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Enhancing large-diameter timber production: Evaluating poplars by genotype and spacing

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ABSTRACT

To meet the increased demand for construction timber, selecting large-diameter hybrid poplar genotypes and optimizing spacing are essential for enhancing stand productivity in Northeast China. In the Daling River Plain, a trial with 12 clones (G1~G12) of *Populus* × *euramericana* at four spacings (2 m×5 m, 3 m×8 m, 4 m×8 m, 4 m×10 m) was conducted. Over a 14-year rotation, tree height, diameter at breast height, survival rate, individual tree volume, growing stock, and timber yield were measured and analyzed. Results showed that while tree height was minimally affected, diameter at breast height, survival rate, and growing stock were significantly influenced by genotype and spacing. Higher spacings inhibited growth but increased variability within the stand. Diameter at breast height in the 2 m×5 m spacing reached the large-diameter standard (24 cm) and provided a higher growing stock. The minimum density required for larger-diameter wood (diameter at breast height over 35 cm) was the 4 m×8 m spacing. GGE-Biplots identified the top five genotypes as G2, G4, G11, G1, and G10. Genotypes G4, G10, and G1 were suitable for low-density plantations, with G4 performing best, achieving a 95 % improvement in survival rate and a 105 % increase in growing stock. Genotypes G2 and G11 were ideal for high-density plantations, with G2 showing the best results, increasing survival rate by 36 % and growing stock by 56 %. The optimal period for early selection in *P.* × *euramericana* is the 4th to 5th year after afforestation. The best design, D1×G2, yielded 513 $m^3 \cdot ha^{-1}$ of timber and 288.52 $m^3 \cdot ha^{-1}$ of large-diameter wood. These findings support the establishment of large-diameter poplar plantations, aiding future breeding efforts and increasing stand productivity.

1. Introduction

Global demand for wood-based panels is predicted to increase further in the coming years (Norhazaedawati et al., 2022). China ranks first in both production and consumption of wood-based panels, its production in 2020 reached 311 million m^3 and its consumption was 296 million m^3 (FAO, 2023). China's production and consumption of wood-based panels have been increasing simultaneously, with consumption growing at a faster rate than production (Yu et al., 2022). In recent years, China's import of forest products has exceeded 120 million m^3 due to increasing demand (State Forestry Bureau of China, 2019). Currently, increasing domestic production of wood is an effective way for China to solve this problem.

It has been predicted that approximately 50 % of the wood supply for industries will be sourced from rapidly growing plantations by the year 2050 (Sedjo, 2001). Fast-growing tree species of the genus *Populus* are considered important to produce more wood in the future (Van Acker et al., 2016). Currently, China's poplar plantations cover an area of 7.5 million hectares, accounting for nearly one-third of the global poplar plantation area (Zhu et al.,. 2024a,2024b). Among the genus *Populus*, *Populus* × *euramericana* is a species formed from the interbreeding of *Populus* section *Aigeiros*, whose parents are *Populus deltoides* and *Populus nigra*. It is a major tree species in plantations of the temperate zone, both for industrial and ecological purposes (FAO, 2016). *P.* × *euramericana* exhibits rapid growth and a broad adaptability, making it extensively cultivated in temperate regions worldwide (Dickmann et al., 2001;

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Cooke and Rood, 2007). *P.* × *euramericana* wood is primarily used in industrial applications such as the production of pulp, plywood, wooden panels, and energy. The paper industry and bio-energy sectors need fast growing poplar plantations, while the production of plywood and wooden panels relies on the use of large-diameter poplar timbers (Dickmann et al., 2001). Due to that, plywood products in China have the highest production share among wood-based panel products, making up around 69 % of wood-based panel consumption (Yu et al., 2022). Currently, in addition to improving plantation productivity, there is also an urgent need to address the cultivation of large-diameter plantations (with a top diameter inside bark of ≥ 24 cm and a log length of ≥ 2.5 m) that are intended to produce high quantities and exhibit good quality in China's forestry industry (State Forestry Bureau of China, 2013).

