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Effects of Fertilization and Drip Irrigation on the Growth of *Populus × canadensis* 'Zhongliao 1' Plantation and on Soil Physicochemical Properties and Enzyme Activities

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Abstract: Poplars are crucial for timber supply and ecological protection in China. Enhancing the growth of poplar plantations and improving soil fertility in arid, and semi-arid poor soil regions are key aspects of sustainable forest management. Fertilization (FTL) and drip irrigation (DI) are among the most widely used methods globally for increasing yield and soil productivity. This study conducted field experiments on FTL and DI in a 10-year-old *Populus × canadensis* 'Zhongliao 1' (cultivation varieties of *P. canadensis* in northern China) plantation. DI limits were set according to soil moisture at 60% (S1), 70% (S2), and 80% (S3) of field capacity; nitrogen FTL rates were set at 100% of the baseline fertilization amount (100% BFA, N 643.20 g·year^{-1}, P 473.37 g·year^{-1}, and K 492.29 g·year^{-1}) (F1), 70% BFA (F2), 130% BFA (F3), and 160% BFA (F4). The treatments of drip irrigation and fertigation (DIF) were H1 (100% BFA, 60% FC), H2 (100% BFA, 80% FC), H3 (160% BFA, 60% FC), and H4 (160% BFA, 80% FC), along with a control group (CK) without any management, totaling 12 experimental combinations. The results showed that the H4 had the most significant promoting effect on the height, DBH, and volume increments. All treatments had little effect on the soil bulk density of the plantation but significantly impacted soil capillary porosity and pH. Compared to DI, soil nutrient and organic matter content were more sensitive to FTL. Appropriate FTL and DI can increase soil sucrase activity. Soil urease activity tended to increase with higher FTL rates, and higher DI levels also positively influenced urease activity. Excessive or insufficient soil moisture and nutrients negatively impacted soil cellulase and catalase activities. Correlation analysis revealed no significant correlation between the growth of *P. × canadensis* 'Zhongliao 1' and soil nutrient content, but significant or highly significant correlations existed between growth and soil porosity and related enzyme activities. Comprehensive evaluation using a membership function indicated that high FTL levels (F4) were more conducive to the simultaneous improvement of the growth and soil fertility of the plantation, followed by H4 and F1, suggesting that high FTL is the key factor affecting the growth of 10-year-old *P. × canadensis* 'Zhongliao 1' plantations and the restoration of stand productivity, with moisture being secondary.

Keywords: poplar plantation; fertilization and drip irrigation; soil physicochemical properties; enzyme activities; sustainable operation and management

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1. Introduction

Populus spp. is one of the most widely distributed and extensively cultivated tree species globally, known for its broad phenotypic diversity and environmental adaptability [1]. It has become crucial for global timber supply, bioenergy production, and ecological protection [2,3]. Currently, poplar plantations cover approximately 9.4 million hectares worldwide [4], and they are a vital component of forestry production, renewable bioresources, and forest carbon sinks in northern China [5]. China leads the world in poplar plantation area, with 7.57 million hectares (according to the 2018 Ninth Forest Inventory of China) [6], representing 13% of the country's total planted forest area, making it the top choice for afforestation in five major reserve forest regions [7].

However, poplar varieties exhibit substantial growth variability across different regions, influenced by site conditions [8]. Their growth can rapidly deplete soil fertility, especially in short-rotation plantations where frequent timber harvesting limits nutrient cycling [9]. Additionally, many poplar plantations are established in resource-limited, arid, or semi-arid regions, often with extensive management practices. As these stands mature, the water consumption of poplar plantations can exceed the precipitation, leading to significant unintended soil moisture depletion [10,11]. This can result in decreased productivity, reduced ecological functions, and soil degradation over time [12]. Climate change projections indicate a decrease in summer precipitation and rising temperatures in the North China Plain [13], which may exacerbate land desertification, soil erosion, and soil fertility decline [14]. These challenges present significant obstacles for poplar, a species with high water and nutrient demands.

Field practices have demonstrated that irrigation and fertilization are crucial for enhancing plant growth and productivity, especially under conditions of limited soil moisture and nutrient availability [15–17]. These practices have been widely adopted in the cultivation of poplar plantations in China [18,19]. However, irrigation and fertilization can also have environmental impacts; improper irrigation can lead to water waste [20], soil compaction, and reduced water-use efficiency [21], while long-term fertilization is likely to reduce the enzyme activity of soil [22] and may not always enhance plantation productivity, particularly given the high environmental and economic costs [4]. Furthermore, the overall irrigation management in Chinese plantations is relatively low, with timing often based on farmers′ experience, potentially reducing irrigation water efficiency and limiting the full growth potential of trees [23].

Soil enzymes are proteins with catalytic activity secreted or released by microorganisms, fine roots, and soil animals. They participate in critical ecological processes (such as organic matter decomposition, soil microbial nutrient acquisition, and material cycling flow in soil ecosystems) and are sensitive indicators of soil quality evaluation [24]. Water and fertilizer regulation is essential for the soil microcosm, physiological growth, and yield quality. Up to now, drip irrigation, one of the most widely used and water-efficient irrigation methods globally, offers precise soil moisture regulation according to plant root water demand and soil characteristics [25,26]. This method is commonly used in agricultural and horticultural irrigation management [27–30] and can result in higher water-use efficiency and lower leaching compared to surface water irrigation [31]. In addition, a study has shown that different water–fertilizer combination treatments and irrigation treatments were applied to the crop and there were significant increases in catalase, sucrase, and polyphenol oxidase in the soil with increasing irrigation amounts [32]. It is well known that fertigation, an agricultural technique integrating irrigation and fertilization, typically focuses on optimizing timing, moisture patterns, and application intensity to enhance resource use efficiency [33]. Drip irrigation and fertigation (DIF) are currently effective practices in artificial afforestation for improving resource use efficiency [34,35]. However, current research on water and nutrient management in poplar plantations often considers only individual factors [23,36–39], and there is a lack of studies on how water and nutrient supply under DIF conditions affect poplar plantation growth and soil properties.

Therefore, it is imperative to use more diversified and resource-efficient planting systems, coupled with effective water-saving and environmentally friendly irrigation and fertilization practices, to cultivate poplar trees that are of high quality, fast-growing, and high-yielding. In light of these challenges, this study focuses on a 10-year-old plantation of the P. × *canadensis* 'Zhongliao 1' (cultivation varieties of *P. canadensis* in northern China) variety, an important cultivar suitable for the Liaoning region of China. The specific objectives of this study are (i) to compare the growth differences in *P.* × *canadensis* 'Zhongliao 1' under different DIF treatments; (ii) to analyze the effects of these treatments on soil enzyme activity in the *P.* × *canadensis* 'Zhongliao 1' plantation; and (iii) to elucidate how DIF treatments alter soil nutrient and physical properties in the *P.* × *canadensis* 'Zhongliao 1' plantation. We hope to provide insights into water and nutrient management models for long-term poplar cultivation in resource-limited regions, thereby enhancing the quality and efficiency of plantations.

