Journal of Environmental Management 90 (2009) 2762–2770

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Poplar plantation has the potential to alter the water balance in semiarid Inner Mongolia

Burkhard Wilske [a,*], Nan Lu [a], Long Wei [b,c], Shiping Chen [b], Tonggang Zha [d], Chenfeng Liu [d], Wenting Xu [b], Asko Noormets [e], Jianhui Huang [b], Yafen Wei [b,c], Jun Chen [d], Zhiqiang Zhang [d], Jian Ni [b,f], Ge Sun [e], Kirk Guo [b], Steve McNulty [e], Ranjeet John [a], Xingguo Han [b], Guanghui Lin [b,**], Jiquan Chen [a]

[a] *Department of Environmental Sciences, The University of Toledo, Mail Stop #604, Toledo, OH 43606, USA*
[b] *Key State Laboratory of Vegetation and Environmental Change, Institute of Botany, The Chinese Academy of Sciences, Xiangshan, Beijing 100093, China*
[c] *Graduate University of Chinese Academy of Science, Beijing 100049, China*
[d] *Key Lab Soil and Water Conservation and Desertification Combating, Water and Soil Conservation College, Beijing Forestry University, Beijing 100083, China*
[e] *Southern Global Climate Change Program, USDA Forest Service, Southern Research Station, Raleigh, NC 27606, USA*
[f] *Alfred Wegener Institute for Polar and Marine Research, Telegrafenberg A43, D-14473 Potsdam, Germany*

ARTICLE INFO

Article history:
Received 1 August 2008
Received in revised form
6 February 2009
Accepted 7 March 2009
Available online 16 April 2009

Keywords:
Semiarid
Evapotranspiration
Poplar plantation
Water balance

ABSTRACT

Poplar plantation is the most dominant broadleaf forest type in northern China. Since the mid-1990s plantation was intensified to combat desertification along China's northwestern border, i.e., within Inner Mongolia (IM). This evoked much concern regarding the ecological and environmental effects on areas that naturally grow grass or shrub vegetation. To highlight potential consequences of large-scale poplar plantations on the water budget within semiarid IM, we compared the growing season water balance (evapotranspiration (ET) and precipitation (PPT)) of a 3-yr old poplar plantation (Kp_3) and a natural shrubland (Ks) in the Kubuqi Desert in western IM, and a 6-yr old poplar plantation (Bp_6) growing under sub-humid climate near Beijing. The results showed that, despite 33% lower PPT at Kp_3, ET was 2% higher at Kp_3 (228 mm) as compared with Ks (223 mm) in May–September 2006. The difference derived mainly from higher ET at the plantation during drier periods of the growing season, which also indicated that the poplars must have partly transpired groundwater. Estimated growing season ET at Bp_6 was about 550 mm and more than 100% higher than at Kp_3. It is estimated that increases in leaf area index and net radiation at Kp_3 provide future potential for the poplars in Kubuqi to exceed the present ET and ET of the natural shrubland by 100–200%. These increases in ET are only possible through the permanent use of groundwater either directly by the trees or through increased irrigation. This may significantly change the water balance in the area (e.g., high ET at the cost of a reduction in the water table), which renders large-scale plantations a questionable tool in sustainable arid-land management.

1. Introduction

Poplar plantation is the most dominant broadleaf forest in northern China (FAO Forestry Department, 2007). By 2003, poplar contributed 13.5% of China's total forest plantation with >50% being young and middle-aged stock (Chinese Forestry Society, 2003). Since the foundation of the People's Republic of China, poplar has been planted in various types of shelter belts to protect farmland and settlements (Fu and Hou, 1995; Zhang and Hou, 1995). With the launch of the "Three North Project" (1978) and its successors ("Combating Desertification Project" 1991; The "Great Green Wall", 2002), poplar plantation in the Inner Mongolian Autonomous Region (IM) was promoted to stop progressive desertification (Jiang et al., 2006; Wang et al., 2004). By 2010, forest plantation in IM may cover roughly $36–72 \times 10^3$ km^2 (Inner Mongolia News, 2006), which is equivalent to 6–12% of the grass- and shrub-lands in this semiarid area.

Biogeographically, IM represents the eastern extension of the 8000 km Central Asian steppe belt, which frames similarly large desert areas and includes only marginal tree populations. Although poplar species such as *Populus simonii* Corr., *Populus pseudosimonii* Kitag. and *Populus euphratica* Olve. are native to IM, they have not formed forests that cover extensive land surfaces but have rather grown in cohorts at favored sites (Li et al., 2005; Liu et al., 2007). Their scattered natural distribution is in agreement with the

* Corresponding author. Tel.: +1 419 530 4278; fax: +1 419 530 4421.
** Corresponding author. Tel.: +86 10 62836233; fax: +86 10 82593840.
E-mail addresses: Burkhard.Wilske@utoledo.edu (B. Wilske), ghlin@ibcas.ac.cn (G. Lin).

0301-4797/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2009.03.004

understanding that poplars thrive under conditions of shallow water tables by extending their roots to the water-saturated zone and transpiring groundwater (Chang et al., 2006; Nagler et al., 2007; Snyder and Williams, 2000). With respect to sustainable arid-land management, it seems therefore worth to investigate the water use of large plantations that consist of species similar or related to those apparently depending on direct access to groundwater.

Water deficit is becoming a serious problem in northern China due to population growth and large-scale exploitation of water and land resources (e.g., Chang et al., 2006). Increases in temperature and the frequency of extreme droughts in northern China may exacerbate the problem (Ma and Fu, 2006; Wang et al., 2001). Potential evapotranspiration (PET) in most parts of northeast China increased by 35 mm/decade since 1954 (Thomas, 2000). Decreasing water tables were responsible for decreasing diversity in plant species around river basins (Chen et al., 2006).

This study tested the hypothesis that large-scale poplar plantations may have significantly negative effects on the water balance in semiarid IM, and may therefore be counterproductive for combating desertification in the long term. Estimates of ET derived from eddy covariance (EC) measurements of water vapor fluxes represent a contemporary approach to assessing water losses from different land surfaces and vegetation types. We compared ET and its driving parameters during the growing season of 2006 at a 3-yr old poplar plantation (Kp_3) and an adjacent shrubland (Ks) in the Kubuqi Desert in IM. We focused on the growing season, because the Kubuqi Desert has a summer-rain climate and the dominant vegetation at both sites was deciduous. To approximate potential increases in ET by poplar plantations, we also compared ET at Kp_3 with ET at a 6-yr old plantation (Bp_6), which grows under sub-humid climate south of Beijing but is the only other poplar site with EC measurements in China.

2. Materials and methods

2.1. Study sites

Evapotranspiration and related climate parameters were measured in three ecosystems in northeast China: (1) a 3-yr old poplar plantation (Kp_3) and (2) a natural shrubland (Ks) in the Kubuqi Desert in western Inner Mongolia, and (3) a 6-yr old poplar plantation (Bp_6) growing under sub-humid climate near Beijing (Table 1).

The Kubuqi Desert forms a conspicuous 400-km long and 15–50 km wide band of sand dunes between the southern side of the Yellow River and the northern part of the Mu Us land in the northern Ordos Plateau (1000–1500 m a.s.l.). The climate is characterized by cold and dry winters and hot summers with the main precipitation. Monthly mean temperature is 24 °C for July and −11 °C for January based on data from 1957 to 2000 recorded by the five closest meteorological stations (i.e., 100–160 km around study sites: No. 53336, 53446, 53513, 53529, 53543; China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn, China Meteorological Administration, 2006).

Table 1
Characteristics of the study sites in the Kubuqi Desert (K) and near Beijing (Bp_6).

	(Bp_6)	(Kp_3)	(Ks)
Vegetation	*Populus* sp.	*Populus* sp.	*Artemisia* sp.
Coordinates			
N	39°31′50″	40°32′18″	40°22′51″
E	116°15′07″	108°41′37″	108°32′55″
Year planted	2000	2003	
Height 2006, m	11.5 ± na	2.2 ± 0.8	0.55 ± 0.11
Trees/0.01 km^2	2500	~1500	
Max. LAI 2006[a]	1.96	0.38 ± 0.22	0.30 ± 0.34
Soil type	Sandy soil	Sand	Sandy soil
Mean annual temperature (°C)	11.5	6.3	6.3
Maximum mean temperature (°C) (mth)	(July)	24 (July)	24 (July)
PPT mean (mm)	569	318 ± 93[b]	318 ± 93[b]

[a] August 2006.
[b] Avg. 1991–2000 from the closest station no. 53446.

