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Evaluation of the cumulative effect of drip irrigation and fertigation on productivity in a poplar plantation

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Abstract

• ***Key message*** **Combined drip irrigation and fertigation significantly increased stem volume and biomass production in a poplar plantation, and showed a cumulative effect over years. The promoting effects were mainly attributable to increased nitrogen and water availability in the surface soil through the combined management.**

• ***Context*** Fast-growing and high-yielding poplar plantations have been identified as major commercial forests in China. Intensive management of irrigation and fertilization can greatly increase productivity of plantations. Quantitative investigations on the cumulative effect of drip irrigation and fertigation over years are quite infrequent.

• ***Aims*** We aimed to quantitatively evaluate the effects of drip irrigation and fertigation plans on tree growth and productivity in a poplar plantation, and to analyze their possible cumulative promoting effect over multiple years.

• ***Methods*** Treatments including nine drip irrigation and fertigation combinations, and single furrow irrigation in spring as control, were conducted in a poplar plantation for three successive years. The combined treatments consist of three irrigation levels (WP_{-75}, WP_{-50}, and WP_{-25}, in ascending order) and three levels of nitrogen addition (N_{60}, N_{120}, and N_{180}, in ascending order). Soil nitrogen and water content were measured throughout the 3 years. Based on tree surveys, tree growth, volume, and biomass production were evaluated each year.

• ***Results*** Nitrogen and water availability in the surface soil increased in the drip irrigation- and fertigation-treated plots. Drip irrigation and fertigation treatments resulted in significant higher growth, stem volume, and biomass productions compared to control. Biomass increments in drip irrigation- and fertigation-treated plots were 4.8–50.0, 5.3–26.5, and 4.3–52.2% higher than control in the three experimental years, respectively, with $WP_{-25}N_{180}$ and $WP_{-50}N_{180}$ recording the highest increments. Fertigation showed cumulative effects over multiple years and the positive effects increased with the dosage. However, irrigation showed little cumulative effect and the greatest effect was obtained under medium level.

• ***Conclusion*** Combined drip irrigation and fertigation greatly promoted the plantation productivity. The combined management effect varied with application plans and plantation ages, and showed a cumulative effect over years.

Keywords Drip irrigation · Fertigation · Nitrogen addition · Biomass equations · Productivity in forest plantations · *Populus* × *euramericana* "Guariento"

1 Introduction

Globally, water and nutrients have been accepted as fundamental factors for plant growth that act complementarily to and interactively with each other and are thus widely applied in intensive agriculture, horticulture, agroforestry, and even plantation forestry (Morgan 1984; Stanturf et al. 2001; Rajput and Patel 2006; Li and Liu 2010). Increases in production in intensively managed forests have been obtained by improving resource availability by amending the available water and nutrients (Coyle and Coleman 2005). However, it is difficult to isolate the effects of water and nitrogen availabilities. Water deficit limits nitrogen uptake

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whereas over-supplement of water may cause nutrient losses through leaching. On the other hand, addition of nitrogen is assumed to be able to mitigate the negative effects of water deficit by improving foliar nitrogen concentration and photosynthesis, root growth and absorption, water use efficiency, etc. (Alsafar and Al-hassan 2009; Shirazi et al. 2014). Over-application of water and fertilizers would not only result in an increased cost but also cause reduction of water and fertilizer use efficiency and increased risk of nitrate pollution (Kowalenko and Bittman 2000; Sylvester-Bradley et al. 2012). Evaluation of application regimes of water and fertilizer is thus important for improving productivity and resource use efficiency, and reducing the risk of environmental pollution and the waste of water resources.

At present, the combined management of irrigation and fertilization has been widely applied to the cultivation of crops and fruit orchards around the world. Many studies have suggested that such an approach can ensure that the supplies of water and fertilizer are synchronized (Morgan 1984; Li and Liu 2010), thus significantly increasing the yield of crops and fruiters, and improving the water and nutrients use efficiency while achieving sustainable use of water and nitrogen (Yohannes and Tadesse 1998; Shirazi et al. 2014). The interactive effects of water and nitrogen availabilities on crop and fruiter productivity have been well documented (Rajput and Patel 2006; Yang et al. 2015). In contrast, few studies have examined the interactive effects of water and nitrogen availabilities on tree growth and productivity in plantations (but see Ibrahim et al. 1998; Coleman et al. 2004; Dong et al. 2011). Thus far, studies on tree species in response to combined water and nitrogen management have been reported more for specimens grown in pots rather than in the field. Further, these studies are mostly coupled with conventional irrigation and fertilization techniques. Field experiments and high-efficiency irrigation and fertilization techniques are needed to expand our limited understanding of the effects of water and nitrogen on tree growth and biomass production in forest plantations.

Poplar is one of the most promising short-rotation species used in forest plantations (Perry et al. 2001; Dickmann 2006). Vigorously developing fast-growing and high-yielding poplar plantations have been identified as the main solution to the shortage in the domestic supply of wood fiber in China (Wang et al. 2015; Yan et al. 2015b). In China, there exists 10.1 million ha of poplars, the largest area in the world (Yan et al. 2016). However, the productivity under the existing silvicultural practices is far less than its potential productivity and is lower than the international medium level productivity, which can be mainly attributed to use of inefficient silvicultural practices such as irrigation and fertilization management (Xi et al. 2013; Yan et al. 2016). Therefore, additional research is needed to enhance productivity of poplar plantations through improving the irrigation and fertilization management.

