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Responses of Fine Root Traits and Soil Nitrogen to Fertilization Methods and Nitrogen Application Amounts in a Poplar Plantation

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Abstract: Inappropriate fertilization management practices have led to low timber production in intensive plantation systems in China. Thus, optimized conventional or advanced fertilization management practices are needed. We aimed to quantify whether optimized furrow fertilization (FF) is comparable to advanced drip fertigation (DF) and to make recommendations regarding fertilization management strategies for poplar plantations. A completely randomized block design experiment with two fertilization methods (DF and FF) and four N application amounts (F_0: 0, F_1: 68, F_2: 113, and F_3: 158 kg $N \cdot ha^{-1} \cdot yr^{-1}$) was carried out on a *Populus* × *euramericana* cv. 'Guariento' plantation. Fine root biomass density (FRBD), fine root length density (FRLD), specific root length (SRL), soil total nitrogen (STN), soil inorganic nitrogen (SIN), soil ammonium (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were measured. The productivity increment was calculated based on tree surveys. The results showed that FRBD and FRLD decreased with the soil depth, and more than 86% was distributed within the 40 cm soil depth. FRBD, FRLD, productivity increment and soil N increased with an increasing amount of N application. DF treatments achieved 117%, 94% and 10% higher FRBD, FRLD and productivity increments, respectively, than did FF treatments. The averages of STN, SIN, NH_4^+-N and NO_3^--N under FF were higher than those under DF, leading to higher concentrations of residual NO_3^--N in deep soil. Beneficial management practices for fine root growth were evaluated in the following order: water coupled with N > only N ≥ only water > control. FRBD was positively correlated with the productivity increment. Therefore, fine root extension to increase soil resource absorption yields greater productivity under DF treatments. Drip fertilization is recommended as a better fertilization method to greatly promote the growth of fine roots, as well as productivity and residual lower soil N for poplar plantations.

Keywords: drip fertigation; optimized furrow fertilization; soil nitrogen; fine root traits; poplar plantation

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1. Introduction

Poplar is one of the most important species for timber use and is widely planted in North America, Asia and Europe [1]. In China, there exist 8.54 million ha of poplar plantations, constituting 18.14% of the national plantation area, the largest in the world [2,3]. Due to the higher nitrogen (N) requirements for high productivity in poplar than in most other plantation species, N fertilization is widely used in poplar plantations [4,5]. However, the average productivity under existing silvicultural practices is approximately 15 $m^3 \cdot ha^{-1} \cdot yr^{-1}$, which is far lower than the highest international level of productivity (53 $m^3 \cdot ha^{-1} \cdot yr^{-1}$), and outdated fertilization methods and inappropriate N application rates are the main reasons for the low average productivity in China [6,7]. Therefore, there is a need for optimized conventional or advanced fertilization methods, as well as appropriate N application rates, to address this problem.

Conventional fertilization methods, such as furrow, hole, annular and radiation fertilization are currently the major approaches to fertilization management practices in plantations or orchards [6]. To increase productivity or yield, overuse of N fertilization is a common practice in China. In this mode of fertilization management, the N concentration in the root zone soil may be in excess of that required by plants for growth during the first period of fertilization. After this period, the N concentration diminishes gradually until deficit levels are reached, which inhibits plant growth [8]. Although optimized conventional fertilization methods [6], such as adjusting fertilizer application rates as well as the frequency, application distance and furrow depth, have been applied to solve the aforementioned problems, there is currently a lack of information on whether optimized conventional fertilization methods can efficiently achieve high productivity with low environmental risk.

In recent years, many advanced fertilization methods have been studied regarding their potential to improve yield production efficiently and without high environmental risk, such as sprinkling fertilization, exponential fertilization, layered fertilization and drip fertigation (DF) [9,10]. DF is an advanced fertilization technique, and its advantages include supplying fertilizer directly to the root zone, increasing resource-use efficiency, reducing N loss, reducing the need for fertilizer applications, improving soil fertility and reducing labor costs [9,11–13]. To date, DF has been increasingly applied for the cultivation of plantations worldwide [3,4,14], but few studies have investigated its intensive use in timber-producing plantations.

The selection of the optimal fertilization method can be evaluated by collectively considering the availability and distribution of soil nutrients, plant root growth and yield [15]. Among these parameters, the morphological characteristics (such as root length, specific root length, root diameter and root volume) and spatial configuration of fine roots can significantly affect soil water content, nutrient transformation and plant nutrient-use efficiency [16]. In addition, specific root length can be used as an indicator of environmental changes [17]. Moreover, fine root growth can be affected by spatiotemporal variations in water and nutrients [15]. To date, the effects of soil N availability on fine root biomass and morphology have been extensively studied, but the results are inconsistent due to variation in the diversity of tree species, the timing of sampling, specific soil properties and site conditions among the studies. Some studies have shown that root length or biomass increase with increased soil N availability [18–20], whereas other studies have shown no such relationship [21] or even the opposite relationship [22]. Because fertilization management practices can directly affect soil N availability, it is important to measure the N distribution in the soil. Most tree roots mainly take up N from soil in inorganic forms (NH_4^+-N and NO_3^--N), and chemical N fertilizers are often used to supply sufficient inorganic N in order to achieve high yields. Previous research has revealed that the overuse of N fertilizer leads to excessive N concentrations in the soil profile and is associated with NO_3^--N leaching and N_2O emission to the environment. In addition, it causes underground water pollution and atmospheric pollution [23]. Therefore, understanding the spatial distribution of soil N and the characteristics of fine root traits, as well as their interactions to increase nutrient availability in the rhizosphere, will be beneficial for both meeting the N demands of plants and making decisions involving fertilization management strategies in poplar plantations [24,25].

The species *Populus* × *euramericana* cv. 'Guariento' has received much attention in northern China because of its high growth rate and timber output [3,10,26]. Previous studies on the effects of N applications on this species have concentrated mainly on yield responses [3,4], nutrient uptake [27], and aboveground biomass [28]. DF and optimized furrow fertilization (FF) may promote NO_3^--N leaching, necessitating the careful calculation of fertilizer rates to minimize that risk. Hence, a two-year field experiment involving DF and optimized FF was conducted on a *Populus* × *euramericana* cv. 'Guariento' plantation in the North China Plain. This study was undertaken to achieve two objectives: (1) to quantitatively evaluate the fine root traits, productivity increment and residual soil N responses to different fertilization methods and N application rates; and (2) to make recommendations regarding fertilization management strategies for poplar plantations.