Clones are predominantly used to establish most poplar plantations due to the simplicity of vegetative propagation. Clonal forestry provides convenience in managing and reproducing trees, ensures consistent genetic material, minimizes growth variation within the forest stand, and produces wood that meets uniform specifications, making it suitable for industrial production (Wu, 2019). Hence, it is imperative to select genotypes that exhibit both high and consistent productivity, along with exceptional stress tolerance and disease resistance (Nelson et al., 2018; Fang et al., 2021; Steenackers et al., 1996). Researchers frequently study the genotype × environment effect of multi-environment tests to select high-yield and stable-yielding genotypes and develop ideal clones for different specific environments (Miller, 2018; Yu and Pulkkinen, 2003). Studies indicated that initial planting spacing affects the growth of poplar plantations, with higher density limiting space for individual trees and slowing diameter growth, while lower density promoting faster diameter growth and earlier harvesting (Benomar et al., 2012; Fang et al., 1999; Jiang et al., 2007; Larocque, 1999; Wang et al., 2024; Zhu et al., 2022). Spacing and genotype are crucial factors that can be readily determined in single-site poplar plantations (Ceulemans and Deraedt, 1999). However, there are currently few reports on long-term genotype × spacing testing of hybrid poplar trees in representative areas.

To optimize the utilization of plantation productivity, conducting multi-environment test research can help identify the most appropriate silvicultural genotypes and initial stand density settings, considering the longer management cycle of large-diameter poplars (White et al., 2007; Sixto et al., 2015). We selected 12 genotypes with exceptional growth from hybrid poplars and conducted a spacing trial in Northeast China. With recent advancements in wood processing technology, the standard for large-diameter timber has been lowered. We hypothesize that denser spacings can produce more large-diameter timber per hectare and that the best genotypes can increase survival rates and growing stock by more than 40 %. Additionally, we aim to address the following questions: (1) What is the maximum genetic improvement achievable with the ideal genotype? (2) When can early selection of hybrid poplar be conducted to reduce the breeding cycle? (3) Which genotype × spacing design yields the best timber?

2. Materials and methods

2.1. Study site

The test site is situated at Jincheng Original Breeding Farm (41°21′N, 121°39′E) in Linghai City, Jinzhou City, Liaoning Province. It has a northern temperate continental climate with four distinct seasons, rain and higher temperature in the same season, and sufficient sunshine. The annual average temperature is 8.0–8.7℃, the annual precipitation is 550–620 mm, and the frost-free period is 160–180 days; the soil type is sandy soil, pH 7.2–8.7, and the groundwater level is 4.5–5 m.

2.2. Experimental design

The experimental materials comprised 12 genotypes of *P.* × *euramericana* hybridized by our research team (Table 1). We employed a randomized block design with three blocks, each containing four subplots. The initial spacings for the subplots were 2 m × 5 m (1000 plants • ha $^{-1}$, D1), 3 m × 8 m (416 plants • ha $^{-1}$, D2), 4 m × 8 m (312 plants • ha $^{-1}$, D3), and 4 m × 10 m (250 plants • ha $^{-1}$, D4). Each subplot included all 12 genotypes, with the number of plants per genotype ranging from 10 to 32. Planting was conducted using the root piles method in autumn 2007. In the first year after planting, we performed weeding, and in the 3rd, 5th, and 7th years, we pruned only the lowest layer of branches. After these three prunings, the branch-free height of the trunk should reach at least 8 m.

2.3. Sampling and measurement

2.3.1. Measuring diameter and height and calculating growth

In March 2022, each tree in the plantation was measured, and the number of surviving trees was counted. The tree height (H) was measured with a height meter (Blume-Leiss, Model BL7 ALTIMeter, accuracy of 0.1 m); the diameter at breast height (DBH) was measured with a tree circumference ruler (OOTDTY, X37B9FF101636, accuracy of 0.1 cm).

The calculation formulas of individual tree volume (V), survival rate (SR), and growing stock (GS) are as follows (Zhao and Cheng, 1994):

$$V = 0.19328321 \times DBH^2 \times H + 0.007734354 \times DBH \times H + 0.82141915 \times DBH \quad (1)$$

$$SR = N_S / N_P \quad (2)$$

$$GS = V \times SR_i \quad (3)$$

With N_S the number of survivors, N_P the number of initial plants and ' $_i$ ' the spacing, i=1, 2, 3, 4.

