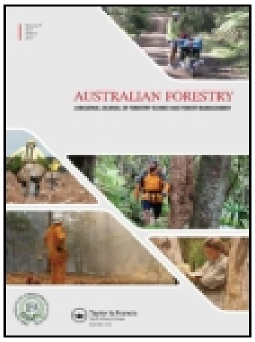

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The effects of subsurface irrigation at different soil water potential thresholds on the growth and transpiration of *Populus tomentosa* in the North China Plain

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Summary

In order to find the optimal subsurface drip irrigation (SDI) scheduling for mature triploid *Populus tomentosa* plantations in the North China Plain, a field experiment was conducted in 2010 and 2011 to investigate the effects of SDI at different soil water potential (SWP) thresholds on the growth and transpiration of a *P. tomentosa* plantation when it was six and seven years old. The experiment included three SWP treatments, which initiated irrigation when the SWP at 20 cm depth and 10 cm distance from a drip emitter reached −25 (T_{25}), −50 (T_{50}) and −75 (T_{75}) kPa, respectively. A control non-irrigation treatment (CK) was also included. Long-term SWP, soil water content (SWC), transpiration, tree growth, meteorological factors and groundwater level were monitored. Results showed that SDI influenced the SWC only in 0–80 cm of soil. From April to July, on average, the cumulative stand-level transpiration on a ground area basis (E) and growth of basal area at breast height accounted for 81% and 93% of their corresponding whole-season values, while the cumulative reference crop potential evapotranspiration (ET_0) was 43% higher than the rainfall. In contrast, from August to October, the growth rate of *P. tomentosa* was very slow, while the cumulative rainfall was 36% higher than ET_0 and the average groundwater level was relatively high (125 cm). Relative to CK, the E under the SWP treatments was significantly ($P < 0.05$) increased by 20–73%. Decreasing the SWP irrigation threshold from −25 to −50 kPa significantly reduced E by 31% ($P < 0.05$), but decreasing the threshold from −50 to −75 kPa did not further reduce *P. tomentosa* E. Relative to CK, T_{25}, T_{50} and T_{75} increased the annual above-ground dry biomass (ADB) increment by 54% ($P < 0.05$), 34% ($P < 0.05$) and 24% ($P > 0.05$) in 2010, and by 28% ($P > 0.05$), 29% ($P > 0.05$) and 32% ($P < 0.05$) in 2011, respectively. However, no significant difference in ADB increment was detected among the SWP treatments. Based on these results, it can be concluded that when planting *P. tomentosa* at sites with similar characteristics to ours in the North China Plain: (1) SDI could be promoted in the cultivation of *P. tomentosa* to improve tree growth; (2) a range of −50 to −75 kPa at a depth of 20 cm and 10 cm distant from a drip emitter is recommended as the irrigation threshold for scheduling SDI in *P. tomentosa* plantations and (3) irrigation should be applied between April and July, while drainage should be implemented between August and October.

Keywords: trickle irrigation; soil water potential; sap flow; irrigation scheduling; *Populus tomentosa*

Introduction

Triploid *Populus tomentosa*, an important clone for short-rotation pulpwood forestry, plays the key role in fast-growing and high-yielding poplar plantations in the North China Plain (Kang and Zhu 2002). However, at present, the average productivity of *P. tomentosa* plantations in this region is only 12 m^3 ha^{-1} y^{-1} (Ma *et al.* 2005; Zhang *et al.* 2009; Sun *et al.* 2012), which is much lower than the potential productivity of >40 m^3 ha^{-1} y^{-1} (Zhu *et al.* 1995). It is imperative to increase the productivity of these existing *P. tomentosa* plantations by using efficient intensive silvicultural practices, consequently helping to satisfy increasing demand for wood resources. Soil water availability is a very important limiting factor to *P. tomentosa* growth (Dong *et al.* 2011; Ren *et al.* 2011; Sun *et al.* 2012). Therefore, in the North China Plain, where the climate is always very dry in spring and early summer, irrigation has been used as the critical intensive silvicultural practice to increase the productivity of *P. tomentosa* plantations (Li 2008; Ren *et al.* 2011; Sun *et al.* 2012) by improving soil water availability within the root zone.

Flood, hole and furrow irrigation are the conventional irrigation methods used in poplar plantations in China (Jia *et al.* 2004; Ma *et al.* 2004; Zheng 2006; Li 2008; Ren *et al.* 2011; Sun *et al.* 2012). However, these not only waste a lot of water and cause large percolation losses, but also can constrain plantation productivity due to frequent soil moisture deficits between irrigation events. Therefore, in order to increase the productivity of poplar plantations and meanwhile achieve sustainable use of water, water-saving and high-efficiency irrigation techniques must be adopted. Drip irrigation is such an irrigation technique

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that has been widely applied to the cultivation of poplar plantations around the world (Hansen 1988; Dickmann *et al.* 1996; Ceulemans and Deraedt 1999; Coyle and Coleman 2005; Musselman *et al.* 2007; O'Neill *et al.* 2010), but rarely to poplar plantations in China (but see Jia *et al.* 2004; Shi *et al.* 2004, 2011). Generally, drip irrigation can greatly increase the productivity of poplar plantations (Hansen 1988; Dickmann *et al.* 1996; Jia *et al.* 2004; Coyle and Coleman 2005; Shi *et al.* 2011), although other studies covering a range of poplar clones, climates, stand ages and irrigation treatments report no or even negative effects on growth (Hansen 1988; Dickmann *et al.* 1996; Musselman *et al.* 2007). Thus, while it may be possible to increase the productivity of *P. tomentosa* plantations by using drip irrigation, its actual effect was unknown.