2. Materials and Methods

2.1. Study Site

A field experiment was carried out on former agricultural land in the district of Shunyi, a northern suburb of Beijing, China (40°05′48.7″ N and 116°49′35.6″ W), in a flat, low alluvial region of the Chaobai River. The elevation at the site was approximately 28 m above sea level [3,10]. The region was classified as having a warm-temperate, semi-humid, continental, monsoon climate (dry and windy in spring, hot and rainy in summer) and has an average annual temperature of 11.5 °C. The highest monthly temperature reached 40.5 °C in July and August, and the lowest was −19.1 °C in January. The mean annual precipitation is approximately 560 mm, of which 11% occurs between March and May, 70% occurs between June and August and 16% occurs between September and November. There are approximately 195 frost-free days per annum, and the monthly average underground water ranges from 6 m to 13 m in depth. These meteorological data were based on 4 years (2011–2014) of data from Shunyi District meteorological stations. Table 1 shows the basic physical and chemical properties of the soil [10]. The soil texture at the study site is sandy loam, according to the USDA classification system [3]. There are no stones larger than 2 mm in the soil. The soil data represent the average values from five random soil profiles from the experimental site in 2012, with each soil profile having three layers (0–20 cm, 20–40 cm and 40–60 cm).

Table 1. Physical and chemical properties of the soil at the experimental site.

Depth cm	Sand %	Silt %	Clay %	Soil Texture (USDA Classification)	Bulk Density $g \cdot cm^{-3}$	Organic Matter $g \cdot kg^{-1}$	Total N $g \cdot kg^{-1}$	NH_4^+-N $mg \cdot kg^{-1}$	NO_3^--N $mg \cdot kg^{-1}$	Available P $mg \cdot kg^{-1}$
0–20	69.96 ± 0.62	29.52 ± 0.64	0.52 ± 0.02	Sandy loam	1.68 ± 0.02	10.73 ± 0.20	0.58 ± 0.05	5.12 ± 0.05	3.88 ± 0.43	4.91 ± 0.97
20–40	67.19 ± 0.79	32.28 ± 0.77	0.53 ± 0.02	Sandy loam	1.64 ± 0.01	6.65 ± 0.29	0.49 ± 0.09	5.34 ± 0.44	2.56 ± 0.30	4.74 ± 0.69
40–60	63.52 ± 0.98	35.92 ± 0.96	0.56 ± 0.02	Sandy loam	1.62 ± 0.01	5.78 ± 0.23	0.44 ± 0.01	4.22 ± 0.39	6.63 ± 0.32	5.02 ± 0.68

Note: Soil texture is according to the USDA classification system; total N represents soil total nitrogen (SIN); NH_4^+-N and NO_3^--N represent soil ammonium and nitrate nitrogen; available P represents available phosphorous. The data are the average values from five random soil profiles in the experimental site in 2012, with each soil profile having three layers. Data are mean ± SE ($n = 5$).

2.2. Plant Material

A 4 ha experimental plantation was established with 3-year-old poplar clonal trees of *Populus × euramericana* cv. 'Guariento' in the spring of 2011. *Populus × euramericana* cv. 'Guariento' is a hybrid between the American black poplar (*Populus deltoides* cl. '8/67') and the European black poplar (*Populus* nigra) [3]. In northern China, the growing season is from March to October and leaf shedding occurs in November. The trees were planted with an alternate narrow- (6 m) and wide-row (12 m) spacing scheme with a within-row spacing of 4 m, resulting in a planting density of 300 trees·ha^{-1}. The average stem height and base diameter of the trees were 7.0 m and 5.0 cm, respectively. A surface drip irrigation tube system was installed in the plantation in the spring of 2012. The system was established such that one drip pipe was laid along each tree row. The emitter interval spacing was 1.0 m, and the flow rate was approximately 2 L·h^{-1}. After 1 year, no significant differences in tree diameter at breast height (DBH = 10.35 ± 0.35 cm, tree diameter at 1.3 m, $p > 0.05$) or height (H = 10.22 ± 0.45 m, $p > 0.05$) were observed from the treatments at the beginning of the experiment (March of 2013). The fertilization experiment was conducted from 2013 to 2014.

2.3. Experimental Design

The experiment was arranged in a completely randomized block design with 3 replicate blocks. Each block had 8 plots (72 m × 18 m, 38 trees·plot^{-1}). There was a buffer of at least a 16 m between adjacent plots. Therefore, 22 trees in each plot were included in the experiment, and the buffer reduced the likelihood that N fertilizer applied to one plot was transported to another plot. The experiment consisted of two fertilization methods and four N application rates, eight treatments in total. The fertilization methods included furrow fertilization (FF) and drip fertigation (DF). For the FF, a trench was dug underneath the emitter, which was away from the tree (approximately 1.0 m), and the length, width and depth of the trench were 0.8 m, 0.2 m and 0.15 m, respectively. The application frequency was set to 6 times greater than that of conventional FF (1–2 applications in the spring and autumn) [10,29]. The 4 N application rates were as follows: 0 (F_0), 68 (F_1), 113 (F_2) and 158 (F_3) kg $N\cdot ha^{-1}$. N fertilizer was applied as a urea solution (46% N, approximately 95 g $N\cdot L^{-1}$) which was injected directly into the main line of the drip system via a hydraulic-driven injector (Mix Rite Model 2504, Tefen, Israel). Treatment of FF_0 represents the conventional management practice in the north of China, which involves no irrigation or fertilization during the growing season. DF_0 represents only drip irrigation, DF_2 represents drip fertigation with a moderate N application rate and FF_2 represents furrow fertilization with a moderate N application rate. Before the leaf expansion period, furrow irrigation (approximately 3800 $m^3\cdot ha^{-1}\cdot yr^{-1}$) was applied to all the treatments to promote leaf expansion and tree growth. Weeds were controlled during the experimental period using herbicides. The specific applications of water and N fertilizer in each treatment are summarized in Table 2.

Table 2. Experimental design and implementation overview at the study site.

Treatment	Spring Irrigation ($m^3\cdot ha^{-1}\cdot yr^{-1}$)	Irrigation Amount ($m^3\cdot ha^{-1}\cdot yr^{-1}$)	Fertilizer Rate ($kg\ N\cdot ha^{-1}\cdot yr^{-1}$)	Fertilization Frequency (times yr^{-1})
DF_1	3800	1395	68	6
DF_2	3800	1485	113	6
DF_3	3800	1580	158	6
DF_0	3800	1485	0	0
FF_1	3800	0	68	6
FF_2	3800	0	113	6
FF_3	3800	0	158	6
FF_0	3800	0	0	0

Note: The six N applications each year occurred on 28 April, 20 May, 13 June, 30 June, 26 July and 17 August for 2013, and 21 April, 12 May, 7 June, 7 July, 2 August and 28 August for 2014.

2.4. Sample Collection and Analysis

The diameter at breast height (DBH at 1.3 m, cm) and height (H, m) of each tree in the field was measured at the beginning of the experiment (March) and at the end of growing season (November). Standard trees (average trees) were marked in each plot. Points for soil and root sampling were randomly selected under the standard trees in each plot in November of 2013 and 2014. Each soil core was collected underneath the emitter at approximately 1.0 m away from the nearest standard tree. The soil cores were extracted using a cylindrical soil core (5 cm inner diameter and 20 cm length for soil sampling, 10 cm inner diameter and 20 cm length for root sampling) at 3 depth intervals: 0–20 cm, 20–40 cm and 40–60 cm (because most of the fine poplar roots were distributed above 40 cm [30], soil sampling down to 60 cm was appropriate for the research purposes of this study to examine the spatial distribution of soil N). A total of 72 soil samples and 72 root samples were collected in each year.