2. Materials and Methods

2.1. Experiment Site

The field experiment was conducted at the Heishan Experimental Base of the Poplar Research Institute in Liaoning Province, China (122°41′45″ E, 41°61′00″ N). The site is located in the lower reaches of the Songliao Plain, at an elevation of 39.0 m. The region experiences a temperate continental monsoon climate, characterized by distinct seasons and synchronous precipitation and heat. The area is dominated by SSW winds throughout the year, with a pronounced monsoon influence. The soil in the experimental site was classified according to the World Soil Resources Reference Base (WRB), and its type was confirmed to be sandy loam soil [40]. The soil in the experimental field was classified according to the World Soil Resources Reference Base (WRB), and its type was confirmed to be sandy loam. Surveys before the experiment showed that the initial properties of the surface soil (0–20 cm) were as follows: pH_{H2O} 7.08, 1.17 $g{\cdot}kg^{-1}$ total N, 0.37 $g{\cdot}kg^{-1}$ total P, 10.52 $g{\cdot}kg^{-1}$ total K, 90.82 $mg{\cdot}kg^{-1}$ available N, 22.71 $mg{\cdot}kg^{-1}$ available P, 86.68 $mg{\cdot}kg^{-1}$ available K, 23.93 $g{\cdot}kg^{-1}$ organic matter, soil water content 16.50%, porosity 33.91%, and bulk density 1.71 $g{\cdot}cm^{-3}$. The average annual temperature is 8.3 °C, with a maximum of 35.0 °C and a minimum of −27.6 °C. The frost-free period lasts for 165 days. The site receives an average of 2550.4 h of sunshine per year, with an average annual precipitation of 568.4 mm, primarily concentrated in July and August. The average annual potential evapotranspiration is 1798.8 mm. Notably, the annual evaporation rate is 3.16 times higher than the annual rainfall, indicating the critical importance of irrigation for the growth and cultivation of plantations in this region.

2.2. Experiment Design

The tested poplar variety is *P.* × *canadensis* 'Zhongliao 1' with a tree age of 10 years old (planted in the spring of 2013 using 30 cm long cuttings). The planting spacing was 4 m × 6 m, and the total experimental forest area was 10.6 hectares. In late September 2022, we installed a surface drip irrigation system in the experimental forest, with emitters having a flow rate of 2 $L{\cdot}h^{-1}$ and spaced 50 cm apart. The drip irrigation pipes were laid along the rows between the trees. The drip irrigation and fertilization experiment began in early May 2023, using a randomized block design with three blocks. Each block included 12 subplots: 4 DIF treatments (H1, H2, H3, and H4), 4 fertilization-only treatments (F1, F2, F3, and F4), 3 drip irrigation-only treatments (S1, S2, and S3), and 1 control group without any treatments (CK) (Table 1). The area of the subplot was 40 m × 60 m, including 100 trees, and one separate tree row (4 m spacing) was set between subplots.

Table 1. Design of water and fertilizer coupling experiment.

Treatments		Fertigation Amounts (g)			Drip Irrigation Thresholds
		N	P	K	
Drip irrigation and fertilization	H1	643.20	473.37	492.29	60% of field capacity
	H2	643.20	473.37	492.29	80% of field capacity
	H3	1029.12	757.39	787.66	60% of field capacity
	H4	1029.12	757.39	787.66	80% of field capacity
Only fertilization	F1	450.24	331.36	344.60	non-irrigation
	F2	643.20	473.37	492.29	non-irrigation
	F3	836.16	615.38	639.97	non-irrigation
	F4	1029.12	757.39	787.66	non-irrigation
Only drip irrigation	S1	0	0	0	80% of field capacity
	S2	0	0	0	70% of field capacity
	S3	0	0	0	60% of field capacity
Non-irrigation and non-fertigation	CK	0	0	0	non-irrigation

The baseline fertilization amount (BFA) in this study was determined based on the method by Lan et al. [41]. At the end of the 2021 and 2022 growing seasons, we measured the biomass of roots, stems, branches, and leaves, as well as the N, P, and K nutrient content of these organs for three standard trees (the average tree height (H), average crown width (CW), and average diameter at breast height (DBH) are 19.78 ± 0.62 m, 6.96 ± 0.89 m, and 25.07 ± 1.03 cm, respectively). The annual nutrient uptake of N, P, and K by the entire *P.* × *canadensis* cv. 'Zhongliao 1' was used to determine the BFA per tree (N 643.20 g·year^{-1}, P 473.37 g·year^{-1}, and K 492.29 g·year^{-1}) (Table 2), and four fertilization levels were set: 70% BFA, 100% BFA, 130% BFA, and 160% BFA. The fertilizer used was a water-soluble compound fertilizer (Monbond, Hebei Monband Water Soluble Fertilizer Co., Ltd., Shijiazhuang, China), with the main components being urea (N content ≥ 46%), monoammonium phosphate (N content ≥ 12%, P_2O_5 ≥ 60%), and potassium chloride (K_2O ≥ 60%). The annual fertilization amount per tree was evenly distributed across four stages, completed with irrigation in mid-May, mid-June, mid-July, and mid-August of 2023. Before each fertilization, the drip irrigation system was run for 1 h to ensure uniform distribution of the fertilizer in the root zone. The initiation and termination of the drip irrigation were based on data collected by soil moisture sensors (EC-5, Decagon Devices Inc., Pullman, WA, USA) installed in the drip irrigation system. Irrigation commenced when the soil moisture data at a depth of 20 cm fell below the set levels of field capacity (60%, 70%, and 80% of field capacity), and each irrigation session lasted for 8 h.

2.3. Measurement of Growth Traits

In early May 2023, prior to the experimental treatment, and in late October 2023, after the growing season had concluded, 50 sample plants with comparable growth status were randomly selected for each treatment. The Spiegel-Relaskop (Diangjiang Technology Co., Ltd., Shanghai, China) and tape measure (YM-CL001, Yuma Tools Co., Ltd., Zhengzhou, China) were utilized to measure the H and DBH of the sample plants, respectively. The estimation of trunk volume is based on the method of Peng et al. [42]. It can be expressed as follows:

$$V = g_{1.3} \times H \times f_{1.3} \quad (1)$$

where V is the trunk volume; $g_{1.3}$ is the basal area; H is the tree height; and $f_{1.3}$ is the breast height form factor ($f_{1.3}$ = 0.44; considered an estimate). The above survey and statistics results are shown in Table 3.

Table 2. Standard wood traits survey and annual BFA of *P.* × *canadensis* 'Zhongliao 1'.

Organs	Biomass (kg)	Cumulative Absorption of Nutrient Elements (g)			Annual Absorption of Nutrient Elements (g)		
		N	P	K	N	P	K
Trunk	307.99	1187.74	803.17	839.66	643.20	473.37	492.29
					70% of Annual Absorption of Nutrient Elements (g)		
					N	P	K
Branch	124.65	779.95	474.27	588.24	450.24	331.36	344.60
					130% of Annual Absorption of Nutrient Elements (g)		
					N	P	K
Root	54.58	371.40	296.06	414.55	836.16	615.38	639.97
Leaf	14.71	325.81	85.69	131.55	160% of Annual Absorption of Nutrient Elements (g)		
					N	P	K
Total	1416.27	2264.92	1659.18	1973.82	1029.12	757.39	787.66

Table 3. Survey and statistics on growth characteristics (mean ± standard deviation).