Determination of appropriate irrigation timing is crucial to efficient drip irrigation (Bucks *et al.* 1981; Hanson *et al.* 2003). In China, the irrigation timing for poplar plantations is commonly determined by conventional experience (Jia *et al.* 2004; Ma *et al.* 2004). However, applying this method to drip irrigation will limit its advantage of allowing timely and precise application of water in the root zone. A good alternative may be to schedule drip irrigation using soil water potential (SWP) as an index of soil water availability. Using this method, irrigation is based on monitoring actual soil water conditions, and evaporation and precipitation need not be measured. Negative off-site effects of drainage losses can also be minimised by choosing an appropriate target SWP threshold (Hodnett *et al.* 1990; Shock and Wang 2011). Furthermore, using a tensiometer to measure SWP is rapid, cheap and easy to do (Hodnett *et al.* 1990). Currently, this method has been widely used in agricultural and horticultural water management (Shock and Wang 2011), but rarely applied in water management in poplar plantations (but see Hansen 1988; Shock *et al.* 2002; O'Neill *et al.* 2010). A good understanding of the effects of SWP on growth and water use of *P. tomentosa* will help to efficiently apply this method to drip irrigation scheduling in *P. tomentosa* plantations (Kang and Wan 2005; Wang *et al.* 2007; Liu *et al.* 2012). However, to our knowledge, no attempts have been made to investigate the response of growth and water use of *P. tomentosa* plantations to SWP under drip irrigation, and even for plantations of other poplar species this information is very limited (Hansen 1988).

Thus, in order to find the optimal subsurface drip irrigation (SDI) scheduling for *P. tomentosa* plantations in the North China Plain, this study was conducted with three objectives: (1) to investigate the effects of different SWP irrigation thresholds on growth and transpiration of a *P. tomentosa* plantation under SDI in the North China Plain; (2) to find an appropriate SWP irrigation threshold for *P. tomentosa* SDI scheduling in the North China Plain and (3) to make recommendations related to irrigation water management for *P. tomentosa* plantations in the North China Plain, according to the seasonal tree growth pattern and variation of groundwater level and meteorological factors.

Materials and methods

Study site and experimental conditions

The experiments were conducted during 2010 and 2011 in a commercial *P. tomentosa* pulpwood plantation in Gaotang County, Shandong Province, China (36°58′N, 116°14′E; 27 m elevation). The site has a warm temperate monsoon climate, with a mean annual rainfall of 545 mm, a mean annual free surface evaporation of 1880 mm and a mean annual temperature of 13.2°C. The soil of the study site is developed from deep fine-textured quaternary alluvium.

In spring 2005, the 3.9 ha experimental plantation (B301 *P. tomentos*a clone) was established on a very flat site with uniform soil. The soil texture was silt in the upper 120 cm layer, but became silt loam below a depth of 120 cm. Details of other physical and chemical properties of the soil can be found in Xi *et al.* (2013). The trees were planted using an alternate wide (6 m) and narrow (2 m) row spacing scheme; the intra-row spacing was 1 m and stand density was 2500 trees ha^{-1}. In 2005 and 2006, the wide gaps were inter-cropped with flood-irrigated cotton. In 2007–2009, with no intercropping and no irrigation, herbicide was regularly applied throughout the plantation for weed control.

Two years (April 2008) before conducting the irrigation experiment, a SDI system was installed in half of the area (nine tree belts wide (72 m) and 270 m long) of the plantation. However, the system was not used in 2008–2009, in order to guarantee the tree roots disturbed during the installation of irrigation system had sufficient time to recover. Three drip laterals for each tree belt were installed at a depth of 20 cm: one was placed in the middle of the narrow row zone and the other two were in the wide row zone and about 60 cm distant from the tree line. The laterals had 2 L h^{-1} in-line labyrinth-type drippers at a spacing of 50 cm from each other.