After removing roots and plant residues, each soil sample was thoroughly mixed, sieved (2 mm), placed in plastic bags and transported to the lab. The samples were later partitioned to measure soil water content (via the drying method), and the concentrations of NH_4^+-N (via indophenol blue colorimetry) and NO_3^--N (via dual wave-length colorimetry) [31,32] were measured using a continuous flow analysis instrument (AA3, Bran and Luebbe, Norderstedt, Germany). The remaining soil samples were air-dried, ground and sieved (0.15 mm) in preparation for STN using H_2SO_4-H_2O_2 digestion, and then they were measured using a Kjeldahl nitrogen meter (Hangzhou, Zhejiang, China) [32]. Inorganic N was calculated as the sum of ammonium and nitrate.

Each root sample was gently rinsed with fresh water to separate the roots from the soil particles and organic materials. Two sieves (0.8 and 0.125 mm mesh) were used to avoid losing fine roots. After washing, the roots were placed in fresh water, and all living roots < 2 mm in diameter were manually collected from the residual soil particles and organic materials using forceps and filters. Living roots were distinguished from dead roots by their lighter color and greater resilience; yellow-brown or brown fine roots were living, while black roots were dead [33]. All living fine roots in each layer were digitally scanned using a flatbed scanner at 400 dpi, and the files were saved in tif format. The root images were analyzed using image analysis software (WinRHIZO Pro 2008a, Regent Instruments Inc., Canada) for root length. The roots were then placed into labeled envelopes and oven-dried at 65–70 °C to a constant mass (for at least 48 h), and then weighed to estimate the fine root biomass [29,34].

Tree growth data were used to calculate the productivity increment ($m^3\ ha^{-1}$) using the following formula:

$$P = \left[g_{1.3} \times (H_{end} + 3) \times f - g_{1.3} \times \left(H_{begin} + 3\right) \times f\right] \times N \qquad (1)$$

where P is the productivity increment, $g_{1.3}$ is the cross-sectional area at breast height, H_{begin} is tree height at the beginning of growing season, H_{end} is the tree height at the end of the growing season, f is the experimental form factor and N is the tree density in the field (300 tree ha^{-1}). The factor f was determined by comparing several approaches to stem volume calculation based on destructive sampling of average tree stems from 2012–2014, and a form factor of 0.41 was obtained from the Newton approximation method as the relatively accurate value for this plantation [3].

2.5. Data Analysis

The fine root trait variables which were calculated included fine root biomass density (FRBD, $g \cdot m^{-3}$ soil) = fine root biomass/volume of soil block; fine root length density (FRLD, $m \cdot m^{-3}$ soil) = fine root length/volume of soil block and specific root length (SRL, $m \cdot g^{-1}$) = fine root length/fine root biomass. All data were expressed as the means ± standard errors.

The Kolmogorov–Smirnov test and the Levene test were used to verify the assumptions of normality and homogeneity of the variance of the data for each variable before further analysis. The variables that did not conform to these assumptions were mathematically transformed using logarithms or reciprocal functions. Multivariate-way ANOVAs were carried out to determine the effects of the year of experiment (Y), fertilization methods (M), fertilizer amount (A) and soil layer (S) on fine root traits and soil N ($p < 0.05$). One-way ANOVA was used to test the differences between N addition treatments (Duncan's test, $P = 0.05$). An independent-sample test was used to test for differences between two fertilization methods. Pearson correlations were used to measure the degree of association between the fine root traits and soil N. Linear relationships were assessed to examine the relationships between FRBD and productivity increments. All statistical analyses were performed using SPSS, version 20.0 (SPSS Inc., Chicago, IL, USA). All figures and tables were produced using Excel 2016.

3. Results

3.1. FRBD, FRLD and SRL

The significance levels were analyzed for the effects of the year of experiment, fertilization method, fertilizer amount, soil layers and their interactions on FRBD, FRLD and SRL (Table 3). The effects of the year of experiment (Y), fertilization method (M), fertilizer amount (A), soil layers (S) and Y × S, M × S and Y × M × S interactions on FRBD, FRLD and SRL were all statistically significant ($p < 0.001$ or $p < 0.05$), but the effects of Y × A and Y × M × A interactions were not significant ($p > 0.05$). (Table 3).

Table 3. *p* values of repeated measures ANOVA for the year of experiment (Y), fertilization method (M), fertilizer amount (A), soil layers (S) and their interactions on fine root biomass density (FRBD), fine root length density (FRLD) and specific root length (SRL) of fine roots in a poplar plantation.

Source of Variation	df	FRBD	FRLD	SRL
Year of experiment (Y)	1	<0.001	<0.001	<0.001
Fertilization method (M)	1	<0.001	<0.001	<0.001
Fertilizer amount (A)	4	<0.001	<0.001	0.013
Soil layers (S)	2	<0.001	<0.001	<0.001
Y × M	1	0.435	0.064	<0.001
Y × A	1	0.135	0.545	0.719
Y × S	2	<0.001	<0.001	0.002
M × S	2	<0.001	<0.001	<0.001
A × S	8	<0.001	<0.001	0.472
M × A	3	<0.001	<0.001	0.707
Y × M × S	2	0.012	<0.001	<0.001
Y × M × A	1	0.298	0.130	0.370
M × S × A	6	<0.001	<0.001	0.946
Y × S × A	2	0.180	0.025	0.419
Y × M × S × A	2	0.203	0.004	0.824

FRBD and FRLD decreased with increasing soil layer depth (Figure 1a–d), and SRL tended to be greater at a depth of 40–60 cm under the FF method (Figure 1e,f). FRBD and FRLD were increased with the amount of N applied (0–180 kg·ha^{-1}) under treatments of $DF_{0–3}$ and $FF_{0–3}$, but showed a tendency to increase initially and then decrease with the N application amount under the FF method in 2014 (Figure 1a–d).

Most of the fine roots were concentrated at a depth of 0–40 cm, with FRBD and FRLD at this depth accounting for 81%–89% and 86%–90%, respectively, of the total under each treatment. In the first 20 cm depth, both FRBD and FRLD were significantly higher in the DF- than the FF-treated plots for almost all the N treatments tested (Figure 1a–d). At 40–60 cm soil depth, the average FRBD and FRLD with DF were 117% and 94% higher than with FF, respectively (Figure 1).

Comparing the two fertilization methods, the average FRBD and FRLD were higher with the DF method than with the FF method. They were significantly enhanced, by 101%–86% and 50%–66%, compared to the FF method in 2013 and 2014, respectively. Comparing the four N application levels, the average FRBD and FRLD with treatments of $DF_{0–3}$ were significantly higher than with treatments of $FF_{0–3}$, from 0–180 kg ·ha^{-1}, in the years of 2013 and 2014. The values of SRL with the FF method were higher than with the DF method in 2013 and 2014. SRL tended to be higher at a depth of 40–60 cm, especially for the FF method in 2013. SRL was higher in 2013 than in 2014 (Figure 1e,f).