2.3.2. Sampling of discs

In this study, growing stock is the most relevant indicator for productivity. The top five genotypes (G4, G1, G11, G2, and G10) that exhibited the highest growing stock were selected based on the results. A total of 60 trees were the source of discs, with 3 trees(determined through analyzing DBH distribution) per genotype per spacing. The annual growth ring widths were measured on 1.3 m (breast height) discs to obtain annual growth for early selection calculations.

2.4. Data analysis

2.4.1. Genetic parameter calculation

The random effects model (Liu et al., 2021) used to extract the variance component is:

$$y_{ij} = \mu + D_i + G_j + DG_{ij} + e_{ij} \quad (4)$$

With y_{ij} the observed value of genotype 'j' at the 'i'-th spacing, μ the

Table 1
Twelve *P.* × *euramericana* genotypes.

Genotype Number	Name
G1	*P.* × *euramericana* 'J2'
G2	*P.* × *euramericana* 'Bofeng 3'
G3	*P.* × *euramericana* 'Guariento'
G4	*P.* × *euramericana* 'Bofeng 1'
G5	*P.* × *euramericana* '141'
G6	*P.* × *euramericana* '170'
G7	*P.* × *euramericana* 'Bofeng 2'
G8	*P.* × *euramericana* '184'
G9	*P.* × *euramericana* 'Lingfeng 5'
G10	*P.* × *euramericana* '288'
G11	*P.* × *euramericana* '334'
G12	*P.* × *euramericana* '347'

mean of all observed values, D_i the effect of spacing, G_j the effect of genotype, DG_{ij} the interaction effect of genotype and spacing, and e_{ij} the random error.

We used the broad sense heritability of traits because it plays a crucial role in clonal forestry breeding (White and Adams, 2007). The heritability of growth traits formula is:

$$H_B^2=V_G/[V_G+V_e] \tag{5}$$

With H_B^2 the heritability of the trait, V_G the variance component of the genotype, and V_e the variance component of the random error.

The formula for calculating genetic gain is (White and Adams, 2007):

$$\Delta G=(A_s-A_p)\times H_B^2 \tag{6}$$

With ΔG the genetic gain of the trait, A_s and A_p the average trait of the selected genotypes and the total population respectively.

The formula of the trait type-B correlation (r_b) between spacings is (White and Adams, 2007):

$$r_b=V_G/(V_G+V_{GE}) \tag{7}$$

The GGEBiplotGUI package in R is used to generate GGE-Biplots (Yan and Tinker, 2006).

The formula for calculating early selection efficiency is (White and Adams, 2007):

$$E=R_P\times T_e / T_l \tag{8}$$

With E is the early selection efficiency, R_P the early and late trait correlation coefficient, T_l and T_e the early and late related ages respectively.

2.4.2. Yield calculation

After conducting stem analysis on the selected 60 trees, calculations of total and large-diameter timber yield were performed. The calculation formula for large diameter yield is (Zhao and Cheng, 1994):

$$\Sigma V_L=\Sigma 1/3\pi(R_{ij}^2+r_{ij}^2+R_{ij}r_{ij})\times h \tag{9}$$

With ΣV_L is the large-diameter the timber yield, R is the diameter at the bottom, r the top diameter inside bark of 24 cm, h the log length. R_{ij} and r_{ij} the value of genotype 'j' at the 'i'-th spacing.

The calculation formula for large diameter ratio(LR) is (State Forestry Bureau of China, 2013):

$$LR=\Sigma V_L / \Sigma V \tag{10}$$

With LR the large diameter ratio, ΣV the total timber yield.

3. Results

3.1. Stand growth

An analysis of descriptive statistics and multiple comparisons was conducted on the DBH, height, individual tree volume(V), survival rate, and growing stock of the 14 years old stand, as shown in Table 2. The results showed that the DBH of D1 and D2 was significantly lower ($P<0.01$) than that of D3 and D4, among which D1 had the smallest DBH; the coefficient of variation of DBH increased with the increase in spacing. There is no significant difference in height between D2 and D3, but both are significantly lower than D4 and significantly higher than D1. The coefficient of variation (CV) of height ranges from 7.6 % to 10.5 %, and the CV of height is smaller than the CV of DBH. Spacing has a strong negative correlation with V. Out of the four spacings, the V of D3 has the largest minimum value (0.39 m^3). Additionally, D3 has the lowest intra-stand variation coefficient of 23.4 %. The survival rates varied between 38.8 % and 69.5 % across different spacings. The survival rates of the three lower densities (D2, D3, and D4) did not differ significantly, but all of them were significantly higher than D1, which showed the lower survival rate of 38.8 %. The growing stock treated with various spacings ranged from 191.8 (D4) to 311.9 m^3ha^{-1} (D1). Significant differences are present in the survival rate and growing stock between different spacings ($P < 0.01$), the survival rate decreased with the increase in spacing, while the growing stock was opposite.