The vegetation in the Kubuqi Desert consists mainly of shrub steppe dominated by the species *Artemisia ordosica* Krasch. and *Hedysarum mongolicum* Turcz. More than 200 km^2 were afforested with fast-growing poplar to immobilize sand dunes and sandy land since 1998. The plantation area is projected to increase to 700 km^2 in the coming years.

Two study sites were located opposite the eastern end of the alluvial fans of the Yellow River's tributaries. One EC tower recorded for a 3-yr old poplar plantation (Kp_3) about 6 km south of the river in an area of lower sand dunes. Poplars of 1.5–2.0 m height were planted with an intercrop of *Glycyrrhiza uralensis* Fisch. The plantation covered an area of 3.73 km^2. Tree growth varied strongly within the plantation. Some trees had grown to a height of 4 m, while others had experienced a setback in height from the planted sapling and maintained a shrubby growth. Corresponding to the tree growth, the leaf area index (LAI, see Section 2.2) varied strongly within the plantation (Table 1).

The water table was 1–4 m below the ground surface depending on the sand dune topography. Point source drip irrigation provided water to the young trees during long droughts. Individual irrigation periods lasted 11 h. About 1.46×10^6 l km^{-2} were supplied per irrigation period (equal to PPT = 1.46 mm). Trees were irrigated nine times from April to September 2005. In 2006, the trees were irrigated two times in April, and one time in May and June.

The second EC tower (Ks) was located 20 km to the south within a natural shrubland dominated by *A. ordosica*. *A. ordosica* is a minor deciduous shrub of 0.6–1 m height (Xiao et al., 2003). Average shrub coverage around the tower was 17–23%. The soil was a sandy soil (Zhang, 1994). Based on the soil water potentials at both sites (0–50 cm), available soil moisture was about twice as high at Ks as compared to Kp_3 (Jing Xie, pers. com., Beijing Forestry University).

The third EC tower (Bp_6) recorded for a 6-yr old poplar plantation encompassing about 0.8 km^2 in the southern suburbs of Beijing (30 m a.s.l.) and about 680 km east of Kp_3. The climate is warmer (~5 °C in annual mean temperature) and more humid (~80% higher annual mean PPT) than in the Kubuqi Desert (Table 1). Trees were planted in a 2 m × 2 m spacing. Canopy height had increased 1 m from 2005 to 2006. LAI showed similar maxima of 1.91 and 1.96 in August 2005 and 2006, respectively.

2.2. Eddy covariance instrumentation and micrometeorology

Net exchange of water vapor was measured by means of the eddy covariance (EC) technique (Baldocchi et al., 1988). The EC towers were equipped with identical instrumentation including a LI-7500 open-path infrared gas analyzer (IRGA; Li-Cor, Lincoln, NE, USA), a CSAT3 3-dimensional sonic anemometer (Campbell Scientific Inc. (CSI), Logan, USA), and a CR5000 data logger (CSI). Net radiation (R_n, W m^{-2}) was measured with Q-7.1 net radiometers (Radiation and Energy Balance Systems Inc., REBS, Bellevue, WA, USA) five meters above the canopy. Soil heat flux (G) was measured using three soil heat plates (HFT-3, REBS). Precipitation (PPT, mm) was measured with tipping bucket rain gauges TE525 (CSI). Air temperature (T_a, °C) and relative humidity (RH, %) were recorded at three heights with HMP45AC probes (Vaisala, Helsinki, Finland). Soil water content (VWC, %) was measured using CS616 probes (CSI) at depths of 10, 20, 30, 50 cm at the Kubuqi sites, and at 20 cm depth south of Beijing. LAI was estimated by means of hemispherical photography (Nikon Coolpix with a FC-E8 fisheye lens) and Gap Light Analyzer software (GLA Version 2.0).

2.3. Data processing

ET and related climate parameters were calculated for the growing season (May–September) of 2006. These months also provided the highest data coverage (Table 2). Latent heat flux (LE) was calculated as the 30-min mean covariance of vertical wind speed and water vapor concentration. Wind coordinates were defined according to planar fit (Wilczak et al., 2001) and the fluxes were adjusted for air density fluctuations (Webb et al., 1980). Conversion to ET was made by dividing LE by the temperature-dependent constant of vaporization. Quality control was applied to ET data to exclude non-representative measurements. The screening rejected the following observations: (1) concurrent to rain events; (2) out of range records; (3) low turbulence, i.e., with the friction velocity $u^* < 0.1\ \mathrm{m\,s^{-1}}$, (4) stationarity indices of CO_2, H_2O, and $T_a > 1$; (5) with LI-7500 values of the Automatic Gain Control (AGC) >75% for Ks and Kp_3 and >85% for Bp_6; and (6) sample density <17,000 30-min^{-1}. Quality tests for the period May–September 2006 led to total gap percentages of 27%, 31%, and 45% for Ks, Kp_3 and Bp_6, respectively. After applying all quality control criteria, the accepted 30-min ET records ranged from 0 to 0.354 mm in the desert and from 0 to 0.505 mm in the sub-humid environment.

Energy balance closure (EBC) was used as an additional measure to assess the quality of flux data (Anthoni et al., 2002). EBC was calculated from net radiation, soil heat flux, latent heat and sensible heat ($R_n - G = LE + H$). Thirty-minute EBC varied with time of day, R_n and u^* for the three canopies. The EBC mean and standard deviation were consistently high and low, respectively, with 30-min values obtained from the daytime period 9:00–15:00 h including further screening for the median u^* range of 0.55–0.75 $\mathrm{m\,s^{-1}}$ and $R_n > 400\ \mathrm{W\,m^{-2}}$ (max R_n was 800 $\mathrm{W\,m^{-2}}$). Based on these conditions, the EBC was 81%, 82% and 92% for Ks, Kp_3 and Bp_6, respectively.

Gaps in ET were filled with the dynamic linear regression method using the PROC GLM procedure in SAS (SAS Institute Inc., Cary, NC, USA). We evaluated the relationship between ET, available energy ($R_n - G$) and vapor pressure deficit according to Alavi et al. (2006):

$$ET = \alpha \times (R_n - G) + \beta \times VPD + \zeta$$

with α and β being the estimated coefficients, and ζ being the residuals from the regression model. The parameters were allowed to vary by month, and were estimated separately for day- and night periods. Gap filling allowed for direct comparison of the total growing season ET between Kp_3 and Ks but it could not amend a sufficient time period for Bp_6. Instead, representative periods and averages thereof were compared. The poplar plantations and the shrubland were compared on the basis of daily, monthly and growing season integrated ET. The control of climate variables on ET was examined using non-gap-filled data (ngf). Statistics on the significance of site differences and the climate control on ET were evaluated using S-Plus (S-Plus 6.1, Insightful Corp., Seattle, WA, USA).

Table 2
Monthly and five-mth total ET, PPT, ET/PPT ratio, PPT frequency, and ET data coverage for the poplar plantation near Beijing (Bp_6), and the poplar plantation (Kp_3) and shrubland (Ks) in the Kubuqi Desert.

