Revised MS page 42, Line 9-10*);

Line 16: change “(DOY: from 190 to 250)” to “(DOY 190-250)” (*see in Revised MS page 42, Line 14*);

Line 20: correct “in the no stressed” to “those in unstressed” (*see in Revised MS page 42, Line 21*);

Line 21: add “a” before “significantly” (*see in Revised MS page 42, Line 22*);

Line 22: change “wet year” to “wet years” (*see in Revised MS page 42, Line 23);*

Line 23: revise “July and August, before” to “July/August before” (*see in Revised MS page 42, Line 24*);

Line 24: add “a” before “mean value” (*see in Revised MS page 42, Line 26*);

Line 26: change “between” to “among the”, and revise “depicts” to “presents” (*see in Revised MS page 42, Line 27*);

18. Page 360 in BGD,

Line 3: correct “during” to “that of”, and change “than in dry year” to “than that in dry years” (*see in Revised MS page 42, Line 30-31*);

Line 4: correct “year” to “years” (*see in Revised MS page 42, Line 32*);

Line 6: revise the sentence to “The changes of $LE/LE_{eq}$ value varied between 0.4 and 1.0” (*see in Revised MS page 43, Line 1-2*);

Line 7: change “of four years” to “of the four years” (*see in Revised MS page 43, Line 3*);

Line 10: correct “was” to “were” (*see in Revised MS page 43, Line 5*);

Line 11: revise “was observed” to “existed” (*see in Revised MS page 43, Line 6*);

Line 14: change “the studied years were” to “the four years was” (*see in Revised MS page 43, Line 9*);

Line 16: revise “than in dry year” to “than that in dry year”; correct “non-stressed” to “unstressed” (*see in Revised MS page 43, Line 11*);

Line 18: change “show” to “was” (*see in Revised MS page 43, Line 13-14*);

Line 21: change “one” to “a”, and correct “eddy covariance” to “EC techniques” (*see in Revised MS page 43, Line 18-19*);

Line 22-24: change “daily” to “daytime”, and correct “value” to “values” (*see in Revised MS page 43, Line 20-21);*

Line 26: change “with 50 site-year” to “with the 50 site-year” (*see in Revised MS page 43, Line 23*);

19. Page 361 in BGD,

Line 1-2: delete the sentence "It should be … additional measurements." (*see* in *Revised MS page 43, Line 24-25*);

Line 4: correct "between" to "among the" (*see* in *Revised MS page 43, Line 27*);

Line 5-6: revise the sentence "At our site…energy balance closure" to "In addition to the known reasons for decreasing energy balance closure" (*see* in *Revised MS page 43, Line 28-29*);

Line 7-8: revise the sentence "management operations … partial felling," to "management operations at our site (e.g., irrigation, tilling and partial felling)" (*see* in *Revised MS page 43, Line 30-31*);

Line 10-11: delete the sentence "to the extent that … turbulent flux data," (*see* in *Revised MS page 44, Line 2-3*);

Line 16: delete "and" (*see* in *Revised MS page 44, Line 7*);

Line 19: revise "even at specific forest site" to "by even at any site" (*see* in *Revised MS page 44, Line 10*);

Line 21: revise "was" to "were" (*see* in *Revised MS page 44, Line 11*);

Line 23-25: correct "avaiability" to "availability"; change "timescale" to "scale", correct "was" to "appeared", correct "precipitation amount of growing season" to "growing season precipitation" (*see* in *Revised MS page 44, Line 14-15*);

Line 28-29 in BGD: revised the sentence "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," as "β varied from 0.18 to 0.71, with a mean of 0.35 ± 0.15 during the most of growing season in 2008 and non-stressed periods in other 3 years," (*see* in *Revised MS page 44, Line 18-20*);

20. Page 362 in BGD,

Line 1-2: correct "in a deciduous forest" to "for a deciduous forest", change ". Similar to" to ", similar to"; and delete "of Bowen ratio" (*see* in *Revised MS page 44, Line 20-22*);

Line 3: correct "in a deciduous" to "a deciduous" (*see* in *Revised MS page 44, Line 23*);

Line 7: change "Loblolly" to "loblolly" (*see* in *Revised MS page 44, Line 27*);

Line 9: change "resulted" to "might be resulted" (*see* in *Revised MS page 44, Line 31*);

Line 21: change "dependent on" to "dependent of" (*see* in *Revised MS page 45, Line 10*);

Line 25: correct "exchange of ecosystem" to "exchange of an ecosystem" (*see* in *Revised MS page 45, Line 14*);

21. Page 363 in BGD,

Line 3-5: correct the sentence "similar to Kutsch et al. (2008), Rs 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)" to "similar to $R_s$ 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; Kutsch et al. 2008; Li et al., 2012)" (*see in Revised MS page 45, Line 19-21*);

Line 6-7: revise "were much higher than in" to "was much higher than that in" (*see in Revised MS page 45, Line 22-23*);

Line 19-20: revise "impacted" to "also influenced"; and change "(soil evaporation, canopy structure and turbulence)" to "(e.g., soil evaporation, canopy structure and turbulence)" (*see in Revised MS page 46, Line 7-9*);

Line 22: change "over 50%" to "~ 50%" (*see in Revised MS page 46, Line 11*);

Line 23: change "for a vineyard" to "in a vineyard"; change "due to" to "likely due to" (*see in Revised MS page 46, Line 11-12*);

Line 25: revise "timescale" to "scale" (*see in Revised MS page 46, Line 14*);

22. Page 364 in BGD,

Line 1: revise "not" to "not be" (*see in Revised MS page 46, Line 20*);

Line 2: change "(such as…)" to "(e.g., ... )" (*see in Revised MS page 46, Line 20*);

Line 3: change "factors" to "roles", and revise "were" to "seemed" (*see in Revised MS page 46, Line 21-22*);

Line 4: correct "than in wet years" to "than that in wet years" (*see in Revised MS page 46, Line 22*);

Line 5: revise the sentence "but no impact … in earlier studies." to "but not in dry years." (*see in Revised MS page 46, Line 23-24*);

Line 6: change "in this site, similar to" to "at our site, which is" (*see in Revised MS page 46, Line 25*);

Line 8: delete the sentence "which ranged from 0.58 to 1.06" (*see in Revised MS page 46, Line 27*);

Line 9: change "(ranging from 0.39 to 0.46)" to "(0.39-0.46)" (*see in Revised MS page 46, Line 28*);

Line 15: delete "universal" (*see in Revised MS page 47, Line 1*);

Line 20: revise "coefficient" to "coefficients" (*see in Revised MS page 47 Line 6*);

Page 365 in BGD,

Line 24: add text "First author also thanks the scholarship support by Beijing Municipality Educational Committee under the graduate student training program." (*see in Revised MS page 49, Line 3-4);*

Page 376 in BGD: revised Table 2. (*see in Revised MS page 56);*

Page 380 in BGD: revise the Figure 2, revise the caption to "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)." (*see in Revised MS page 62*);

## References in reply:


Chen, R., Kang, E., Zhang, Z., Zhao, W., Song, K., Zhang, J., and Lan, Y.: Estimation of tree transpiration and response of tree conductance to meteorological variables in desert-oasis system of Northwest China, Science in China Series D: Earth Sciences, 47, 9-20, 2004.

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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~~climate, the ~~long-term~~ sustainability of these plantations needs to be evaluated. Currently, the understanding of the acclimation of the species to the semiarid environment is limited, ~~energy partitioning and canopy resistance to water vapor and $CO_2$ in poplar plantations is limited,~~ impeding ~~an accurate~~ assessments of their long-term success and impact on the environment. ~~true ecosystem functions.~~ In ~~T~~this study we examine~~d~~ 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. The partitioning of ~~A~~available energy ~~(Net radiation $R_n$ minus Soil Heat Flux, *G*) partitioning~~ to latent heat (LE) decreased from 0.62 to 0.53 under meteorological drought. A concomitant increase in~~and~~ sensible heat ($H$) ~~heat~~ resulted in the increase of a Bowen ratio from 0.83 to 1.57. ~~was responsive to climatological drought, with 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 ($\beta = H$/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 surface resistance ($R_s$) normalized by leaf area index (LAI) (i.e., $R_s$:LAI) increased by 50% and became ~~$R_s$ 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 (Ω =0.45 and 0.39 in wet and dry years, respectively)~~,~~ and the LE/$LE_{eq}$ ratio ~~ranged~~ ranging from 0.81 and 0.68 in wet and dry years, respectively. In general, the dry ~~surface conditions~~climate dominated ~~in this~~the poplar plantation ecosystem regardless of soil water availability suggesting that fast-growing and water use-intensive species like poplar plantations are poorly ~~adapted~~ suited for the water limited region. The required irrigation for sustaining these forests also presents a thread to the adjacent ecosystems because of their role in reducing ground water table, and may compromise long-term sustainability and livelihoods in the 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, indiscriminate use pf the same species beyond its 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 changesplanting 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).