Treatments	H (m)		DBH (cm)		V (m^3)	
	May	October	May	October	May	October
H1	19.54 ± 0.30	20.93 ± 0.37	25.97 ± 0.53	27.40 ± 0.46	0.431 ± 0.03	0.518 ± 0.03
H2	19.31 ± 0.13	20.86 ± 0.17	25.23 ± 0.34	26.88 ± 0.42	0.402 ± 0.01	0.496 ± 0.02
H3	18.55 ± 0.09	20.00 ± 0.07	25.42 ± 0.17	26.95 ± 0.10	0.394 ± 0.01	0.481 ± 0.01
H4	20.53 ± 0.38	22.18 ± 0.39	25.55 ± 0.49	27.28 ± 0.54	0.442 ± 0.02	0.547 ± 0.03
F1	20.53 ± 0.38	21.99 ± 0.04	25.57 ± 0.16	26.86 ± 0.13	0.395 ± 0.01	0.473 ± 0.01
F2	20.54 ± 0.42	21.75 ± 0.18	25.99 ± 0.44	27.20 ± 0.40	0.407 ± 0.02	0.477 ± 0.02
F3	18.30 ± 0.23	19.74 ± 0.27	25.18 ± 0.28	26.53 ± 0.27	0.372 ± 0.01	0.447 ± 0.01
F4	19.04 ± 0.22	20.34 ± 0.30	25.19 ± 0.30	26.45 ± 0.29	0.392 ± 0.01	0.464 ± 0.02
S1	19.65 ± 0.13	21.07 ± 0.15	24.81 ± 0.29	26.34 ± 0.29	0.388 ± 0.01	0.472 ± 0.01
S2	21.01 ± 0.40	22.52 ± 0.39	23.99 ± 0.27	25.55 ± 0.26	0.387 ± 0.01	0.476 ± 0.02
S3	19.07 ± 0.24	20.37 ± 0.31	25.40 ± 1.62	26.78 ± 1.04	0.438 ± 0.03	0.520 ± 0.04
CK	19.55 ± 0.03	20.67 ± 0.19	24.99 ± 0.74	26.07 ± 0.15	0.392 ± 0.02	0.453 ± 0.03

After the three standard trees were felled, their leaves, branches, trunks, and root systems (including the tap root, thick root, and fine root) were carefully distinguished and fully collected. Concurrently, we gathered the soil containing fine and capillary roots, washed it with water, and screened it through a 60-mesh sieve to extract as many fine roots as possible. These roots were then placed in the laboratory to dry naturally before further processing. The collected organ samples were dried in an oven at 105 °C for 2 h and subsequently dried at 65 °C until reaching a constant weight, with their dry matter weights considered as biomass. The dried organs were then crushed, ground, and passed through a sieve with a hole diameter of 0.15 mm (100 mesh). The N content was determined using a fully automatic Kjeldahl nitrogen analyzer (Foss Tecator Kjeltec7500, Eden Prairie, MN, USA), while the P content was determined by molybdenum antimony anti-spectrophotometry, and K content was determined by atomic absorption method [43]. All elemental determinations were conducted with assistance from Ruiyuan Biotechnology Co., Ltd. (Nanjing, China). Finally, the total amount of each element in every organ of the standard wood was calculated, with the total for each element being the product of its content and the corresponding biomass.

2.4. Soil Sample Collection

On 20 October 2023, we sampled soil in each subplot using 36 sample quadrats (1 m × 1 m). In each subplot, the distance between the drippers was 50 cm, each of our sample quadrats was a square formed by 8 drippers, and the soil sampling point was the central area of the square of the random sample quadrat. Weeds and litter covering the quadrats were cleared before collecting soil samples. The cutting ring method [44] was employed to extract soil samples from the 0–20 cm layer at the center of each small quadrat to measure soil bulk density and porosity. Using PVC pipes (10 cm in height × 5 cm in diameter), 3 undisturbed soil samples were randomly collected from each small quadrat′s 0–20 cm layer, combined into a single soil sample, sealed with a safety film, and transported to a refrigerator at 4 °C for analysis of soil pH, nutrients, and enzyme activities.

2.5. Determination of Soil Physicochemical Properties and Enzyme Activities

A total of 10g of the soil sample was weighed to make an extract with a water-to-soil ratio of 5:1, and then a pH meter was used (IS139, Shanghai Yimai Instrument Technology Co., Ltd., Shanghai, China) to measure its pH value (pH_{H2O}). Soil bulk density and capillary porosity were determined through the ring knife-soaking method [44]. Total soil nitrogen (TN) was analyzed using a Kjeldahl nitrogen analyzer (Foss Tecator Kjeltec7500, Eden Prairie, MN, USA). The ammonium N content in the soil was determined using a 2 $mol \cdot L^{-1}$ KCl extraction followed by the indophenol blue colorimetric method, and the nitrate N content was assessed using ultraviolet spectrophotometry. The available nitrogen (AN) in the soil is defined as the sum of ammonium N and nitrate N. Total phosphorus (TP) in the soil was quantified through the $NaHCO_3$ leaching–molybdenum antimony colorimetric method. Both total potassium (TK) and available potassium (AK) were measured using the ammonium acetate leaching–flame photometry method. The soil organic matter (OM) was analyzed using the potassium dichromate–H_2SO_4 oxidation method with external heating. Soil enzyme activities were cultured and extracted utilizing an Activity Assay Kit (Activity Assay Kit, boxbio, Nanjing, China), with soil urease, catalase, sucrase, and cellulase activities being quantified using a microplate reader (Tecan, infinite E plex, Männedorf, Switzerland). Specifically, urease activity (UA) was determined through the phenol-sodium hypochlorite colorimetric method, catalase activity (CaA) was measured using the $KMnO_4$ titration method, and sucrase activity (SA) and cellulase activity (CeA) were assessed using the 3.5-dinitrosalicylic acid colorimetric method. All of these experiments were performed with the help of Ruiyuan Biotechnology Co., Ltd. (Nanjing, China).

2.6. Data Analysis

Measured data are expressed as mean ± standard deviation. Although the sample trees with relatively uniform tree height, DBH, and volume growth were selected as the research objects for fertilization and drip irrigation, ensuring complete consistency was still challenging. Therefore, their growth amount was utilized as the measurement index in this study. The fuzzy mathematical affiliation function was used to calculate the composite score [45]. Statistical calculations were performed using Excel (Version 2019, Microsoft Corp, Albuquerque, NM, USA) and SPSS (Version 21, IBM Corp, Armonk, NY, USA). The correlation heat maps between soil and plant traits were completed by Origin (Version 2021, OriginLab Inc., Northampton, MA, USA). One-way ANOVAs and Duncan′s methods were used for ANOVAs and multiple comparisons (α = 0.05).