As poplar has higher nutrient requirements than most plantation tree species (Rennenberg et al. 2010; Wang et al. 2015), addition of nitrogen has been used as a critical silvicultural practice in poplar plantations (Stanturf et al. 2001; Coleman et al. 2004). Given that fertilizer application in crops has been substantially increasing in common cropping systems in the region (> 500 kg N ha^{-1} year^{-1}) (Zhu et al. 2005; Dai et al. 2006), an economical, highly efficient management system with relatively lower nitrogen addition is expected for the plantation forests. Fertilizer-savings and high-efficiency techniques such as fertigation have been increasingly applied to the cultivation of plantations around the world (Stanturf et al. 2001; O'Neill et al. 2014). Especially, drip fertigation has the advantages of supplying nitrogen fertilizer directly to the root zone, increasing nitrogen use efficiency, and reducing the amount of fertilizers at the soil surface relative to conventional fertilization techniques (Tarkalson et al. 2009). In addition, in the North China Plain, where the climate is always very dry in spring and early summer, irrigation has been the most basic management practice for the poplar plantations (Xi et al. 2014). Moreover, the sandy soil in this region shows a substantial demand for irrigation. However, water-savings and high-efficiency irrigation techniques, such as drip irrigation, which is increasingly applied around the world (Hansen 1988; Dickmann et al. 1996; Ceulemans and Deraedt 1999; O'Neill et al. 2014), are not well tested in the plantations in this region. Although previous studies have shown that proper management using either drip irrigation or fertigation may significantly affect the growth and physiology of polar plantations (Xi et al. 2014; Wang et al. 2015), the cumulative effect of drip irrigation and fertigation on tree growth and biomass production remains to be studied. Quantitative studies are urgently needed on the proper management of drip irrigation and fertigation to maximize resources use efficiency and productivity for the poplar plantations in China.

Hence, we conducted a 3-year field experiment on the effects of drip irrigation and fertilization on a hybrid poplar plantation, cultivated on sandy soils in the North China Plain. This study was undertaken to achieve two objectives: (1) to quantitatively evaluate the effects of different management plans that used various levels of irrigation and fertilization on tree growth, stem volume, and biomass production and (2) to analyze the effect of drip irrigation and fertigation to make recommendations in relation to their cumulative promoting effect over multiple years.

2 Materials and methods

2.1 Site description

The experiment was conducted at a research field in Shunyi District, the northern suburb of Beijing, China (40° 05′ 48.7″ N and 116° 49′ 35.6″ W; 28 m above sea level). The study site is characterized by a warm temperate continental climate with annual mean temperature of 11.5 °C and average frost-free period of about 195 days. The precipitation was 644, 573, and 457 mm in the growing season of 2012, 2013, and 2014, respectively, of which 7–15% occurred between March and May (40–94 mm), 57–78% occurred between July and August (260–448 mm), and 15–31% occurred between September and October (88–141 mm). The soil is a sandy loam and the deep soil is mainly composed of silt loam having many meters with an underground water level of about −12 m. Soil physical properties are given in Table 1.

2.2 Plant material

A 4-ha poplar clonal (*Populus* × *euramericana* "Guariento") plantation was established in the spring of 2011 with 3-year-old seedlings. The *Populus* × *euramericana* "Guariento" a hybrid between the American black poplar (*P. deltoides* cl. "8/67") and the European black poplar (*Populus nigra*) was used. The species has many advantages including a straight trunk, gradually tapering, narrow canopy, excellent texture, fast-growing, and high-yielding. The growing season is from March to October with leaf shedding in November in the north of China. The seedlings were planted using an alternate wide (12 m) and narrow (6 m) row spacing scheme, the intra-row spacing was 4 m and planting density was 400 trees ha^{-1}. The drip irrigation pipe was laid along each tree row at the beginning of 2012, and it roughly supplied water flow at a rate of 2 L h^{-1} during operation.

2.3 Experimental design

The plantation was divided into 30 equivalent blocks (0.13 ha each). The field experiment included ten management plans that were arranged in a randomized block design with three replicates per management plan. The description of the plans, each receiving a different water and nutrient supply regime, is given in Table 2. Nine treatments were combinations of three surface drip irrigation treatments and three fertigation treatments applied in the growing seasons. Urea (60, 120, and 180 kg N ha^{-1} $year^{-1}$, denoted as N_{60}, N_{120}, and N_{180}, respectively) was dissolved in water, and the fertilizer application was split across six times each year. The surface drip irrigation treatments were conducted when soil water potentials (SWP) at 20-cm soil depth under the drip emitter reached −75, −50, and −25 kPa (denoted as WP_{-75}, WP_{-50}, and WP_{-25}, respectively). This setting was determined by referring to previous studies of our research team on the irrigation threshold for scheduling drip irrigation in poplar plantations (Xi et al. 2014). For each treatment, nine tensiometers were installed to monitor SWP, with ceramic cups at 20 cm depth under the drip emitter. The tensiometer data were read every day at about 7 a.m. from April to October over the 3 years. The tenth plan was the control, representing the conventional management followed in this region, i.e., trees were neither drip-irrigated nor fertilized. On April 1 each year, the beginning of the growing season, furrow irrigation was applied to both the control and treatments to promote leaf expansion.

The amount of irrigation to be applied was determined by referring to the estimated irrigation hours (h), which was calculated using the following formula (Allen et al. 1999):

$$h = \left[V \times \left(SWC_{after} – SWC_{before}\right)\right] / V_{water\ flow} \quad (1)$$

$$V = 1/3 \times 3.14 \times R^2 \times H \quad (2)$$

where SWC_{after} is the soil moisture content after irrigation (designed as 75% field capacity), SWC_{before} is the soil water content before irrigation, $V_{\mathrm{water\ flow}}$ is water flow (2 L h^{-1} in this study), V is the volume of wetting, R is the radius of wetting (50 cm in this study), and H is the depth of wetting (50 cm in this study). The actual irrigation amount was determined by reading the flow meter each time.

2.4 Measurements

2.4.1 Tree diameter and height growth

A survey covering every tree in the experimental field was conducted at the beginning of the experiment (March 2012) and at the end of each growing season. All the trees were marked on the stem at breast height (1.3 m) with a paint marker before the experiment. Diameter at breast height (DBH, cm) and height (H, m) of each tree were measured. These data were then used to determine the annual increment in the stand basal area (BA, m^2 ha^{-1}), stem volume (SV, m^3 ha^{-1}), and biomass production (kg ha^{-1}).