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 may even 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 forests, clearly require large quantities of irrigation in water limited areas such as northern China.

However, over the past 50 years, northern China has experienced the decline of the water table, land degradation, large increases in surface air temperature and severe droughts (Ding et al., 2007; Qiu et al., 2012; Wang et al., 2008; Zhang et al., 2014), while the wide-spread use of irrigation has been cited as one of possible causes for these impacts. Therefore, studying the drought response of poplars under water shortage is essential for effective management of water resource over this region and avoiding the use of water-intensive species in ecological restoration and reforestation efforts if the environmental resources are not sufficient. Whereas, most of previous and current studies are only concentrated on the water balance of forest ecosystem other than the interactions between forest ecosystem and environment, it is clear that exploring the energy partitioning and ecosystem response to drought is central important for understanding forest water and carbon cycling processes (Guo et al., 2010; Jamiyansharav et al., 2011; Sun et al., 2010; Takagi et al., 2009; Wu et al., 2007), and thus understanding the adaption and long term sustainability of plantation establish in water limited regions.

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; Zhang et al., 2005b) 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 goal of the current study was to examine how forest water and energy balances vary under different climatic conditions and how to best manage the plantation forests to maximize ecological benefits in water limited region. Therefore, we evaluated~~The~~ drought responses in energy partitioning in a ten-~~year~~ year-old poplar (*Populus euramericana* CV. "74/76") plantation on sandy soil in northern China~~ was evaluated in this study~~. We hypothesized that ~~the~~ drought would trigger significant changes in the surface ~~conductance~~resistance~~, transpiration~~ and energy partitioning in the water-demanding poplar species. 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 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, 30m a.s.l.). The trees were planted in 1998 with 3 m × 2 m spacing, dead or low-vigor trees were ~~replanted and replanted~~ replaced with new saplings in 2001 and 2003. The stand characteristics over the four years of study are ~~given~~ provided 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 ±1.6cm. The average leaf area index (LAI) of the stand increased ~~year by year~~over time. During the growing season, shrubs as the understory layer were ~~present at~~ low at 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~~, with a mean (1990–2009) annual temperature ~~is~~ of 11.6 ℃, and maximum and minimum ~~extreme~~ temperatures ~~reaches~~ are 40.6 ℃ and -27.4 ℃, respectively~~ (1990–2009)~~. The ~~Annual~~ annual precipitation ranges from 262 mm to 1058 mm (1952-2000), with ~~a long-term (1952-2000)~~an average of 556 mm, of which ~~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 the total sunshine-hour~~s~~ 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 southeast (during growing season) and northwest (during non-growing season).~~mostly in the southern and northwest directions.~~

The study area ~~belongs to~~is on the alluvial plain of the Yongding River, and is flat with an average slope~~s less than~~ of < 5°. The upper two meter of the soil ~~layer~~ is mostly composed of well drained fluvial sand with bulk density of 1.43~1.47 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~~annual average of 16.5 m below the ground in the past nine years (2001 to 2009), and has declined at an average rate of 0.6 m per year. The maximum pan evaporation occurs from May ~~to~~ 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.~~-~~.~~Thus, irrigation was periodically applied to meet the water deficit to the plantations at our study site~~. The amount of flood irrigation was applied ~~water~~ by pumping groundwater and ~~was~~ back calculated based on the records of the water meters from three wells on a weekly basis from 2006 through 2009. 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~~ a 32m ~~central instrument~~ tower in the center of the study site, which was established in June of 2005. The foot-print of the eddy flux covariance system, was about 1 km x 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~~ calculated based on the eddy-covariance (EC) ~~technique~~principles. 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 towards a predominant wind direction (southeast) with a slightly vertical angle (< 20 degree) and downwind of the sonic anemometer in the predominant wind direction~~The $CO_2$/$H_2O$ sensor~~

~~head was installed downwind of the sonic anemometer in the predominant wind direction, and;~~ ~~the~~ 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~~This was increased to about 18 m before the start of the growing season in 2007, ~~to about 18 m,~~ 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 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 22.5m ~~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 20 and 50cm.~~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~~The raw 10 Hz data were processed with an EC Processor, version 2.3 (Noormets et al., 2010). The program is designed for reprocessing ~~eddy covariance~~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 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 ($\mu_*$) below which flux loss occurred was determined from the seasonal binned relationship between nighttime turbulent flux of $CO_2$ and friction velocity ($\mu_*$) (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). 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 (< 2h) 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.

Four year study period was classified into “wet” and “dry” year distinctively. The dry year referred to the meteorological drought when yearly precipitation less than 75% of the 20-year average according to the National Standard of People's Republic of China (GB/T 20481-2006) (China, 2006)..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’ while , and 2006 and 2009 were ‘dry’ year, respectively. 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 μμmol$m^{-2}s^{-1}$,. the The controlling processes regulations of surface exchange are often different during nocturnal periods (Mahrt, 1999), and with heat fluxes at night are typically weaker and markedly less reliable station than those 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:,

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

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

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

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

*Based on the daytime half-hourly and daytime totals of turbulent energy fluxes, the energy balance ratio ($E_{BR}$) is calculated as Eq. (3),* The energy balance ratio ($E_{BR}$) is calculated as Eq. (3) (Gu et al., 1999):

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

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),

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

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

During midday periods (from 10:00 to 15:00 LST), the *Penman-Monteith* approximation was inverted to calculate the surface resistance ($R_s$) in Eq. (45) (Kumagai et al., 2004):,

$$R_s=\frac{\rho c_p(\delta_e/\mathrm{LE})}{\gamma}+\left(\frac{\Delta}{\gamma}\beta-1\right)R_a \quad (45)$$

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$^{-1}$) indicates indicating the atmospheric demand (Wilson et al., 2002b) and is calculated in Eq.(5)as,:

$$R_i = \frac{\rho c_p \delta_e}{\gamma A} \qquad (~~5~~6)$$

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

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

$$R_a = r_{a,m} + r_b = \frac{\mu}{\mu_*^2} + 6.2\mu_*^{-2/3} \qquad (~~6~~7)$$

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

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

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma(1 + \frac{R_s}{R_a})} \qquad (~~7~~8)$$

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

$$LE_{eq} = \frac{\Delta(R_n - G)}{\Delta + \gamma} \qquad (~~8~~9)$$

~~The 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).~~

The ratio $LE/LE_{eq}$, which is also known as the Priestley–Taylor *α*, ~~can denote~~reflects the control of evaporation by atmospheric and physiological factors, $LE/LE_{eq}$ characterizes the surface dryness of ecosystem. It, therefore, indicates whether soil water supply for evapotranspiration of an ecosystem is under limitation or not.~~and characterizes the surface dryness of ecosystem.~~ An $LE/LE_{eq}$ of < 1 represents an ~~dry~~ ecosystem ~~that undergoes~~under water stress~~ limitations in water supply~~, and, therefore, experiences reductions in evapotranspiration~~,~~ ; whereas $LE/LE_{eq}$ of > 1.26 ~~signifies~~ indicates an~~a wet ecosystems~~ ecosystems ~~where the~~of unrestricted water supply ~~is unrestricted~~ and only available energy limits evaporation (Arain et al., 2003). The $LE/LE_{eq}$ ~~was generally related to~~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 ~~to compare the environmental factors, the energy fluxes~~for quantifying the changes of all biophysical variables, energy fluxes, and bulk parameters among 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 ratio~~s values with the other two as the control variables~~. All analyses were accessed at α = 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 in 2007 and 2008. Generally, over 90% precipitation of each year occurred in ~~the growing season (i.e.,~~ 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).~~Long-term~~

~~drought stress (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~~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).~~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 57mm of the total annual precipitation~~(57 mm), and a few large precipitation events (~~P~~ > 25 mm $d^{-1}$) in July~~ also presented a large portion of the total annual sum~~ were recorded. The amount of rainfall in 2009 was smallest among the four years, ~~and~~ during which 195mm of irrigation was applied from March to September~~, mostly in the early growing season, but~~. ~~there~~ There were several short and scattered droughts ~~periods~~ across the growing season of 2009 (Fig.2d). Despite ~~above~~the higher-than- normal rainfall in the two wet years, there was no flooding or overland runoff~~ occurred even during intensive rain events because of the high infiltration capacity of the sandy soil.~~.

The growing season $T_a$ in 2008 was significantly lower than that in 2007 and 2009 ~~during growing season~~ ($p$ < 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 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.2 e-h) ~~reached~~was 1.3 ± 0.7 kPa. ~~Mean~~ 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 with the same period in 2006 and 2008 ($p$ < 0.001). Furthermore, the VPD ~~of June 2009~~ was the highest in June 2009 (i.e., 2.3 ± 1.1 kPa, $p$ < 0.05) and~~ in 2008 was~~ the lowest in 2008 (i.e., 1.0 ± 0.5 kPa, $p$ < 0.01).