Experimental design

In April 2010, the field area with drip laterals was divided into nine equal experimental plots, each three tree belts wide (24 m) and 90 m long. Three SWP treatments (T_{25}, T_{50}, T_{75}) were designed for this study. Trees in the treatments T_{25}, T_{50} and T_{75} were irrigated when the average SWP at 20 cm depth and 10 cm distant from a drip emitter reached −25, −50 and −75 kPa, respectively. Three replicates were set for each SWP treatment. All the SWP experimental plots were following a randomised block design. As poplar has been traditionally cultivated as a rainfed crop in this area, a control non-irrigation treatment (CK) with three replicates was also included in this research. One-third of the three tree belts (90 m long) adjacent to the irrigated area was divided into three equal experimental plots (each three tree belts wide and 30 m long), which were used as the replicated plots of CK. Because the CK treatment was not included in our preliminary experimental design, the three replicated plots of CK had to be grouped when this research commenced on April 2010. For each treatment, the middle area of the second replicated plot was used for measuring SWP, soil water content (SWC) and trunk sap flux, and the middle tree belts in all plots were used for measuring tree growth.

At the start of the experiment, that is in April 2010, the average tree diameters at breast height (DBH, 1.3 m above ground) of the T_{25}, T_{50}, T_{75} and CK treatments were 9.26 ± 0.29, 9.01 ± 0.15, 8.96 ± 0.16 and 9.17 ± 0.11 cm (no significant treatment difference, $P > 0.05$), respectively; the average tree heights were 12.26 ± 0.08, 11.98 ± 0.13, 11.94 ± 0.14 and 12.03 ± 0.19 m (no significant treatment difference, $P > 0.05$), respectively.

Irrigation management

Before treatments commenced every year, irrigation was applied once to the SWP treatments to promote leaf expansion. The date of leaf expansion irrigation was 13 April in 2010 and 7 April in 2011, and the corresponding irrigation amounts were 17 and 14 mm, respectively.

After SWP treatments commenced, irrigation was applied only when the average SWP of a treatment reached its targeted values. In 2010, the number of irrigation events (including leaf expansion irrigation) was 22, 11 and 7 for T_{25}, T_{50} and T_{75}, and in 2011, the values were 21, 10 and 6, respectively. The total irrigation amount for T_{25}, T_{50} and T_{75} was 336, 307 and 300 mm in 2010 and 323, 291 and 274 mm in 2011, respectively. Averaged over the two experimental years, the average duration of each irrigation interval was 5, 10 and 14 days for T_{25}, T_{50} and T_{75}, respectively.

According to the transpiration characteristics of *P. tomentosa* observed in this plantation by Li (2010), the irrigation level for the SWP treatments was arbitrarily set at 120% of the reference crop potential evapotranspiration (ET_0) (calculated using the Penman-Monteith equation (Allen *et al.* 1998) based on meteorological data from an on-site automatic weather station). That is to say, the irrigation quota was calculated based on 120% of the cumulative ET_0 between two irrigations (Equation (1)):

$$m = 120\% ET_0 - P(1 - \lambda), \tag{1}$$

where m is irrigation quota (mm); P is the cumulative rainfall between two irrigations (mm); λ is canopy rainfall interception (%), which was assumed to be 15%. This was the mean of the interception losses in a *P. davidiana* plantation with stand characteristics similar to ours (13%) (Pan and Shangguan 2005) and in warm temperate deciduous broadleaf forest in China (18%) (Wen and Liu 1995). Since the groundwater table was relatively low during irrigation, groundwater recharge was neglected when calculating the irrigation quota.

Measurements

Soil water potential and soil water content

For each SWP treatment, six tensiometers were installed to monitor SWP, with ceramic cups at 20 cm depth and 10 cm distant from the drip emitter. The tensiometer data were recorded manually at about 7 a.m. every day from April to October in 2010 and 2011.

SWC of the three SWP treatments was measured using the tube probe (TRIME-IPH, IMKO Inc., Ettlingen, Germany). In April 2011, for each SWP treatment, three access tubes of 2 m length were installed for the TDR tube probe at about 5 cm distant from the drip emitter. The measurements of the SWC profile were taken at 0.2 m intervals from the soil surface to a depth of 1.7 m. The measurements were made within time intervals of less than 15 d from the end of May to October 2011.

Meteorological factors and groundwater level

Meteorological data were measured from 2008 to 2011 in a standard automatic weather station (Delta-T Devices Ltd., Cambridge, UK) located 250 m from the experiment plots. Variables measured included global solar radiation, photosynthetically active radiation, air temperature, air relative humidity, wind speed, wind direction and rainfall. Groundwater level was measured manually at intervals no greater than 10 days from August 2009 to October 2012 in two tube wells, located in the north-east and south-west of the experimental plantation, respectively.

Transpiration

Sap flux was recorded continuously from early April to the end of October 2010. For each treatment, three average-sized trees were selected to measure sap flow. One set of thermal dissipation probes (TDP30, Dynamax Inc., Houston, TX, USA), each 30 mm long, 1.2 mm in diameter and spaced 40 mm apart vertically, was installed into the sapwood about 1.3 m above the ground on the southern aspect of each sample tree. Each probe was waterproofed using sealant. The probe assembly and stem were wrapped with reflective bubble insulation to reduce thermal gradients. Sap flux was recorded every 10 s, and 10-min means were stored on a data logger (Model DL2e, Delta-T Devices Inc., Cambridge, UK). Sap flux was assumed to be uniform across the entire sapwood area since information of the radial and circumferential variation of sap flux throughout sapwood was lacking for our study site. The stand-level transpiration on a ground area basis (E) in each plot of each treatment was estimated using Equation (2).

$$E = J_s \left(SA_{plot} / A_G \right), \tag{2}$$

where J_s (cm d^{-1}) is the mean stand sap flux; SA_{plot} (cm^2) and A_G (cm^2) are the total sapwood area and the ground area of a plot, respectively.

