Article

Effect of Initial Planting Density on Growth Traits and Wood Properties of Triploid Chinese White Poplar (*Populus tomentosa*) Plantation

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Abstract: Planting density primarily affects the yield and wood quality of plantations. There are multiple reports on the effects of planting density on growth traits and wood properties in young triploid Chinese white poplar (*Populus tomentosa*) plantations. Nevertheless, assessment of the effects of initial planting density is lacking for plantations older than ten years. Here, an 11-year-old plant density trial (2490, 1665, 1110, 832, 624, 499, and 416 trees/hm²) established with four hybrid clones (S86, B301, B331 and 1316) in northern China was used to determine the effect of initial planting density on growth traits (diameter at breast height (DBH), tree height (H), stem volume (SV) and stand wood volume (SWV)), basic wood density (BWD), and fiber properties (fiber length (FL), fiber width (FW), and the ratio of fiber length to width (FL/FW)). A total of 84 trees from four clones were sampled. In this study, the initial planting density had a highly significant effect on growth traits ($p < 0.001$) and had a moderate effect on FL. Overall, the reduction in initial planting density led to the increase in DBH, H, SV, and FL/FW. Triploid hybrid clones planted at 416 trees/hm² had the largest DBH, H, SV, FL/FW and the smallest SWV and FW. Clonal effects were also significant ($p < 0.05$) for all studied traits except for FL. Clone S86 had a higher growth rate and the largest BWD and FW. Clones–initial planting densities interaction was insignificant for all growth traits and wood properties. A weak and positive estimated correlation between BWD and growth traits (H, SV, SWV) within each planting density was seen. Our results demonstrate that an appropriate reduction in initial density in triploid Chinese white poplar plantations with long rotation is a suitable strategy to promote tree growth and retain excellent wood processing characteristics.

Keywords: initial planting density; *Populus tomentosa*; growth traits; basic wood density; fiber properties; triploid hybrid clones

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1. Introduction

Planting density is an important cultivation factor for stand wood production. It affects the survival rate, tree growth, wood quality, wood yield, and biodiversity of plantation [1,2]. For example, there is a negative correlation between planting density and stem volume (SV). At low planting densities, the individual tree volume growth increases [3,4]. According to Johnstone's findings [5], the initial planting density positively affects the mean diameter of hybrid poplars. In terms of 9-year mean diameter, the trees with the widest spacing (4.5 m × 4.5 m) were about twice as large as those with the closest spacing (1.5 m × 1.5 m). There was a strong influence of planting density on hybrid poplar trees individual stem dimensions or volume after 8 and 14 years in southern Quebec, Canada [6]. Liziniewicz et al. [7] recorded that the mean height of 23-year-old lodgepole pine increased with increasing initial planting density. The initial planting density also

affects wood properties, such as basic wood density (BWD) [8–10], fiber traits [10], and wood chemical composition [11]. Ahmed et al. [12] reported that the planting density influence on growth traits and wood properties is greater than that of the wood chemical composition. Research on guapuruvu [13] showed that planting density only significantly affected the fiber length (FL) and fiber wall thickness. Therefore, the initial planting density choice is crucial to maximize growth rate and optimize wood quality.

Chinese white poplar (*Populus tomentosa*) is a fast-growing native tree species in China. A natural triploid ($2n = 3x = 57$) Chinese white poplar was first discovered by Zhu [14] in 1992, and it was believed to be the product of hybridization between normal ($1n$) egg cells and natural ($2n$) pollen. Combined with the heterosis and ploidy of its parents, the triploid hybrid clones exhibit outstanding growth, fiber traits, and stress resistance. Higher growth rate, longer fibers, higher cellulose and holocellulose content, and lower lignin content characterize the triploid hybrid clones of Chinese white poplar [14,15]. The superior growth traits and wood properties of triploid hybrid clones make them become the preferred species in the pulp and paper industries and the sawn timber industry. As a high-yield fiber source, triploid hybrid clones are widely cultivated in northern China, especially in Shandong, Shanxi, Henan, Hebei, and other provinces.

Previous studies documented the influence of initial planting density on growth traits and wood properties of triploid hybrid clones of Chinese white poplar. For example, Wang et al. [16] reported that the initial planting density significantly affected diameter at breast height (DBH) and SV in a 4-year-old triploid Chinese white poplar plantation. The effects of initial planting density were significant for the DBH, tree height (H), SV, and BWD of a 3-year-old triploid Chinese white poplar plantation [17–19]. However, the initial planting densities and clone–initial planting density interactions had no significant effects on fiber properties or wood chemical components [18,19]. Triploid white poplar root distribution characteristics, root biomass, and its effect on water and soil nutrients under the wide-and-narrow spacing scheme were studied by Xi et al. [20] and Di et al. [21]. Additionally, the initial planting density was found to affect the root distribution of triploid Chinese white poplar significantly. Bo et al. [22] used a 9-year Chinese white poplar plantation in the North China Plain as material to evaluate the effect of planting density on growth traits. Their results show that planting density had significant effects on average tree H, DBH, SV, and stand wood volume (SWV).