	Site	May	June	July	August	September	∑	Mean	SD
Maximum daily ET (mm)	Bp_6	5.5	3.8	6.0	6.7	1.2			
	Kp_3	3.1	2.1	3.0	3.9	1.9			
	Ks	1.6	2.0	2.8	3.3	1.6			
Monthly ET (mm)	Bp_6	56.2	38.7	87.2	60.0	3.8	245.9[a]	49.2	30.8
	Kp_3	34.4	43.9	59.1	57.4	33.0	227.8	45.6	12.3
	Ks	25.5	34.6	66.2	69.2	27.6	223.1	44.6	21.4
ET/PPT	Bp_6[a]	0.9	0.6	0.4	0.8	0.3		0.5	
	Kp_3	1.2	7.7	2.2	0.8	2.4		1.5	
	Ks	0.7	3.8	0.9	0.9	1.5		1.0	
Monthly PPT (mm)	Bp_6[b]	65.7	63.7	240[c]	78.3	11.0	458.7	91.7	86.8
	Kp_3	27.8	5.7	27.3	73.2	13.8	147.8	29.6	26.1
	Ks	37.4	9.2	75.8	79.9	18.2	220.5	44.1	32.5
PPT frequency (d/mth)	Bp_6	10	9	13	10	8			
	Kp_3	7	3	11	10	6			
	Ks	7	3	13	8	7			
ET data coverage %	Bp_6	52	42	73	39	5			
	Kp_3	100	100	100	100	89			
	Ks	74	100	100	100	89			

[a] ET and ET/PPT ratio for Bp_6 is underestimated due to lower ET data coverage for the 5-mth-growing season.
[b] Complete PPT for Bp_6 was obtained from local meteorological station.
[c] 65.7 mm on 31 July.

3. Results

3.1. ET in semiarid IM

Growing season PPT accounted for ca. 95% of the annual PPT at a 3-yr old poplar plantation (Kp_3) and a natural shrubland (Ks) in the Kubuqi Desert in 2006. Irrigation at Kp_3 added less than 3 mm PPT based on the total quantity of water pumped in May and June 2006. Except for July, the monthly PPT ratio Ks/Kp_3 was on average 1.33 (±0.21 SD), i.e., for each mm at Kp_3 the Ks site received 1.33 mm (Table 2). In July, more than 78% of the difference in PPT between Ks and Kp_3 was due to two individual rainstorms (on July 2 and 14). Without the amount of PPT provided by these rainstorms, the PPT ratio Ks/Kp_3 was 1.39 and similar to the multiple-month average.

The LAI was not significantly different between Kp_3 and Ks (Table 1). However, the total ET of the growing season 2006 was already 4.8 mm or 2% higher at Kp_3 than Ks despite 33% lesser PPT at the poplar plantation as compared with the shrubland (Table 2, Fig. 1a). The maximum daily ET was not significantly different between Kp_3 and Ks in June, July and September 2006 (Table 2). However, maximum ET was about 50% (3.1 vs. 1.6 mm) and 15% (3.9 vs. 3.3 mm) higher at the 3-yr old poplar plantation than the adjacent shrubland in May and August, respectively.

A concurrent tripartite pattern in monthly PPT and ET indicated that the poplar plantation used more water than the shrubland particularly during the dry periods. While at both sites no PPT was recorded for April, the frequency and relative amounts of PPT were similar at both sites and higher in July–August than in May–June and September (Fig. 1f, Table 2). ET was significantly higher at Kp_3 than at Ks during the drier periods May–June and September, whereas the opposite was observed during the wetter period July–August (Fig. 1a, Table 2).

The growing season ET/PPT ratio was 1.5 at Kp_3 and 1.0 at Ks (Table 2). The missing sensitivity of ET at Kp_3 relative to a long dry period in June in connection with a multiple-month ratio of ET/PPT > 1 suggests also that at least parts of the plantation had already tapped groundwater (Fig. 1f, Table 2: e.g., ET/PPT = 7.7).

We checked the individual ET-controlling parameters for significant differences between sites during the drier and wetter periods (Table 3). Mean R_n during the daytime was 3–15 $\mathrm{W\,m^{-2}}$ higher at Ks than at Kp_3 throughout all periods (Table 3, Fig. 1d). Daytime VPD was on average 0.05 kPa higher at Ks in May–June and July–August. Air temperature during the day was not significantly different indicating a fairly equal temperature distribution

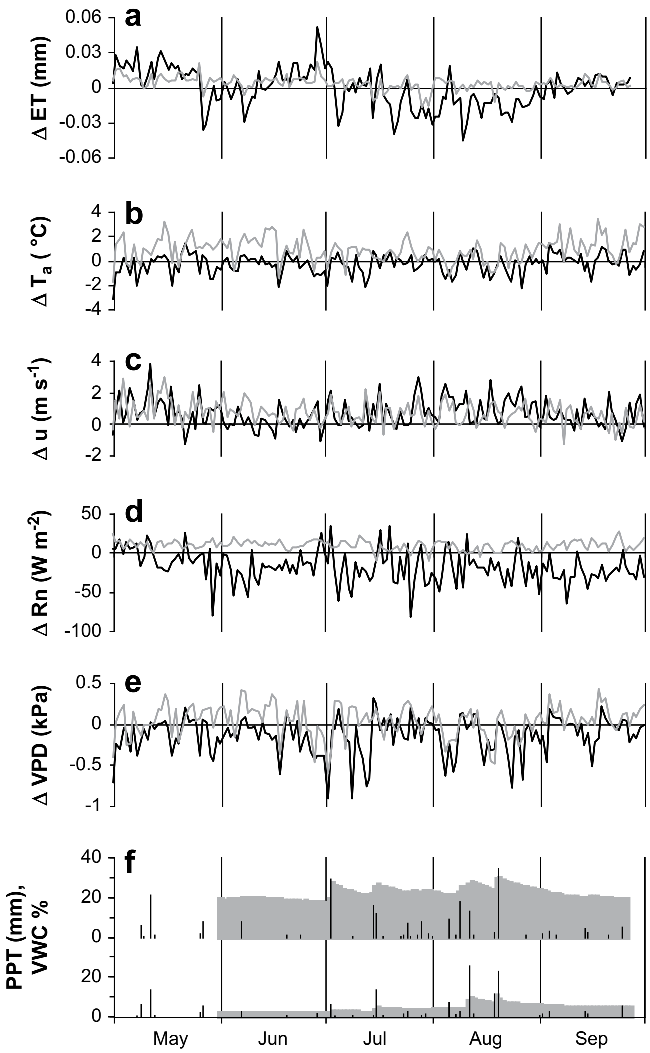

Fig. 1. Differences in ET and climate parameters between poplar plantation (Kp_3) and shrubland (Ks) in 2006. Plots (a)–(e) show differences di = (Kp_3 – Ks) in parameter means for day (black) and nighttime (grey) (positive values = Kp_3 > Ks). Plot (f) shows daily PPT (bars) and average VWC (grey area) at Ks (upper plot) and Kp_3 (lower plot).

throughout the area. Thus, daytime R_n, VPD and T_a did not explain higher ET at Kp_3 as compared to Ks. Similarly, mean wind speed ($\overline{u}$) was higher at Kp_3 than at Ks from May to August (Fig. 1c) but not significantly different in September (Table 3). Mean daily $\overline{u}$ at Kp_3 and difference in $\overline{u}$ between Kp_3 and Ks were not different in May–June and July–August (Wilcoxon Rank, down to 0.01 m s^{-1}), which assigned lower weight to the influence of wind speed on differences in ET between Kp_3 and Ks.

Nighttime mean values of R_n, T_a and VPD were significantly higher at Kp_3 than at Ks, except for VPD in July–August. However, total ET during the nights was 8–20% of the daytime ET at both sites. Hence, higher nighttime values of T_a, R_n, and VPD could only account for less than 20% of the differences between ET at Kp_3 and Ks.

Soil volumetric water contents (VWC, 0–30 cm) were significantly different and varied from 2 to 14% and 18 to 32% at Kp_3 and Ks, respectively (Fig. 1f). Daily average VWC in the shrubland was at least 3% higher during the period July–August than in June and September (one sided T-test, $p = 0.001$). The transition from June to July marked both the transition from higher ET at Kp_3 to higher ET at Ks, and from the drier season to the wetter season with frequent PPT (Fig. 1a and f). Differences in VWC between both sites showed some coherence with this trend (Fig. 2). ET was higher at Ks than Kp_3 when the difference in VWC (VWC Kp_3 – VWC Ks) exceeded a threshold of −17%, which marked the period in which the shrubland received significantly more PPT than the poplar site (155.7 vs. 100.5 mm).