Table 1 Physical properties of soil at the study sites

Depth cm	Particle size distribution			Bulk density g cm^{-3}	Field capacity mm	Soil texture (USDA classification)
	Sand %	Silt %	Clay %			
0–20	79.9	29.5	0.52	1.68	25.4	Sandy
20–40	67.2	32.3	0.53	1.64	29.1	Sandy loam
40–60	63.5	35.9	0.56	1.62	31.8	Sandy loam
60–120	46.6	52.8	0.62	1.60	100.2	Slit loam

Table 2 Experimental design and implementation overview in study sites

Treatment	Irrigation when the *SWP* at 20-cm depth (kPa)	Fertilize amount (kg ha^{-1} $year^{-1}$ N)	Irrigation amount (m^3 ha^{-1} $year^{-1}$)			Irrigation times (times $year^{-1}$)		
			2012	2013	2014	2012	2013	2014
$WP_{-75}N_{60}$	−75	60	3981	4297	3865	7	10	10
$WP_{-75}N_{120}$	−75	120	4102	4374	3949	7	10	10
$WP_{-75}N_{180}$	−75	180	4188	4492	4036	7	10	10
$WP_{-50}N_{60}$	−50	60	4512	4864	4393	12	15	17
$WP_{-50}N_{120}$	−50	120	4597	4923	4437	12	15	17
$WP_{-50}N_{180}$	−50	180	4633	5077	4511	12	15	17
$WP_{-25}N_{60}$	−25	60	5025	5489	4899	19	24	23
$WP_{-25}N_{120}$	−25	120	5088	5592	4975	19	24	23
$WP_{-25}N_{180}$	−25	180	5104	5683	5082	19	24	23
Control	Non-irrigation	0	3544	3898	3636	1	1	1

SWP is soil water potential. The six N application times were May 5, June 1, June 21, July 8, August 2, and August 29 in 2012; April 28, May 20, June 13, June 30, July 26, and August 17 in 2013; and April 21, May 12, June 7, July 7, August 2, and August 28 in 2014

2.4.2 Stem volume

Stem volume of each tree was calculated based on the annual survey using the average experimental form factor method (Lynch and Schumacher 1941) as follows:

$$SV = g_{1.3} \times (H + 3) \times f \qquad (3)$$

where SV is stem volume of an individual tree, $g_{1.3}$ is cross area at breast height, H is tree height, and f is the experimental form factor.

The experimental form factor estimate for this study was determined by comparing several approaches of stem volume calculation based on destructive sampling of average tree stems in 2012 and 2013, and a form factor of 0.041 was obtained from the Newton Approximation method as the relatively accurate one for this plantation (Yan. 2016).

2.4.3 Tree biomass

Based on tree inventories at the beginning of the experiment and after each growing season in the subsequent years, an average tree from each management plan was harvested for destructive biomass sampling. A total of 40 trees were harvested throughout the experiment. The sampled trees were separated into leaves, branches, trunk, and roots. Fresh mass of all tissues was weighed in the field, and representative subsamples were taken to the laboratory to determine their water content. The tissues were oven-dried to constant weight at 65 °C for dry mass determination. Generalized allometric equations of tree components (stem, branches, leaves, roots) were established for the experimental poplar plantation as functions of DBH and height (Table 3). These equations were used for estimating the biomass of tree components after each survey.

2.4.4 Soil nitrogen and soil water content

Field surveys for soil nutrients were conducted at the beginning of the experiment (March 2012) and at the end of each growing season. Six trees with average size were selected from tree belts of every treatment in the middle of the plantation for location determination of soil sampling. Soil sample cores were taken 1 m apart from each selected tree and directly below the drip emitter. The cores were sampled in 0–60 cm of the soil at 20-cm intervals (i.e., 0–20, 20–40, and 40–60 cm) at each location. N concentration was analyzed using the Kjeldahl method.

Time domain reflectometry (TDR) was used for determination of soil water content (SWC, m^3 m^{-3}). Three TDR tube probes were installed in each treatment and control plot under the drip emitters. Measurements of soil water content were taken at 20-cm intervals from the soil surface to a depth of 100 cm. The measurements were made within time intervals of less than 15 days from April to October over the 3-year treatments.

Table 3 Allometric equations for estimation of tree components biomass from DBH and H measurements for the experimental poplar trees

Tree component	Allometric equation	R^2	*P*
Leaf	$B = 0.1117\ (D^2H)^{0.5342}$	0.91	< 0.0001
Branch	$B = 0.0047\ (D^2H)^{0.9895}$	0.96	< 0.0001
Trunk	$B = 0.0622\ (D^2H)^{0.8143}$	0.95	< 0.0001
Root	$B = 0.0180\ (D^2H)^{0.8242}$	0.97	< 0.0001

B biomass, *D* diameter at breast height, *H* height

2.5 Data analysis

The stem volume in the plantation (m^3 ha^{-1}) was obtained by dividing the sum of the total volume in the block with the block area. Individual tree biomass (kg tree^{-1}) was calculated as the sum of dry weights of the four components namely, leaf, branch, trunk, and roots, and the biomass production in each treatment block (kg ha^{-1}) was obtained by dividing the sum of biomass for all trees in the block with the block area.

ANOVA was used to examine the treatment effects on the increment in BA, H, SV, and biomass in each year of the experiment. The significant differences among treatments were checked using the Tukey test. Significance was set at the $p =$ 0.05 level. SPSS software package was used for statistical analysis. The relationships between cumulative stem volume and biomass increase excess of control and cumulative nitrogen addition and cumulative irrigation amount were analyzed by a regression method for mean values using SigmaPlot 12.5.

3 Results

3.1 Variations of soil nitrogen and water contents throughout the experimental period

At the beginning of the experiment (March 2012), the average total nitrogen (N) ranged 0.54–0.93 g kg^{-1} in the 0–60-cm soil layers. There was no significant difference in total N concentration among the plots of drip irrigation and fertigation management and control (Fig. 1a). After 3 years of the experiment, total N concentrations in the 0–20- and 20–40-cm soil layers were significantly higher in the drip irrigation- and fertigation-