Stand growth was not only affected by initial planting density, but also stand age [23]. Although a range number of studies about the effect of initial planting density on growth traits and wood properties have been performed on plantations less than six years old, no data are available on the effects of initial planting density on the growth traits and wood properties of triploid Chinese white poplar when the plantation is older than ten years. In this study, we examined the wood properties and growth traits of three triploid hybrid clones and one diploid hybrid clone in an 11-year-old Chinese white poplar plantation with seven initial planting densities. The objectives of this study were to: (1) evaluate the effect of initial planting density on growth traits and wood properties, (2) determine clonal effects and the initial planting densities–clones interactions on growth traits and wood properties, and (3) examine the relationships between growth traits and wood properties within initial planting density. Our findings provide new insights into the management of Chinese white poplar plantations.

2. Materials and Methods

2.1. Materials and Description of the Study Site

The study was conducted in the Huayang Forest Tree Nursery, located in the Huabei Great Plain ($36^{\circ}50'–37^{\circ}47'$ N, $113^{\circ}52'–115^{\circ}49'$ E), a flat, alluvial region that experiences warm-temperate, continental, and semi-arid monsoon climate zones. During the year, the average temperature in January is the lowest at -2.5°C , while the average temperature in July is the highest at 27°C . The annual total sunshine hours are about 2575 h with

approximately 198 frost-free days. These meteorological conditions come from 50 years (1960–2010) of data from Wei county meteorological stations.

The materials used in this study were taken from an 11-year-old planting density trial established by the Beijing Forestry University at Wei County, Hebei Province, China. In this experiment, seven initial planting densities, 2 m × 2 m (2490 trees/hm²), 2 m × 3 m (1665 trees/hm²), 3 m × 3 m (1110 trees/hm²), 3 m × 4 m (832 trees/hm²), 4 m × 4 m (624 trees/hm²), 4 m × 5 m (499 trees/hm²), and 4 m × 6 m (416 trees/hm²) with four hybrid clones (S86, B331, B301, and 1316) were used. The trials consisted of three triploid hybrid clones and one diploid clone in each planting density (Table 1). Clone S86, B331, and B301 were triploid with superior traits. The diploid clone 1316 was a superior tree of Chinese white poplar with a higher growth rate in northern China. Under the premise of the same management level, the experiment was established in a two-factor complete randomized block design. Seven planting densities were set up with three replicates and a total of 21 plots. Guard rows were planted around the entire perimeter to reduce edge effects. On each initial planting density, trees were sampled randomly in this study. A total of 84 trees from 4 clones were sampled to assess the effects of initial planting density on growth traits and wood properties of triploid Chinese white poplar. Thinning and fertilization were not carried out during the experiment.

Table 1. Identity and origin of the hybrid clones.

No.	Clone Identity	Parents	Level of Ploidy	Sex
1	B301	(<i>P. tomentosa</i> × <i>P. bolleana</i>) × <i>P. tomentosa</i>	Triploid	female
2	B331	(<i>P. alba</i> × <i>P. glandulosa</i>) × <i>P. tomentosa</i>	Triploid	female
3	S86	(<i>P. tomentosa</i> × <i>P. bolleana</i>) × (<i>P. alba</i> × <i>P. glandulosa</i>)	Triploid	male
4	1316	<i>P. tomentosa</i> × <i>P. tomentosa</i>	Diploid	male

2.2. Measurement of Tree Growth and Evaluation of Fiber Properties

In the winter of 2018, the poplar improvement program of Beijing Forestry University measured the total H and DBH of 11-year-old trees. The DBH and H of each selected tree were measured using a laser vertex and DBH meter tap, respectively. Calculate the SV of each sample according to the volume function used by Chen [24] (Equation (1)):

$$SV = 0.51340 H^{0.826956} D^{1.995375} \quad (1)$$

where SV is stem volume, H is tree height, and D is diameter.

The SWV was calculated using the following equation (Equation (2)):

$$SWV = SV \times N \quad (2)$$

where SWV is the stand wood volume in m³/hm², SV is the mean stem volume of each plot in each replicate in m³, and N is the number of survival trees per square kilometer.

For determining the influence of initial planting density on BWD and fiber traits, a sample tree was randomly selected from each plot, and the total of sampled trees was 84. A 10-cm-thick disk was taken from each sampled tree at breast height. A small rectangular pith-to-bark wood specimen with dimensions of 20 mm vertically × 20 mm radially was cut from the disk. The weight in air of the saturated wood sample and the oven dry weight of the same sample were determined to obtain the BWD of poplar by Smith's [25] maximum moisture content method.

To measure fiber properties, matchstick-sized wood samples were cut from the stem disk and macerated in a boiling 1:1 (v/v) mixture of acetic acid and hydrogen peroxide. After that, an L&W Fiber Tester was used to measure the FL and fiber width (FW) of each sample according to the method described in detail by Zhang et al. [26]. L&W Fiber Tester is based on image analysis. It can measure 50,000 of fibers on each sample in a few minutes. The ratio of fiber length to width (FL/FW) was calculated based on FL and FW measured for each sample.