Higher ET at Kp_3 than at Ks particularly during the initial period of the growing season resulted in significant differences in the intermittent water recharge. The water deficit (calculated as accumulated ET minus accumulated PPT) was significantly larger at Kp_3 than at Ks based on the period May–September (Fig. 3). While the ET/PPT ratio at Ks allowed an intermittent surplus in accumulated of PPT, virtually no PPT-water remained at Kp_3 after mid-May. The water balance at the poplar plantation would not even recover from the deficit until mid-August assuming a higher PPT like at Ks (i.e., ET Kp_3 – PPT Ks).

Differences in ET at both sites under conditions of low soil moisture were highlighted during the first week of May. For 90% of the 5-day period, ET at Ks was on average 30% of the ET at Kp_3 (Fig. 4a). Both sites had received no PPT in more than a month. The diurnal courses of climate variables (T_a, R_n, VPD) showed a high congruency and did not explain the large difference in ET but. Similarly, higher wind speed at Kp_3 than Ks during four of the five daytime periods had obviously no significant effect on the difference in ET between the sites (Fig. 4c).

To address specifically the effect of soil moisture on ET at Kp_3 and Ks, we analyzed the ET data in two subsets including smaller (≤17%) and larger (19–22%) differences in VWC (Fig. 5). Small and

Table 3
Mean half-hour averages per period of ET-controlling parameters tested for significant differences d = (Kp_3 – Ks) applying paired T-test to daily averages (negative values = Ks > Kp_3, ns = p > 0.001).

		May–June		July–August		September	
		d	p	d	p	d	p
T_a (°C)	Day	−0.1	ns	−0.1	ns	−0.1	ns
	Night	0.7	<0.001	0.2	<0.001	0.7	<0.001
$\overline{u}$ (m s^{-1})	Day	0.2	<0.001	0.5	<0.001	0.1	ns
	Night	0.6	<0.001	0.3	<0.001	0.1	ns
R_n (W m^{-2})	Day	−3.0	<0.001	−9.9	0.001	−15.0	<0.001
	Night	9.5	<0.001	4.5	<0.001	7.0	<0.001
VPD (kPa)	Day	−0.05	0.001	−0.05	<0.001	−0.05	ns
	Night	0.01	ns	−0.1	<0.001	0.02	<0.001

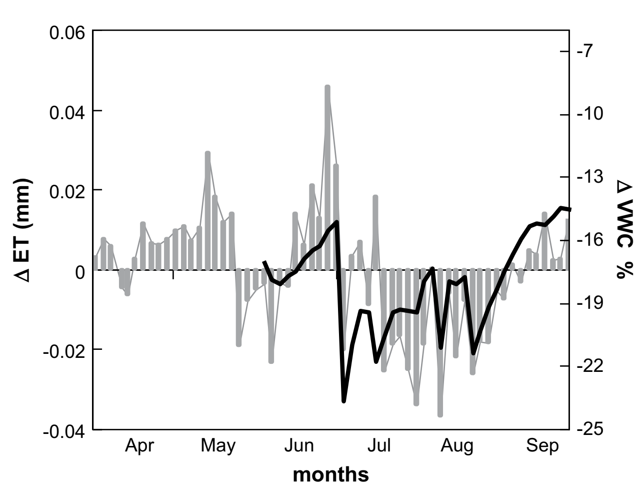

Fig. 2. Difference (Kp_3 – Ks) in ET (grey bars) and soil water content (line) between poplar plantation and shrubland in Kubuqi. ET and VWC represent mean half-hour values of three consecutive daytime periods (6:00–20:30 h). VWC reflects 0–30 cm soil depths.

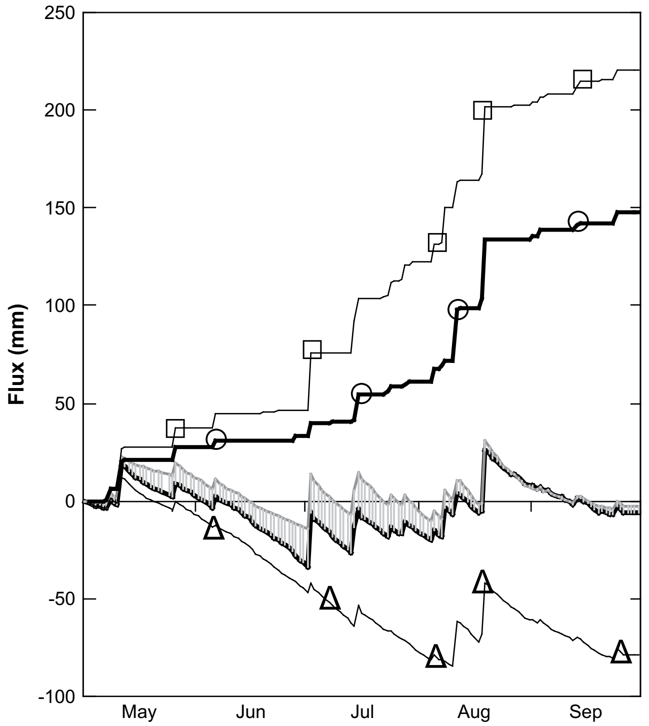

Fig. 3. May–September accumulated precipitation (PPT) at the poplar plantation Kp_3 (○) and the shrubland Ks (□), and accumulated ET minus PPT at Kp_3 (△) and Ks (thin line). The bold line draws for (PPT Ks minus ET Kp_3), and the hatched area outlines the water deficit assuming Kp_3 would have received the same amount of PPT like Ks.

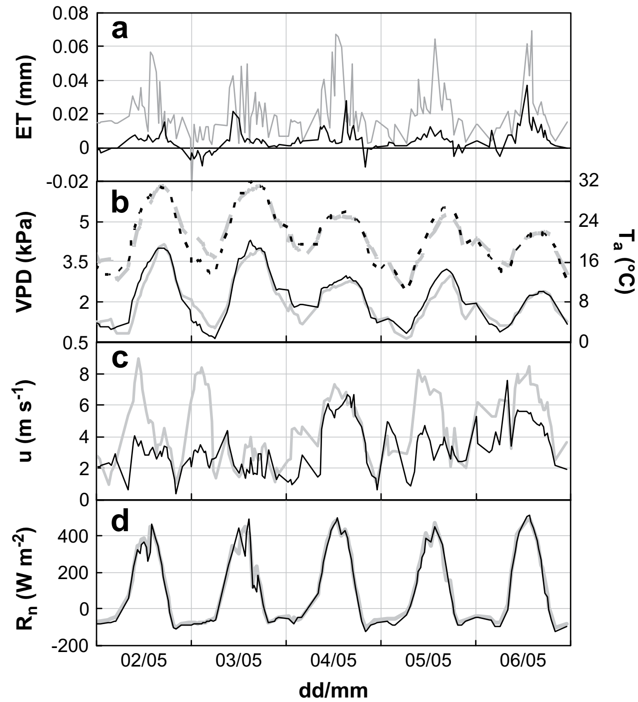

Fig. 4. Differences in ET and similarity in VPD (b, line), air temperature (b, dots), wind speed (c), and net radiation (d) between the poplar plantation (grey) and the shrubland (black) during 5 days in May 2006 (ngf data). Higher wind speed at Kp_3 than Ks during three daytime periods did not affect the ET ratio of ET Ks ≈ 0.3 × ET Kp_3.

large differences in VWC were representative for May, June, September and the wetter months July–August, respectively. Both subsets were then screened for isochronal half-hour periods including negligible differences (δ) in climate parameters (i.e., $\delta T_a < 1$ °C, $\delta R_n < 1$ W m^{-2}, $\delta\bar{u} < 1$ m s^{-1} and δVPD < 1 kPa). Data from 13 days of the growing season passed the screening. ET at Ks was 0.35 × ET Kp_3 when the difference in VWC was small; however ET at Ks was 1.85 × ET Kp_3 when the difference in VWC was large. The result of calculating the slopes as ratio of the drier and wetter month {ET Ks = (3 × 0.35 ET Kp_3 + 2 × 1.85 ET Kp_3)/5-mth ET Kp_3 = 0.95 ET Kp_3} came close to the difference of +2% ET at Kp_3 calculated from gap-filled flux data.