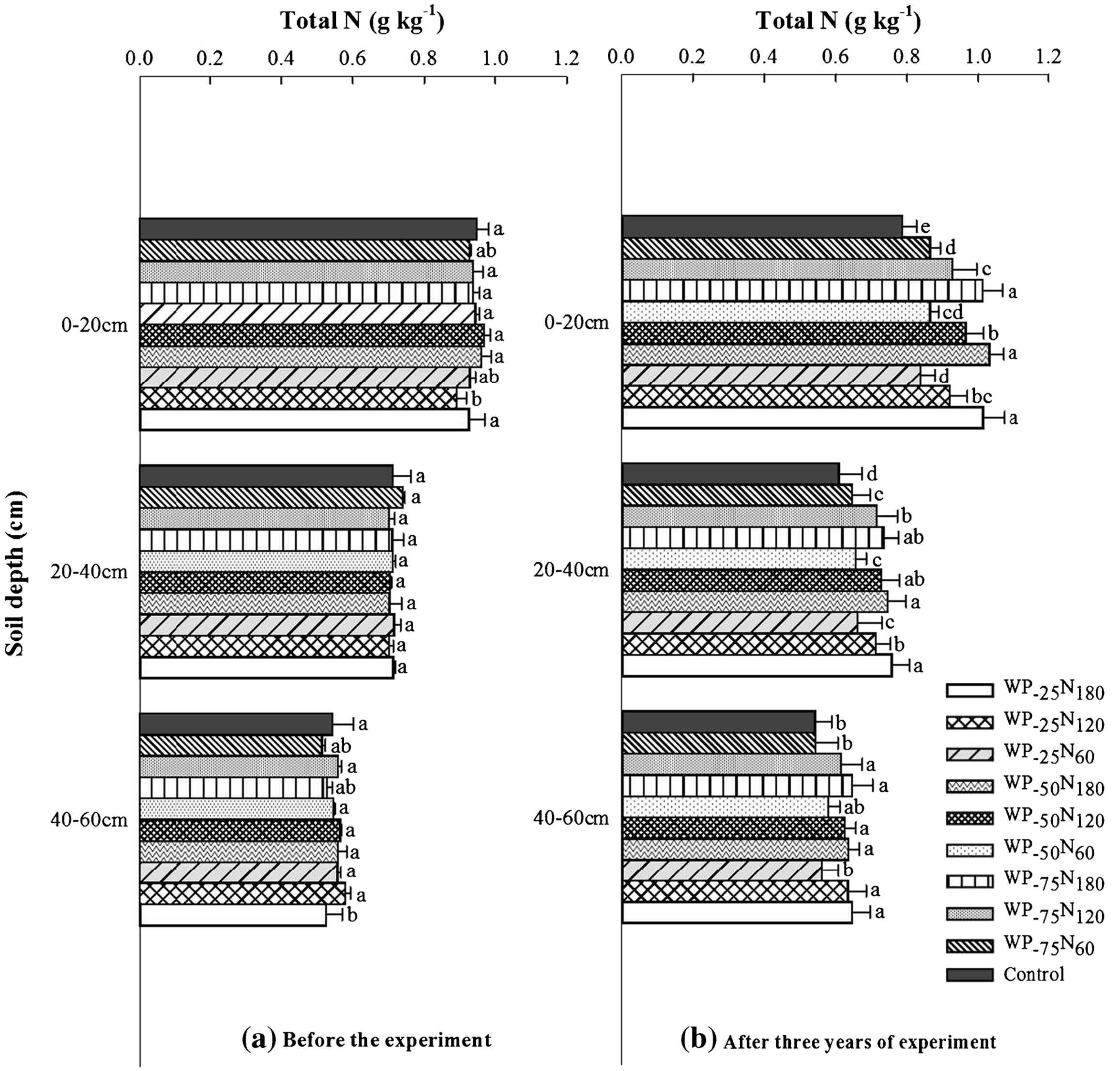

Fig. 1 Multiple comparisons for total N in the 0–60-cm soil layers among management before the experiment (**a**) and after 3 years of experiment (**b**). Values are expressed as means and standard deviations. Different alphabets within the same soil layer indicate significant difference at $p < 0.05$ according to the Tukey test. For abbreviations, see Table 2

treated plots than control plot, especially for the high level of N dose. They were about 10.0–31.3 and 6.1–24.3% higher for the drip irrigation- and fertigation-treated soils than for control ($p < 0.05$), but the difference was not significant for the 40–60-cm soil layer (Fig. 1b).

Overall, during the experiments from 2012 through 2014, the soil water content (SWC) within 20-cm soil depth was highly influenced by drip irrigation and fertigation management (Fig. 2). During the periods of April–June and September–November, the soil water content dynamics varied among the treatments. With increasing level of irrigation, soil water content varied with a higher frequency but with smaller amplitude. Due to ample rainfall from July to September every year, the average soil water content was much higher than that in other periods under all treatments. In the three growing seasons, the average soil water content under all irrigation treatments were much higher than that in control, with the average soil water content under the three levels of drip irrigation being 61–69, 50–56, and 27–55% higher than control, respectively. This indicates that a higher level of drip irrigation resulted in greater surface soil water availability.