Table 2
Traits at different spacings. Multiple comparisons are performed using the Least Significant Difference(LSD) test. Capital letters in the column "mean ± standard deviation" indicate highly significant differences between different spacings ($P < 0.01$). V in the table represents individual tree volume,the same below.

Spacing	Traits	Mean ± SD	Min	Max	CV / %
D4	DBH / cm	35.98 ± 5.15 A	16.50	55.00	14.3
D3		35.21 ± 4.61 A	21.00	55.00	13.1
D2		32.67 ± 5.68 B	19.00	48.50	17.4
D1		29.97 ± 6.51 C	17.00	48.00	21.7
D4	Height / m	28.36 ± 2.17 A	16.65	32.65	7.6
D3		27.65 ± 2.39 B	18.65	32.65	8.6
D2		27.43 ± 2.88 B	14.65	33.65	10.5
D1		26.52 ± 2.20 C	14.65	33.65	8.3
D4	V / m^3	1.10 ± 0.27 A	0.24	2.12	24.8
D3		1.04 ± 0.24 B	0.39	2.19	23.4
D2		0.93 ± 0.29 C	0.28	1.96	30.9
D1		0.80 ± 0.29 D	0.26	1.73	36.9
D4	Survival rate / %	69.52 ± 4.86 A	64.57	74.29	7.0
D3		69.29 ± 6.81 A	65.00	77.14	9.8
D2		60.33 ± 3.77 A	58.15	64.67	6.2
D1		38.76 ± 2.76 B	36.05	41.57	7.1
D4	Growing stock/ m^3 • ha^{-1}	191.80 ± 10.61 C	184.70	204.00	5.5
D3		225.78 ± 17.19 BC	212.87	245.29	7.6
D2		234.20 ± 27.55 B	207.43	262.47	11.7
D1		311.90 ± 23.00 A	285.61	328.34	7.4

3.2. Genotype × spacing

The results presented in Table 3 indicate that spacing, genotype, and the interaction between genotype and spacing significantly impacted DBH, height, V, and growing stock ($P < 0.01$). However, there was no significant correlation between survival rate and the genotype × spacing interaction ($P > 0.05$).

GGE-biplot analysis (Figs. 2, 3, and 4) showed that the first principal component (AXIS1) explained 94.9 % of the variation, while the second principal component (AXIS2) explained only 3.7 %. The combined effect of PC1 and PC2 represents the fitting degree, accounting for over 95 % of the genotype effect and the genotype × spacing interaction effect.

The four dashed lines in Fig. 2 represent the four spacings. Their lengths are positively related to discrimination ability. D1 and D2 have longer lines, indicating greater variation between genotypes within

Table 3
Analysis of variance in 14 years old stands.

Trait	Source	DF	*F* Value	Sig.
DBH / cm	Spacing	3	38.14**	0.000
	Genotype	11	36.70**	0.000
	Genotype × Spacing	33	9.45**	0.000
Height / m	Spacing	3	67.29**	0.000
	Genotype	11	21.66**	0.000
	Genotype × Spacing	33	13.48**	0.000
V / m^3	Spacing	3	29.38**	0.000
	Genotype	11	35.43**	0.000
	Genotype × Spacing	33	6.82**	0.000
Survival rate / %	Spacing	3	22.45**	0.000
	Genotype	11	25.80**	0.000
	Genotype × Spacing	33	1.01	0.465
Growing stock / m^3 • ha^{-1}	Spacing	3	10.41**	0.000
	Genotype	11	22.81**	0.000
	Genotype × Spacing	33	2.32**	0.001

Note: '**' in the table indicates an extremely significant difference ($P<0.01$) and '*' indicates a significant difference ($P<0.01$).