2.3. Statistical Analysis

In this study, the diploid clone (1316) was excluded in the main statistical analysis. Therefore, only three triploid hybrids clones were involved in the main analyses of variance and correlation analysis. Analyses of variance were conducted using the UNIVARIATE procedure of the SPSS software (SPSS for Windows, version 20, SPSS, Chicago, IL, USA). Excel software was used to assist statistical analysis and drawing.

Variation among ramets of the sample clones was analyzed by analysis of variance, using a linear model (Equation (3)) within initial planting density:

$$X_{jk} = \mu + C_j + \varepsilon_{jk} \quad (3)$$

where X_{jk} is an observation on the k th ramet from the j th clone, μ is the general mean, C_j is the effect due to the j th clone, and ε_{jk} is a random error. In the linear model (Equation (3)), the clone–replicate effects were not considered because the three trees per clone were chosen randomly.

The linear model (Equation (4)) was used for joint analyses of the seven initial planting densities together:

$$Y_{ijkl} = \mu + B_i + C_j + S_k + C_j S_k + \varepsilon_{ijkl} \quad (4)$$

where Y_{ijkl} is an observation on the l th tree from the j th clone in the k th planting density at i th block, μ is the overall mean, B_i is the effect due to the i th block, C_j is the effect due to the j th clone, S_k is the effect due to the k th spacing, $C_j S_k$ is the interaction between the j th clone and k th planting density, and ε_{ijkl} is random error. All terms were considered random, except for block, which was considered as a fixed effect.

The phenotypic correlations of clonal means for each pair of traits within initial planting density were calculated and tested for significance according to SPSS PROC CORR software.

3. Results

3.1. Effect of Initial Planting Density on Growth Traits of Triploid Chinese White Poplar

The mean values, range of variation, and coefficients of phenotypic variation for the studied growth traits of the seven planting densities are presented in Table 2. Among the initial planting densities, the studied growth traits of triploid Chinese white poplar trees were significantly better than those of diploid clone 1316. Overall, the DBH, H, and SV of triploid Chinese white poplar decreased with the increase in initial planting density. For triploid hybrid clones, the trees planted at 416 trees/hm² had the largest DBH, H, and SV. The lowest DBH, H, and SV were found for 2490 trees/hm². The DBH, H, and SV differences between the lowest and highest means were 40.59%, 23.80%, and 135.81%, respectively. Clearly, growth was fastest for those planted at 416 trees/hm² and slowest for those planted at 2490 trees/hm². Among the seven initial planting densities, the SWV of triploid white poplar ranged from 145.0037 m³/hm² to 372.4605 m³/hm² after 11 years, with an average of 238.0123 m³/hm². The order of SWV was 1665 trees/hm² > 2490 trees/hm² > 1110 trees/hm² > 832 trees/hm² > 624 trees/hm² > 499 trees/hm² > 416 trees/hm², and the SWV at 1665 trees/hm² was significantly increased by 156.86% compared with that at 416 trees/hm². SV and SWV displayed high phenotypic variation (coefficient of variation (CV) 17.39–38.63%), much higher than DBH and H variations.

Joint variance analyses of all studied growth traits of triploid hybrid clones are shown in Table 3. The initial planting density significantly affected the DBH, H, SV, and SWV of 11-year-old triploid hybrid clones. The effects of the initial planting density on the growth traits of 11-year-old triploid Chinese white poplar are further compared in Figure 1. The DBH of trees planted at 416 trees/hm² was significantly higher than that of trees planted at 832 trees/hm², 1100 trees/hm², 1665 trees/hm², and 2490 trees/hm² (Figure 1a). The H of trees planted at 416 trees/hm² was significantly higher than that of trees planted at 1100 trees/hm², 1665 trees/hm², and 2490 trees/hm² (Figure 1b). The SV of trees planted at 416 trees/hm² was significantly larger than that of trees planted at other densities except 499 trees/hm² (Figure 1c). The SWV of trees planted at 416 trees/hm²

was significantly smaller than that of trees planted at 832 trees/hm², 1110 trees/hm², 1665 trees/hm², 2490 trees/hm². However, the difference among 416 trees/hm², 499 trees/hm², and 624 trees/hm² was not significant (Figure 1d). Therefore, low initial planting density is beneficial to the cultivation of a large diameter in triploid Chinese white poplar.

Table 2. Clone mean ($\pm$ SE), range of variation and coefficients of phenotypic variation (CVp%) of growth traits, BWD, and fiber properties at seven initial planting densities.