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

~~Seasonal and inter-annual~~The energy partitioning trends of daytime total net radiation ($R_n$) ~~among~~ 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, ~~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 t~~The average of daytime total $G$ during the growing season displayed great seasonal and annual differences ~~between~~ among these years ($p < 0.05$), with ~~the value of wet years was~~ a lower value in wet years than that of the dry years ($p < 0.001$). ~~Also~~Additionally, $G$ only accounted for a small proportion of $R_n$, which ranged from 2.1% ~~(~~in 2007~~)~~ to 4.9% ~~(~~in 2006~~)~~. Moreover, the average value of daytime total $S$ among four growing seasons were 0.46 MJ $m^{-2}$, 0.49 MI $m^{-2}$, 0.51 MJ $m^{-2}$, 0.54 MJ $m^{-2}$, respectively. $S/R_n$ varied between 6.0% in 2007 and 6.8% in 2009 and showed no differences between the wet and dry years.

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~~ but August for ~~the year of~~ 2007. The peak value of daytime total LE was 16.61 $MJm^{-2}$, 17.01 MJ $m^{-2}$, 19.72 MJ $m^{-2}$ and 16.27MJ $m^{-2}$, in 2006 to 2009 respectively. $H$ became the main consumer of the growing season $R_n$ in October for dry years and in November for the wet years. ~~$H$ was the dominant factor controlling the growing season $R_n$ (in October for dry years and in November for wet years).~~ Among the four years, LE/($R_n$-$G$) was significantly higher in 2008 (64.8%) than those in 2006 (57.1%), 2007 (60.3%) and 2009 (50.4%) ($p < 0.05$). LE/($R_n$-$G$) was much lower in 2009 than those in ~~the~~ other 3 years ($p < 0.01$). Partitioning of $R_n$ into LE and $H$ differed significantly between the wet and dry years ($F = 17.599$, $p < 0.001$) (Table 3). The average daytime total LE in wet years was greater (6.77 $MJm^{-2}$) than that of dry years (5.72 $MJm^{-2}$, $p < 0.01$). The dominant ~~part in energy partitioning~~turbulent energy flux during the early growing season was sensible heat flux ($H$) with or without drought stress, except in 2006 ~~during which~~when the irrigation were applied (Table 3). Then LE was the ~~dominate~~ dominant driver of energy partitioning during the middle and late growing season ~~even~~ under drought stress.

The seasonal variation of the midday Bowen ratio ($\beta$) displayed rapid and significant trend across the 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~~s, separately~~. The average midday $\beta$ of dry year was greater (1.57) than that of the wet year (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), and had much higher values (> 1) during ~~long-term~~the drought periods in 2007 and 2009, but not in 2006. The Bowen ratio ~~were all~~was 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 of surface resistance ($R_s$) normalized by leaf area index (LAI) (i.e., $R_s$:LAI) in 2008 (54.1 s m$^{-1}$ leaf area) was lowest among four years(i.e., p < 0.05). The $R_S$:LAI in the dry year (106.8 s m$^{-1}$ leaf area) was 50% higher than in the wet year (71.2 s m$^{-1}$ leaf area) (p < 0.001). The $R_S$:LAI in the seasonal drought~~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 s m$^{-1}$) was 50% higher than in the wet year (153.1 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 those in ~~the no-~~unstressed periods ($p < 0.001$). In addition, a significantly negative relationship was found between the $R_s$ and LAI during the wet years (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 s m$^{-1}$ to 77.9 s m$^{-1}$, with a mean value of 74.4 s m$^{-1}$, and showed no difference ~~between~~ among the four growing seasons ($p > 0.05$). Figure 5c ~~depicts~~ 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$^{-1}$, 9.7 to 74.5 s m$^{-1}$, from 2006 to 2009, respectively. $R_a$ in 2007 was significantly higher than ~~during~~ that of the dry years ($p < 0.01$), while $R_a$ in 2008 was smaller than that in dry years ($p < 0.001$). However, there were no significant ~~difference~~ differences between dry and wet years $R_a$ ($p > 0.05$).

~~In this study, the~~The seasonal changes of $LE/LE_{eq}$ value ~~were generally below 1 and > 0.4~~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 ~~was~~ were much smaller. A significantly exponential relationship ~~was observed~~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 ~~studied~~ four years ~~were~~ 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 (*F=9.460*, $p < 0.01$). Compared to the value during ~~non-~~unstressed periods, the decoupling coefficient during the ~~long-term~~seasonal drought periods (#1_06, #2_06; #1_07, #2_07 and #1_09, #2_09, #3_09)~~(#1, #2 in 2006; #1, #2 in 2007 and #1, #2, #3 in 2009)~~ ~~showed~~ was ~~dramatic~~ much lower values.

# 4 Discussion

## 4.1 Energy partitioning and Bowen ratio

The energy balance ratio ($E_{BR}$) is ~~one~~ a way of evaluating scalar flux estimates from ~~eddy covariance~~EC techniques (Chen et al., 2009). In this study, the closure of the energy budget was ~~0.85~~0.88 based on daytime 30-minute fluxes, and ~~over~~ > ~~0.95~~0.96 based on ~~daily~~ 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-year of flux data from 22 in FLUXNET sites, which had energy 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~~ among the biomes, and based on metrics of landscape heterogeneity. ~~At our site, i~~In addition to the ~~reasons~~ known reasons ~~to~~ for decreasing~~e~~ 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 ~~on the plantation site, such as~~(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, ~~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~~ resistance (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 $\beta$ (Chen et al., 2009; Ozdogan et al., 2010). However, the impact of precipitation on the Bowen ratio may vary by even at ~~specificany forest~~ site (Tang et al., 2014). In our study, a detectable response of LE/($R_n$-$G$) and Bowen ratio to drought stress and non-stress periods ~~was~~ 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 ~~time~~scale, the Bowen ratio ~~was~~ appeared linearly related to the total growing season 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, $\beta$ ~~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 during the most part of the growing season in 2008 and non-stressed periods in other 3 years, which was close to 0.42 ~~in~~ for deciduous forests (Wilson et al., 2002b) and 0.55 in a temperate Douglas-fir (Humphreys et al., 2003), ~~Similar~~ 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~~. Seasonal drought stress had a discernible impact on the Bowen ratio of this poplar plantation. However, compared to the reported $\beta$ 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~~ loblolly pine plantation (Sun et al., 2010), the average $\beta$ in wet years were close to the above values. $\beta$ was higher in ~~long-term~~seasonal drought periods and dry years than most temperate coniferous forests (Mean = 1.07, Wilson et al., 2002b), which typically had a higher $\beta$ values. The high $\beta$ 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, 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 findings corroborate the hypothesis that drought would trigger significant changes in energy partitioning of water-demanding poplar species in a water-stressed regionOur 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 of the interactions of climatic and biological factors (Perez et al., 2008; Wilson and Baldocchi, 2000). $R_i$ qualifiesquantifies 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. 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 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 theto 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 the long-termseasonal drought stressed periods were was much higher than that in non-stressed periods. The drought stress during the canopy development in 2007 led to lower leaf area and higher canopy resistance (e.g(Noormets et al., 2008).(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 researches, the $R_s$:LAI in dry years of this poplar plantation was close to that of Euphrates Poplar (*Populus euphratica Oliv.*) (130.2 s m$^{-1}$ leaf area) and smaller than that of Gansu Poplar (*Populus gansuensis Wang et Yang*) (189.4 s m$^{-1}$ leaf area) in northwest China (Chen et al., 2004). In wet years it was similar to that of poplar (58.6 s m$^{-1}$ leaf area) in Iceland (Wilson et al., 2002b), and boreal aspen during the full-leaf period (51.8 s m$^{-1}$ leaf area) in Canada (Blanken et al., 1997).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 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~~ 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 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~~ in a vineyard in Gansu Province in China (t=-29.87, df=741, $p$ < 0.001), likely due to the warm-dry climate of the northern region in China.

On the seasonal ~~time~~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. 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~~).~~), during which the sensitivity of the Bowen ratio on $R_s$ increased with the growing $R_s$. The partial correlation analysis indicated that $R_s$ and $R_i$, respectively, had strong positive and negative effects on $\beta$ in both wet and dry years (Table 4), which could not be detected through correlation analysis (~~such as~~ e.g., the impact of $R_i$ and $R_a$ on $\beta$). Furthermore, both controlling ~~factors of~~roles of $R_s$ and $R_i$ on the Bowen ratio in dry years ~~were~~ seemed greater than that in wet years. Finally, $R_a$ had a significant negative impact on the Bowen ratio in wet years, but ~~no impact~~not in dry years~~, which was not mentioned in earlier studies.~~.