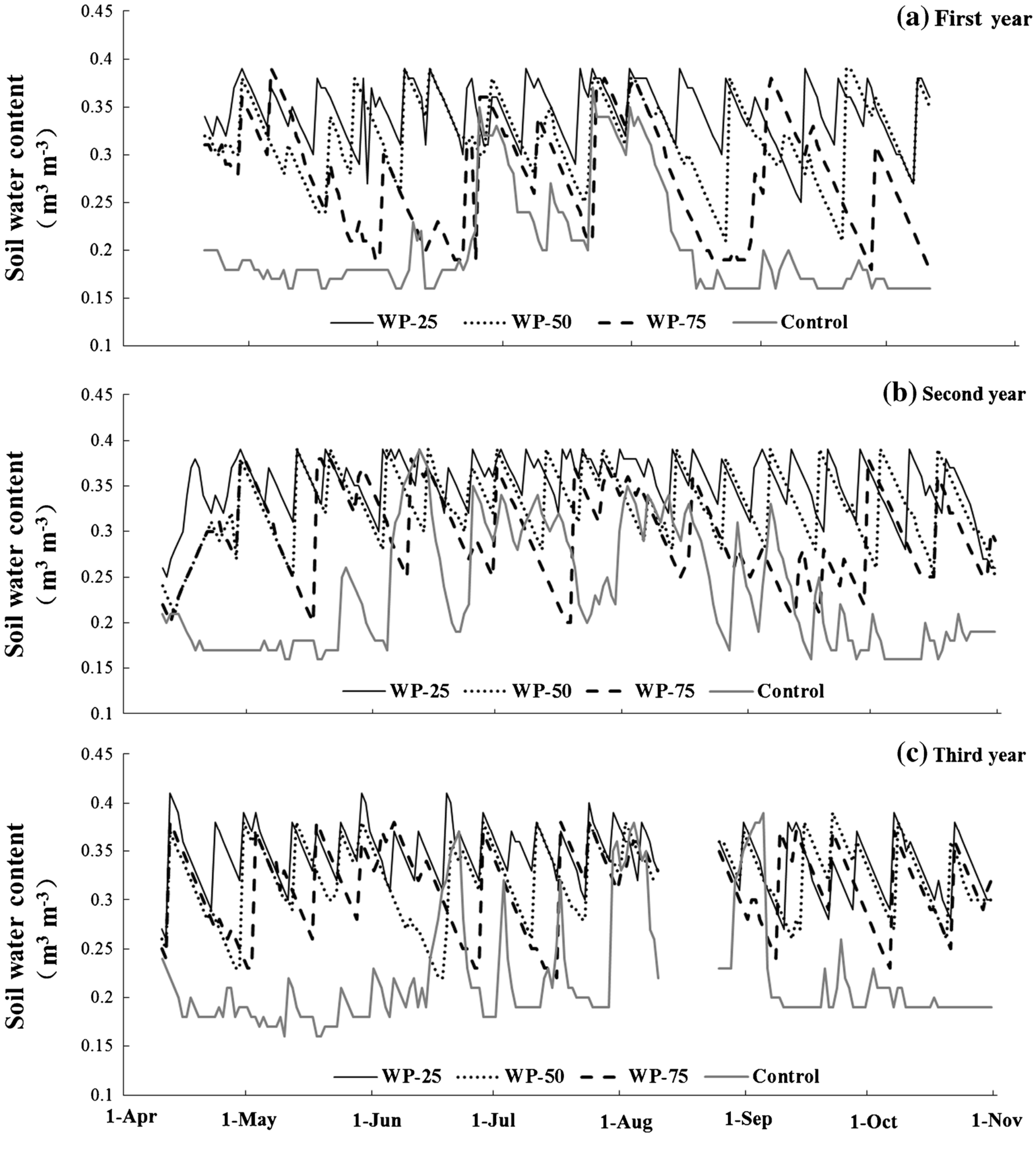

Fig. 2 **a–c** Soil water content at 20-cm depth in different irrigation plans during the growing seasons of the 3 years

3.2 Tree growth and stem volume increment in response to drip irrigation and fertigation management

The growth rate as expressed by the increments in basal area (BA), height (H), and stem volume (SV) indices showed variations throughout the 3 years (Fig. 3). Maximum growth was recorded in the second experimental year (age 5), while the ranking for the other 2 years varied with indices. Increase in H was relatively quicker in the first experimental year (age 4), whereas diameter and volume increments were greater in the third experimental year (age 6). Furthermore, in either of the 3 years, the increments of BA, H, and SV showed differences among the management plans, though it was not always statistically significant between any two treatments. Overall, all the drip irrigation and fertigation treatments showed higher increments than control, and the three indices showed similar trends in the difference among treatments.

In the first year, the treatment $WP_{-25}N_{180}$ yielded the highest increments in BA, H, and SV. The increment in stem volume was 11.5 m^3 ha^{-1} $year^{-1}$ and 8.01 m^3 ha^{-1} $year^{-1}$ for the $WP_{-25}N_{180}$-treated trees and control, respectively. The BA, H, and SV increments in the $WP_{-25}N_{180}$-treated trees was about 28, 58, and 44% higher than control, respectively ($p < 0.05$) (Fig. 3). In the latter 2 years, $WP_{-50}N_{180}$ showed the highest increments in the indices, with $WP_{-25}N_{180}$ ranking the second and not significantly different from $WP_{-50}N_{180}$. The increment in stem volume in the second year was 27.6 m^3 ha^{-1} $year^{-1}$ and 20.5 m^3 ha^{-1} $year^{-1}$ for the $WP_{-50}N_{180}$-treated trees and control, respectively. For the $WP_{-50}N_{180}$-treated trees, the increments in BA, H, and SV was about 18, 27, and 36% higher than those of control in the second year, respectively ($p < 0.05$) (Fig. 3). In the third year, the increments in stem volume was 26.0 m^3 ha^{-1} $year^{-1}$ and 16.6 m^3 ha^{-1} $year^{-1}$ for the $WP_{-50}N_{180}$-treated trees and control, respectively. For the $WP_{-50}N_{180}$-treated trees, the increments in BA, H, and SV was about 28, 44, and 57% higher than those of control, respectively ($p < 0.05$) (Fig. 3).

The significance levels were analyzed for the effects of drip irrigation, fertigation, and their interactions in the 3 years (Table 4). The incremental effect on diameter was statistically significant in almost all tests in the 3 years ($p < 0.001$ or