We did not have enough probes to measure sap flux in all experimental plots, so the J_s of the second replicated plot of a treatment was also used as the J_s of its other two replicated plots. SA_{plot} was estimated by integrating all the individual tree sapwood areas (SA_{tree}) in a plot, which was calculated using an equation describing the relationship between DBH and SA_{tree} developed for five- and six-year-old *P. tomentosa* by Li (2010).

Tree growth

Ten trees were randomly selected from each of the head, middle and tail ends of the second replicated plot of a SWP treatment, respectively, to monitor DBH growth in that specific treatment. For the CK treatment, ten trees were randomly selected from each plot to monitor DBH growth. Measurements were taken at monthly intervals from April to October in 2010 and 2011. In early November 2010 and 2011, DBH was measured for every second tree in all plots. The number of trees measured for each plot was 80–90 and 30–35 in the SWP and CK treatments, respectively. The basal area at breast height (ABH) of sample trees was calculated using their DBH data. Assuming the plant organ biomass partitioning was similar in the four treatments, the above-ground dry biomass (ADB) (sum of dry biomass of stem, branch, bark and foliage) of sample trees was calculated using the allometric equations, with DBH as the independent variable developed for *P. tomentosa* by Song (2009). These equations were established using data collected in three-, five-, six- and seven-year-old *P. tomentosa* plantations (stand density was 2500 trees ha^{-1}) with similar plant organ biomass partitioning, which were planted in our experimental site and received silvicultural practices similar to those applied in our experimental plantation in 2005–2009.

Statistical analysis

One-way ANOVA was carried out to determine the effect of different treatments on *E*. The significant differences among treatments were checked with Duncan's test (P = 0.05). Analysis of covariance (ANCOVA) with initial stand ADB as covariate was used to compare the ADB increment among treatments. When significant ($P < 0.05$) overall treatment effects were detected, differences among treatments were tested using least significant differences (LSD) on the adjusted mean values from the ANCOVA. All data analyses were performed with SPSS software (v. 13.0, SPSS Inc., Chicago IL, USA).

Results

Soil water potential and soil water content

Overall, during the experiments in 2010 and 2011, the SWP for all treatments was kept well above their targeted thresholds (Fig. 1a–c). In October 2011, although the SWP under the T_{25} treatment was below −25 kPa, irrigation was not applied, because at this time most leaves had fallen off. From the start of the experiment to the end of July every year, the SWP varied among the SWP treatments. With increasing targeted thresholds (i.e. less negative), SWP varied with a higher frequency but with smaller amplitude. During the period from April to July, the average SWPs under T_{25}, T_{50} and T_{75} treatments were −19.1, −26.1 and −34.7 kPa in 2010 and −16.8, −24.8 and −32.4 kPa in 2011, respectively. This indicates that a higher target threshold resulted in greater surface soil water availability. Due to ample rainfall (Fig. 1d) from August to October every year, the average SWP under all SWP treatments (except T_{25} treatment in 2011) was much higher than that between April and July (data not shown).

The SWC within 0–80 cm soil depth was influenced by SDI (from SWC profiles in 2011, data not shown). However, the SWC in soil below 80 cm depth increased obviously only when heavy rain occurred (Figs. 1d, 2). This indicates that SDI influenced the SWC only in the 0–80 cm soil layer and had not caused deep percolation.

Groundwater level, reference crop potential evapotranspiration and precipitation

As shown in Figure 3, the groundwater level changed very sharply every year. In 2010, 2011 and 2012, the lowest groundwater level was measured at 367, 388 and 470 cm depth, respectively, while the highest was at 38, 85 and 24 cm depth, respectively. The average change amplitude of groundwater level of the three years was 359 cm. During the growing season of *P. tomentosa*, that is from April to October, the water table always declined sharply from April to mid-June, but then rose rapidly to reach a peak in about September. Afterwards, the water table declined again but at a moderate rate. Overall, the average groundwater level was at a depth of 286 cm between April and July and rose to a depth of 125 cm between August and October.

Table 1 shows the monthly precipitation and ET_0 from April to October (i.e. the growing season of *P. tomentosa*) in 2008–2011. ET_0 was markedly greater than rainfall in April, May, June and October each year. For these four months, the four-year mean cumulative ET_0 was 395 mm, which was 2.7 times as much as the corresponding rainfall. In contrast, rainfall was often much higher than ET_0 in July–September, during which time the four-year mean cumulative rainfall was about 80% higher than the corresponding ET_0.