The average LE/LE$_{eq}$ in the growing season was 0.74 ~~in this~~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)~~ 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), LE/LE$_{eq}$ declined with increasing $R_s$ 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 ~~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 $LE/LE_{eq}$ 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 coefficients between $LE/LE_{eq}$ 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~~seasonal drought periods across growing season, which were reported in other studies (Bagayoko et al., 2007; Bracho et al., 2008; Zha et al., 2013).

### 4.3 Implication for poplar plantation establishment

To our knowledge, there is no and it is hard to develop a metrics for the sustainability of forest plantation, even though there are a couple of studies defining the sustainability of forest plantation by site and plantation productivity for commercial purpose only (e.g. (Richardson et al., 1999; Watt et al., 2005)) other than in a broader sense of the plantation and environment interactions that were our focus in the current paper. Our previous study indicated that annual water use of the plantation was even higher than the annual precipitation (Zhang et al., 2014) and thus the irrigation was applied in dry years by pumping groundwater (Table 1). Such water abstraction for irrigating plantation and agriculture crops have led to the dramatic water table decline in the last 30 years (Zhang et al., 2014). Energy partitioning to latent and sensible heat and surface resistance was dramatically responsive to climatological drought, and as indicated by low $LE/LE_{eq}$ (< 1) and low values of decoupling coefficient (Ω)(Zhu et al., 2014), the dry surface dominated the poplar plantation no matter in wet or dry years, which led to the shortage of water use in poplar plantation. In other words, the poplar plantation would consume much water which comes from precipitation or groundwater to maintain its ecological services, while the required irrigation for sustaining these forests may present a threat to the adjacent ecosystems because of their role in reducing ground water table, and may compromise long-term sustainability and livelihoods in the region. Therefore, from the viewpoint of hydrologic balance as well as interactions with atmosphere, growing poplar trees in a water- stressed region is not sustainable.

## 5 Conclusions

The seasonal drought stress affected the dynamics of individual turbulent energy fluxes and the surface resistances in the poplar plantation during growing seasons. Partitioning of available energy into latent (LE) and sensible heat ($H$) flux responded to meteorological drought and correspondingly displayed 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) in dry years was 33% higher than that in wet years. Accordingly, the contrasting impact 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 overall low LE/LE$_{eq}$ (< 1) of poplar plantations indicated that dry climate dominated in this water limited region, which suggested that the fast-growing and water-intensive species like the poplar plantation are poorly adapted for the water limited regions.

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

| | Tmin | Tmax (℃) | Tmean | P (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 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~~92 | 0.~~86~~87 | 0.~~89~~92 | 0.~~79~~82 | ~~0.99~~1.07 | 0.91 | ~~0.96~~1.04 | 0.~~79~~84 |
| Intercept | ~~15~~20.50 | ~~0~~17.24 | ~~0~~10.72 | ~~8.78~~13.08 | -0.~~76~~63 | ~~0.65~~-0.09 | ~~0.87~~-0.79 | -0.~~41~~30 |
| $R^2$ | 0.~~82~~81 | 0.~~81~~80 | 0.~~83~~81 | 0.~~83~~82 | 0.~~92~~88 | 0.~~93~~81 | 0.~~94~~92 | 0.~~85~~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)(%)* | $\beta$ | $R_s(s\ m^{-1})$ | $R_i\ (s\ m^{-1})$ | $R_a(s\ m^{-1})$ | $\alpha$ | 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); $\beta$: Bowen ratio; $R_s$, the surface resistance; $R_i$, the climatological resistance; $R_a$, the aerodynamic resistance; $\alpha$, the Priestley-Taylor coefficient; $\Omega$, the decoupling coefficient;

[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 ($\beta$) and $R_s$, $R_i$ and $R_a$.

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

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

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

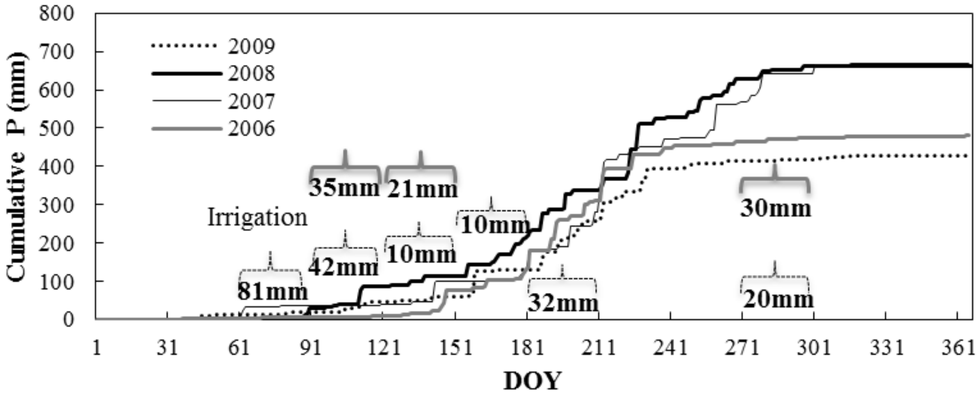
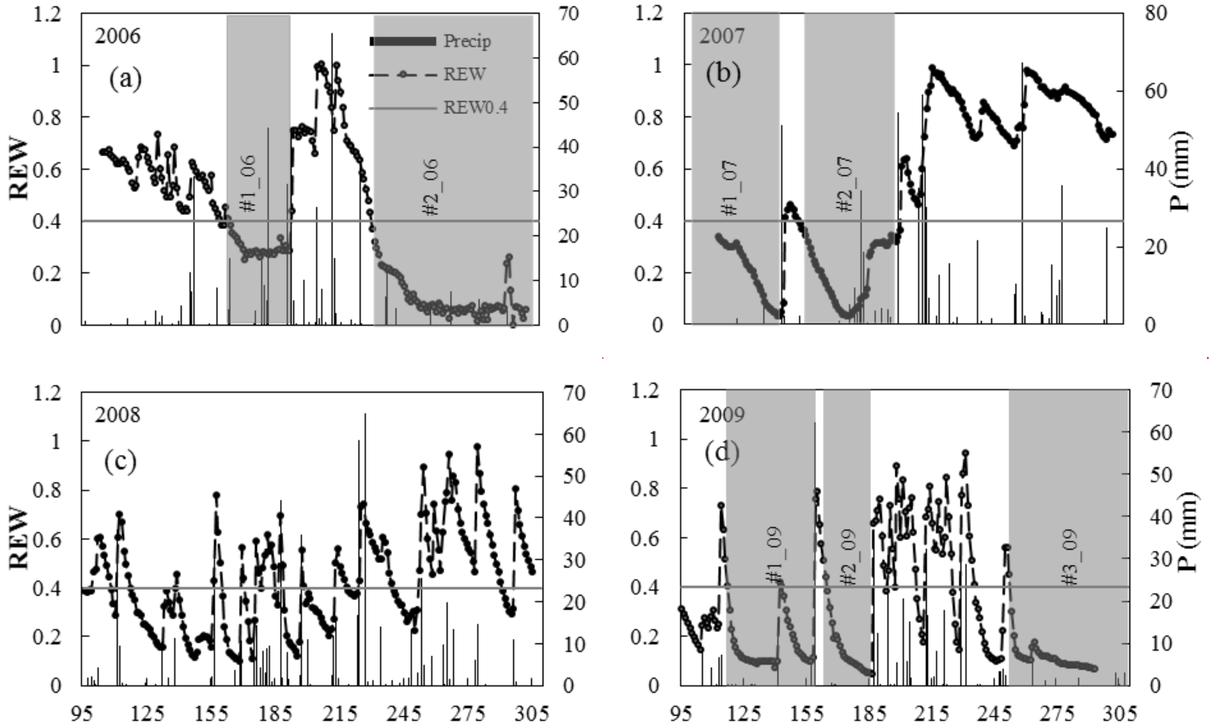
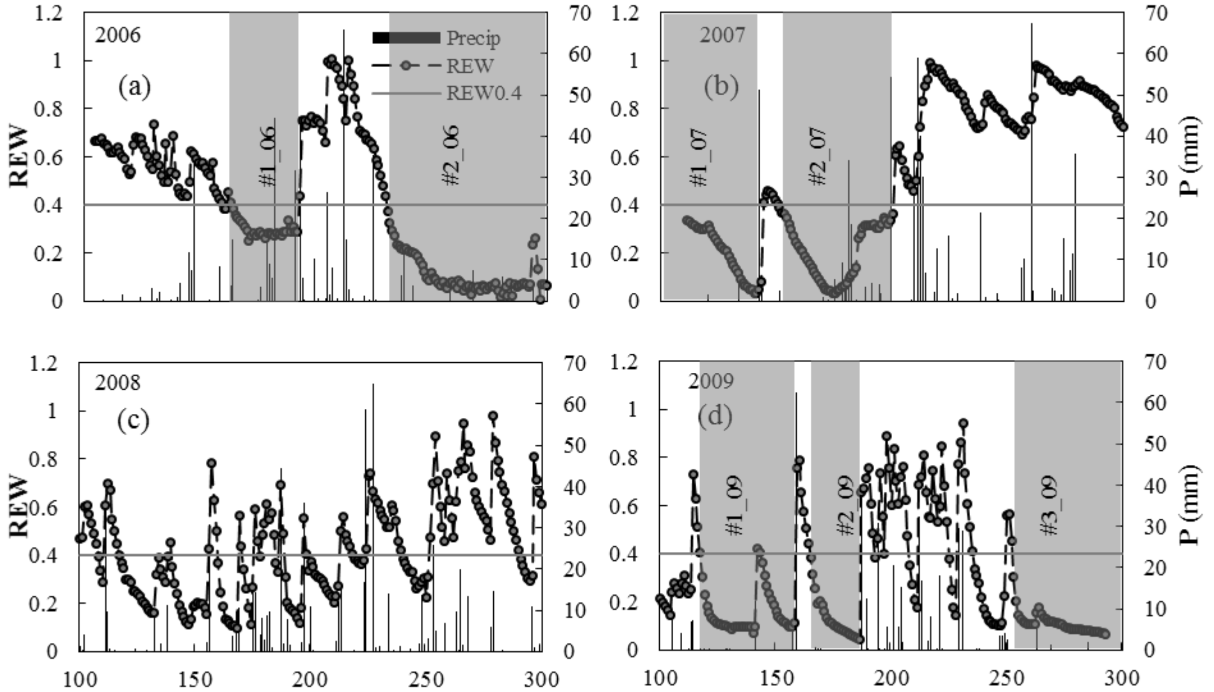