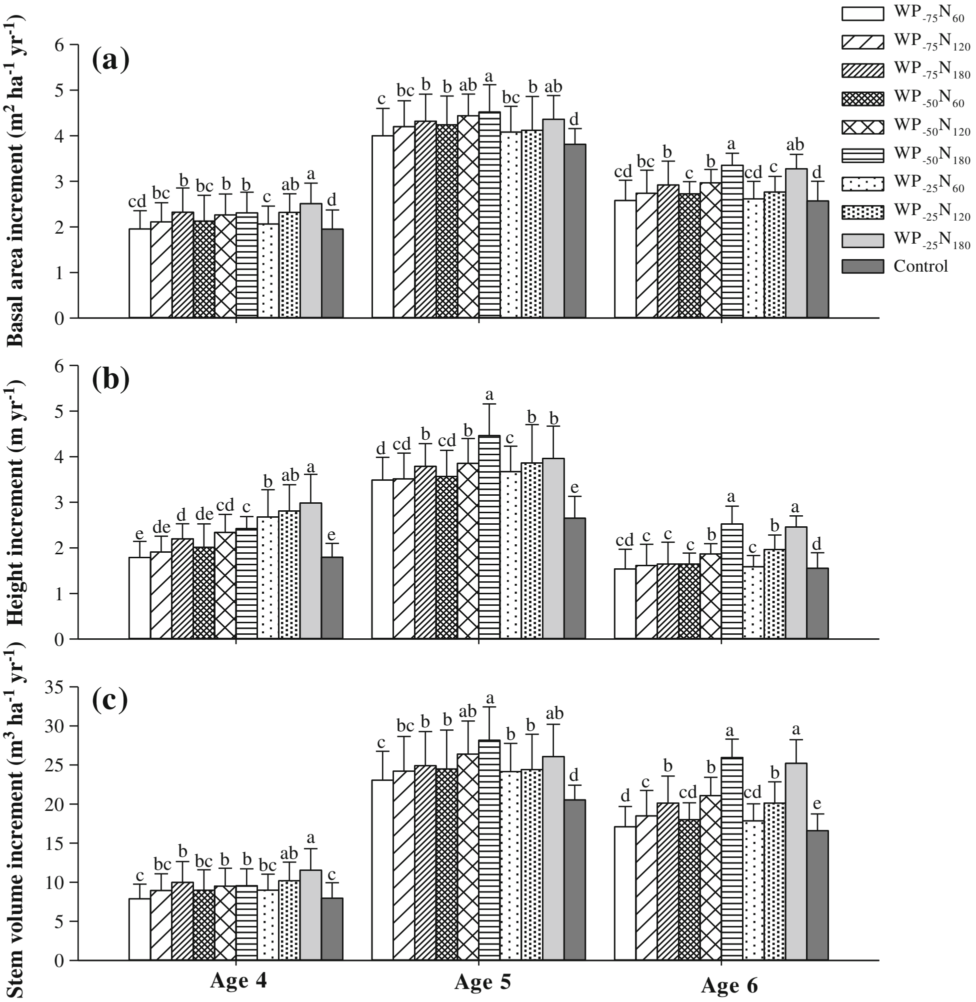

Fig. 3 Multiple comparisons for increments in BA (I_{BA}, **a**), height increment (I_H, **b**), and stem volume increment (I_{SV}, **c**) of the plantation among management regimes by age. Values are expressed as means and standard deviations. Different alphabets within the same age indicate significant difference at $p < 0.05$ according to the Tukey test. For abbreviations, see Table 2

Table 4 The *P* values and significance level of the main effects of irrigation and fertilizer and their interactions on BA increment (I_{BA}), height increment (I_H), and stem volume increment (I_{SV}) for the poplar plantation at age 4, 5, and 6 years

Year/age	Source of variation	*P* value and significance level		
		I_{BA} (m^2 ha^{-1} $year^{-1}$)	I_H (m $year^{-1}$)	I_{SV} (m^3 ha^{-1} $year^{-1}$)
First year/age 4	Irrigation	< 0.001***	< 0.001***	0.007**
	Fertilizer	< 0.001***	0.202 NS	0.055*
	Irrigation × Fertilizer	< 0.001***	0.088 NS	0.002**
Second year/age 5	Irrigation	< 0.001***	0.029*	0.069 NS
	Fertilizer	0.921 NS	0.018**	< 0.001***
	Irrigation × Fertilizer	0.002**	< 0.001***	0.201 NS
Third year/age 6	Irrigation	< 0.001***	0.054 NS	0.013*
	Fertilizer	< 0.001***	< 0.001***	< 0.001***
	Irrigation × Fertilizer	0.003**	< 0.001***	< 0.001***

Significance of analysis of variance factor: NS, not significant; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

$p < 0.01$). The effects on height and stem volume showed some variations across the 3 years. Irrigation tended to affect rapidly and significantly in the first year, but was less significant in later years. On the other hand, fertigation showed obvious cumulative effects and the significance levels increased in the second and third years.

Table 5 presents the ratio of DBH/H throughout the experimental period. There was no obvious positive or negative effect of irrigation and fertigation amounts on DBH/H. However, compared with control, drip irrigation and fertigation treatments showed lower DBH/H, suggesting greater incremental effect on height than diameter.

3.3 Biomass production in response to drip irrigation and fertigation management

The annual biomass production in each of the management blocks in the 3 years was calculated for all components of every tree based on biomass equations (Fig. 4). Similar to the results for stem volume increments, all the drip irrigation and fertigation treatments yielded higher biomass production than control. In the first year of the experimental, compared with a biomass increment of 7045.7 kg ha^{-1} $year^{-1}$ for control, increments of 7385.4–10,571.7 kg ha^{-1} $year^{-1}$ were obtained for the drip irrigation and fertigation treatments, which were 4.8–50.0% higher than for control. Likewise, in the second and third years, the biomass increments under treatments were 5.6–26.5 and 4.3–52.2% higher than control, respectively. Among the nine treatments, WP$_{-25}$N$_{180}$ and WP$_{-50}$N$_{180}$ were ranked the highest for their positive effects on tree growth.

3.4 Cumulative effects of drip irrigation and fertigation over years

To further evaluate the management regimes incorporating the productivity over multiple years, the cumulative increase in stem volume and biomass production in drip irrigation and fertigation treatments relative to that of control as a function of the cumulative amount of N addition and irrigation were analyzed (Fig. 5). In the three irrigation levels, the magnitude of the

Table 5 Multiple comparisons for DBH/H of the plantation among management regimes by age

Treatment	Diameter height ratio DBH/H (×10^{-2})			
	Before experiment/age 3	First year/age 4	Second year/age 5	Third year/age 6
WP$_{-75}$ N$_{60}$	0.70 b	1.01 bc	1.11 bcd	1.16 bcd
WP$_{-75}$ N$_{120}$	0.71 ab	1.00 bc	1.13 bc	1.18 bc
WP$_{-75}$ N$_{180}$	0.70 b	1.01 bc	1.09 cd	1.15 bcd
WP$_{-50}$ N$_{60}$	0.76 ab	1.01 bc	1.14 b	1.19 b
WP$_{-50}$ N$_{120}$	0.71 ab	1.00 bc	1.11 bc	1.16 bcd
WP$_{-50}$ N$_{180}$	0.79 a	1.04 ab	1.11 bcd	1.13 d
WP$_{-25}$ N$_{60}$	0.73 ab	0.94 d	1.07 d	1.12 d
WP$_{-25}$ N$_{120}$	0.74 ab	0.99 c	1.10 cd	1.13 d
WP$_{-25}$ N$_{180}$	0.73 ab	0.98 cd	1.12 bc	1.14 cd
Control	0.72 ab	1.01 a	1.19 a	1.24 a

Values (means) with different alphabets within the column in the same age indicate significant difference at $p < 0.05$, according to the Tukey test. For abbreviations, see Table 2