Transpiration

In 2010, daily *E* of *P. tomentosa* ranged between 0.04 and 4.96 mm d^{-1}, and its annual mean value was 1.76 mm d^{-1} (Fig. 4). Summed by month, *E* was significantly influenced by SWP irrigation threshold ($P < 0.001$). The whole-year *E* of T_{50} (249 mm) and T_{75} (267 mm) was similar ($P = 0.358$), but they were both significantly lower than that of T_{25} (359 mm) ($P < 0.05$). Relative to CK (208 mm), T_{25}, T_{50} and T_{75} significantly ($P < 0.05$) increased the whole-year *E* by 73%, 20% and 29%, respectively. For all treatments, monthly *E* increased dramatically from April to May and declined slowly in June and July, but afterwards decreased sharply until September (data not shown). In general, averaged over the four treatments, the cumulative *E* between April and July accounted for about 81% of the whole-season *E*.

Tree growth

Figure 5 shows the mean monthly ABH increments of randomly selected *P. tomentosa* under different treatments in both experimental years. The months of fastest growth of *P. tomentosa* were May and July, followed by June. Across all treatments, the cumulative ABH growth in these three months accounted for about 84% of the annual ABH growth on average. Growth was relatively slow in April and August, and on average the ABH growth in those months contributed about 9% and 5% of annual growth, respectively. *P. tomentosa* almost stopped growing after August every year.

A comparison of the mean ADB annual increments, calculated from systematically sampled trees within each different treatment, is shown in Table 2. Among the SWP treatments, ANCOVA revealed that SWP irrigation threshold had no significant effects on mean ADB increment in either experimental year. In 2010, the greatest ADB growth was observed in the T_{25} treatment, while the least was in the T_{75} treatment. However, in 2011, this order of ADB increment reversed. In 2010, the mean ADB increments under T_{25} and T_{50} were 54% and 34% greater than that under CK, respectively. These differences were