Overall, the comparison of ET and controlling parameters at Kp_3 and Ks showed that (1) higher ET from the plantation did not result from abiotic factors at the site and (2) the plantation used significantly more water during critical dry periods of the growing season, which also indicated that at least a part of the trees had tapped groundwater.

3.2. ET in the poplar plantations

To estimate the future increase of ET at Kp_3, we compared ET at the 3-yr old poplar plantation with ET at a 6-yr old poplar plantation (Bp_6), which grows under sub-humid climate near Beijing. The main site and vegetation specific differences were a three times higher PPT and a five times higher LAI at Bp_6 (458.7 mm, 1.96 m^2 m^{-2}) as compared with Kp_3 (147.8 mm, 0.38 m^2 m^{-2}), respectively (Tables 1 and 2). Maximum daily ET was up to two times higher at Bp_6 (5.5, 3.8, 6.0, 6.7 mm) than at Kp_3 (3.1, 2.1, 3.0, 3.9 mm) during the months May–August. Total growing season ET was 227.8 mm at Kp_3 and 245.9 mm at Bp_6 based on 98% and 42% data coverage for May–September, respectively (Table 2). Growing season ET extrapolated from monthly data coverage was about 550 mm at Bp_6, and thus, ET was 2.4 times higher at Bp_6 than at Kp_3. The ET/PPT ratios were 1.5 at Kp_3 and, with respect to the ET estimate, about 1.2 at Bp_6. Thus, both ET/PPT ratios indicated replenishment of soil water by groundwater.

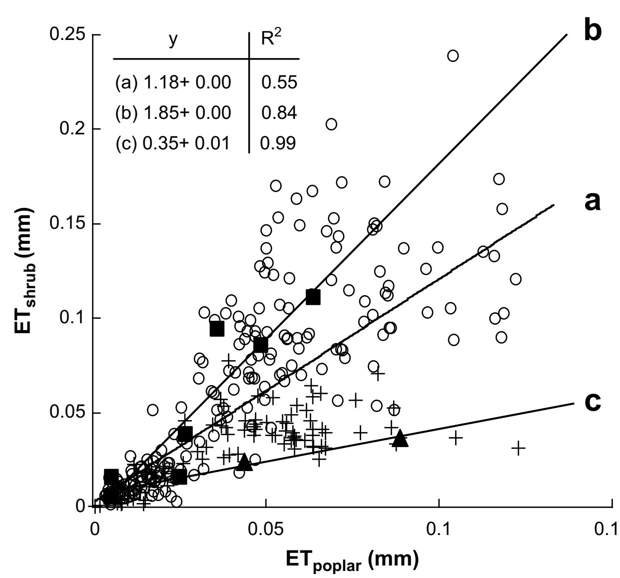

Fig. 5. Relationship between ET at Ks and Kp_3 based on isochronal half-hour ngf data including a difference (δ) in $T_a < 1$ °C between sites. Regression (a) reflects ET of two data subsets, i.e., ET at δVWC = 19–22% (○) and δVWC ≤ 17% (+). The regressions (b) (■, δVWC = 19–22%) and (c) (▲, δVWC ≤ 17%) reflect further screening of the subsets relative to daytime conditions (i.e., $\delta R_n < 1$ W m^{-2}, $\delta\bar{u} < 1$ m s^{-1} and δVPD < 1%).

The same incoming radiation (R_{in}) can result in lower and higher values of net radiation if more radiation is reflected from soil surfaces and absorbed by vegetation, respectively. Daytime R_n was only insignificantly higher at Bp_6 than Kp_3 (Fig. 6). However, the average sum of short- and long-wave R_{in} during daytime was significantly higher at Kp_3 ($422\ W\ m^{-2}\ s$) than at Bp_6 ($308\ W\ m^{-2}\ s$, two-sided T-test, $p = 0.035$). Only 13% of R_{in} was reflected from the closed canopy at Bp_6 whereas 42% was reflected from the sparse canopy cover and sand surface at Kp_3. Hence, further growth of the poplars at Kp_3 can increase canopy interception of R_{in}, which includes a potential increase of almost 30% in R_n, and a large increase in ET provided the trees have access to water.

We compared gap-filled ET data for separate daytime periods to analyze specifically effects of T_a and VPD on the transpiration component at Kp_3 and Bp_6 (Fig. 7). ET was between 40% (September, midday) and 225% (May, afternoon) higher at the 6-yr old plantation as compared with the 3-yr old plantation during separate morning (9:30–10:30), midday (11:30–12:30) and afternoon hours (13:30–14:30) (Fig. 7a). Average 30-min ET of the three periods was 0.16 ± 0.01 mm and 0.06 ± 0.00 mm for Bp_6 and Kp_3, respectively.

We found that T_a and VPD were not the most critical parameters to explain the difference in ET between the sites. VPD, $\overline{u}$ and T_a were on average 0.4 kPa lower, 2.3–3.3 $m\ s^{-1}$ lower and 2.4 °C higher at Bp_6 as compared with Kp_3 (Fig. 7d–e, g–i, m–o). ET was two times higher at Bp_6 than Kp_3 with similar T_a at both sites in July. VPD was similar at both sites in August but ET peaked with 0.26 ± 0.02 mm and 0.09 ± 0.0 mm (mean ± SD) at Bp_6 and Kp_3, respectively (Fig. 7m–o).

ET at Bp_6 showed a significant morning-to-midday increase from May (two-sided T-test, $p = 0.048$) to August ($p = 0.01$) (Fig. 7a–b). In contrast, ET at Kp_3 showed no significant morning-to-midday increase from May to July but only in August ($p = 0.049$) when the monthly PPT accounted for 50% of the growing season PPT. Significant increases in R_n correlated with the morning-to-midday increase in ET at Bp_6 but not at Kp_3 (Fig. 7j–l). The low LAI and thereby limited transpiration were mainly responsible for the absence of significant morning-to-midday increases in ET at Kp_3.

In July, PPT at Bp_6 (240 mm) was nine times higher than at Kp_3 (27.3 mm) but ET at Bp_6 did not increase proportionally. Large amounts of PPT can be expected to increase ET through both transpiration and evaporation of canopy-intercepted rain. However, 77% of PPT at Bp_6 in July occurred during four days, which probably produced a large runoff and left relatively less water in the soil and canopy. Despite of similar substantial amounts in PPT at Bp_6 (78.3 mm) and Kp_3 (73.2 mm) in August, the difference in ET between Bp_6 and Kp_3 increased as compared with July (Fig. 7a–c). The increase in ET at Bp_6 concurred with higher midday R_n and slightly increased VPD and T_a in August as compared with July. Thus, the difference in ET between the canopy with the higher (Bp_6) and lower LAI (Kp_3) increased further with increasing influence of R_n, VPD and T_a. ET increased two times stronger with temperature at Bp_6 than at Kp_3 based on 30-min ngf data screened for maximum similarity in conditions (Fig. 8a and b: $n = 5$–10, $T_a \pm$ SD, °C: 20.4 ± 0.2, 23.6 ± 0.0, 26.1 ± 0.1, VWC = 4–5%, $\overline{u} = 1$–$1.5\ m\ s^{-1}$, difference in VPD ~ 0.2 kPa).

In summary, ET was between 100% and 200% higher at Bp_6 than at Kp_3 by comparing monthly ET, ET during separate day periods, and half-hour ET under conditions of similar R_n and T_a. With increasing canopy cover (LAI), R_n at Kp_3 has the potential to increase more than 25% above the present average at Bp_6. Similarly, evaporation of canopy-intercepted PPT will increase with increasing LAI at Kp_3. Effects of slightly higher T_a and VWC at Bp_6 may be partly equilibrated by higher VPD and wind speed at Kp_3.