3.2. NH_4^+-N, NO_3^--N, SIN and STN

The significance levels were analyzed for the effects of the year of experiment, fertilization method, fertilizer amount, soil layers and their interactions on the soil NH_4^+-N, NO_3^--N, SIN and STN (Table 4). The effects of the fertilization method (M), fertilizer amount (A), soil layers (S) and Y × M, Y × S, M × S, A × S, M × A, Y × M × A and M × S × A interactions on the soil NH_4^+-N, NO_3^--N, SIN and STN were all statistically significant ($p < 0.001$ or $p < 0.05$), but the effects of Y, Y × A, Y × S × A and Y × M × S × A interactions on NO_3^--N were not significant ($p > 0.05$) (Table 4).

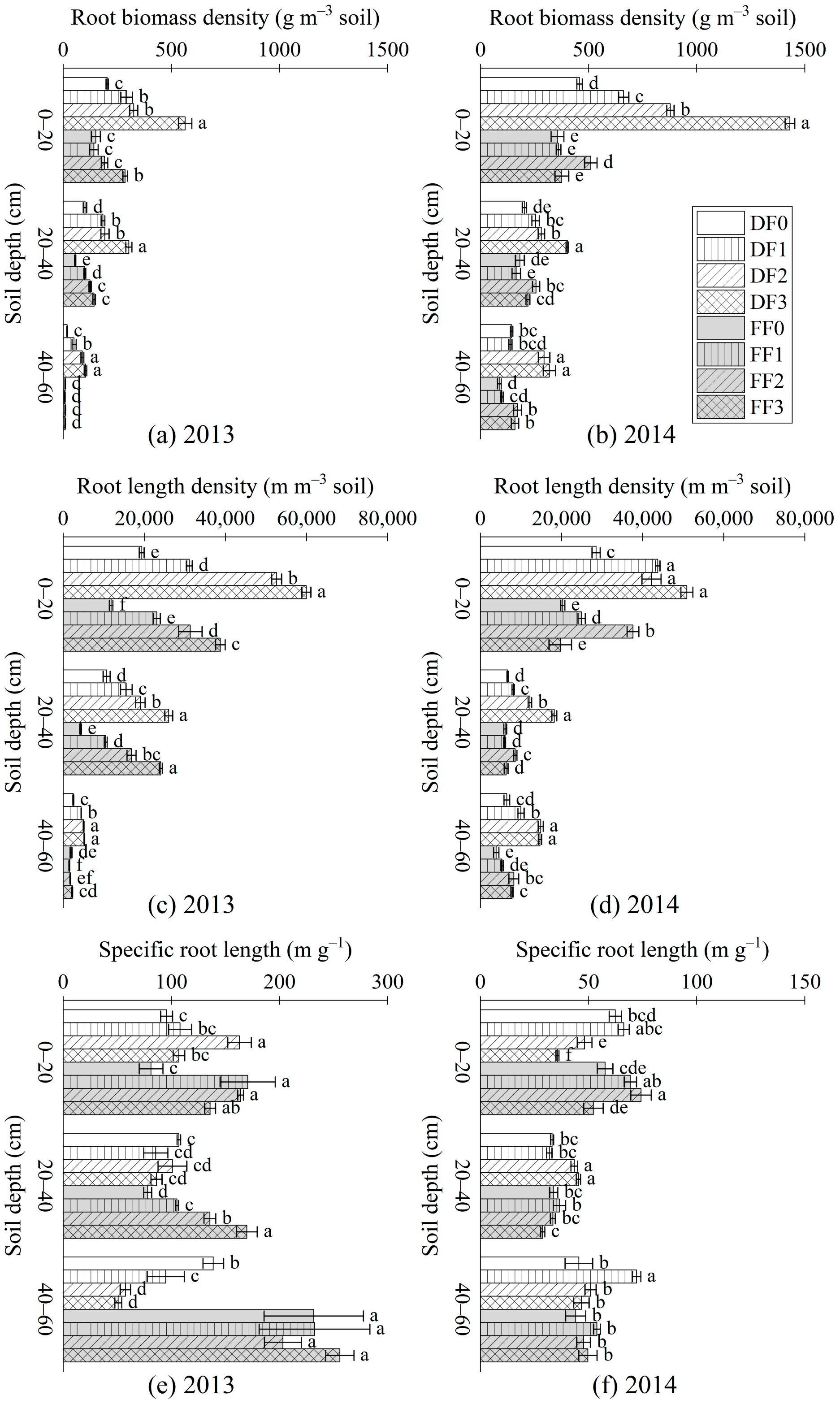


Figure 1. Values of fine root biomass density (FRBD, (**a**): 2103, (**b**): 2014), fine root length density (FRLD, (**c**): 2013, (**d**): 2014) and specific root length (SRL, (**e**): 2013, (**f**): 2014) of each soil core at different soil depths (0–20 cm, 20–40 cm and 40–60 cm, respectively) in a poplar plantation. The data are the means ± SE (*n* = 3). Different lowercase letters within the same soil layer indicate significant differences among eight N addition treatments.

Table 4. *p* values of repeated measures ANOVA for the year of experiment (Y), fertilization method (M), fertilizer amount (A), soil layers (S) and their interactions on the soil NH_4^+-N, NO_3^--N, SIN and STN in a poplar plantation.

Source of Variation	df	NH_4^+-N	NO_3^--N	SIN	STN
Year of experiment (Y)	1	<0.001	0.105	<0.001	0.090
Fertilization method (M)	1	<0.001	<0.001	<0.001	<0.001
Fertilizer amount (A)	4	<0.001	<0.001	<0.001	<0.001
Soil layers (S)	2	<0.001	<0.001	<0.001	<0.001
Y × M	1	<0.001	<0.001	<0.001	0.002
Y × A	1	<0.001	0.069	<0.001	0.289
Y × S	2	<0.001	<0.001	<0.001	<0.001
M × S	2	<0.001	<0.001	<0.001	<0.001
A × S	8	<0.001	<0.001	<0.001	<0.001
M × A	3	<0.001	<0.001	<0.001	<0.001
Y × M × S	2	<0.001	<0.001	0.626	<0.001
Y × M × A	1	<0.001	<0.001	<0.001	<0.001
M × S × A	6	<0.001	<0.001	<0.001	<0.001
Y × S × A	2	<0.001	0.202	<0.001	0.264
Y × M × S × A	2	<0.001	0.465	0.011	0.002

STN decreased with increasing soil layer depth under both DF and FF (Figure 2a,b). SIN, NH_4^+-N and NO_3^--N decreased with increasing soil depth under the FF method, whereas they accumulated within the deep soil under the DF method (Figures 2c,d and 3a–d). The average NO_3^--N in the 40–60 cm soil layer under the FF method was 53% higher than that under DF ($p < 0.05$). Particularly, the concentrations of all N forms tested were clearly higher with the FF than the DF treatments at lower depths (Figure 3c,d).