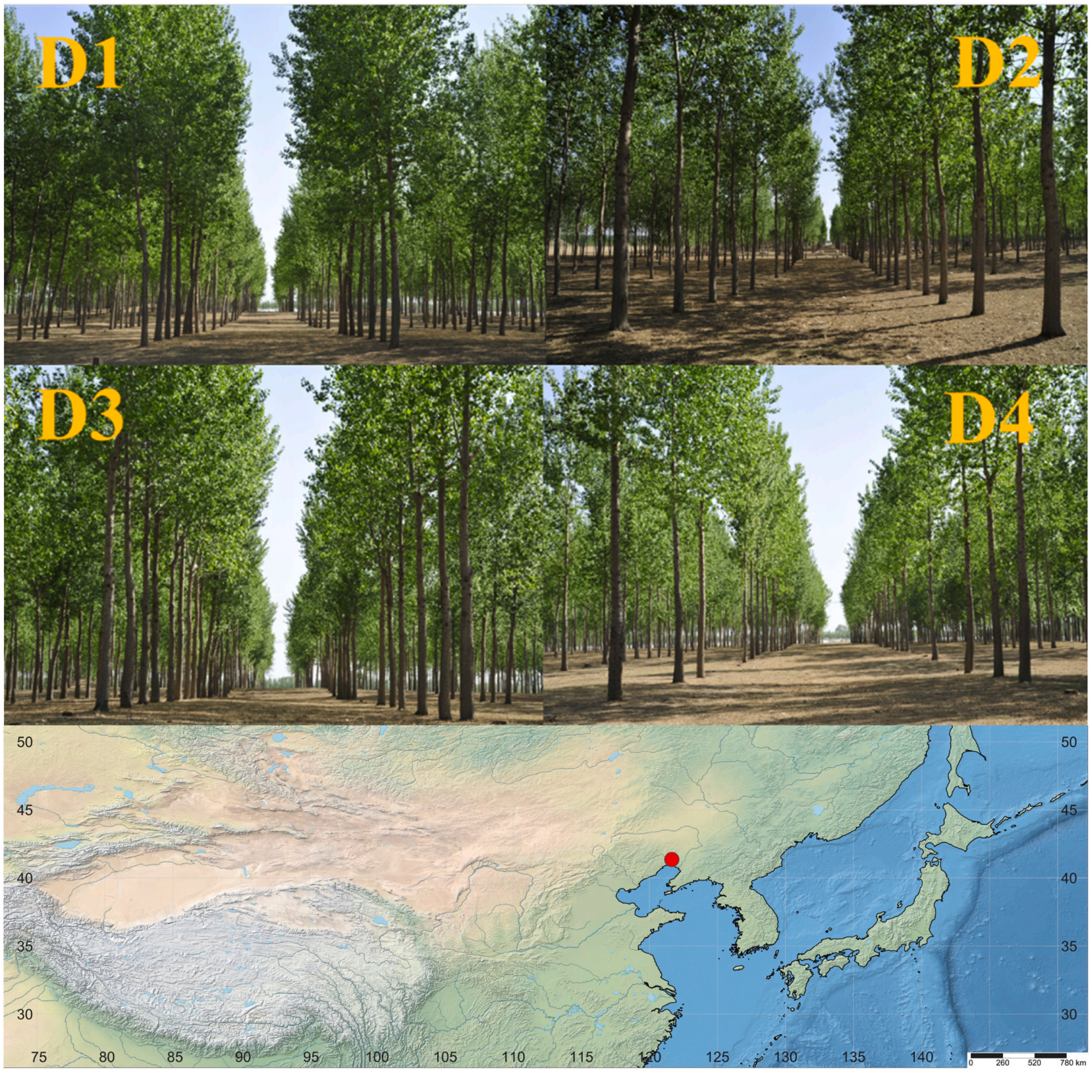

Fig. 1. Plantation of four spacings. D1-D4 are stands with four spacings, and the figure below shows the geographical location of the plantation.