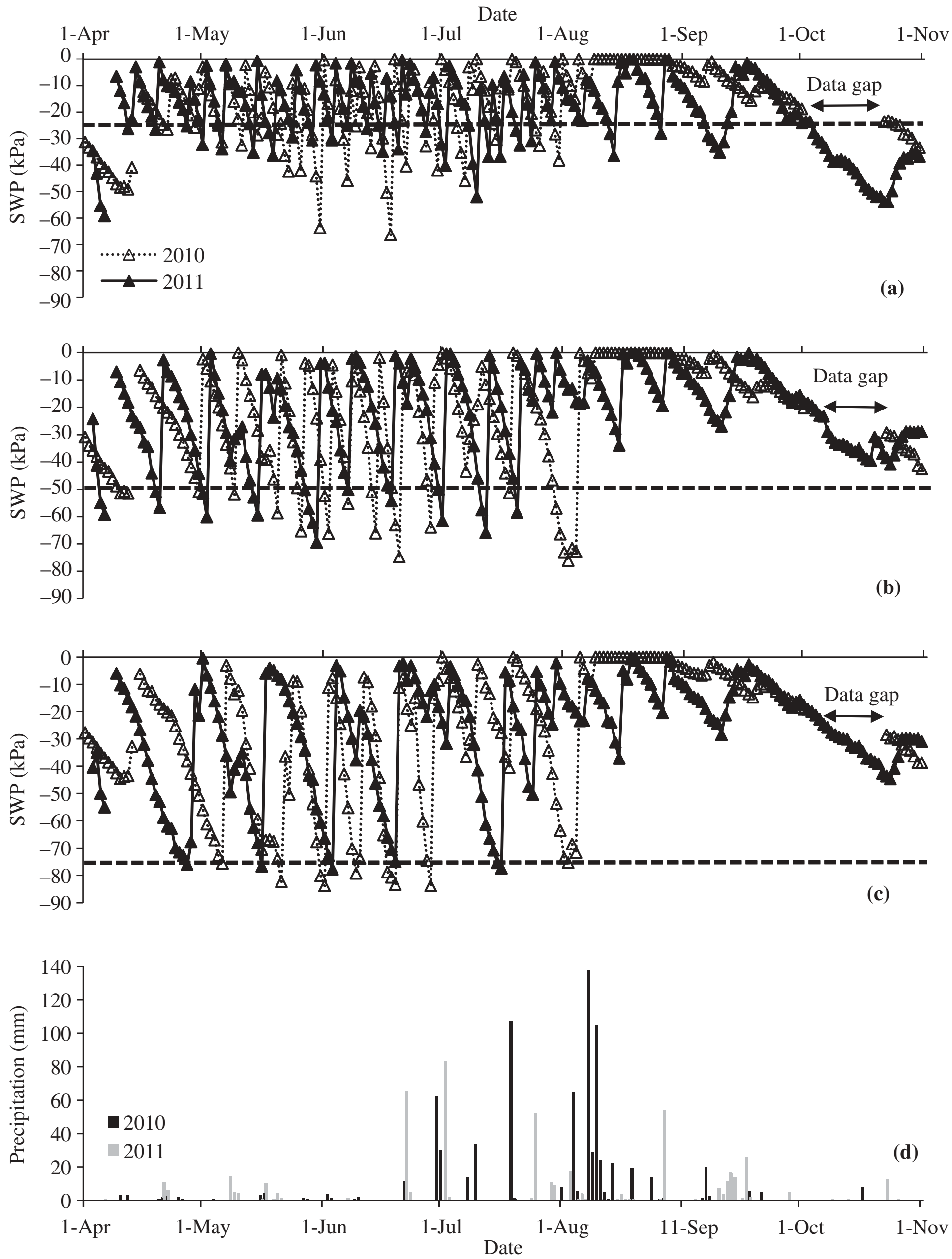

Figure 1. Soil water potential (SWP) variation under (a) T_{25}, (b) T_{50} and (c) T_{75} treatments and (d) precipitation in 2010 and 2011. SWP data gaps in (a), (b) and (c) are due to data lost. Dashed lines in (a), (b) and (c) represent the target thresholds of −25, −50 and −75 kPa, respectively. Due to equipment failure, a large amount of precipitation was not recorded in August 2011

statistically significant ($P < 0.05$), but this significant difference disappeared in 2011, although mean ADB increments under T_{25} and T_{50} were 28% and 29% greater than that under CK, respectively. In contrast, the T_{75} treatment had 32% greater mean ADB increment than CK in 2011, which was statistically significant ($P < 0.05$). However, this significant superiority was not found ($P > 0.05$) in 2010, although mean ADB increment under T_{75} was 24% greater than that under CK.

Discussion and conclusions

Effects of SWP irrigation threshold on transpiration

As soil water availability was markedly improved by SDI (Fig. 1), the *E* of *P. tomentosa* plantations under the SWP treatments was significantly ($P < 0.05$) increased by 20–73% (Fig. 4) in 2010. Similar positive effects of irrigation on poplar transpiration were also observed in other research (Liu *et al.* 1988; Samuelson *et al.* 2007).

SWP irrigation threshold had significant impact on the water use of *P. tomentosa* ($P < 0.001$). In 2010, as the SWP irrigation threshold decreased from −25 to −50 kPa, the *E* of *P. tomentosa* decreased significantly by 31% ($P < 0.05$). However, there was only a slight difference ($P = 0.358$) as the irrigation threshold decreased from −50 to −75 kPa. This was consistent with the results obtained by Kang and Wan (2005), Wang *et al.* (2007) and Liu *et al.* (2012) where plant evapotranspiration always decreased greatly as SWP declined towards a critical value, while below this SWP value it showed little change. It can be

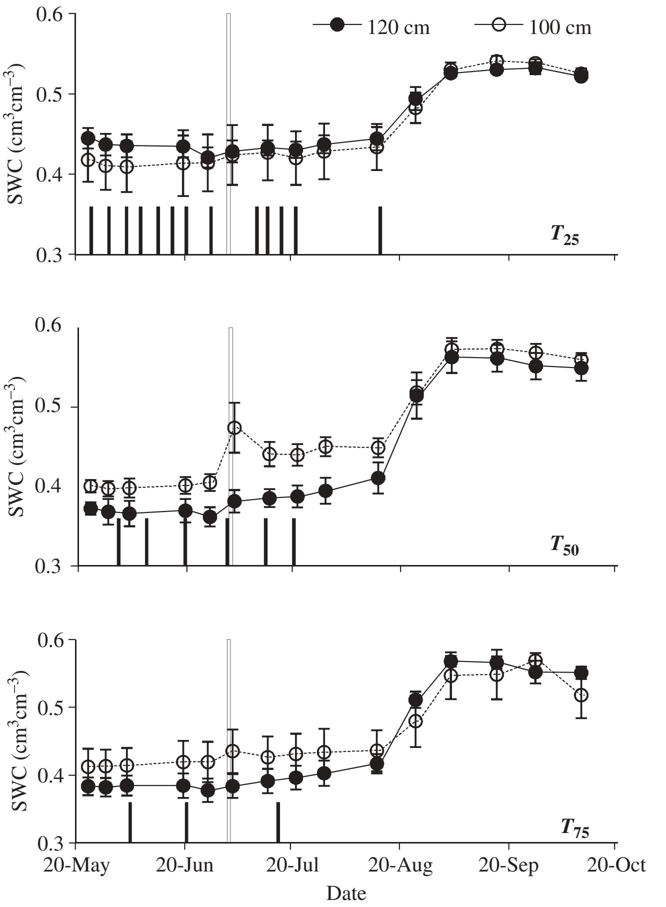

Figure 2. Soil water content (SWC) dynamics at 100 and 120 cm depths under different SWP treatments in 2011. The short solid bars represent irrigation events and the long bar indicates a rainfall of 83 mm

concluded that, in regions with similar soil to our experimental site, decreasing SWP irrigation threshold from −25 to −50 kPa could significantly reduce the E of *P. tomentosa* plantations, but decreasing the threshold from −50 to −75 kPa might not further reduce E.