Figure 1.The cumulative precipitation (P) and periodic irrigation during 2006-2009, irrigation in 2006 and 2009 were separately represented by the solid and dotted brace, respectively.


2006
(a)
Precip
REW
REW0.4
#1_06
#2_06
2007
(b)
#1_07
#2_07
2008
(c)
2009
(d)
#1_09
#2_09
#3_09
REW
P (mm)


2006
(a)
Precip
REW
REW0.4
#1_06
#2_06
2007
(b)
#1_07
#2_07
2008
(c)
2009
(d)
#1_09
#2_09
#3_09
REW
P (mm)

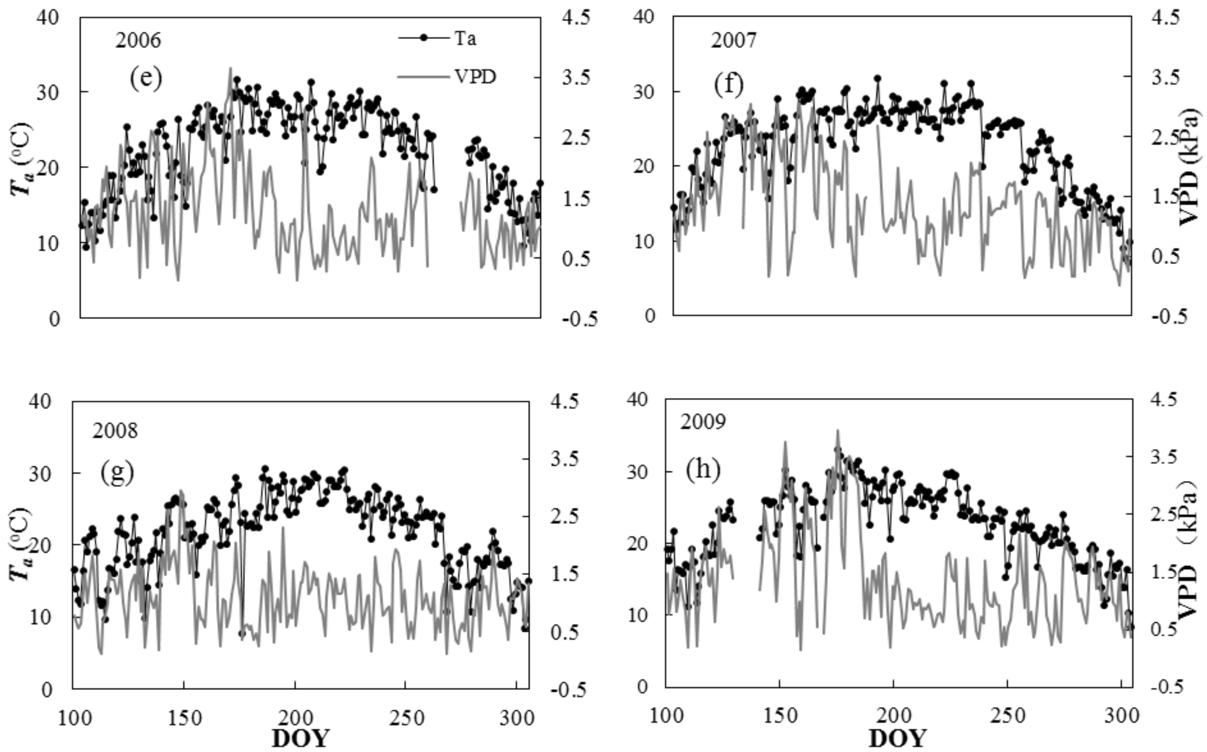
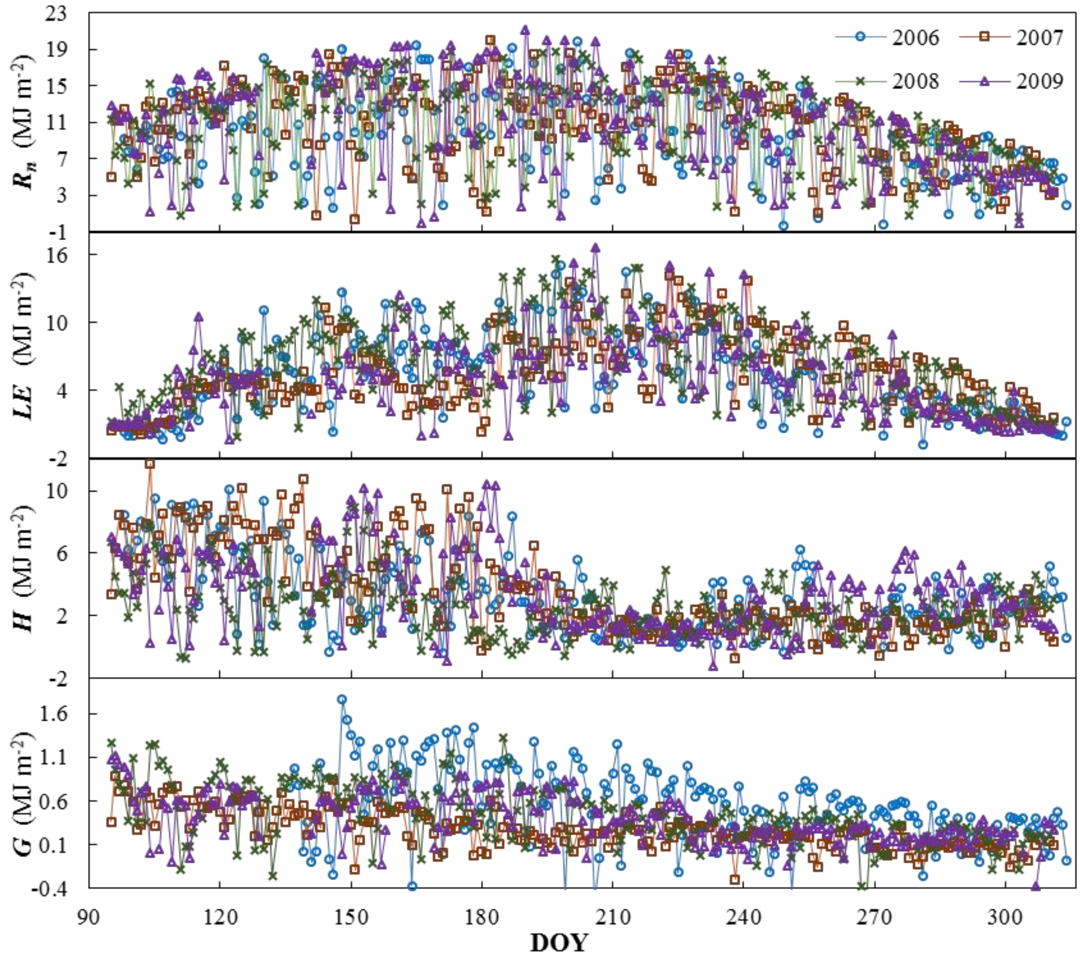