Planting Density/ (trees/Hm ²)	Traits	Triploid Clones			Diploid Clone (1316)	
		Mean $\pm$ SE	Range	CVp%	Mean $\pm$ SE	Range
2490	DBH (cm)	15.30 $\pm$ 2.04	11.40–17.60	13.32	11.87 $\pm$ 1.85	10.00–13.70
	H (m)	17.44 $\pm$ 2.03	13.20–20.00	11.63	14.07 $\pm$ 1.03	13.20–15.20
	SV (m ³)	0.1332 $\pm$ 0.0424	0.0569–0.1909	31.81	0.0668 $\pm$ 0.0243	0.0438–0.0923
	SWV (m ³ /hm ²)	331.6127 $\pm$ 105.4758	141.6810–475.3410	31.81	166.3320 $\pm$ 60.6227	109.0620–229.8270
	BWD (g/cm ³)	0.348 $\pm$ 0.017	0.326–0.374	5.01	0.364 $\pm$ 0.017	0.352–0.384
	FL (mm)	1.009 $\pm$ 0.074	0.880–1.085	7.31	0.787 $\pm$ 0.057	0.740–0.850
	FW (μ m)	24.18 $\pm$ 0.78	23.40–26.00	3.22	21.97 $\pm$ 0.29	21.80–22.30
	FL/FW	41.75 $\pm$ 2.89	36.51–45.38	6.92	35.85 $\pm$ 2.80	33.32–38.85
1665	DBH (cm)	18.83 $\pm$ 1.33	16.50–20.80	7.08	14.63 $\pm$ 0.50	14.10–15.10
	H (m)	20.38 $\pm$ 1.13	18.70–22.90	5.53	16.87 $\pm$ 0.91	16.20–17.90
	SV (m ³)	0.2237 $\pm$ 0.0389	0.1679–0.2980	17.39	0.1148 $\pm$ 0.0090	0.1046–0.1216
	SWV (m ³ /hm ²)	372.4605 $\pm$ 64.7758	279.5535–496.1700	17.39	191.0865 $\pm$ 14.9464	174.1590–202.4640
	BWD (g/cm ³)	0.359 $\pm$ 0.031	0.313–0.421	8.64	0.390 $\pm$ 0.014	0.379–0.406
	FL (mm)	1.080 $\pm$ 0.049	1.019–1.147	4.51	0.827 $\pm$ 0.012	0.820–0.840
	FW (μ m)	24.37 $\pm$ 0.71	23.50–25.70	2.9	21.37 $\pm$ 0.47	21.00–21.90
	FL/FW	44.36 $\pm$ 2.11	41.79–47.59	4.76	38.84 $\pm$ 0.31	38.49–39.10
1110	DBH (cm)	18.43 $\pm$ 3.13	12.80–21.70	16.97	17.23 $\pm$ 2.06	15.80–19.60
	H (m)	20.26 $\pm$ 2.54	14.70–22.50	12.54	19.30 $\pm$ 1.47	17.70–20.60
	SV (m ³)	0.2224 $\pm$ 0.0816	0.0784–0.3184	36.70	0.1809 $\pm$ 0.0544	0.1392–0.2425
	SWV (m ³ /hm ²)	246.8393 $\pm$ 90.5864	87.0240–353.4240	36.70	200.8360 $\pm$ 60.4185	154.5120–269.1750
	BWD (g/cm ³)	0.355 $\pm$ 0.026	0.330–0.408	7.41	0.380 $\pm$ 0.033	0.349–0.414
	FL (mm)	1.048 $\pm$ 0.038	0.967–1.086	3.67	0.850 $\pm$ 0.010	0.840–0.860
	FW (μ m)	23.93 $\pm$ 0.62	23.10–24.50	2.58	21.70 $\pm$ 0.53	21.10–22.10
	FL/FW	43.80 $\pm$ 2.12	40.12–46.58	4.83	39.18 $\pm$ 0.43	38.77–39.62
832	DBH (cm)	20.43 $\pm$ 2.96	13.90–23.40	14.48	17.47 $\pm$ 1.25	16.20–18.70
	H (m)	21.51 $\pm$ 1.60	17.80–23.10	7.45	20.27 $\pm$ 0.96	19.40–21.30
	SV (m ³)	0.2816 $\pm$ 0.0822	0.1083–0.3688	29.19	0.1914 $\pm$ 0.0346	0.1578–0.2270
	SWV (m ³ /hm ²)	234.3004 $\pm$ 68.3838	90.1056–306.8416	29.19	159.2725 $\pm$ 28.8209	131.2896–188.8640
	BWD (g/cm ³)	0.345 $\pm$ 0.020	0.313–0.373	5.77	0.379 $\pm$ 0.015	0.369–0.396
	FL (mm)	1.065 $\pm$ 0.059	0.988–1.165	5.56	0.880 $\pm$ 0.061	0.810–0.920
	FW (μ m)	23.79 $\pm$ 0.62	22.80–24.50	2.60	21.73 $\pm$ 0.25	21.50–22.00
	FL/FW	44.82 $\pm$ 2.93	41.17–49.30	6.53	40.63 $\pm$ 2.83	37.47–42.93
624	DBH (cm)	20.56 $\pm$ 3.49	14.80–25.00	16.98	18.13 $\pm$ 2.40	15.70–20.50
	H (m)	21.20 $\pm$ 2.50	16.20–23.70	11.81	20.30 $\pm$ 2.23	17.90–22.30
	SV (m ³)	0.2871 $\pm$ 0.1109	0.1135–0.4410	38.63	0.2106 $\pm$ 0.0723	0.1387–0.2832
	SWV (m ³ /hm ²)	179.1504 $\pm$ 69.2078	70.8240–275.1840	38.63	131.4352 $\pm$ 45.0853	86.5488–176.7168
	BWD (g/cm ³)	0.360 $\pm$ 0.024	0.325–0.387	6.73	0.388 $\pm$ 0.020	0.371–0.410
	FL (mm)	1.075 $\pm$ 0.059	0.971–1.154	5.47	0.850 $\pm$ 0.036	0.810–0.880
	FW (μ m)	24.08 $\pm$ 0.74	23.00–24.90	3.09	21.60 $\pm$ 0.26	21.30–21.80
	FL/FW	44.66 $\pm$ 2.30	40.29–47.11	5.14	39.39 $\pm$ 1.24	38.12–40.60
499	DBH (cm)	21.51 $\pm$ 3.08	15.40–24.50	14.31	19.17 $\pm$ 0.25	18.90–19.40
	H (m)	21.59 $\pm$ 2.22	17.70–23.80	10.27	20.50 $\pm$ 0.50	20.00–21.00
	SV (m ³)	0.3141 $\pm$ 0.1018	0.1322–0.4117	32.41	0.2311 $\pm$ 0.0107	0.2201–0.2414
	SWV (m ³ /hm ²)	156.7193 $\pm$ 50.7935	65.9678–205.4383	32.41	115.3189 $\pm$ 5.3230	109.8299–120.4586
	BWD (g/cm ³)	0.359 $\pm$ 0.033	0.314–0.432	9.21	0.403 $\pm$ 0.045	0.361–0.451
	FL (mm)	1.099 $\pm$ 0.049	1.041–1.186	4.48	0.907 $\pm$ 0.061	0.840–0.960
	FW (μ m)	24.08 $\pm$ 0.66	23.30–25.10	2.72	21.90 $\pm$ 0.96	20.80–22.60
	FL/FW	45.64 $\pm$ 2.13	42.66–49.83	4.67	41.40 $\pm$ 1.26	40.19–42.70
416	DBH (cm)	22.43 $\pm$ 2.76	16.80–25.60	12.30	18.43 $\pm$ 2.63	15.40–20.10
	H (m)	22.43 $\pm$ 1.39	19.60–24.10	6.22	20.00 $\pm$ 2.03	17.80–21.80
	SV (m ³)	0.3486 $\pm$ 0.0934	0.1711–0.4705	26.80	0.2150 $\pm$ 0.0713	0.1328–0.2593
	SWV (m ³ /hm ²)	145.0037 $\pm$ 38.8554	71.1776–195.7280	26.80	89.4539 $\pm$ 29.6549	55.2448–107.8688
	BWD (g/cm ³)	0.359 $\pm$ 0.042	0.321–0.444	11.75	0.380 $\pm$ 0.012	0.372–0.394
	FL (mm)	1.092 $\pm$ 0.043	1.030–1.141	3.97	0.893 $\pm$ 0.031	0.860–0.920
	FW (μ m)	23.79 $\pm$ 0.46	22.90–24.50	1.93	21.73 $\pm$ 0.29	21.40–21.90
	FL/FW	45.93 $\pm$ 2.01	42.74–48.14	4.38	41.04 $\pm$ 0.89	40.05–41.78