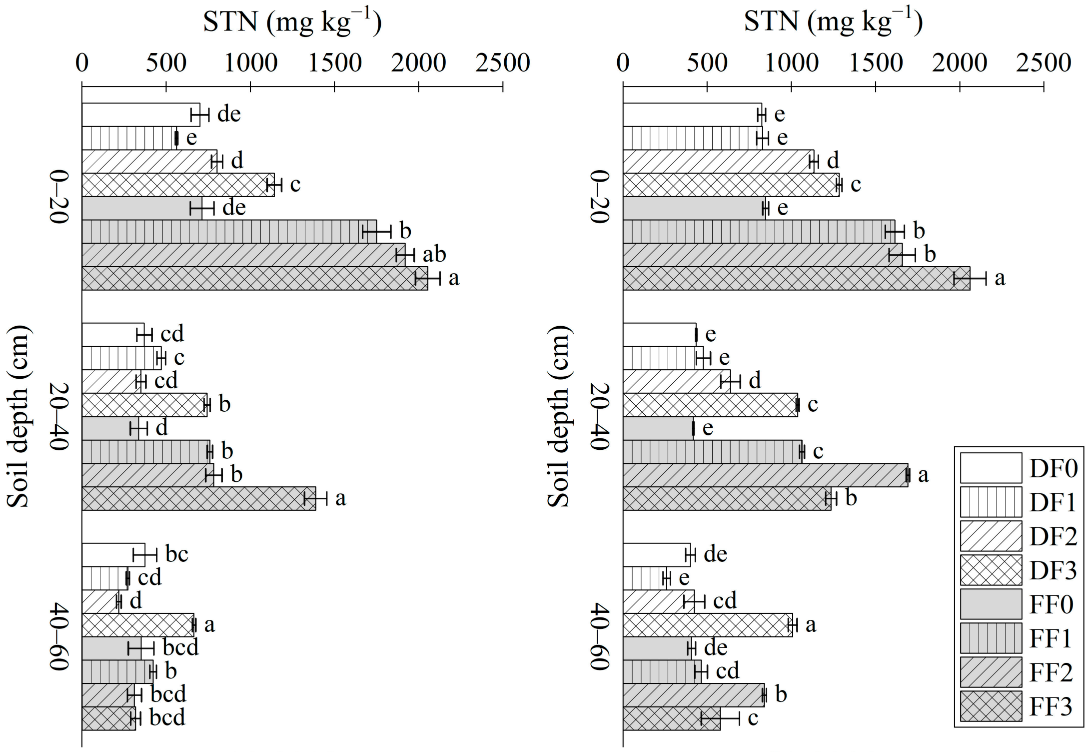
Treatments of $DF_{1–3}$ and $FF_{1–3}$ were significantly higher than the control treatments (DF_0 and FF_0). The average values of STN, SIN, NH_4^+-N and NO_3^--N concentration with the FF method were significantly higher than with the DF method, which improved by 67%, 85%, 8% and 241% in 2013 and by 47%, 280%, 89% and 576% in 2014, respectively. The average concentration of STN, SIN, NH_4^+-N and NO_3^--N were increased with N application amounts under the two fertilization methods.

3.3. Relationships between Fine Root Traits and Soil N

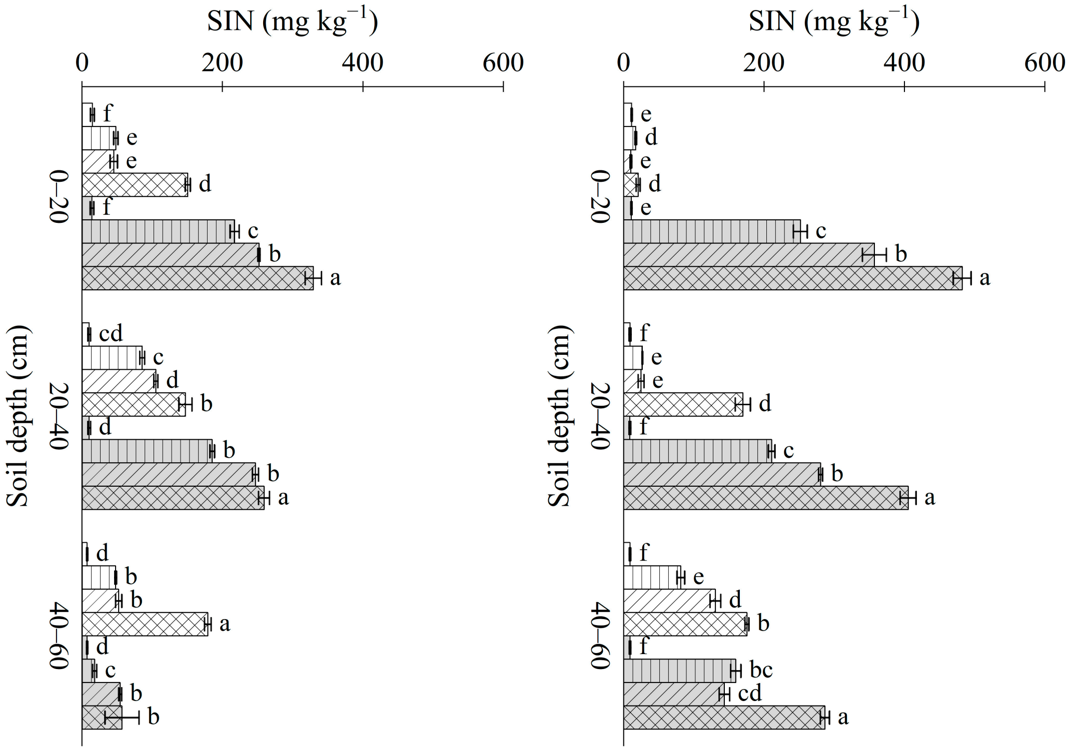
Table 5 shows that FRBD and FRLD, under both the DF and FF methods, were positively correlated with the STN. FRBD and FRLD were not correlated with soil NH_4^+-N, NO_3^--N or SIN under the DF method, but were negatively correlated with SRL. Meanwhile, FRBD and FRLD were positively correlated with soil NH_4^+-N, NO_3^--N and SIN, but negatively correlated with SRL, under the FF method ($p < 0.05$).

3.4. Relationships among N Application Amount, FRBD and Productivity Increment under Two Fertilization Methods

Productivity increment and fine root biomass density increased with increasing N application under DF (Figure 4a,b); 158 kg·ha^{-1} yielded the highest value. However, in FF, these factors showed a trend of first increasing and then decreasing with increasing N application (Figure 4a,b); 113 kg·ha^{-1} yielded the highest FRBD and productivity increment (Figure 4). DF treatments achieved significantly higher productivity increments (by 1%–20%) than did FF treatments ($p < 0.05$). Figure 4c,d show that FRBD was positively correlated with the productivity increment. The linear regression relationship was more significant with DF treatment than with FF treatment.