Figure 2. The seasonal variation of environmental conditions during 2006-2009, a-d ~~include~~: the relative extractable water (REW) (~~The~~ drought periods longer than 20 days ~~across 4 year were marked by grey shade in figures a-d)~~are shaded), daily sum of precipitation (P); e-h ~~include~~: daytime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



2006
2007
2008
2009
$R_n$ (MJ m$^{-2}$)
$LE$ (MJ m$^{-2}$)
$H$ (MJ m$^{-2}$)
$G$ (MJ m$^{-2}$)
23
19
15
11
7
3
-1
16
10
4
-2
10
6
2
-2
1.6
1.1
0.6
0.1
-0.4
90
120
150
180
210
240
270
300
DOY

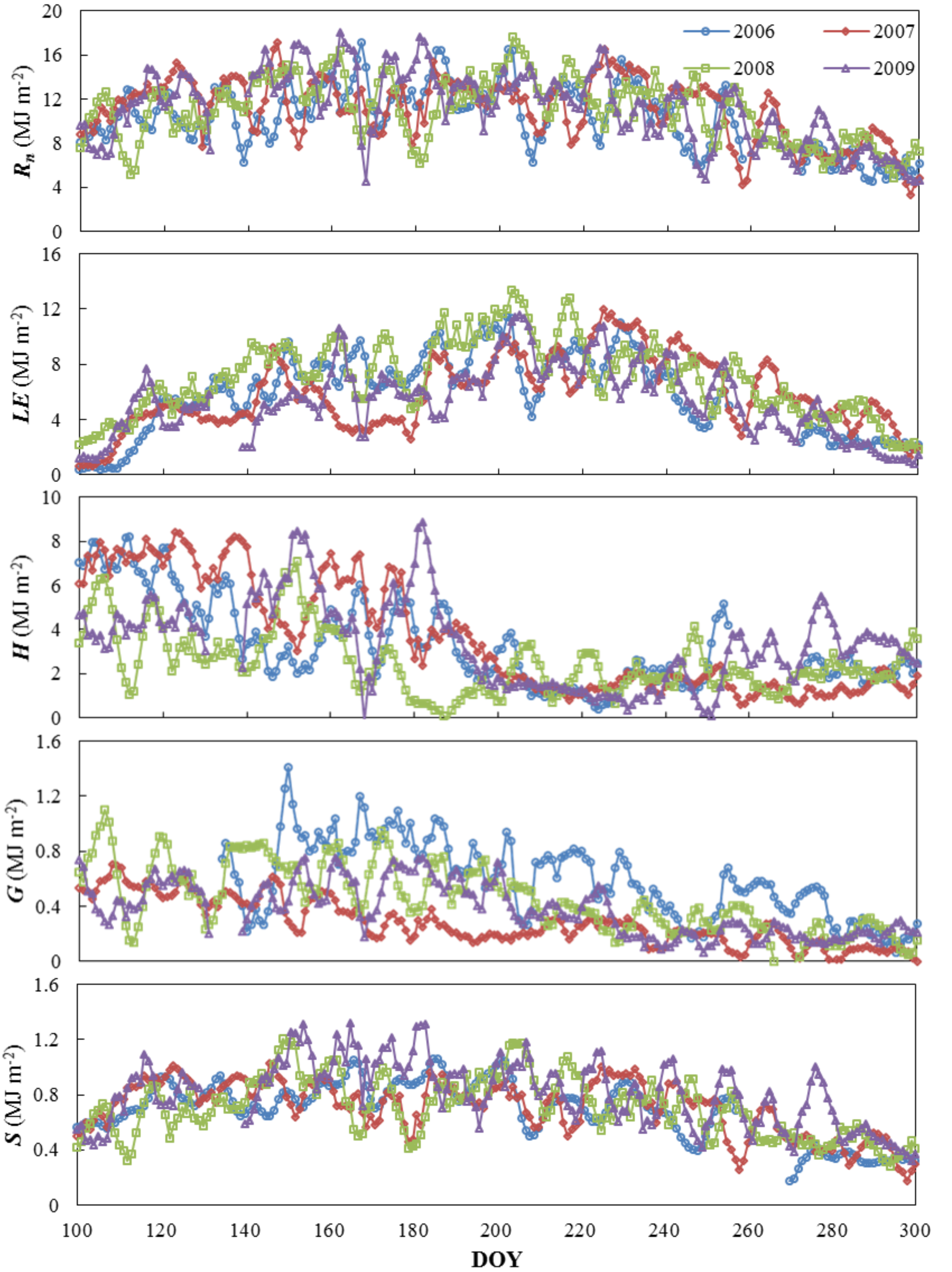



Figure 3. Seasonal patterns of daytime energy components (5-day running average) during the growing season from 2006 to 2009, including net radiation ($R_n$), latent heat (LE), sensible heat ($H$) and soil heat flux ($G$) and heat storage term ($S$).

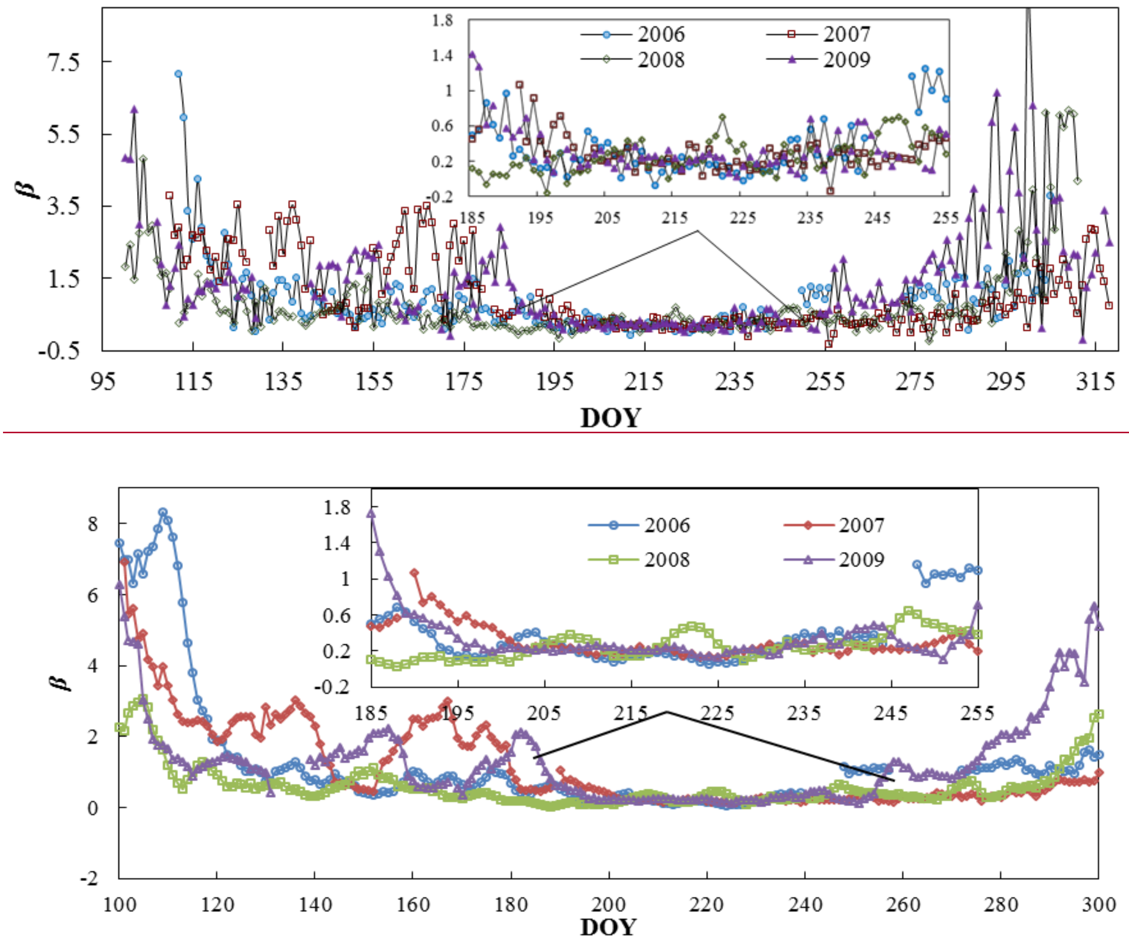
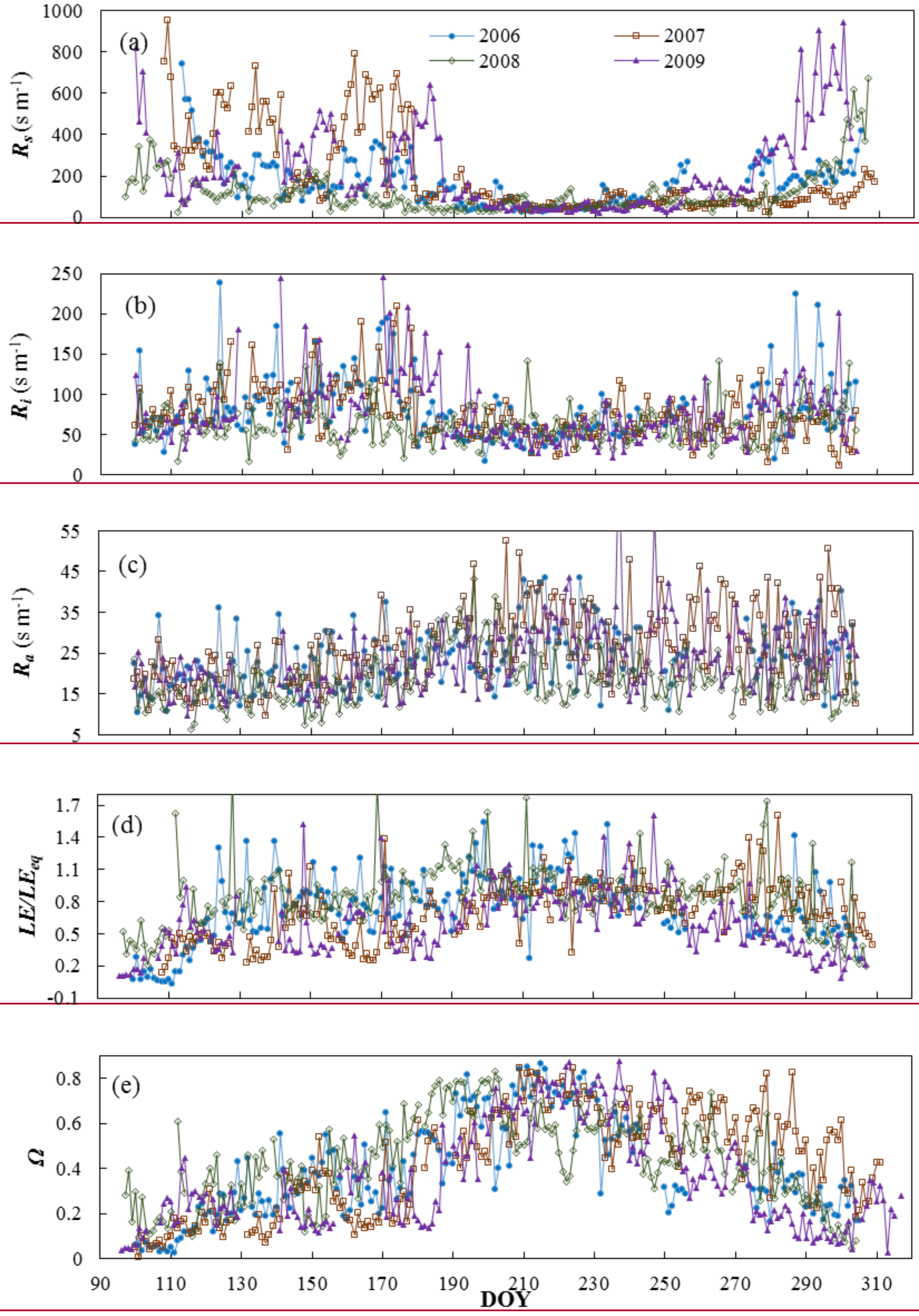