Effects of SWP irrigation threshold on tree growth

Drip irrigation has been demonstrated to be effective in increasing the growth of poplar trees in most cases (Hansen 1988; Dickmann *et al.* 1996; Jia *et al.* 2004; Coyle and Coleman 2005; Shi *et al.* 2011). Consistent with these studies, our results (Table 2) showed that SDI markedly increased the ADB increment of *P. tomentosa* plantations in both years, although the superiority of some SWP treatments to CK was not statistically significant. The higher growth rate of trees under SDI corresponded to their higher transpiration (Fig. 4), which could greatly improve the leaf photosynthesis (Le Maitre and Versfeld 1997; Samuelson *et al.* 2007). One important reason that SDI greatly increased the yield of *P. tomentosa* plantations is that the first part (from April to mid-July) of the growing season was associated with a period when ET_o was much higher than precipitation (Table 1). Note that about one-half of the precipitation in July fell around the end of this month (Fig. 1d). That is to say, for most of July, the climate was still dry. SDI decreased the water stress experienced by *P. tomentosa*, subsequently allowing it to express its yield potential. Another important reason is that the higher surface soil water availability in SDI treatments (Fig. 1) might result in higher soil nutrient uptake. This is because the surface 20 cm soil layer in our experimental site had the highest nutrient content and was the main zone of fine root distribution and water uptake in the 0–90 cm soil layer (Xi *et al.* 2013).

For many plant species under drip irrigation, there exists a specific SWP irrigation threshold range within which the plant yield varies little, but when the SWP is lower than this range the yield will decrease significantly. For example, the yield of a hybrid poplar (Hansen 1988), sweet corn (*Zea mays* L.) (Rivera-Hernández *et al.* 2010), *Leymus chinensis* (Liu *et al.* 2011) and chili pepper (*Capsicum annuum* L.) (Liu *et al.* 2012) varied insignificantly when the SWP irrigation threshold ranged from −30 to −70 kPa, −5 to −30 kPa, −5 to −10 kPa and −10 to −40 kPa, respectively, whereas as the thresholds declined beyond these ranges their yield could decrease significantly. Our results indicated that, as the SWP irrigation threshold varied between −25 and −75 kPa, the yield of mature *P. tomentosa* plantations under SDI would not change significantly, although there were apparent or significant differences in soil water availability, irrigation amount and E among the SWP treatments.

The insensitive growth response of the experimental *P. tomentosa* plantations to SWP irrigation threshold may be attributed to differences in water use efficiency (WUE) and irrigation water use efficiency (IWUE) between the SWP treatments.

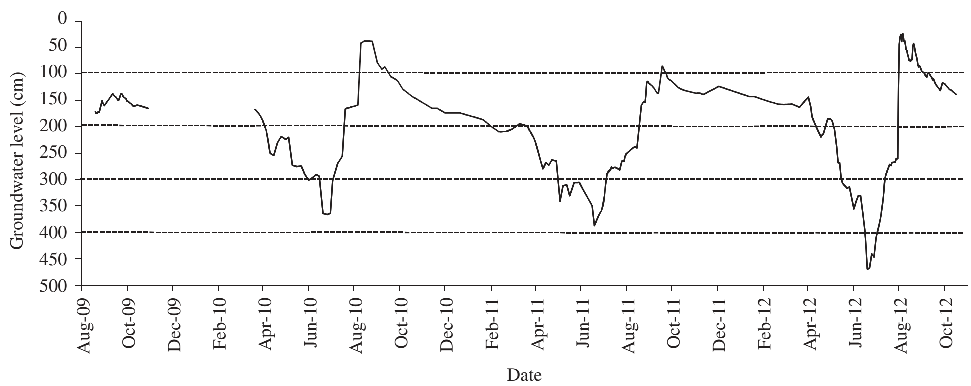

Figure 3. Dynamics of groundwater level from August 2009 to October 2012. Dashed lines indicate the depth of 100, 200, 300 and 400 cm

Table 1. Monthly precipitation and reference crop potential evapotranspiration (ET_0) in the experiment site from April to October 2008–2011

		Month						
Attribute	Year	4	5	6	7	8	9	10
ET_0 (mm)	2008		139	115	98	92	81	64
	2009	97	131	144	95	82	64	75
	2010	80	111	114	101	70	61	59
	2011	96	105	116	97	72	51	47
	Mean	91	121	122	98	79	64	61
Precipitation (mm)	2008		25	40	145	44	43	22
	2009	5	78	134	180	122	88	0
	2010	15	11	83	187	438	36	9
	2011	18	42	72	160	89[a]	90	16
	Mean	13	39	82	168	202[b]	64	12

[a]Due to equipment failure, a large amount of precipitation was not recorded
[b]Calculated using only the data of 2008–2010