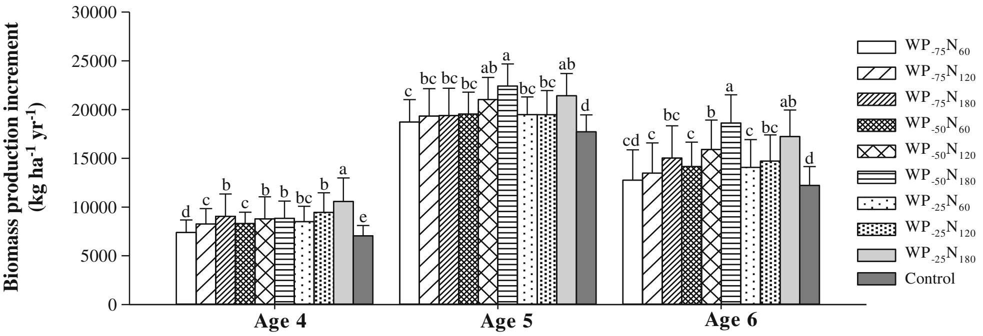

Fig. 4 Multiple comparisons for biomass production increment of the plantation between management regimes by age. Values are expressed as means and standard deviations. Different alphabets within the same age indicate significant difference at $p < 0.05$ according to the Tukey test. For abbreviations, see Table 2

response (differing in slopes) of cumulative stem volume increment in excess of control to addition of N follows a descending sequence of $WP_{-50} > WP_{-25} > WP_{-75}$ (Fig. 5a). The response of cumulative biomass increase in excess of control follows the same sequence (Fig. 5c). These results suggest that the positive effect of the amount of water supplied was conditional and the irrigation level WP_{-50} rather than WP_{-25} allowed the fertilizer to fully exert its role and sustainably promoted the plantation growth over the entire experimental period. On the other hand, in the three fertilization levels, the magnitude of the response of both cumulative stem volume increase and cumulative biomass increase in excess of control to the level of irrigation followed a descending sequence of $N_{180} > N_{120} > N_{60}$ (Fig. 5b, d). This suggests that the positive effect of the amount of fertilizer used on the growth had not reached saturation threshold in this study. The effect of drip irrigation was more significant under sufficient nutrient conditions, whereas in lower fertigation levels (N_{60} and N_{120}) the effects were quite limited in multiple years.

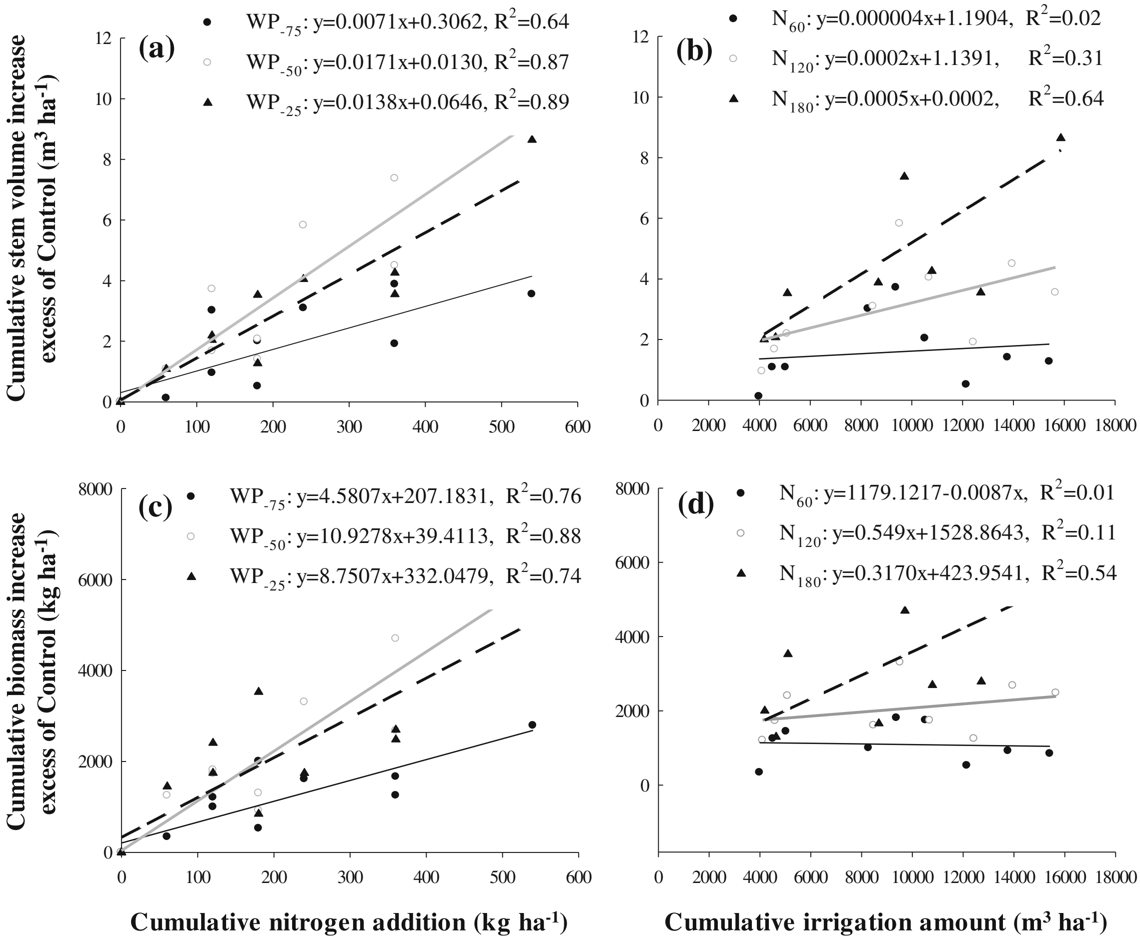

Fig. 5 Relationships between cumulative stem volume and biomass increase in excess of control, and the cumulative nitrogen addition (**a**, **c**) and the cumulative irrigation amount (**b**, **d**)