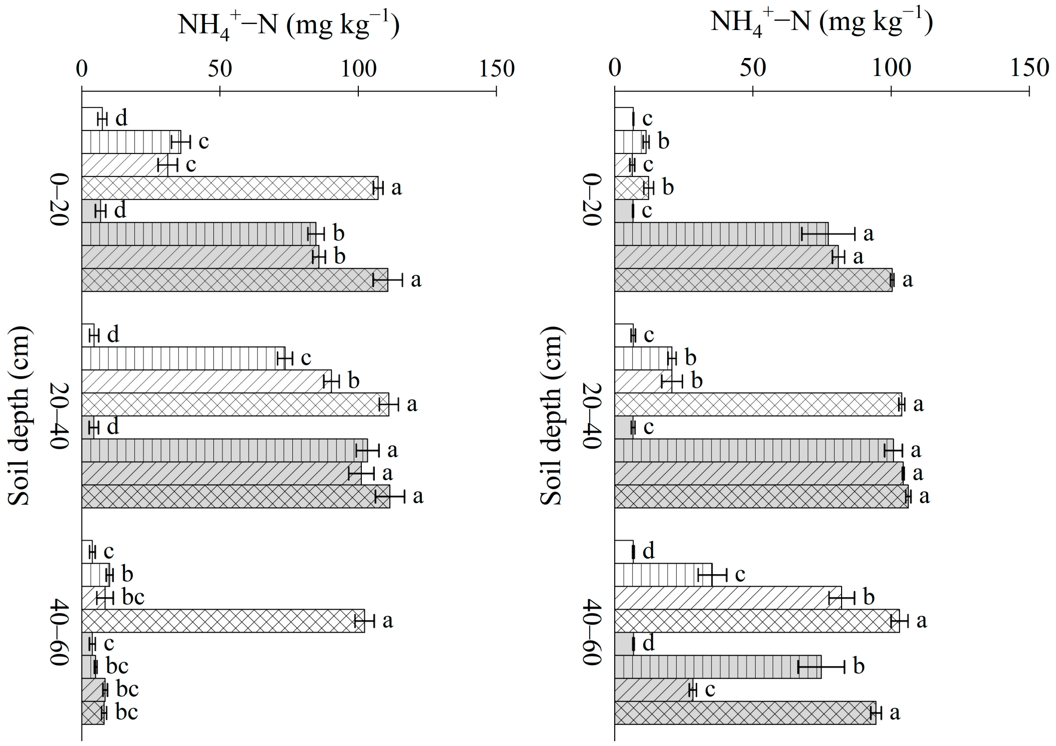


(a) 2013 (b) 2014

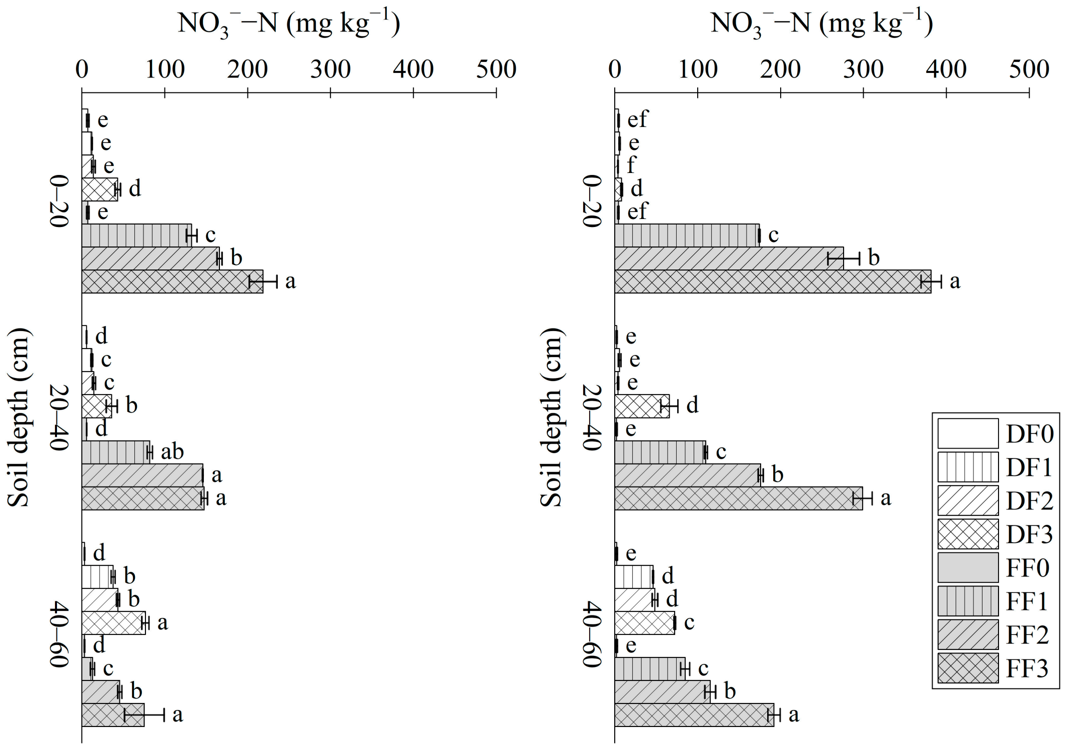


(c) 2013 (d) 2014

Figure 2. Values of total soil nitrogen (STN, (**a**): 2013, (**b**): 2014) and total soil inorganic nitrogen (SIN, (**c**): 2013, (**d**): 2014) at different soil depths (0–20 cm, 20–40 cm and 40–60 cm) in a poplar plantation. The data are the means ± SE (n = 3). Different lowercase letters within the same soil layer indicate significant differences among eight N addition treatments.



(a) 2013 (b) 2014



(c) 2013 (d) 2014

Figure 3. Values of soil ammonium N (NH_4^+-N, (**a**): 2013, (**b**): 2014) and nitrate N (NO_3^--N, (**c**): 2013, (**d**): 2014) at different soil depths (0–20 cm, 20–40 cm and 40–60 cm) in a poplar plantation. The data are the means ± SE ($n = 3$). Different lowercase letters within the same soil layer indicate significant differences among eight N addition treatments.

Table 5. Pearson correlation coefficients between fine root traits and soil N under the drip fertigation (DF) and optimized furrow fertilization (FF) methods in a poplar plantation. Fine root traits are fine root biomass density (FRBD), fine root length density (FRLD) and specific root length (SRL); soil N variables are ammonium N (NH_4^+-N), nitrate N (NO_3^--N), total soil inorganic nitrogen (SIN) and total soil nitrogen (STN). $p < 0.05$ *, $p < 0.01$ **.