H = tree height, DBH = diameter at breast height, SV = stem volume, SWV = stand wood volume, BWD = basic wood density, FL = fiber length, FW = fiber width, FL/FW = fiber length/width.

Table 3. Analyses of variance of growth traits, BWD, and fiber properties of 11-year-old triploid Chinese white poplar at seven planting densities combined.

Traits	Initial Planting Densities		Clones		Clones–Initial Planting Densities	
	F	p	F	p	F	p
DBH	13.975	<0.001	32.214	<0.001	1.121	0.371
H	11.498	<0.001	27.649	<0.001	1.024	0.447
SV	15.577	<0.001	34.568	<0.001	1.668	0.112
SWV	24.863	<0.001	27.075	<0.001	1.097	0.389
BWD	0.797	0.578	25.221	<0.001	0.648	0.788
FL	2.588	0.033	2.045	0.143	0.438	0.938
FW	2.151	0.068	36.446	<0.001	1.602	0.130
FL/FW	3.336	0.009	4.476	0.018	0.851	0.600

Figure 1. The effects of initial planting density on the growth traits of triploid Chinese white poplar: (a) The effects of initial planting density on the DBH. (b) The effects of initial planting density on the H. (c) The effects of initial planting density on the SV. (d) The effects of initial planting density on the SWV. Lowercase letters indicate significance at the $p < 0.05$ level.

3.2. Effect of Initial Planting Density on Basic Wood Density and Fiber Properties of Triploid Chinese White Poplar

The mean values, range of variation, coefficients of the phenotypic variation of BWD, and fiber properties of the 11-year-old triploid hybrid clones within the seven initial planting densities are presented in Table 2. Among the seven initial planting densities, the BWD of triploid Chinese white poplar ranged from 0.345 to 0.360 g/cm³, with an average of 0.355 g/cm³. Additionally, the BWD of diploid clone 1316 ranged from 0.364 to 0.403 g/cm³, with an average of 0.383 g/cm³. Obviously, the BWD of triploid Chinese white poplar trees was slightly lower than that of trees from diploid clone 1316. In addition, triploid hybrid clones planted at a planting density of 624 trees/hm² had

the largest BWD, and those planted at a density of 832 trees/hm² show the lowest BWD. The rank of BWD is 624 trees/hm² > 416 trees/hm² = 499 trees/hm² = 1665 trees/hm² > 1110 trees/hm² > 2490 trees/hm² > 832 trees/hm² (Table 2). As shown as Table 3, initial planting densities had no significant effects on BWD.