Figure 4. Seasonal and inter-annual variability of the midday mean Bowen ratio ($\beta$) (5-day running average) across the growing season, with detailed $\beta$ ~~between~~ during DOY 185~~and~~-255 representing in small pane; Midday means the time course from 10:00 a.m. to 15:00 p.m. at local standard time.


(a)
2006
2007
2008
2009
Rs (s m-1)
(b)
Ri (s m-1)
(c)
Ra (s m-1)
(d)
LE/LEeq
(e)
Ω
DOY

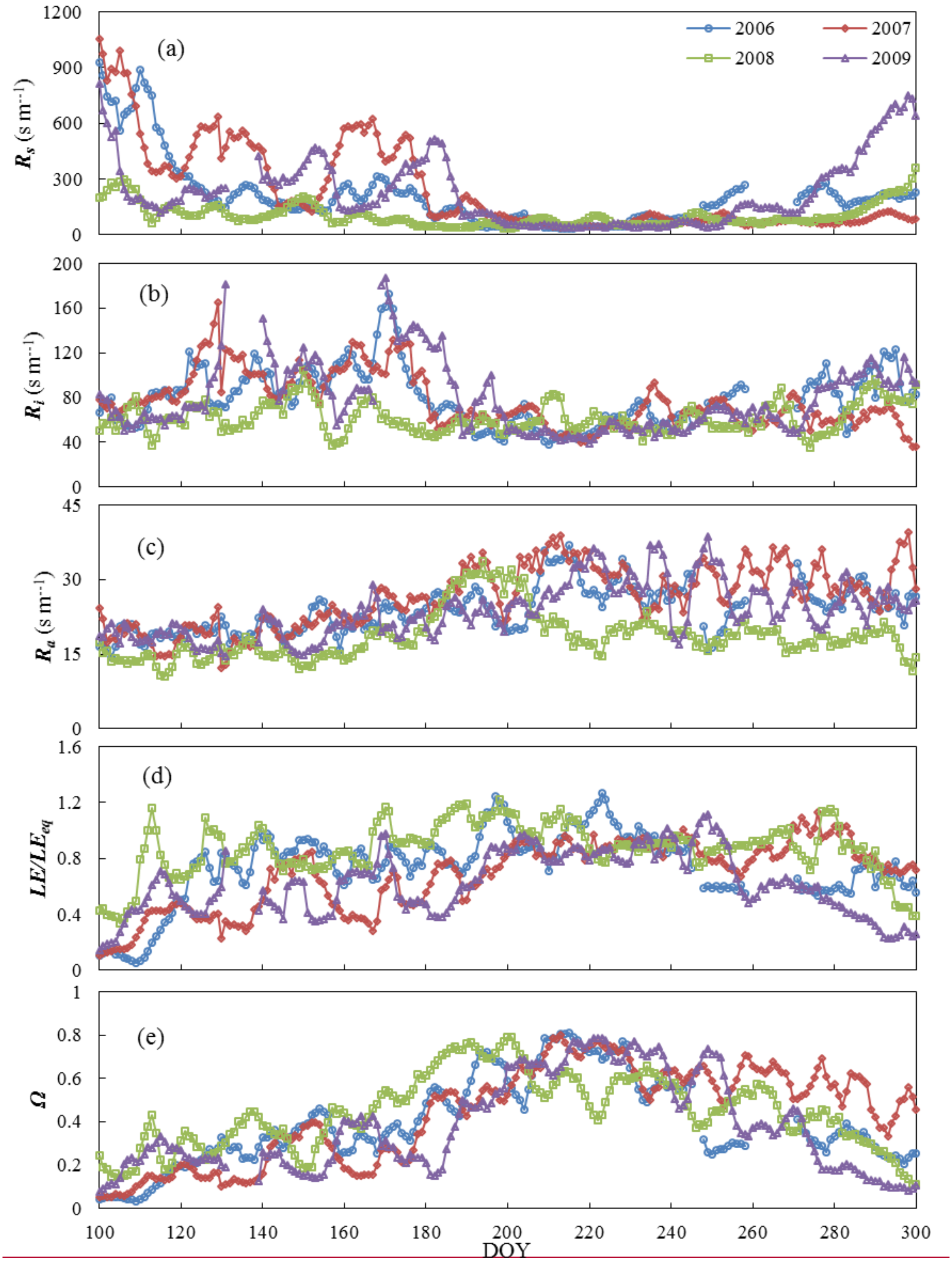



Figure 5. Seasonal dynamics of the midday mean surface resistance ($R_s$), climatological resistance ($R_i$), aerodynamic resistance ($R_a$), LE/LE$_{eq}$ and decoupling coefficient (Ω) (5-day running average) across the growing season from 2006 to 2009. Midday means the time course from 10:00 a.m. to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

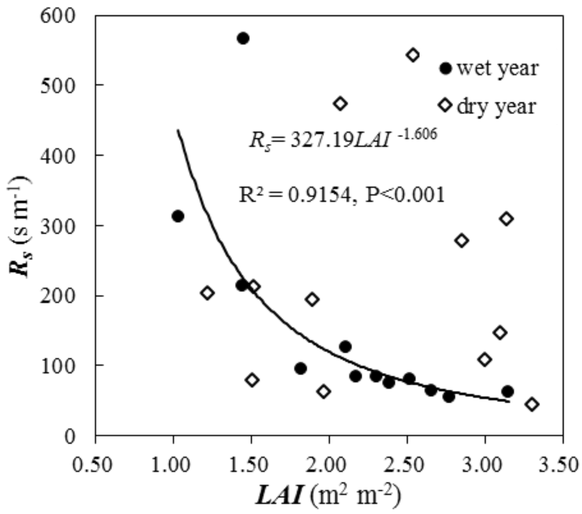



Figure 6. The relationship between leaf area index (LAI) and surface resistance ($R_s$) during growing season of the wet and dry year.