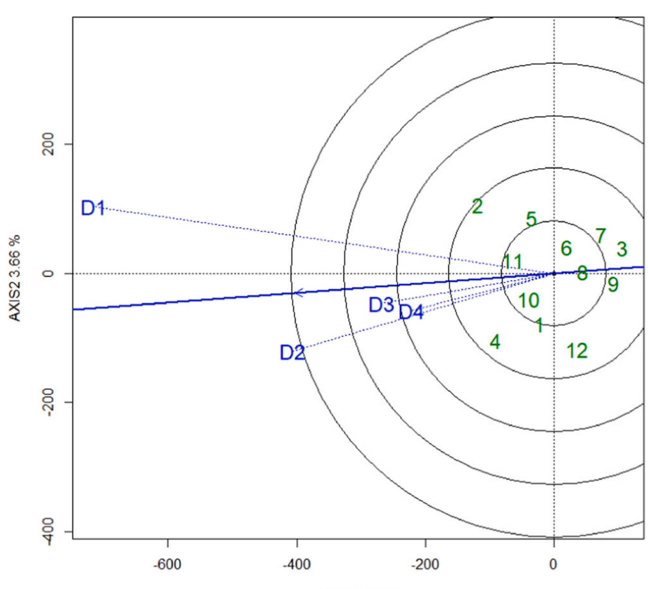

Fig. 2. Discrimination and representativeness of four spacings. The dotted line shows the correlation between spacings.

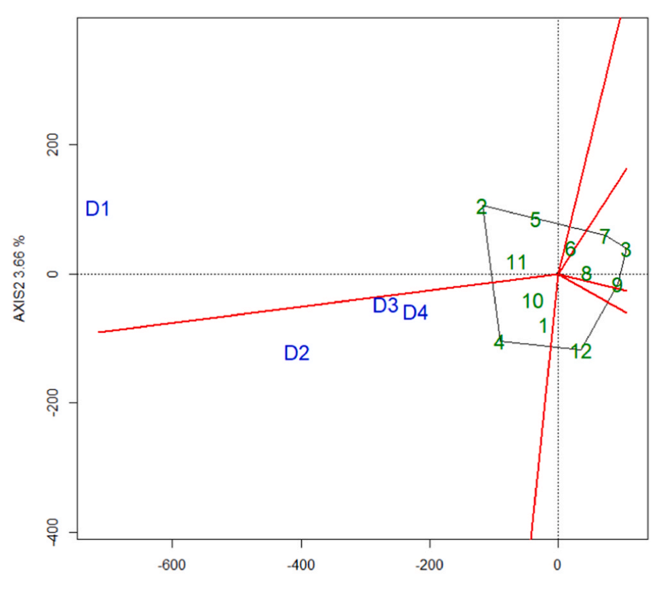

Fig. 3. Biplot of where genotypes performed better. The genotypes in the area formed by two adjacent red lines are good performers.

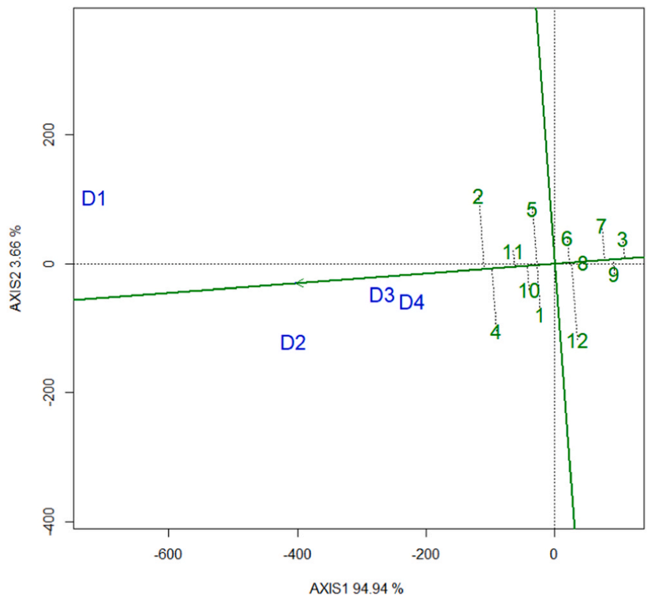

Fig. 4. High-productivity and stability. The closer to the arrow direction, the higher the yield. The longer the dotted line, the lower the stability.

these spacings. The acute angles between the dashed lines and the axes indicate that all four spacings are highly representative. The smaller the angle between two spacings, the greater the correlation; D2, D3, and D4 are more closely related.