In Table 2, the fiber properties of triploid Chinese white poplar trees were longer than those of trees from diploid clone 1316 within the same planting density. Thus, the superior fiber properties of triploid hybrid clones make them become the preferred species in the pulp and paper industries. Triploid Chinese white poplar planted at 499 trees/hm² had the longest FL, and the shortest FL was observed at the planting density of 2490 trees/hm². Trees planted at 1665 trees/hm² had the largest FW, and the smallest FW was seen at planting densities of 416 trees/hm² and 832 trees/hm². The differences between FL and FW of the largest and smallest means were 8.92% and 2.44%, respectively. The planting density of 416 trees/hm² showed the largest FL/FW, and the 2490 trees/hm² planting density showed the lowest ratio. The coefficient variation of fiber properties was smaller than that of growth traits, indicating that fiber properties were relatively stable. Joint variance analysis of fiber properties of triploid hybrid clones showed that initial planting density had a significant effect on FL and FL/FW (Table 3).

Multiple comparisons of the effects of the initial planting density on FL and FL/FW of triploid Chinese white poplar were conducted because initial planting density significantly affected FL and FL/FW (Figure 2). Multiple comparison results show that the FL of trees planted at the density of 2490 trees/hm² was significantly shorter than those planted at the density of 1665, 624, 499, and 416 trees/hm² (Figure 2a). The FL/FW of trees grown at the density of 2490 trees/hm² was significantly smaller than those grown at the density of 1665, 832, 624, 499, and 416 trees/hm² (Figure 2b). The results showed that triploid poplar planted at high initial density was not suitable for the high-quality fiber industry due to the shorter FL and lower FL/FW.

Figure 2. The effects of initial planting density on FL and FL/FW of triploid white poplar: (a) The effects of initial planting density on the FL. (b) The effects of initial planting density on the FL/FW. Lowercase letters indicate significance at the $p < 0.05$ level.

3.3. Clonal Effect and Clones–Initial Planting Densities Interaction on Growth Traits and Wood Properties of Triploid Chinese White Poplar

The results of the analysis of variance for the seven planting densities combined are summarized in Table 3. Significant differences in both growth traits and wood properties were found among the clones (except for FL). Clonal effects had greater effects on FW than planting density owing to its lower P values. Multiple comparisons of the clonal effects on growth traits and wood properties displayed that triploid hybrid clones S86 and B301 were significantly taller than those of clones B331 in DBH, H, SV, and SWV (Figure 3a–d). Therefore, triploid Chinese white poplar S86 and B301, as preferred species, can improve yield of large diameter wood. The BWD and FW of triploid hybrid clone S86 were higher than those of clones B301 and B331 (Figure 3e,f). However, the FL/FW of clone B301 was larger than that of clone S86 and B331 (Figure 3g). In addition, individual tree levels for the tree growth and wood properties of 11-year-old triploid hybrid clones of Chinese white poplar within each initial planting density are presented in Table 4. Within all studied planting densities, clonal effects were significant for growth traits except for the initial densities of 832 and 1665 trees/hm². However, clonal effects were insignificant for all the studied wood properties except for the initial planting density of 1110 trees/hm². Therefore, it was necessary to select a suitable initial planting density to promote tree growth regardless of the clone.

Figure 3. Clonal effects on growth traits and wood properties of triploid Chinese white poplar regardless of planting densities: (a) DBH of triploid Chinese white poplar. (b) H of triploid Chinese white poplar. (c) SV of triploid Chinese white poplar. (d) SWV of triploid Chinese white poplar. (e) BWD of triploid Chinese white poplar. (f) FW of triploid Chinese white poplar. (g) FL/FW of triploid Chinese white poplar. Lowercase letters indicate significance at the $p < 0.05$ level.

Table 4. Analysis of variance results for tree growth and wood properties of 11-year-old triploid Chinese white poplar plantation within each initial planting density.

Planting Density (trees/Hm ²)	<i>p</i>							
	DBH	H	SV	SWV	BWD	FL	FW	FL/FW
2490	0.012	0.168	0.022	0.022	0.125	0.959	0.125	0.722
1665	0.679	0.791	0.657	0.657	0.373	0.976	0.038	0.410
1110	0.055	0.019	0.034	0.034	0.006	0.021	<0.001	0.003
832	0.162	0.158	0.139	0.139	0.021	0.699	0.139	0.637
624	0.010	0.010	0.012	0.012	0.125	0.065	<0.001	0.033
499	0.016	0.048	0.008	0.008	0.169	0.888	0.011	0.700
416	0.035	0.038	0.030	0.030	0.033	0.675	0.216	0.336

No significant clones–initial planting densities interaction for growth traits, wood density, and fiber properties was found in this study (Table 3). Therefore, when the plantation rotation of triploid white poplar was longer than eleven years, the clones–initial planting densities interaction for tree growth and wood quality could be ignored.