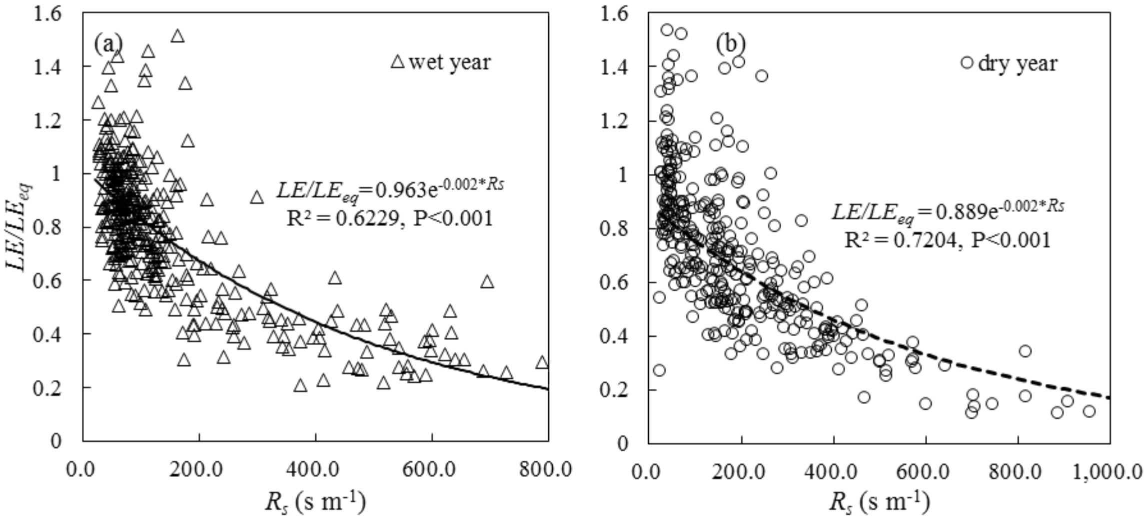



Figure 7. The relationships between surface resistance ($R_s$) and $LE/LE_{eq}$ (Priestley-Taylor coefficient) during growing season of the wet (a) and dry (b) year.

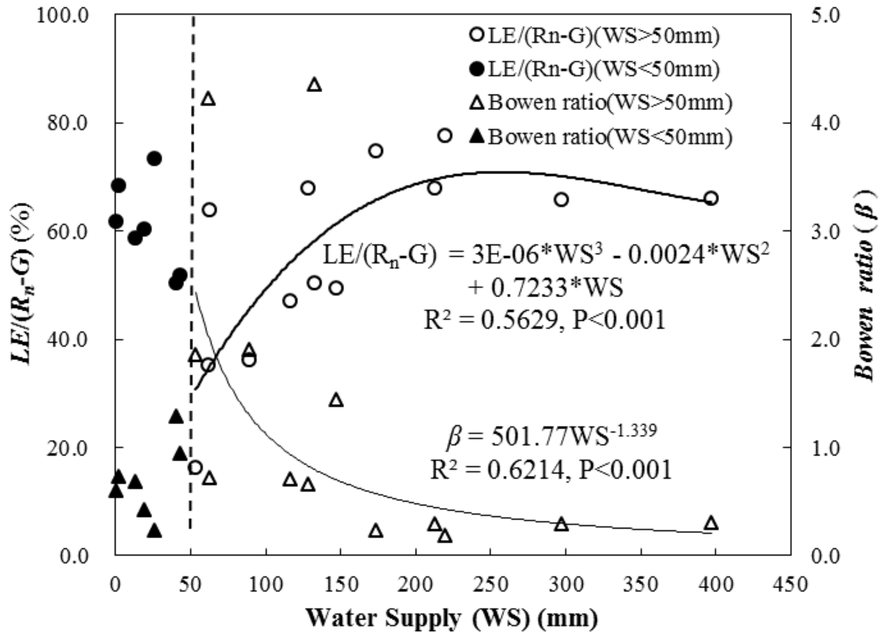
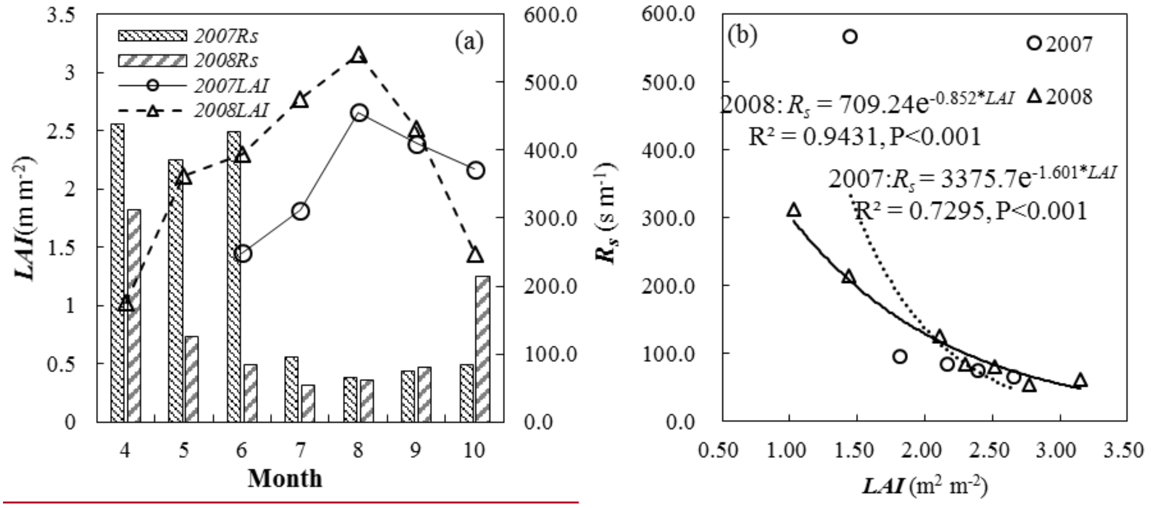



Figure 8. The response of Bowen ratio and LE/($R_n$-$G$) on Water Supply (WS) (including precipitation (P) and irrigation (I) during individual period)of the different periods across four growing seasons.



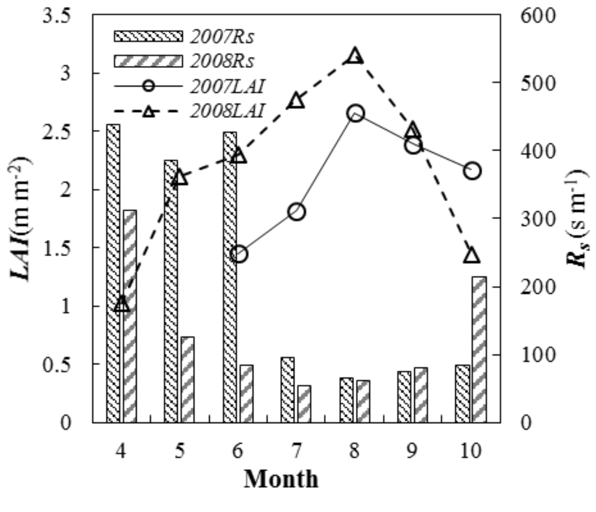




Figure 9. Seasonal variations of monthly average LAI and $R_s$ ~~(a), and the response of $R_s$ on LAI (b)~~ during the growing season in wet year 2007 and 2008.

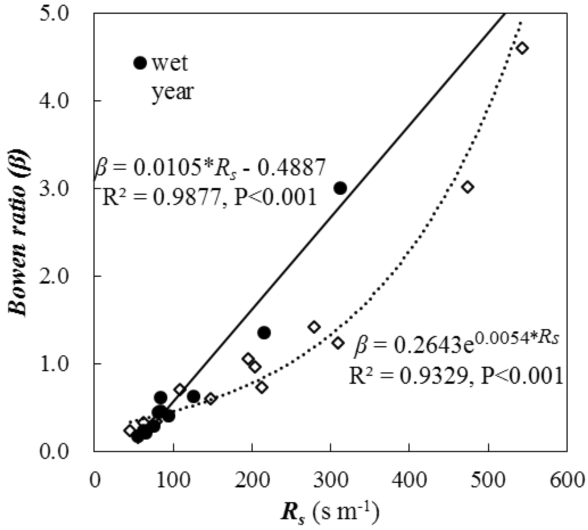



Figure 10. Response of monthly average Bowen ratio ($\beta$) on surface resistance ($R_s$) in the wet and dry year.