3. Results

3.1. Tree Height and DBH Growth Characteristics of P. × canadensis 'Zhongliao 1'

Figures 1 and 2 show the variation in tree height and DBH increment, respectively. The results indicate that drip irrigation and fertilization effectively promoted height growth in the 10-year-old *P. × canadensis* 'Zhongliao 1'. Compared to the CK, the increase in tree height (HI) was significant under all treatments, except for F2. The highest HI values under the three conditions—DIF, fertilization only, and drip irrigation only—were observed in treatments H4 (1.65 m), F1 (1.46 m), and S2 (1.51 m), representing increases of 47.76%, 30.75%, and 35.22% over the CK, respectively. The ranking of DBH increment (DBHI) was as follows: H4 > H2 > S2 > H3 > S1 > H1 > S3 > F3 > F1 > F4 > F2 > CK. Similar to HI, the differences in DBHI between the drip irrigation and fertilization treatments and the CK were significant, except for the F2 treatment. Specifically, the DBHI values for H4 (1.73 cm), F3 (1.35 cm), and S2 (1.57 cm) were 1.61, 1.25, and 1.45 times those of the CK, respectively. Overall, an appropriate combination of drip irrigation and fertilization was more beneficial for the height and DBH growth of *P.* × *canadensis* 'Zhongliao 1', with the H4 treatment showing the best performance.

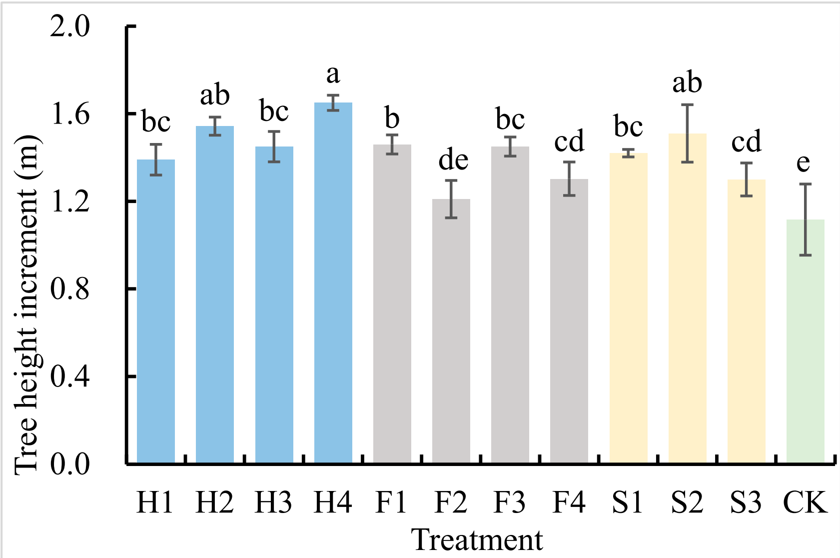

Figure 1. Tree height increment (HI) of *P.* × *canadensis* 'Zhongliao 1' under different fertilization and drip irrigation treatments. Broken lines with different letters indicate a significant difference ($p < 0.05$) as determined by analysis of variance and Duncan's multiple range test.

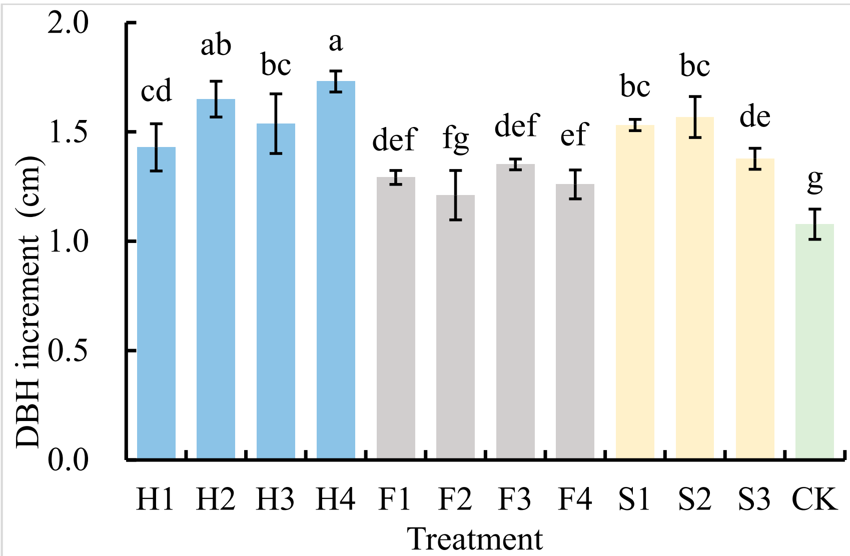

Figure 2. DBH increment (DBHI) of *P.* × *canadensis* 'Zhongliao 1' under different fertilization and drip irrigation treatments. Broken lines with different letters indicate a significant difference ($p < 0.05$) as determined by analysis of variance and Duncan's multiple range test.

3.2. Volume Change in P. × canadensis 'Zhongliao 1'

Figure 3 shows that the volume increment (VI) per tree in the CK was minimal in the 11th year (only 0.060 m^3), while drip irrigation and fertilization treatments significantly increased the volume per tree. Overall, the positive effect of DIF on volume growth was the most pronounced, followed by drip irrigation. The H4 treatment resulted in the highest VI (0.105 m^3), which was 39.07% and 19.44% higher than the best-performing treatments under fertilization only (F3) and drip irrigation only (S2), respectively, with the differences among these three treatments being statistically significant. Compared to the CK, H4, F3, and S2 increased the volume by 74.13%, 25.21%, and 45.79%, respectively, all reaching significant levels of difference. These results indicate that the H4 treatment is more conducive to the volume growth of *P. × canadensis* 'Zhongliao 1', consistent with the observed trends in height and DBH growth.

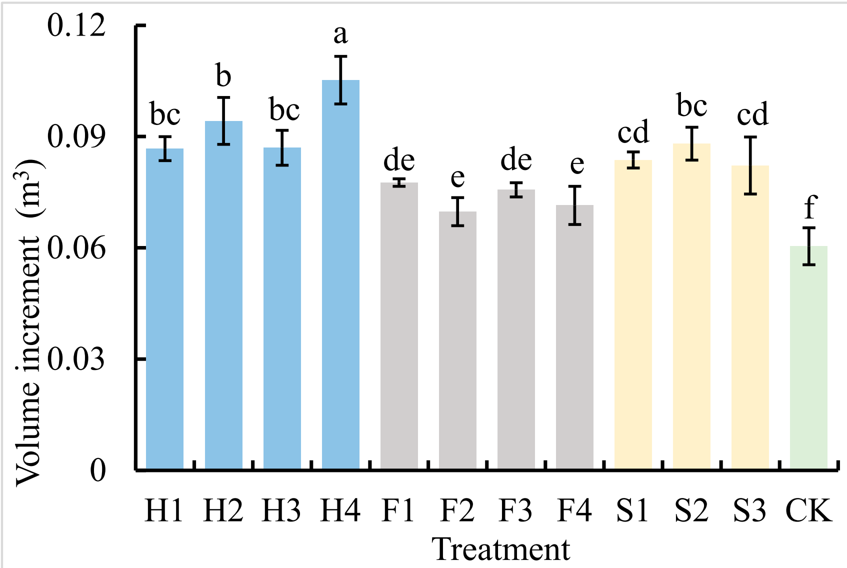

Figure 3. Volume increment (VI) of *P. × canadensis* 'Zhongliao 1' under different fertilization and drip irrigation treatments. Broken lines with different letters indicate a significant difference ($p < 0.05$) as determined by analysis of variance and Duncan's multiple range test.