3.4. Phenotypic Correlations between Growth Traits, Basic Wood Density, and Fiber Properties within Planting Density

The estimated phenotypic correlations between the growth traits, BWD, and fiber properties of the 11-year-old triploid Chinese white poplar plantation for each planting density are presented in Table 5. A weak and positive estimated correlation between BWD and growth traits within each planting density was seen. A positive or significantly positive estimated correlation was found between growth traits and FL and FL/FW within each planting density. The 2490, 1665, and 499 trees/hm² planting densities showed a positive estimated correlation between growth traits and FW. However, a negative correlation between growth traits and FW was found at 1110, 832, 624, and 416 trees/hm² planting densities. Among the wood properties, a weak and positive estimated correlation between BWD and FL was observed, except for the 416 trees/hm² planting density. A significant positive estimated correlation between FL and FL/FW was seen. However, FW and FL/FW showed a negative estimated correlation. There were some strong positive autocorrelations among SV, SWV, H, and DBH, because SV and SWV derive from H and DBH.

Table 5. Estimated phenotypic correlations between growth traits, wood basic density, and fiber properties of the three triploid hybrid clones at seven planting densities.

Planting Density (trees/Hm ²)	Trait	H	SV	SWV	BWD	FL	FW	FL/FW
2490	DBH	0.836 **	0.984 **	0.984 **	0.003	0.152	0.164	0.085
	H		0.891 **	0.891 **	0.149	0.199	0.128	0.157
	SV			1.000 **	0.004	0.211	0.169	0.146
	SWV				0.004	0.211	0.169	0.146
	BWD					0.503	0.586	0.265
	FL						0.370	0.896 **
	FW							−0.08
	FL/FW							
1665	DBH	0.627	0.969 **	0.969 **	0.318	0.732 *	0.209	0.548
	H		0.796 *	0.796 *	0.497	0.329	0.352	0.094
	SV			1.000 **	0.390	0.660	0.249	0.457
	SWV				0.390	0.660	0.249	0.457
	BWD					0.098	0.808 **	−0.385
	FL						0.219	0.821 **
	FW							−0.377
	FL/FW							

Table 5. Cont.

Planting Density (trees/Hm ²)	Trait	H	SV	SWV	BWD	FL	FW	FL/FW
1110	DBH	0.919 **	0.992 **	0.992 **	0.105	0.898 **	−0.309	0.843 **
	H		0.934 **	0.934 **	0.243	0.816 **	−0.296	0.767 *
	SV			1.000 **	0.116	0.889 **	−0.359	0.862 **
	SWV				0.116	0.889 **	−0.359	0.862 **
	BWD					0.232	0.639	−0.182
	FL						−0.166	0.849 **
	FW							−0.659
	FL/FW							
832	DBH	0.900 **	0.995 **	0.995 **	0.275	0.726 *	−0.416	0.785 *
	H		0.909 **	0.909 **	0.505	0.612	−0.309	0.652
	SV			1.000 **	0.239	0.746 *	−0.444	0.815 **
	SWV				0.239	0.746 *	−0.444	0.815 **
	BWD					0.067	0.494	−0.139
	FL						−0.161	0.916 **
	FW							−0.542
	FL/FW							
624	DBH	0.956 **	0.996 **	0.996 **	0.330	0.751 *	−0.187	0.902 **
	H		0.952 **	0.952 **	0.372	0.821 **	−0.097	0.916 **
	SV			1.000 **	0.363	0.747 *	−0.147	0.874 **
	SWV				0.363	0.747 *	−0.147	0.874 **
	BWD					0.479	0.250	0.336
	FL						0.380	0.827 **
	FW							−0.203
	FL/FW							
499	DBH	0.859 **	0.987 **	0.987 **	0.612	0.443	0.372	0.186
	H		0.796 *	0.796 *	0.430	0.670 *	0.394	0.399
	SV			1.000 **	0.609	0.321	0.414	0.043
	SWV				0.609	0.321	0.414	0.043
	BWD					0.038	0.301	−0.149
	FL						0.241	0.819 **
	FW							−0.357
	FL/FW							
416	DBH	0.943 **	0.994 **	0.994 **	0.425	0.197	−0.453	0.354
	H		0.954 **	0.954 **	0.509	0.261	−0.183	0.297
	SV			1.000 **	0.505	0.161	−0.422	0.307
	SWV				0.505	0.161	−0.422	0.307
	BWD					−0.251	−0.172	−0.157
	FL						−0.017	0.904 **
	FW							−0.439
	FL/FW							

** significantly correlated at the 0.01 level, * significant correlation at 0.05 level.

4. Discussion

Initial planting density determines the intensity of resource competition among individual trees [27]. At high plantation density, the intraspecific competition is fierce [28], and individual trees grow slowly or die [3,29,30]. Trees under low planting density may gain a greater allocation of ecological factors such as light, water and nutrients [31], thereby increasing the DBH, H, and SV of the trees. Thus, the growth status of trees differs under different initial planting densities. Several studies on the loblolly pine [32], oak [33,34], and poplar [12] also found that the average growth traits significantly increased with decreasing planting density. On the contrary, some studies showed that spacing has little or limited impact on average tree height growth [35–37].