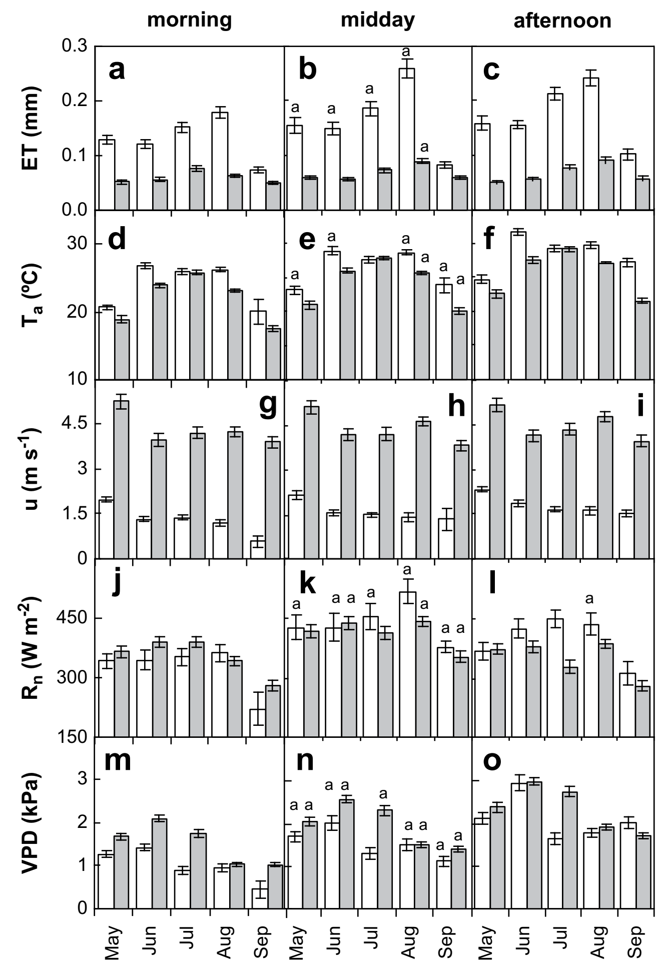

Fig. 7. ET and climate parameters at Bp_6 (white) and Kp_3 (grey) in the morning (9:30–10:30), midday (11:30–12:30), and afternoon (13:30–14:30) during May–September. Values represent mean ± SD of three 30-min periods. Significant difference ($p < 0.05$) to previous hours is indicated with "a".

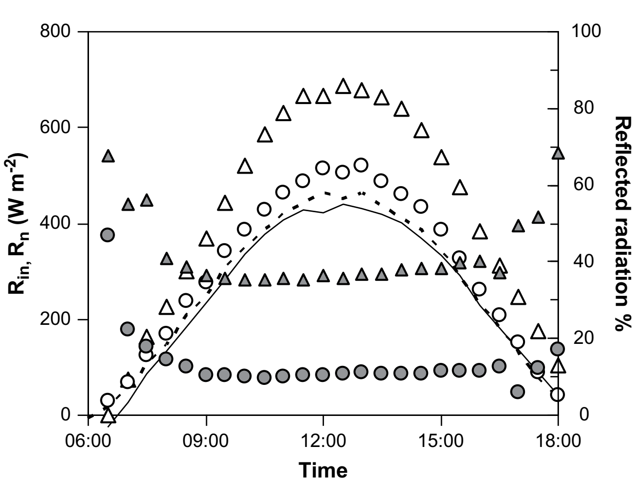

Fig. 6. Mean incoming radiation (short + long wave; open symbols), net radiation (lines), and reflected radiation (filled symbols) at the 3-yr old (Kp_3: triangles and solid line) and 6-yr old plantation (Bp_6: circles and dotted line) during daytimes in the growing season 2006.

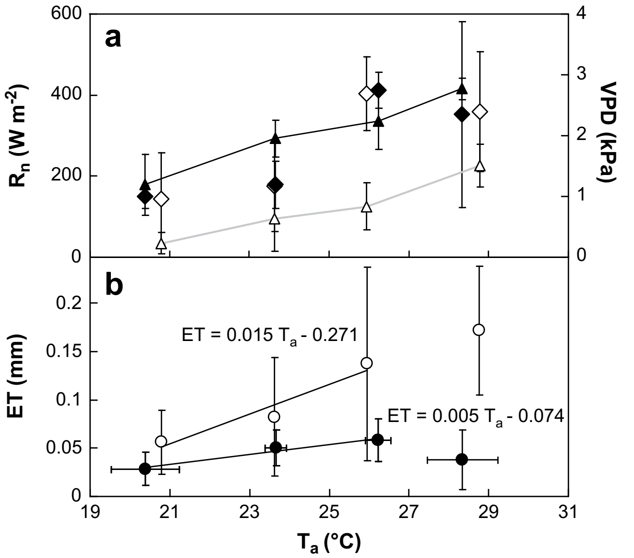

Fig. 8. Half-hour ET (mean ± SD, $n = 5–10$) at the poplar plantations Bp_6 (open symbols) and Kp_3 (filled symbols) as derived from screening ngf data for maximum climate similarity. Parameter ranges were VWC = 4–5% and $\overline{u} = 1.0–1.5\ m\ s^{-1}$. Residual data were screened for similar air temperatures, similarity in R_n (◇) and VPD (△, constant difference ≈ 0.2 kPa). The regression explains ET $Kp_3 \approx 0.3 \times$ ET Bp_6 excluding ET at $T_a > 28$ °C.

4. Discussion

4.1. Elevated ET with poplar plantations

Growing season ET was 227.8 mm and 2% higher at a 3-yr old poplar plantation than at a nearby shrubland in the Kubuqi Desert even though the poplar plantation received 33% less PPT. ET was higher at Ks than Kp_3 during the wet period of the growing season. For this period, we can also assume that the evaporation fraction of ET was higher from saturated soil surfaces at Ks than from the better draining sand at Kp_3. Conversely, ET was higher at Kp_3 than at Ks particularly during the initial period of the growing season. This resulted in a larger deficit in the intermittent water recharge at Kp_3 and may already include detrimental effects on the remaining natural vegetation (e.g., Chen et al., 2006).

Higher ET/PPT ratios and lower sensitivity to both long dry periods and to major amounts of PPT at Kp_3 as compared with Ks indicated that a part of the trees had switched their reliance from soil water of the unsaturated zone to groundwater (Cox et al., 2005). This assumption was corroborated by the large diversity in tree stature and LAI at Kp_3. The phenological diversity pointed to large differences in water stress within the plantation, which also suggested that some of the trees had tapped groundwater and were relatively independent from PPT and soil moisture in the unsaturated zone. Nagler et al. (2007) found similar differences in tree height and LAI at the dry and wet sites of a flood-irrigated 3-yr old poplar plantation at the Lower Colorado River, California. Newly established poplars can sink their roots into aquifers at 1–3 m depth within a single year following flood events (Nagler et al., 2005). The amount of irrigation at Kp_3 was obviously not sufficient to enhance growth of young trees that could not connect to groundwater. ET contribution from young poplars can be significantly affected by water stress (Nagler et al., 2003). However, once poplars have tapped groundwater, this can supply the whole need of their transpiration (Snyder and Williams, 2000). Overall, the evidences suggest that groundwater can support considerable increments in tree growth, transpiration and ET at Kp_3.

Estimated growing season ET and maximum daily ET were up to 100% higher at a 6-yr old poplar plantation than at Kp_3. ET was even 200% higher at Bp_6 than at Kp_3 with respect to separate daytime periods and half-hour periods including high similarity in ET-controlling climate variables. Certain factors that control the evaporation component in ET will be always more limiting at Kp_3 than Bp_6, e.g., PPT including higher availability of soil moisture and canopy-intercepted rain. Closed-canopy ecosystems may intercept 10–50% of PPT (Waring and Running, 1998). However, other major drivers of ET (e.g., R_n, VPD and $\overline{u}$; Monteith, 1965) may equilibrate some of the previous effects. The trigger capacity of VPD at Kp_3 in 2006 was obviously limited by a low LAI and thereby curbed transpiration (Mott and Parkhurst, 1991). Net radiation explained a major part of the daily variation in ET at Bp_6 and Kp_3. However, R_n at Kp_3 has the potential to increase with growing LAI more than 25% beyond the benchmark of Bp_6. Higher R_n, VPD and $\overline{u}$ at Kp_3 will increase both the contribution of transpiration to ET and the evaporation of canopy-intercepted rain. These potential increases in some of the major drivers of ET give reason to assume future growing season ET at Kp_3 may be similar or even higher than at Bp_6 in 2006.