3.3. Soil pH and Physical Properties of P. × canadensis 'Zhongliao 1' Plantation

The pH test results (Table 4) showed that both drip irrigation alone and fertilization alone (except for F3) significantly reduced the soil pH in the plantation. The most pronounced decreases were observed in the F4 and S3 treatments, with reductions of 38.79% and 24.66% compared to the CK, respectively. Although all four DIF treatments also reduced soil pH, the decreases were not statistically significant.

Overall, the impact of DIF on soil pH was weaker than that of fertilization alone, and fertilization was weaker than drip irrigation. Analysis of the soil physical properties revealed that drip irrigation and fertilization reduced BD and increased ToP, although these changes were not statistically significant. Drip irrigation and fertilization also increased CP, with the H1, H2, H4, and F3 treatments showing significant increases of 43.14%, 35.78%, 41.23%, and 34.97%, respectively, compared to the CK. However, the differences in NCP among the treatments were not significant (Table 4).

Table 4. Effects of fertilization and drip irrigation treatment on soil pH and physical properties.

Treatments	pH_{H2O} Valve	BD ($g{\cdot}cm^{-3}$)	ToP (%)	CP (%)	NCP (%)
H1	6.88 ± 0.17 abc	1.58 ± 0.05 a	38.98 ± 1.37 a	35.24 ± 3.07 a	3.74 ± 2.94 a
H2	7.52 ± 0.65 ab	1.53 ± 0.01 a	43.76 ± 2.94 a	33.43 ± 5.28 a	10.33 ± 3.25 a
H3	7.47 ± 0.72 ab	1.61 ± 0.03 a	38.62 ± 4.70 a	31.44 ± 2.59 ab	7.18 ± 2.81 a
H4	7.53 ± 0.63 a	1.60 ± 0.09 a	43.14 ± 1.24 a	34.77 ± 0.34 a	8.37 ± 0.96 a
F1	6.12 ± 0.30 cd	1.58 ± 0.07 a	41.30 ±2.94 a	31.92 ± 1.97 ab	9.38 ± 1.03 a
F2	6.71 ± 0.16 bc	1.57 ± 0.04 a	40.74 ± 3.11 a	31.44 ± 1.76 ab	9.31 ± 4.07 a
F3	7.37 ± 0.32 ab	1.59 ± 0.02 a	37.74 ±1.95 a	33.23 ± 2.58 a	4.51 ± 0.76 a
F4	5.44 ± 0.23 d	1.62 ± 0.07 a	44.05 ± 9.66 a	30.14 ± 1.50 ab	13.91 ± 8.91 a
S1	6.46 ± 0.34 c	1.57 ± 0.08 a	40.62 ± 2.99 a	31.97 ± 0.21 ab	8.66 ± 2.83 a
S2	6.53 ± 0.59 c	1.66 ± 0.04 a	38.42 ± 2.69 a	27.79 ± 1.80 ab	10.63 ± 4.25 a
S3	6.06 ± 0.38 cd	1.62 ± 0.03 a	40.29 ± 1.51 a	32.24 ± 2.71 ab	8.05 ± 4.15 a
CK	7.55 ± 0.35 a	1.68 ± 0.12 a	34.14 ± 5.69 a	24.62 ± 3.86 b	9.52 ± 5.69 a

The different letters indicate a significant difference ($p < 0.05$) as determined by analysis of variance and Duncan's multiple range test in the table.

3.4. Soil Nutrient Contents of P. × canadensis 'Zhongliao 1' Plantation

Soil nutrient content is shown in Table 5. Drip irrigation and fertilization increased the TN, with the highest TN levels observed in the F2 and F4 treatments, significantly higher than in the CK. The impact of drip irrigation on TP was not significant, but the F1 and F4 fertilization treatments significantly increased the total phosphorus content.

Table 5. Soil nutrient contents under different fertilization and drip irrigation treatments.

Treatments	TN ($g{\cdot}kg^{-1}$)	TP ($g{\cdot}kg^{-1}$)	TK ($g{\cdot}kg^{-1}$)	AN ($mg{\cdot}kg^{-1}$)	AK ($mg{\cdot}kg^{-1}$)	OM ($g{\cdot}kg^{-1}$)
H1	1.77 ± 0.38 abc	0.37 ± 0.03 d	10.39 ± 0.74 c	94.17 ± 18.74 cd	189.34 ± 35.62 c	28.81 ± 6.17 b
H2	1.49 ± 0.08 c	0.44 ± 0.08 cd	10.74 ± 1.00 bc	76.76 ± 19.33 d	232.31 ± 42.43 bc	24.25 ± 0.77 b
H3	1.55 ± 0.36 c	0.49 ± 0.17 cd	11.33 ± 2.20 bc	107.45 ± 10.84 c	333.30 ± 114.09 bc	27.65 ± 7.24 b
H4	1.85 ± 0.30 abc	0.51 ± 0.13 cd	12.08 ± 0.84 bc	95.24 ± 8.30 cd	357.18 ± 120.63 bc	30.08 ± 5.63 ab
F1	1.73 ± 0.20 abc	0.81 ± 0.05 b	13.18 ± 2.32 b	115.53 ± 16.99 c	416.29 ± 152.87 ab	28.52 ± 1.89 b
F2	1.98 ± 0.27 ab	0.45 ± 0.07 cd	10.95 ± 1.78 bc	111.64 ± 17.10 c	342.75 ± 54.85 bc	37.80 ± 7.43 a
F3	1.61 ± 0.08 bc	0.52 ± 0.08 cd	10.12 ± 0.27 c	75.67 ± 18.65 d	212.97 ± 32.26 c	24.73 ± 3.88 b
F4	2.12 ± 0.06 a	0.96 ± 0.07 a	15.57 ± 2.28 a	277.57 ± 18.05 a	540.14 ± 140.81 a	32.38 ± 0.54 ab
S1	1.67 ± 0.125 bc	0.61 ± 0.09 c	12.13 ± 0.84 bc	97.16 ± 13.51 cd	301.92 ± 49.94 bc	26.81 ± 4.22 b
S2	1.51 ± 0.09 c	0.52 ± 0.02 cd	11.02 ± 0.98 bc	118.37 ± 8.62 c	244.32 ± 105.77 bc	26.20 ± 3.55 b
S3	1.58 ± 0.07 bc	0.49 ± 0.07 cd	11.71 ± 0.36 bc	145.67 ± 1.12 b	287.62 ± 134.73 bc	27.68 ± 3.11 b
CK	1.47 ± 0.19 c	0.49 ± 0.09 cd	10.68 ± 0.61 bc	95.77 ± 15.44 cd	189.13 ± 73.49 c	23.78 ± 4.32 b

The different letters indicate a significant difference ($p < 0.05$) as determined by analysis of variance and Duncan's multiple range test in the table.