Methods	Traits	NH_4^+-N	NO_3^--N	SIN	STN
DF	FRBD	0.15	−0.09	0.06	0.86 **
	FRLD	0.03	−0.19	−0.07	0.82 **
	SRL	−0.59 **	−0.55 **	−0.61 **	0.06
FF	FRBD	0.50 **	0.66 **	0.63 **	0.88 **
	FRLD	0.55 **	0.74 **	0.71 **	0.93 **
	SRL	−0.37 *	−0.24	−0.29	−0.47 **

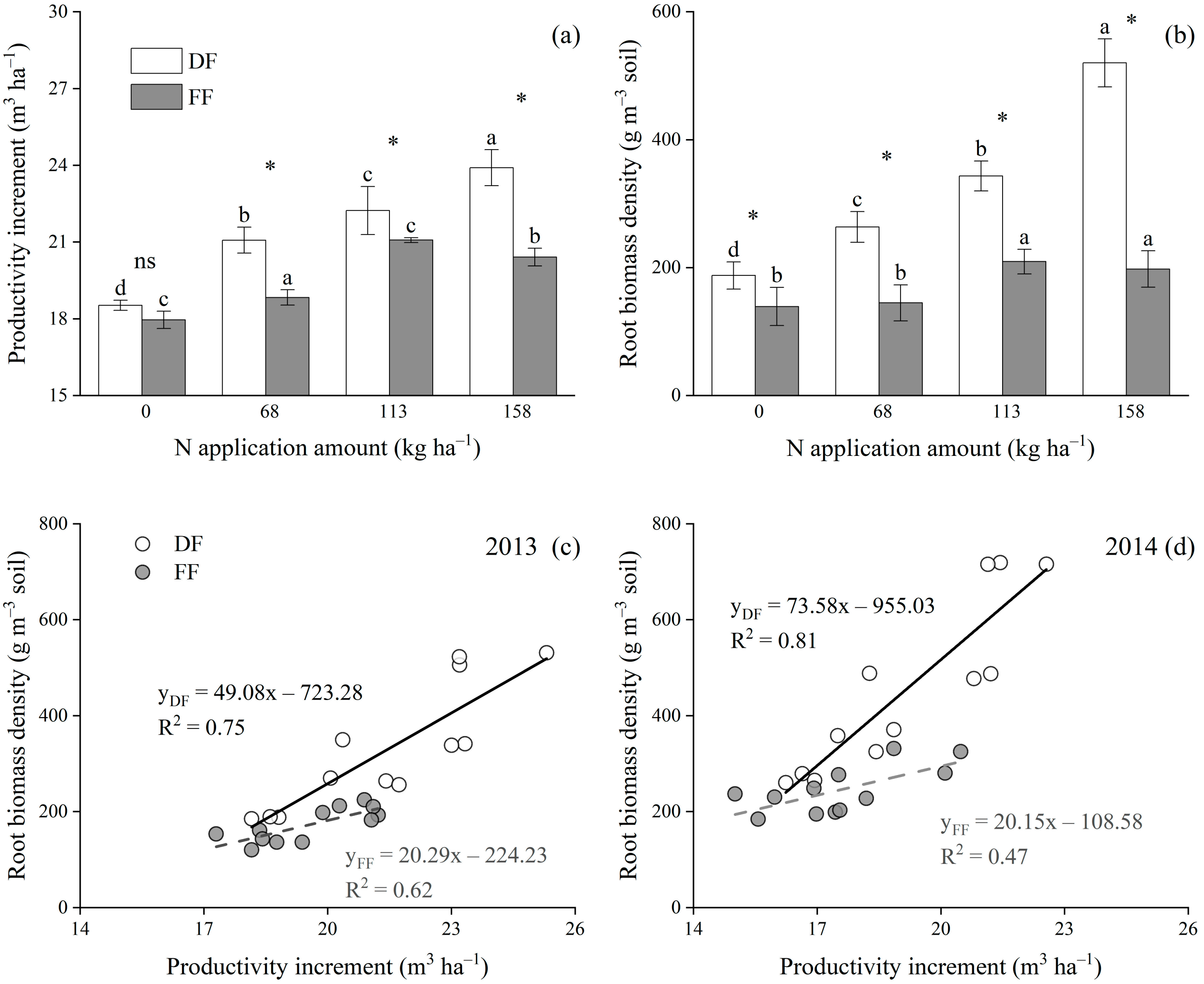


Figure 4. Relationships between productivity increment and N application amount (**a**), fine root biomass density and N application amount (**b**) and productivity increment and fine root biomass density ((**c**): 2013, (**d**): 2014) under DF and FF methods. Solid black circles represent DF; hollow circles represent FF. Different small letters labeling the bars indicate significant differences among N application rates at the 0.05 level, and * indicates a significant difference between the two fertilization methods at the 0.05 level.

4. Discussion

4.1. Influence of Fertilization Methods and Application Rates on Fine Root Traits

Fine roots are vital organs that provide water and mineral nutrients to plants. They not only determine soil's utilization effectiveness and potential, but also reflect the distribution pattern of water and mineral nutrients in soils [35,36]. In this study, fine root biomass density and fine root length density decreased with soil depth in all of the treatments, and more than 86% and 89% of the total FRBD and FRLD was distributed within the 40 cm soil depth. Similarly, the fine root distribution within the surface soil layer has been reported in plantations of other species under different site conditions [37–40]. This phenomenon can be attributed to the role of the surface soil layer as the main provider of soil N and water for plant roots [41]. Soil N was mainly concentrated within 40 cm of soil depth in all treatments, which may have favored the proliferation of fine roots. Nonetheless, fine root development should be affected by both nutrients and water along the soil profile. It is certain that the soil's water distribution along the profile would change according to the irrigation method. The affecting mechanism should include water application and absorption efficiency along different soil layers, and this may be investigated in our future works. Furthermore, the average FRBD and FRLD in the 40–60 cm soil layer were 117% and 94% higher with DF than with FF, implying that DF could promote extension of fine roots to greater soil depths. We speculate that the fine root distribution pattern observed in our study was the result of the integrated effects of both intrinsic tree characteristics and fertilization methods [37,39,42].

In this study, FRBD and FRLD were increased with increasing N application more significantly under DF than under FF (Figure 1). High-frequency DF is conducive to maintaining a stable water and N status in the root zone, as water and urea liquid are simultaneously applied in this method [42,43]. A potential reason for the greater average FRBD and FRLD under the DF method than under the FF method is the greater proportion of photosynthate allocation to fine roots [41]. In practice, FF methods usually require that an artificial gully be dug that reaches the trees, resulting in damage of the fine roots to some extent. This might disrupt root growth balance and decrease the amount of roots. As the roots start to recover and regrow, the system becomes a sink of C and N [44]. Additionally, greater amounts of resource inputs are consumed during the recovery and regrowth processes of fine roots. Accordingly, by consuming the same amount of resources, DF achieved higher fine root biomass and fine root length than FF.