The mean stand transpiration ranged from $2.3\ mm\ d^{-1}$ to $9.3\ mm\ d^{-1}$ during growing seasons as assessed by sap flow measurements of shelterbelt trees and natural poplar stands in semiarid and arid environments in China and the USA (Fig. 9; Chang et al., 2006; Gazal et al., 2006; Nagler et al., 2007; Pataki et al., 2005; Schaeffer et al., 2000). The average ET/LAI ratio, alternatively the increase of ET with LAI, suggests an increase of ca. $1.9\ mm\ d^{-1}$ per unit increase LAI. The range of daily ET from sap flow included poplar growth of different age, under different salinity, and close to perennial and ephemeral streams. The values reflected the transpiration but not the evaporation fraction and outline that ET at the 6-yr old plantation was not extremely high but can be similar or higher under semiarid climate. The comparison with other plantations indicated also that the LAI at Bp_6 did not benchmark a final

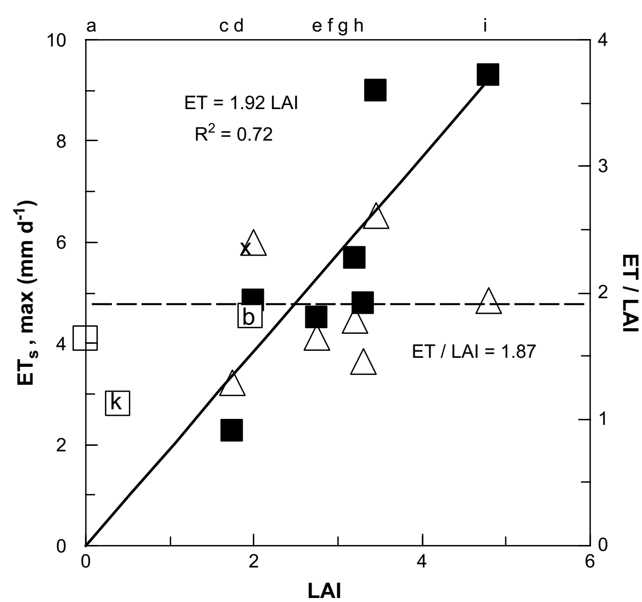

Fig. 9. Relation between LAI and stand transpiration (ET_S) of poplar as estimated from sap flow measurements in semiarid/arid environments. The plot shows the regression of ET_S vs. LAI (based on data ■, solid line, left equation) and the average of the ET/LAI ratios (data △, dashed line). Letters a–i on top of chart refer to data below (a) Chang et al., 2006; (c, e) Gazal et al., 2006; (d, f) Schaeffer et al., 2000; (g, i) Pataki et al., 2005; (h) Nagler et al., 2007. Letters in the chart indicate growing season maximum ET d^{-1} at k = Kp_3 and b = Bp_6; x indicates ET/LAI at Bp_6. Note that (a) did not report LAI.

value but may still increase in the future (up to the twofold, e.g., Nagler et al., 2007). Provided most of the trees at Kp_3 tap groundwater, and considering the number of uncertainties related to future LAI and effects of VPD and canopy-intercepted rain, it seems appropriate to assess future increases in ET at Kp_3 of 100, 150, and 200% as underestimated, most probable, and not impossible, respectively.

4.2. Shifts in the water balance

Poplar shelter belts represent a common measure to protect farmland from high wind speed, rapid desiccation and soil erosion (Cao, 1983; Chang et al., 2006). However, regarding large-scale plantations in semiarid areas one may consider that forests use more water than grass- or shrubland (e.g., Farley et al., 2005). Even ET of a natural oak savanna can exceed the ET of coexisting grassland in a semiarid climate by almost 30% (Baldocchi et al., 2004). For this the trees need to use water of deeper soil layers as compared with grasses and shrubs. Drought years and decreasing water tables led to a major dieback of pine species in IM in the 1920s (Liang et al., 2003) and diminish currently the scattered natural poplar populations (Liu et al., 2007). Hence, we may consider two future scenarios for the plantation in the Kubuqi Desert: (1) the majority of poplars cannot connect roots to the groundwater but will suffer from permanent water stress or die. Such a development has been reported from other plantations in IM, which proved to be economically costly and ecologically unsustainable (e.g., trees dying without irrigation; Jiang et al., 2006). (2) The majority of trees connect roots to the groundwater. Then, the plantation grows towards the crown closure of a forest and may consume 100–200% more water than shrubland.

To illustrate the effect of large-scale poplar plantations on the water balance, we can compare the increased water consumption with the water volume of the nearby Yellow River. The 700 km^2 of poplar plantations projected for the area may consume a water volume during the growing season equivalent to 1–2% of the concurrent mean stream flow of the Yellow River (58×10^9 m^3 yr^{-1}, http://www.yellowriver.gov.cn/eng/about_yr/jj_13362425174.html). In contrast, the ET/PPT ratio for the natural shrubland suggests that it has a no net effect on groundwater. This is in agreement with stable-isotope studies showing *A. ordosica* and native grasses use only water available at soil depths <65 cm and do not connect roots to the groundwater (Cheng et al., 2006; Ohte et al., 2003). With the poplars draining more water than appropriate to their micro-catchment (i.e., the surrounding area not shared with other plants; e.g., Shachak et al., 2008), lower water contents at deeper levels imply allocation of incoming PPT over a larger soil column. This may have effects similar to severe drought years for the remaining natural vegetation. Nagler et al. (2008) suggested diverting agricultural or urban water sources back to natural ecosystems, but they consider this being often impractical due to the high human demands for water in arid environments. Sun et al. (2006) suggested a large decrease in water yield following massive afforestation in the Yellow River Basin including a reduction in water yield of 15–100 mm yr^{-1} along the eastern border of IM. The same authors outline those areas with PPT < 400 mm yr^{-1} may not [author addendum: provide sufficient water to] support growth of forests.

The current study gives reason to discuss depletion of local groundwater resources owing to large-scale afforestation with poplar. For a sustainable water balance, initiatives of shrubland conservation seem more appropriate than planting poplars. However, the study relied on a limited data set that did not allow validation through, e.g., ET models, which can reflect differences in climate variables (e.g., PPT, R_n, and T_a) and help predicting the exact water expenditure of plantations. At present none of the alternative measures against desertification seem more attractive than large poplar plantations, which produce timber and help offsetting industrial carbon dioxide emissions. More studies are needed to better explain the impacts of large-scale poplar plantations on the ecosystems and water balance in semiarid IM. Data that allow correlation of ET to annual/inter-annual changes in the water table would significantly increase the explanatory power of future studies.

5. Conclusions

The monthly maximum in daily ET was on average 20% higher and 40% lower at a 3-yr old poplar plantation as compared to an adjacent shrubland growing under semiarid climate in Inner Mongolia, and a 6-yr old poplar plantation growing under sub-humid climate near Beijing, respectively. Despite lower PPT and ET at the poplar site in IM as compared to the Beijing site, the ET/PPT ratio was significantly higher under the semiarid climate than the sub-humid climate. The poplar plantation in IM elevated growing season ET by 2% and the ET/PPT ratio by 50% from 1.0 to 1.5 as compared to natural shrubland. This change in the water balance corroborated that the growth of poplar plantations in this area is only possible if trees have access to groundwater, either by irrigation or with roots tapping groundwater. The growth of the plantation will further increase the water loss as apparent from maximum daily ET of the two plantations and ET at similar temperatures. With respect to the effect of increased ET with poplars, we conclude that massive plantation in semiarid IM produces foreseeable consequences such as decreasing water tables and increasing water stress at regional scales. This exercise seems counterproductive in combating desertification in long terms and can be further complicated with altered climate in the future (i.e., higher temperature and low precipitation; IPCC, 2007).

Acknowledgements

The study was conducted as part of the Northern Eurasia Earth Science Program (NEESPI) and supported by the National Aeronautics and Space Administration (NASA) Grant (NEWS 2004 NRA: NN-H-04-Z-YS-005-N) of the Land-Cover/Land-Use Program, a "100 Talents" Project to GH Lin and a Knowledge Innovation Project of the Chinese Academy of Sciences (KSCX2-SW-127), financial support for the two eddy towers in Kubuqi from the Institute of Botany, CAS, and the US–China Carbon Consortium (USCCC), which promotes collaborative research among institutions in the US and China.