Except for the F4 treatment, which had a TK significantly higher than the CK (1.46 times that of CK), other treatments maintained relatively stable TK levels. Additionally, high fertilization (F4) and high irrigation (S3) significantly increased the AN, while low fertilization (F1) and high fertilization (F4) significantly increased the AK. The highest OM was found in the F2 treatment, significantly higher than in the CK, followed by the F4 and H4 treatments.

3.5. Soil Enzyme Activity of P. × canadensis 'Zhongliao 1' Plantation

Table 6 shows the effects of fertilization and drip irrigation on soil enzyme activity. For UA, the highest activity was observed in the S3 treatment, which was 0.10 $mg{\cdot}g^{-1}$ higher than that of the CK. This difference was significant compared to the other nine treatments, except for H1 and S1, where the differences were not significant. The results for CaA indicated that the highest soil catalase activity was found in the F3 treatment, which significantly differed from the CK. However, the H4, F4, and F3 treatments significantly reduced catalase activity, with reductions of 33.24%, 8.98%, and 10.02% compared to CK, respectively. The results for SA showed the following activity ranking: H4 > F3 > S1 > F1 > H2 > H1 > F2 > S3 > S2 > H3 > CK > F4. Among these treatments, the sucrase activity under H4 was significantly higher than in the other ten treatments and was 1.95 times that of the CK. Additionally, compared to the CK, all treatments except H3 and F4 showed significantly higher sucrase activity. However, both drip irrigation and fertilization reduced CeA, with all treatments except S3 showing significantly lower CeA compared to CK.

Table 6. Effects of fertilization and irrigation treatment on soil enzyme activities.

Treatments	UA ($mg \cdot g^{-1}$)	CeA ($U \cdot g^{-1}$)	CaA ($mg \cdot g^{-1}$)	SA ($mg \cdot g^{-1}$)
H1	0.47 ± 0.03 abc	16.87 ± 2.52 cd	7.62 ± 0.32 bc	52.23 ± 4.35 def
H2	0.43 ± 0.05 bcd	15.54 ± 1.23 cde	8.17 ± 0.24 ab	56.69 ± 3.43 cde
H3	0.39 ± 0.03 cd	13.02 ± 1.83 e	7.79 ± 0.30 bc	42.95 ± 3.06 gh
H4	0.40 ± 0.05 cd	19.00 ± 2.25 bc	5.12 ± 0.42 e	79.11 ± 4.25 a
F1	0.40 ± 0.03 cd	13.19 ± 2.09 e	8.16 ± 0.32 ab	58.32 ± 4.59 cd
F2	0.41 ± 0.05 cd	15.70 ± 1.15 cde	7.18 ± 0.33 cd	51.73 ± 5.02 def
F3	0.42 ± 0.02 bcd	18.19 ± 1.05 bc	8.56 ± 0.39 a	71.22 ± 3.90 b
F4	0.43 ± 0.04 bcd	14.19 ± 1.84 de	6.98 ± 0.44 d	37.08 ± 3.24 h
S1	0.49 ± 0.05 ab	16.72 ± 1.12 cd	7.61 ± 0.39 bc	63.37 ± 4.48 c
S2	0.35 ± 0.05 d	17.59 ± 2.21 bcd	6.59 ± 0.26 d	48.34 ± 1.70 fg
S3	0.52 ± 0.05 a	20.97 ± 1.86 ab	7.65 ± 0.37 bc	49.91 ± 2.86 ef
CK	0.42 ± 0.06 bcd	23.59 ± 2.46 a	7.67 ± 0.33 bc	40.52 ± 4.57 h

The different letters indicate a significant difference ($p < 0.05$) as determined by analysis of variance and Duncan's multiple range test in the table.

3.6. Correlation Analysis of Soil Physicochemical Properties and Plant Treatments

Correlation analysis results (Figure 4) indicate extremely significant positive correlations among HI, DBHI, and VI ($p < 0.01$). Both HI and VI exhibit extremely significant positive correlations with CP, ToP, and SA. Additionally, DBHI shows a significant positive correlation with SA ($p < 0.05$). Conversely, HI and CeA, as well as VI and CaA, exhibit extremely significant negative correlations ($p < 0.01$), while DBHI and CaA demonstrate a significant negative correlation ($p < 0.05$). The correlations between soil physicochemical properties reveal that UA is significantly positively correlated with CaA. pH is significantly negatively correlated with NCP, significantly positively correlated with SA, and extremely significantly negatively correlated with TP, TK, AN, and AK. ToP is extremely significantly positively correlated with both CP and NCP and extremely significantly negatively correlated with BD. NCP is also significantly correlated with CP and TP, while CeA shows significant correlations with BD, CP, TP, and AK. Furthermore, SA is extremely significantly negatively correlated with AN, and TK, AN, and AK exhibit extremely significant positive correlations with each other, as well as with TN and TP.

3.7. Comprehensive Evaluation of Different Treatments of Fertilization and Irrigation Regulation

The membership function method was used to comprehensively evaluate the plant traits (HI, DBHI, and VI) and soil traits (T, TP, TK, AN, AK, OM, UA, CeA, CaA, SA, and CP) under different treatments (Table 7). The results showed that the comprehensive scores under fertilization and drip irrigation treatments were higher than those of the CK, and the top three scores were F4, H4, and F1.