4 Discussions

4.1 Combined drip irrigation and fertigation could greatly promote the plantation productivity

The present experiment demonstrated the coupling effect of drip irrigation and fertigation on tree growth, suggesting the higher efficiency of using these simultaneously and in combination for better management (Li and Liu 2010; Kong et al. 2011; Guan et al. 2013). The productivity under control, which was characterized by low levels of irrigation and fertilization, was much lower than that of other management regimes with higher levels of irrigation and fertilization. The observed results that have also been reported for other tree species may partially be attributed to a homogenization and transportation of nutrients by water for efficient absorption. In a study with young Norway spruce, the absolute biomass doubled after irrigation and liquid fertilization (Iivonen et al. 2006). Coleman et al. (2004) found that aboveground biomass accumulation responded positively to irrigation and fertilization in sycamore and suggested that improved resource availability in soil caused the large increases in growth. Dong et al. (2011) revealed that a combined management of water, N, and P could achieve maximum biomass of *Populus tomentosa* seedlings because soil water improved N availability and absorption by roots. In our study, the 3-year experiment resulted in higher concentrations of soil total N only in the 0–20- and 20–40-cm soil layers of drip irrigation- and fertigation-treated plots than control, whereas the difference was not significant for the 40–60-cm soil layer, suggesting the leakage of N to deep layers should be limited. Drip irrigation combined with fertigation resulted in greater surface soil water and nutrient availability (Figs. 1 and 2). Combined management significantly increased stem volume and biomass production, and showed a cumulative effect over years. The promoting effects should mainly be attributable to increased nitrogen and water availability in the surface soil through the drip irrigation and fertigation management. It can be deduced that under conventional management in our study site the trees may suffer from insufficient supplies of N and water in the growing season, which might reduce tree growth and lead to more biomass allocation to roots (Ibrahim et al. 1998). Furthermore, it is difficult to isolate the effects of water and N availability because water provides the medium for N uptake by roots (Yan et al. 2016). Drip irrigation could provide a consistent moisture regime in the soil, which might accelerate root growth and result in the optimum availability of nutrients, and hence enhance tree growth (Ramniwas et al. 2013). In this study, drip irrigation and fertigation might have led to the appropriate distribution and adequate availability of nutrients and moisture in the root zone of the trees, which could have enhanced the uptake of nutrients.

The significant promoting effects of both drip irrigation and fertigation in our study might be partially due to the proper timing of irrigation and fertigation. Instead of the conventional fertilization of once or twice each growing season, yearly N addition in this study was supplied six times through drip irrigation. It has been suggested that under a drip irrigation system, fertigation events can be scheduled as often as daily to synchronize the nutrient supply with the plant nutrient requirement and thus promote plant growth (Stanturf et al. 2001). An experiment with *P. tomentosa* plantation by our research group also revealed that higher application frequency (four times per year) increased N uptake of trees and had positive effect on the growth (Wang et al. 2015). Therefore, the high N application frequency in this study coupled with drip irrigation resulted in significantly promoting growth, and was especially observed for fertilization treatments. Moreover, this combination regime was able to synchronize the supplies of nutrient and water, making their interactive effect positive. The management plan yielding the highest plantation productivity included surface drip irrigation that was launched at a soil water potential of −50 kPa with fertigation of 180 kg N ha^{-1} $year^{-1}$ that were applied six times during the growing season.

4.2 Effects of drip irrigation and fertigation vary with plantation ages

Although both drip irrigation and fertigation management showed promoting effect on the plantation growth, our results revealed some differences between in the magnitude of their impact across experimental years. Drip irrigation exerted its effect rapidly and the significance tended to reduce over the years, whereas the effects of fertilization tended to increase with time (Table 4). This was consistent with previous reports for poplar plantations that showed that the root system was not well developed in early ages and thus was more sensitive to surface drip irrigation. In older trees, the root system went deeper and showed greater absorption ability. Thus, its sensitivity to irrigation gradually decreased but that to fertilization using drips increased (Kong et al. 2011; Wang et al. 2015; Yan et al. 2015a). In addition, a general delay in the growth effect of nitrogen from the time of fertilization could be another reason for the increasing effect of N addition in older trees (Granlund et al. 2005; Wudneh et al. 2014). Based on these findings, intensive management of water and nutrient is recommended in the cultivation of rapid-growing poplar plantations with the emphasis on irrigation in the first year and on fertilization from the second year onwards.

4.3 Effect of fertigation positively increases and is cumulative while the effect of irrigation is restricted

The three levels of N that were applied in this study were lower than common applications following conventional fertilization methods for North American poplar. In a non-irrigated *P. tomentosa* plantation, Liu recommended a N addition rate of 350 kg ha^{-1} $year^{-1}$, and for a flood-irrigated *P. tomentosa* plantation, and Ren recommended N addition rates between 380 and 500 kg ha^{-1} $year^{-1}$ (Rennenberg et al. 2010; Wang et al. 2015). Proper N addition rate under drip irrigation may be lower than that for conventional fertilization and can exert greater effect without loss of N due to leaching (Lee and Jose 2003). In this study, fertigation positively promoted growth and the highest level of 180 kg N ha^{-1} $year^{-1}$ should be within the range of proper dose. In addition, fertigation showed a cumulative and consistently positive effect over the entire study period with the application rates used in this study (Fig. 5a, c). In the lower fertigation levels, effects of irrigation were restricted and a weak positive response in growth was seen with increase in irrigation (Fig. 5b, d). These also demonstrate the advantage of drip irrigation and fertigation management in the absorption and utilization of both water and nutrients, and the fertigation amount of 180 kg N ha^{-1} $year^{-1}$ can obtain high productivity for the plantation across these ages.

On the other hand, the medium level of irrigation (WP_{-50}) in this experiment resulted in the greatest promoting effect on the plantation growth, and further increase in water supply did not further increase this effect. Under this irrigation plan, fertigation promoted the increment in stem volume and biomass production to the maximum (Fig. 5a, c). This suggests that the leaching loss of N was limited and the fertilizer had fully exerted its role and sustainably promoted the plantation growth over the entire experimental period. Moreover, it also implies that the irrigation amount commonly applied to such plantations can be markedly reduced.

5 Conclusions

Management using a combined drip irrigation and fertigation could markedly improve availability and absorption of water and nutrients in soil, resulting in substantial increases in diameter and height growth, stem volume, and biomass production of poplar plantations grown in fields with sandy soil in the North China Plain. The enhanced stem volume and biomass were mainly attributable to increased nitrogen and water availability in the surface soil through the combined management. And, the management showed a cumulative effect over years. It can be deduced that, in fields with soil similar to our experimental site, this management plan can be generalized as an effective management regime of water and nutrient in fast-growing forest plantations.

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Compliance with ethical standards

Data availability The manuscript has no associated data or data archiving is not mandated.

Conflict of interest The authors declare that they have no conflict of interest.

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