References

Alavi, N., Warland, J.S., Berg, A.A., 2006. Filling gaps in evapotranspiration measurements for water budget studies: evaluation of a Kalman filtering approach. Agricultural and Forest Meteorology 141, 57–66.
Anthoni, P.M., Unsworth, M.H., Law, B.E., Irvine, J., Baldocchi, D.D., Van Tuyl, S., Moore, D., 2002. Seasonal differences in carbon and water vapor exchange in young and old-growth ponderosa pine ecosystems. Agricultural and Forest Meteorology 111, 203–222.
Baldocchi, D.D., Xu, L.K., Kiang, N., 2004. How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak–grass savanna and an annual grassland. Agricultural and Forest Meteorology 123, 13–39.
Baldocchi, D.D., Hicks, B.B., Meyers, T.P., 1988. Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340.
Cao, X.S., 1983. Farmland Shelter Forestry. China Forestry Press, Beijing.
Chang, X., Zhao, W., Zhang, Z., Su, Y., 2006. Sap flow and tree conductance of shelter-belt in arid region of China. Agricultural and Forest Meteorology 138, 132–141.

Chen, Y.-N., Zilliacus, H., Li, W.-H., Zhang, H.-F., Chen, Y.-P., 2006. Ground-water level affects plant species diversity along the lower reaches of the Tarim river, Western China. Journal of Arid Environments 66, 231–246.

Cheng, X., An, S., Li, B., Chen, J., Lin, G., Liu, Y., Luo, Y., Liu, S., 2006. Summer rain pulse size and rainwater uptake by three dominant desert plants in a desertified grassland ecosystem in northwestern China. Plant Ecology 184, 1–12.

Chinese Forestry Society, National Poplar Commission, 2003. Forest resource, timber production and poplar culture in China. In: 1st International Conference on the Future of Poplar, Rome. http://www.fao.org/forestry/site/20587/en/.

Cox, G., Fischer, D., Hart, S., 2005. Non-response of native cottonwood trees to water additions during summer drought. Western North American Naturalist 65, 175–185.

FAO Forestry Department, 2007. Country profile China. http://www.fao.org/forestry/site/countryinfo/en/.

Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology 11, 1565–1576.

Fu, J., Hou, O.-J., 1995. Development of farmland shelterbelts in the semiarid region of northeastern Inner Mongolia. In: Invited Paper for IUFRO 20th World Congress. http://www.fao.org/docrep/w0312e/w0312e04.htm.

Gazal, R.M., Scott, R.L., Goodrich, D.C., Williams, D.G., 2006. Controls on transpiration in a semiarid riparian cottonwood forest. Agricultural and Forest Meteorology 137, 56–67.

Inner Mongolia News, 2006. Green Great Wall in Inner Mongolia. http://english.nmgnews.com.cn/eng/article/20060710/49243_1.html.

IPCC WGII, 2007. Climate change 2007: impacts, adaptation and vulnerability. In: Working Group II, IPCC 4th Assessment Report, http://www.ipcc.ch.

Jiang, G.M., Han, X.G., Wu, J.G., 2006. Restoration and management of the Inner Mongolia Grassland require a sustainable strategy. Ambio 35, 269–270.

Li, G.T., Yang, Z.X., Van Slycken, J., Zhang, W.D., 2005. Conservation of genetic resources of the European black poplar (*Populus nigra* L.) in China. Plant Genetic Resources Newsletter 143, 46–50.

Liang, E.Y., Shao, X.M., Kong, Z.C., Lin, J.X., 2003. The extreme drought in the 1920s and its effect on tree growth deduced from tree ring analysis: a case study in North China. Annals of Forest Science 60, 145–152.

Liu, P.X., Peng, J.F., Chen, F.H., 2007. Hydrological response of *Populus euphratica* Olve. radial growth in Ejinaa Banner, Inner Mongolia. Journal of Integrative Plant Biology 49, 150–156.

Ma, Z.G., Fu, C.B., 2006. Some evidence of drying trend over northern China from 1951 to 2004. Chinese Science Bulletin 51, 2913–2925.

Monteith, J.L., 1965. Evaporation and environment. The state and movement of water in living organisms. In: Symposium Society Experimental Biology, 19. Academic Press, New York, pp. 205–234.

Mott, K.A., Parkhurst, D.F., 1991. Stomatal responses to humidity in air and helox. Plant, Cell and Environment 14, 509–515.

Nagler, P.L., Glenn, E.P., Hinojosa-Huerta, O., Zamora, F., Howard, K., 2008. Riparian vegetation dynamics and evapotranspiration in the riparian corridor in the delta of the Colorado River, Mexico. Journal of Environmental Management 88, 864–874.

Nagler, P.L., Glenn, E.P., Thompson, T.L., 2003. Comparison of transpiration rates among saltcedar, cottonwood and willow trees by sap flow and canopy temperature methods. Agricultural and Forest Meteorology 116, 73–89.

Nagler, P.L., Hinojosa-Huerta, O., Glenn, E., Garcia-Hernandez, J., Romo, R., Curtis, C., Huete, A., Nelson, S., 2005. Regeneration of native trees in the presence of invasive saltcedar in the Colorado River delta, Mexico. Conservation Biology 19, 1842–1852.

Nagler, P.L., Jetton, A., Fleming, J., Didan, K., Glenn, E., Erker, J., Morino, K., Milliken, J., Gloss, S., 2007. Evapotranspiration in a cottonwood (*Populus fremontii*) restoration plantation estimated by sap flow and remote sensing methods. Agricultural and Forest Meteorology 144, 95–110.

Ohte, N., Koba, K., Yoshikawa, K., Sugimoto, A., Matsuo, N., Kabeya, N., Wang, L.H., 2003. Water utilization of natural and planted trees in the semiarid desert of Inner Mongolia, China. Ecological Applications 13, 337–351.

Pataki, D.E., Busch, S.E., Gardner, P., Solomon, D.K., Ehleringer, J.R., 2005. Ecohydrology in a Colorado River riparian forest: implications for the decline of *Populus fremontii*. Ecological Applications 15, 1009–1018.

Schaeffer, S.M., Williams, D.G., Goodrich, D.C., 2000. Transpiration of cottonwood/willow forest estimated from sap flux. Agricultural and Forest Meteorology 105, 257–270.

Shachak, M., Boeken, B., Groner, E., Kadmon, R., Lubin, Y., Meron, E., Ne'eman, G., Perevolotsky, A., Shkedy, Y., Ungar, E.D., 2008. Woody species as landscape modulators and their effect on biodiversity patterns. BioScience 58, 209–221.

Snyder, K.A., Williams, D.G., 2000. Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. Agricultural and Forest Meteorology 105, 227–240.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S., Vose, J.M., 2006. Potential water yield reduction due to forestation across China. Journal of Hydrology 328, 548–558.

Thomas, A., 2000. Spatial and temporal characteristics of potential evapotranspiration trends over China. International Journal of Climatology 20, 381–396.

Wang, S., Gong, D., Zhu, D., 2001. Twentieth-century climatic warming in China in the context of the Holocene. Holocene 11, 313–321.

Wang, S., van Kooten, G.C., Wilson, B., 2004. Mosaic of reform: forest policy in post-1978 China. Forest Policy and Economics 6, 71–83.

Waring, R.H., Running, S.W., 1998. Forest Ecosystems: Analysis at Multiple Scales. Academic Press, NY.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of the flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society 106, 85–100.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorology 99, 127–150.

Xiao, C.W., Zhou, G.S., Ceulemans, R., 2003. Effects of elevated temperature on growth and gas exchange in dominant plant species from Maowusu Sandland, China. Photosynthetica 41, 565–569.

Zhang, F., Hou, O.J., 1995. Erosion control development in China: The Shelterbelt System in Chifeng. In: IUFRO 20th Congress. http://www.fao.org/docrep/w0312e/w0312e04.htm.

Zhang, X.S., 1994. The ecological background of the Maowusu sandland: principles and optimal models for grassland management. Acta Phytoecologica Sinica 18, 1–6 (in Chinese).