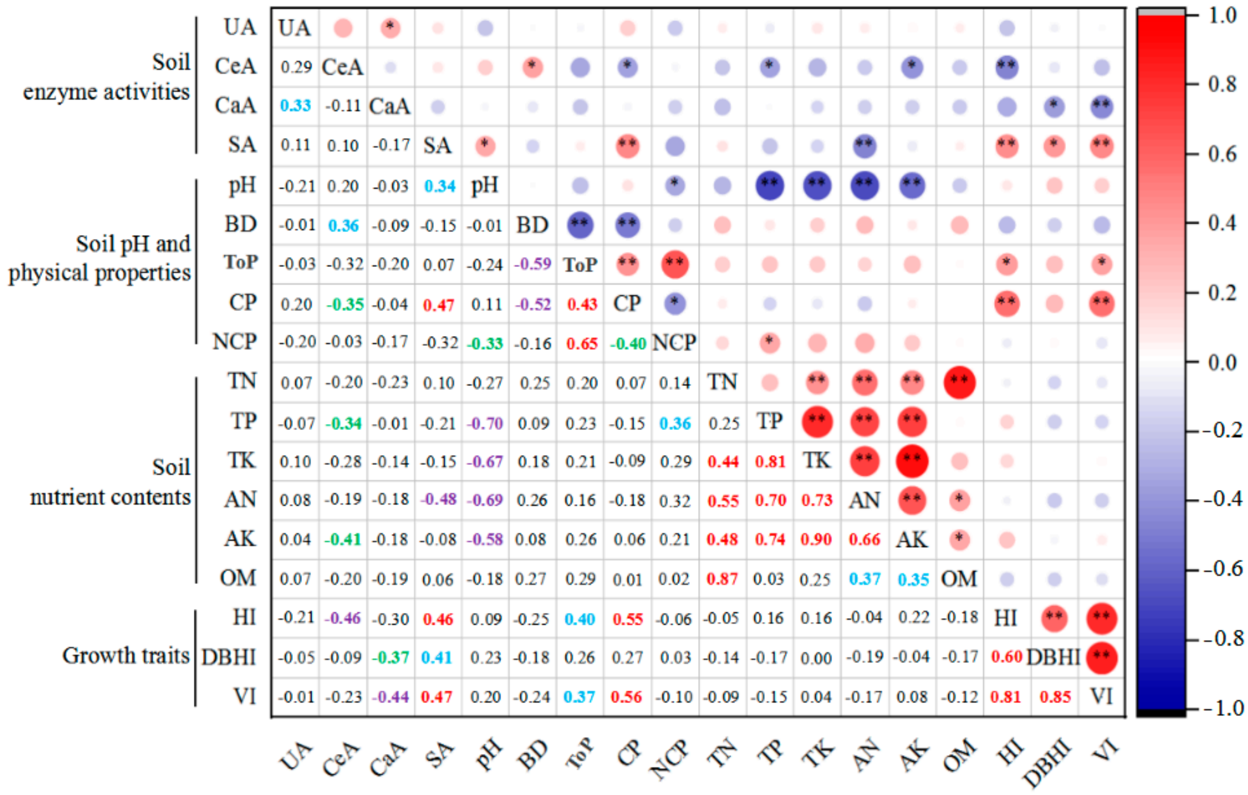

Figure 4. Correlation analysis of soil and plant traits. The red font indicates a significant positive correlation ($p < 0.01$), the blue font indicates a significant positive correlation ($p < 0.05$), the purple font indicates a significant negative correlation ($p < 0.01$), the green font indicates a significant negative correlation ($p < 0.05$), and the black font indicates that there is a positive or negative correlation but it is not significant. The upper right corner is the level of significance, the size and color of the circle indicate the degree of correlation, the color from white to dark blue indicates a stronger negative correlation, and the color from white to deep red indicates a stronger positive correlation. The '*' means $p < 0.05$, and the '**' means $p < 0.01$. The right color column represents the correlation coefficient.

Table 7. Comprehensive evaluation of plant traits and soil physicochemical properties.

Treatments	Comprehensive Score	Ranking	Treatments	Comprehensive Score	Ranking
H1	0.297	11	F3	0.319	8
H2	0.313	9	F4	0.706	1
H3	0.330	7	S1	0.426	4
H4	0.518	2	S2	0.301	10
F1	0.485	3	S3	0.416	5
F2	0.363	6	CK	0.175	12

4. Discussion

Water and nutrients are the two primary resources limiting plant growth [46,47]. To date, optimizing and enhancing field water and fertilizer management systems remains the most effective strategy for ensuring adequate resource acquisition by plants and is a key focus of current research [28,48,49]. Poplars, known for their rapid growth and high water and nutrient demands, are widely used in timber production [11,50,51]. However, many poplar plantations are either extensively managed or left unmanaged for extended periods. Limited innovation in irrigation theory and technology has prevented these plantations from fulfilling the initial expectations of combining timber production with environmental protection and enhancement [52]. This is particularly evident in arid or nutrient-poor regions, where stand functions and productivity are far from satisfactory [53,54].

The integration of drip irrigation and fertilization technology is lauded as the most advanced water and fertilizer management approach, significantly improving crop water and nutrient use efficiency and yield [55,56]. For trees, height, DBH, and volume are not only crucial indicators in forest resource surveys but also vital parameters reflecting forest growth, productivity, and ecological functions [57]. Thus, examining changes in these stand factors under combined water and fertilizer treatments is essential for evaluating stand growth characteristics. Research has shown that appropriate water and fertilizer coupling significantly promotes the growth and water-nutrient use efficiency of young mango trees (*Mangifera indica*) [58] and supports the overall growth of Masson pine (*Pinus massoniana*) seedlings [59]. In this study, both fertilization and drip irrigation enhanced the height, DBH, and volume growth of 10-year-old *P.* × *canadensis* 'Zhongliao 1', indicating that these practices are crucial for sustaining the growth and wood production of this poplar variety, consistent with previous findings on *P. tomentosa* [60]. Moreover, annual growth rates of 10-year-old *P.* × *canadensis* 'Zhongliao 1' varied under different fertilization levels and drip irrigation treatments. As fertilization and irrigation levels increased, the increments in height, DBH, and volume varied, likely due to differences in nutrient and water uptake efficiency under varying soil conditions during the growth period [61]. This suggests that higher fertilization or irrigation levels do not necessarily lead to better growth. Compared to single fertilization or irrigation measures, the management strategy combining high fertilization and high irrigation (H4) more effectively stimulated the rapid growth of 10-year-old *P.* × *canadensis* 'Zhongliao 1', further verifying that the combined effects of water and fertilizer can indeed achieve the dual goals of enhancing both water and nutrient availability [59,62].

Plant growth is closely related to environmental factors, and changes in soil physical and chemical properties inevitably trigger stress responses in plants [63,64]. Among the various methods that can alter soil physical and chemical properties, irrigation and fertilization are among the most direct and effective approaches. Drip irrigation not only reduces groundwater consumption but also effectively decreases soil nutrient leaching [65]. Therefore, exploring soil property changes under fertilization and drip irrigation conditions is of great significance for the growth and practical management of plantations, including aspects such as soil pH, physical characteristics, and nutrient content. Our research found that both single fertilization and irrigation generally led to a decrease in soil pH in poplar plantations, possibly due to irrigation water input causing originally saline and slightly alkaline soils to acidify [66]. The application of fertilizers, particularly nitrogen fertilizers, can lead to the oxidation of NH_4^+ to NO_3^- in the soil, generating H^+ ions and lowering soil pH [67,68]. However, under combined water and fertilizer treatments, soil pH remained relatively stable, suggesting that reasonable fertilization paired with irrigation can maintain soil sustainability even in alkaline soils [58].

In addition to pH, soil permeability is a critical physical property that not only influences soil microbial activity and plant growth but also affects soil water movement and retention [22,69]. In this study, while fertilization and drip irrigation did not significantly affect soil bulk density and total porosity in the plantation, they did lead to a notable improvement in soil capillary porosity. These findings suggest that the enhanced aeration of soils resulting from the combined application of water and fertilizer is vital for promoting the effective functioning of soil structure in poplar plantations. Furthermore, our research also revealed that high fertilization levels significantly increased the content of nutrient elements (N, P, K, available N, and available K) and organic matter in the soil, providing a solid foundation for the growth and development of poplar roots, consistent with previous studies [70]. Overall, single drip irrigation had minimal impact on soil nutrient and organic matter content, reflecting the high water demand of poplars. The input of an appropriate amount of drip irrigation water did not lead to nutrient leaching, further demonstrating the advantages of drip irrigation technology [65,66]. Compared to single fertilization, soil nutrient and organic matter content were relatively lower under drip fertigation, possibly because drip irrigation better facilitated plant nutrient absorption, reducing nutrient residues in the soil [58,59]. Future studies should measure and analyze the nutrient content, biomass, and ecological stoichiometry of different organs (root, stem, leaf, and branch) of *P.* × *canadensis* 'Zhongliao 1' to further validate our hypotheses.