To date, the results regarding the effects of soil N availability on fine root production are still inconclusive. Some studies have found that fertilizer application variably affects soil N mineralization and increases plant uptake of soil N via plant-mediated mechanisms, such as increases in fine root biomass and length [44]. In the present study, FRBD and FRLD increased with N application rates under the DF method. Poplar fine roots are considered highly plastic, and some studies have reported that poplar roots proliferate in the presence of increased N [45]. Artacho and Bonomelli [20] proposed that higher N concentrations in roots could increase the speed of fine root turnover or increase the N concentrations in leaves, which could then increase the availability of photosynthates and promote greater root growth. However, under the FF method, N application had a relatively small effect on FRBD (Figure 1). Similarly, Price et al. [46] studied the fine root production dynamics in an intensively managed sweetgum (*Liquidambar styraciflua* L.) coppice and reported no differences between the two studied fertilizer treatments. Other studies have also reported reductions in fine root growth with N application. Jia et al. [22] studied the responses of belowground biological processes to soil N availability in *Larix gmelinii* and *Fraxinus mandshurica* plantations and reported that, compared with the control treatment, the N fertilization treatment induced 52% and 25% decreases in fine root biomass in larch and ash, respectively. Rytter et al. [47] considered that, in absolute terms, a lower standing fine root biomass develops where N availability is high due to the simultaneous increase in turnover rate and decrease in standing fine root biomass. In summary of the abovementioned results, the relationship between available soil N and fine root growth is complex, and multiple factors, such as tree species diversity and site conditions, as mentioned above, should be considered when designing experiments. We found that, compared with the four fertilization practices, the different management practices benefited fine root growth (FRBD) in the following order: water coupled with N (DF_2) > N application alone (FF_2) $\geq$ water application alone (DF_0) > control (FF_0) (Figure 1). This result confirmed that soil resource availability affected fine root growth [15].

4.2. Influence of Fertilization Methods and Application Rates on Soil N

The spatial and temporal distribution of N in soil are heterogeneous. Thus, understanding the distribution of soil N under different fertilization methods is helpful for developing appropriate management strategies for poplar plantations. In this study, we found that soil N decreased with soil depth under the FF method (Figures 2 and 3), which corroborates the results of previous works [43,48]. However, the vertical distributions of SIN, NH_4^+-N and NO_3^--N under DF differed. These inorganic forms of N increasingly accumulated within the deep soil layer with increasing N application (Figures 2 and 3). This result is similar to Li's findings concerning subsurface DF [49]. The results also showed that the average STN, SIN, NH_4^+-N and NO_3^--N values under FF were higher than those under DF (Figures 2 and 3), which is consistent with Qi and Huang's findings [43,50]. More time was required for available N (NH_4^+-N and NO_3^--N) to be hydrolyzed and transformed from urea under the FF method than under the DF method; the former released more available N into the soil in the short term than the latter [10]. As a result of the movement of available N with water flow and its redistribution, available N accumulated in the deeper soil layers.

Irrigation and fertilization are linked, and inappropriate fertilization methods and fertilization applications can greatly increase nutrient losses [51]. In the present study, inappropriate fertilization methods significantly enhanced the concentration of NO_3^--N in the soil (Figures 2–4). The average concentration of NO_3^--N in the 40–60 cm soil layer was 53% higher under the FF method than under the DF method. This result demonstrated that the FF method led to higher concentrations of inorganic N in the soil and caused the deep migration of large concentrations of NO_3^--N, which may increase the risk of N leaching.

4.3. Relationships among Soil N, Fine Root Traits and Productivity Increment

Fine root distribution is largely influenced by soil resource availability [52]. In this study, under the DF method, both FRBD and FRLD were positively correlated with STN, but not with SIN, NH_4^+-N or NO_3^--N. In contrast, under the FF method, FRBD and FRLD were positively correlated with STN, SIN, NH_4^+-N and NO_3^--N (Table 5). These differences between treatments may reflect the different fertilization methods that were used. FRBD and FRLD, as well as STN, decreased with increasing soil depth under all treatments, indicating a greater proportion of fine roots in the surface soil layer than in deeper layers in response to ample moisture and nitrogen availability [41,52,53]. A larger portion of the SIN was efficiently absorbed by fine roots under the DF method, which led to lower available soil N, ultimately reflecting the observed weaker relationship between SIN and fine root traits. However, negative relationships between FRBD and nutrient supplies in beech (*Fagus sylvatica* L.) forests and tropical rainforests have been reported [54,55].

Our results show that productivity increments and FRBD increased with increasing N application under DF (Figure 4a,b). This indicates that drip fertigation is an efficient silvicultural practice to increase the fine root and tree growth on poplar plantations, which is similar to the findings of previous studies. For example, Yan et al. reported a significant cumulative effect of N fertigation on productivity in poplar plantation, with 180 kg·ha^{-1} N application achieving the highest increments [3]. However, through the results of the DF method, we were unable to achieve the optimal N application rate for the poplar plantation with the existing gradient, which indicated that a further improvement in productivity could be achieved with increased fertilization. Xi et al. recommended an optimal N application rate of 192 kg·ha^{-1} for a 3–5-year-old poplar plantation under drip fertigation [28]. Thus, we speculated that drip fertigation positively promoted fine root growth and productivity, and that the highest level of 180 kg N·ha^{-1} yr^{-1} would be within the range of an optimal N application rate. However, with FF, they showed trends of first increasing and then decreasing with the increasing N application rate. This result implies that fine root growth and productivity did not increase with the fertilization rate when it was above 158 kg N ·ha^{-1} under FF, which has also been observed in other studies. For example, Wang reported that the use of an N application rate above 115 kg N·ha^{-1} yr^{-1} did not result in growth nor N uptake benefits [4]. Hochmuth summarized the findings of more than 15 fertilization trials under drip irrigation and concluded that tomato yield did not increase with the fertilization rate when it was above 227 kg N·ha^{-1} yr^{-1} [56].

The positive correlation between fine root biomass density and productivity increment were observed under the DF and FF methods (Figure 4c,d). The results were in accordance with previous research [20,57] which has suggested that fine root extension to increase soil resource absorption yields greater productivity. However, the opposite results were obtained for pine seedlings; the effects of the plasticity of fine root growth on stem growth resulted in increased allocation of biomass to foliage and decreased allocation to fine roots [58]. In our study, ample availability of N and water contributed to higher FRBD and productivity increments under the DF method.

5. Conclusions

In summary, drip fertilization achieved higher fine root biomass density, fine root length density and productivity increments than optimized furrow fertilization, whereas optimized furrow fertilization contributed to higher concentrations of STN, SIN, $NH_4{}^+$-N and $NO_3{}^-$-N than drip fertigation. Therefore, drip fertigation is recommended as a superior fertilization method, as it greatly promoted the growth of fine roots as well as productivity and residual lower soil N on the poplar plantation. It is suggested that fine roots adjust their growth and morphology in response to N availability, which varies along with the soil profile and the fertilization method. It can be deduced that, in fields with similar soil types to that of our experimental site, the practice of drip fertilization management can be generalized as an effective management regime in fast-growing forest plantations.

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