In contrast, at the early stage of stand development, higher tree height was observed in higher planting density. For example, the H of radiata pine [38] at the ages of 3–5 years was greater in high planting densities than in a low planting density. This could be because

increased competition results in more biomass allocated to tree elongation [39]. In this study, decreasing plantation densities greatly increased the H, DBH, and SV of 11-year-old triploid Chinese white poplar, following typical density effect results. The results are consistent with the study about the 9-year Chinese white poplar [22] plantation in North China Plain by Bo et al. As shown as Table 3, that initial planting density had a significant effect on SWV, which was consistent with the study about China fir [40]. Additionally, our study showed that the SWV decreased after an initial increase. The maximum SWV was found at the density of 1665 trees/hm². Perhaps due to light, water, and other environmental factors, there was no significant difference in the stand volume of poplars with a planting density of 2490 trees/hm² and 1665 trees/hm² (Figure 1d). Therefore, determining the suitable density of the triploid poplar plantation and adjusting it according to the dynamic change of stand growth process by thinning and rearing can ensure the full growth and development of stand individuals, maximize the use of limited stand space, and obtain the maximum benefit of stand.

According to density tests at home and abroad, whether BWD is affected by planting density is not completely consistent due to different tree species, site conditions, and afforestation density. Some studies on poplar [12], rubber tree [41,42], and teak [43] showed that the BWD has a negative relationship with the plantation density. In our study, no significant effect of initial planting density on the BWD was found, contrary to what had been previously reported [44,45]. Higher planting densities in poplar plantations achieve increased biomass with almost the same wood quality obtainable with lower densities based on our results. Contrasting results may be due to differences between species, environmental conditions, and the planting density tested [13]. For the fiber properties, the variation of FL within a planting density is controversial in woody species. Some studies have shown that FL was not affected by planting density in *P. xiaohai* [46] and rubber tree [42] because the FL development is strongly controlled by inheritance [47]. Instead, an increase in average values of the FL of the 38-year-old poplar [12] plantation with the decrease in plantation density was reported. In addition, the FL of the 5-year-old triploid Chinese white poplar [48] plantation decreased linearly with the trunk height. Thus, FL differences within planting densities might result from different genotypes, environmental factors, sample location in stem, and stand age. In the present study, planting density had significant effects on FL and FL/FW, suggesting that the fiber quality of triploid white poplar plantation could be improved by applying a suitable planting density.

According to joint variance analysis of all studied growth traits and wood properties (Table 3), the influence of initial planting density on growth traits is greater than that on wood properties, suggesting that the wood properties of triploid hybrid clones of Chinese white poplar were under stronger genetic control than growth traits. Our findings are consistent with the results described by Zhang et al. [26,49,50].

During the planting density experiment of white poplar, tree growth and wood properties were also affected by the clone used. Zhang et al. [17] reported that clonal effects significantly altered H and SWV of 3-year-old triploid Chinese white poplar. Subsequently, Zhang et al. [18,19] also documented that clonal significantly affected the BWD, FL, and FW of 3-year-old triploid Chinese white poplar plantation. In this study, clonal effects were significant for all studied growth traits and wood properties except for FL, suggesting that both growth traits and wood properties were genetically controlled in triploid Chinese white poplar.

Some previous studies reported a positive correlation between FL and growth rate in *Populus* [26,51,52]. Thus, the FL of trees with higher growth rates was longer. A positive or significantly positive estimated correlation was found between growth traits and FL within each planting density in the present study. Therefore, it is crucial to select the ideal planting density to optimize productivity and wood quality.

The BWD findings contrasted with some former studies. For example, negative genetic correlations exist between the BWD and growth traits in Douglas fir [53] and poplar [12]. In this study, a weak and positive estimated correlation between BWD and

growth traits within each planting density was found. Our findings conflict with the findings described by Zhang et al. [26] in a 5-year-old triploid Chinese white poplar plantation. These differences may be related to species, environmental conditions, and cambium ages of samples.

Additionally, there were some strong positive auto-correlations among SV, SWV, H and DBH, because SV and SWV derived from H and DBH. The results are similar to the research results on the Norway spruce [54] and poplar [12], which suggests that selecting suitable plantation density could be beneficial for improving growth traits.

5. Conclusions

To assess the effects of initial planting density on growth traits and wood properties, a total of 84 trees from 4 clones were sampled from an 11-year-old triploid Chinese white poplar plantation, including seven initial planting densities (2490, 1665, 1110, 832, 624, 499, and 416 trees/hm²). The initial planting density had a highly significant effect on growth traits ($p < 0.001$) and had a moderate effect on FL. Clonal effects were also significant ($p < 0.05$) for all studied traits except for FL. Clone S86 had a higher growth rate and the largest BWD and FW. Clones–initial planting densities showed no significant differences in growth traits and wood properties. A weak and positive estimated correlation between BWD and growth traits within each planting density existed. Our data support that an appropriate reduction in initial density in poplar plantations with a long rotation is a suitable strategy to promote tree growth and retain excellent wood processing characteristics. The results in this study were based on a small number of triploid clones, several initial planting densities, and a small amount of sampled tree for wood properties derived from a single site. Further research is needed to fully assess the effects of the initial planting density on growth traits and wood properties.

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