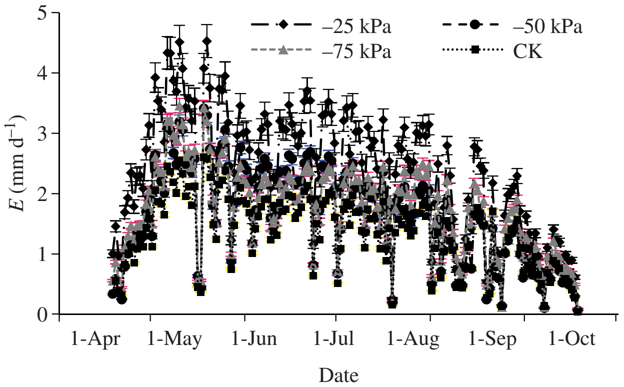

Figure 4. Mean daily transpiration of *Populus tomentosa* on a ground area basis (E) under different treatments in 2010

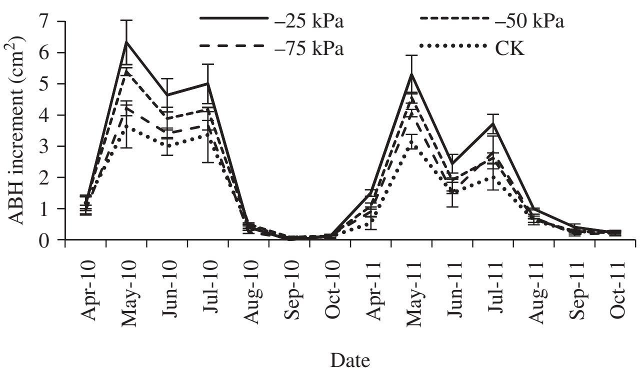

Figure 5. Monthly basal area at breast height (ABH) increments of *P. tomentosa* under different treatments in 2010 and 2011. Data are means of randomly selected trees within each treatment

According to the results of Kang and Wan (2005), Wang *et al.* (2007) and Liu *et al.* (2012), the WUE and IWUE of *P. tomentosa* plantations might increase as the SWP irrigation threshold decreased. This could subsequently mean that the ADB increment was similar in the higher and lower irrigation threshold treatments, although the E and/or irrigation amount was lower in the latter treatment.

Table 2. Adjusted mean increments of above-ground dry biomass (ADB) per hectare in different treatments in 2010 and 2011

	ADB increment[a] (mg ha^{-1})	
Treatment	2010	2011
T_{25}	17.5(1.2) a	14.3(1.2) ab
T_{50}	15.3(1.2) a	14.5(1.1) ab
T_{75}	14.1(1.2) ab	14.8(1.1) a
CK	11.4(1.2) b	11.2(1.1) b

Data are means (standard error). Different lower-case letters within the same column in the same year indicate significant difference at $P < 0.05$ according to LSD test

In 2010, both the T_{25} and T_{50} treatments had significantly higher mean ADB increment than CK, but relative to T_{25} the irrigation amount was lower and the E was significantly reduced in T_{50}. In contrast, in 2011, only the T_{75} treatments with the least irrigation had significant advantage in mean ADB increment relative to CK. Therefore, a range of −50 to −75 kPa is recommended as the threshold for initiating SDI in *P. tomentosa* plantations in the North China Plain.

Overall, based on the positive effect on tree growth, SDI could be promoted in the cultivation of *P. tomentosa* plantations in the North China Plain, especially considering it did not cause deep percolation (Fig. 2).

Irrigation management strategies

The main water use stage of *P. tomentosa* was from April to July (Fig. 4), during which period the cumulative E accounted for 81% of the whole growing season water use on average. This was consistent with the cumulative ABH growth in this period, which accounted for 93% (mean of four treatments and averaged over two years) of its total growing season value. These results indicate that April–July is the key water requirement period of *P. tomentosa*. However, from April to July in our study site, the cumulative ET_0 was 43% higher than the rainfall (Table 2), indicating that during this period the rain water was not enough to meet the evapotranspiration of *P. tomentosa* plantations. Consequently, we concluded that irrigation should be implemented from April to July when planting *P. tomentosa* at sites with similar characteristics to ours in the North China Plain.

From August to October every year, due to the relatively high groundwater level (Fig. 3) (reaching about 125 cm depth (mean of 2009–2012) on average) and the heavy rainfall (156% higher than ET_0 in August (Fig. 1d, Table 2)), a large part of the root zone in our plantation was excessively moist (rooting depth of fine roots was about 180 cm (Xi *et al.* 2013)), which is indicated by the variation of SWP (Fig. 1a–c) and SWC (Fig. 2). It is a reasonable assumption that as the low oxygen concentration within the excessively moist root zone might inhibit the root water uptake of *P. tomentosa* (Feddes *et al.* 1978), *E* therefore decreased sharply and the tree growth of *P. tomentosa* almost stopped in August and September (Figs. 4 and 5) when the climate was still very warm. However, as indicated by the seasonal tree growth pattern of a *P. tomentosa* plantation located about 80 km west from our experimental site (Sun *et al.* 2012), the growth of our experimental plantations should not stop in August and September if the soil was not excessively moist. It seems likely that drainage should be applied from August to October when planting *P. tomentosa* at sites with similar characteristics to ours in the North China Plain.

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