Studies have shown that various enzymes secreted by plant roots, soil microbes, and animals drive soil nutrient transformation, release, and cycling [66,71,72], and their activity is an important indicator of soil fertility and health [24]. Reasonable water and fertilizer management strategies help increase soil enzyme activity, thereby promoting organic matter mineralization, urea decomposition, and soil nutrient cycling [73]. In this study, soil urease activity increased with the level of fertilization, likely due to enhanced root metabolism and increased amino acid secretion by the roots of *P.* × *canadensis* 'Zhongliao 1' [74]. Higher drip irrigation volumes also positively influenced urease activity, possibly because water input increased enzyme diffusion rates [75]. Soil catalase, a redox enzyme, plays a critical role in quenching reactive oxygen species (ROS) in the soil and protecting cells from oxidative stress [76]. Research indicates that appropriate irrigation and fertilization can effectively increase soil microbial abundance and enhance catalase activity, thereby improving soil fertility [77]. However, excessive irrigation and fertilization may inhibit soil microbial activity, reducing catalase activity [58,78], a trend also observed in this study. Additionally, our research found that fertilization and drip irrigation improved soil sucrase activity, ensuring enhanced soil fertility. However, excessive fertilization reduced sucrase activity, primarily due to the decrease in soil pH caused by high fertilization levels [73]. High cellulase activity in soil reflects a stronger ability to decompose organic matter and release soil nutrients [79]. In this study, soil cellulase activity decreased due to fertilization and drip irrigation, potentially because cellulase activity was more sensitive to local temperature drops when soil samples were collected. Additionally, increased enzyme reaction products due to fertilizer input may have resulted in feedback inhibition, lowering enzyme activity. Conversely, water input likely enhanced the mobility of microbes, nutrients, and enzymes within the soil, leading to a gradual increase in cellulase activity with higher volumes of drip irrigation [75].

A correlation analysis reflects the degree of association between multiple target traits [80]. In this study, a significant positive correlation was observed among poplar height, diameter at breast height (DBH), and volume increment, indicating that these three growth traits maintain synchronization in growth under varying water and fertilizer management conditions. This finding aligns with the tree height–DBH growth model [81]. Notably, tree height and volume increment exhibited a significant positive relationship with soil capillary porosity, total porosity, and sucrase activity. In contrast, tree height showed a negative correlation with soil cellulase activity, while volume increment was negatively correlated with soil catalase activity. Additionally, an increase in DBH was positively correlated with sucrase activity but negatively correlated with catalase activity. Furthermore, we observed no apparent correlation between soil nutrient levels and the growth of this plantation, which diverges from the findings of previous studies [60]. Consequently, fertilization and drip irrigation likely influenced the growth of *P.* × *canadensis* 'Zhongliao 1' by altering soil physical structure and enzyme activity.

This comprehensive evaluation suggested that a higher fertilizer amount was more conducive to the simultaneous growth of the artificial forest and soil fertility, while a high fertilizer amount combined with high drip irrigation ranked second in effectiveness. This indicates that the adverse effects of poor soil on forest growth may be more pronounced than those of drought. The phenomenon is likely to be related to the extreme weather (frequent rainfall) in the year of fertilization, where the more arid soil gained relatively more water in the year, which weakened the role of the dropper. This also highlights that the increasing supply of exogenous nutrients as the stand ages could be a critical factor limiting the sustainable development of stands in the region, underscoring the importance of further exploration of optimal water and fertilizer management strategies. As is well known, the growth of forest trees is a long-term process, and their response to environmental changes often exhibits a lag [82]. Additionally, long-term growth may be influenced by legacy effects in the soil [83]. In this study, the short cycles of fertilization and drip irrigation treatments may have prevented the full growth response of *P.* × *canadensis* 'Zhongliao 1' from being realized in the early stages of the experiment. Furthermore, research has demonstrated that long-term fertilization and drip irrigation significantly affect the physical and chemical properties of soil, as well as the composition of soil microorganisms and related enzyme activities [66,84]. Short-term experimental treatments may not adequately capture the dynamic characteristics of these changes, leaving the extent of the *P.* × *canadensis* 'Zhongliao 1' response to long-term dynamics uncertain. Therefore, a future task will be to continue monitoring the dynamic changes in the growth of the *P.* × *canadensis* 'Zhongliao 1' plantation and soil properties under fertilization and drip irrigation conditions, in order to elucidate the interactions between forest growth factors and environmental factors. This focus is essential for achieving the sustainable management and development of poplar plantations.

5. Conclusions

This study investigated the effects of different fertilization and drip irrigation treatments on the main growth traits of 10-year-old *P.* × *canadensis* 'Zhongliao 1', as well as the changes in soil physicochemical properties and enzyme activities in the plantation. The results indicated that different levels of fertilization and drip irrigation had varying impacts on the growth of the poplar plantation, soil fertility, and related enzyme activities. Under the H4 treatment (160% BFA + 80% FC), the increments in tree height, DBH, and volume were the greatest. In terms of soil physical properties, soil capillary porosity and pH were more responsive to fertilization and drip irrigation, while changes in soil bulk density were minimal. Compared to DI treatments, soil nutrient and organic matter content were more sensitive to fertilization. Soil urease activity increased with higher fertilization rates, and high irrigation levels had a positive effect on urease activity. Excessive or insufficient soil moisture and nutrients were found to inhibit soil catalase activity. Fertilization and drip irrigation contributed to an increase in soil sucrase activity but reduced soil cellulase activity; high fertilization levels, in particular, decreased soil sucrase activity. Furthermore, the observed changes in growth are likely due to fertilization and drip irrigation altering soil capillary porosity and related enzyme activities. A comprehensive evaluation of the responses in growth, soil capillary porosity, and enzyme activities revealed that 160% BFA was most beneficial for the simultaneous improvement of plantation growth and soil fertility, with the fertilization and drip irrigation mode at 160% BFA + 80% FC being the second most effective. This suggests that the key limiting factor for the growth of *P.* × *canadensis* 'Zhongliao 1' and the enhancement of stand productivity in the study area may be the poor soil quality. However, for trees with a long growth cycle, the one-year experimental observation presents certain limitations. Therefore, it is essential to continue the fertilization and drip irrigation experiments to further analyze the dynamic changes in both aboveground and underground characteristics of this stand over the coming years, or even longer. Additionally, we plan to monitor further indicators, including plant traits (such as elemental content, stoichiometric characteristics, and photosynthetic traits), soil fertility, and the composition and structure of soil microbial communities. This comprehensive approach aims to explore how to achieve sustainable management, as well as enhance the quality and efficiency of poplar plantations through fertilization and drip irrigation.

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