In Fig. 3, each pair of adjacent red lines divides an area; if it contains any spacing, it is a meta-environment (ME). Specifically, D2, D3, and D4 belong to one ME, representing low density, while D1 belongs to another ME, representing high density. Genotypes G4, G10, and G1 perform well in the low-density ME, with genotype G4 being the best. Genotypes G2, G11, and G5 are suitable for the high-density ME, with genotype G2 being the best.

Fig. 4 shows that the spacings are separated into two types. The top five genotypes (G2, G4, G11, G1, and G10) have a high growing stock. Genotype G3 exhibits the lowest yield. Although genotype G2 has the largest growing stock, it is most suitable for D1. Similarly, genotype G4 is the best choice for the low-density ME. Despite relatively lower growing stock, both genotypes G11 and G10 exhibit excellent adaptability and stability, making them suitable for different spacings.

3.3. Genetic parameters

Table 4 shows the outcomes of the random effects model, while Table 5 presents the computed H_B^2 and r_b. The rankings of HB² for DBH, V, and height are as follows: 0.25 > 0.23 > 0.08. The H_B^2 of growing stock and survival rate is substantial, indicating a significant genetic influence. The r_b results revealed that height, DBH, and V were all influenced by the genotype × spacing interaction ($r_b < 0.7$), whereas growing stock and survival rate exhibited a strong correlation with the different genotypes.

Table 4
Variance components.

Groups	Height	DBH	V	Growing stock	Survival rate
Genotype × Spacing	0.94 ±0.97	18.65 ±4.32	0.04 ±0.20	3429.00 ±58.56	0.0001 ±0.0115
Genotype	0.15 ±0.39	4.17 ±2.04	0.01 ±0.10	13535.00 ±116.34	0.0711 ±0.2667
Spacing	1.23 ±1.11	2.41 ±1.55	0.01 ±0.09	1769.00 ±42.06	0.0205 ±0.1432
Residual	4.26 ±2.06	22.8 ±4.78	0.07 ±0.26	7940.00 ±89.11	0.0344 ±0.1856

Note: Number of obs: 144, groups: Genotype × Spacing, 48; Genotype, 12; Spacing, 4.

Table 5
Genetic parameters of tested poplars. H_B^2 is used to measure the influence of genetic factors on traits, while r_b is used to describe the correlation between traits in different environments.

Trait	H_B^2	r_b
Height	0.08	0.14
DBH	0.25	0.18
V	0.23	0.19
Growing stock	0.79	0.80
Survival rate	0.86	1.00

The genetic gains from replacing two selected genotypes are shown in Table 6. The survival rate and growing stock of the high-density ME increased approximately twofold, while the survival rate and growing stock of the low-density ME increased by 36 % and 56 %, respectively.

The early selection efficiency is presented in Table 7. DBH shows a significant correlation between the thirteenth year and the third year, with a coefficient of only 0.294; at the fourth year, it shows an extremely significant correlation, with the coefficient gradually increasing from 0.559 to 0.994. V also correlated strongly with the late stand at 3 years, with a coefficient of 0.331, and from 4 to 13 years, it increased from 0.525 to 0.993. Early selection efficiency for DBH and V peaks at 4 years and 5 years, respectively, and then decreases.

3.4. Large diameter timber yield

The design D1×G2 has the highest total timber yield at 513.66 m^3•ha^{-1}, followed by D1×G4 with 414.07 m^3•ha^{-1}, and the lowest is D4×G1 with 119.76 m^3•ha^{-1}. Large diameter ratios exceeding 80 % are observed in D3×G1, D4×G4, D4×G2, and D4×G1, ranging from 82 % to 88 %. The designs with the highest large-diameter timber yield are D1×G2 and D1×G4, but their large diameter ratios are approximately 56 %. Out of all the designs, only D1×G11 does not yield any large diameter wood.

4. Discussion

4.1. Effect of spacing on stands

As spacing increases, the variation of stand DBH also increases (Qian et al., 2022; Bo et al., 2020). However, height does not show a significant correlation with spacing (Khan and Chaudhry, 2007; Bisaria et al., 1999; DeBell et al., 1993). Similar tests on poplar trees reported greater productivity at higher densities and longer rotations with more flexible management at lower densities (Strong and Hansen, 1993). Our findings in this study are consistent with these previous studies. The DBH, height, V, and survival rate of *P.* × *euramericana* all showed a significant decrease as spacing increased, while growing stock showed the opposite trend. A low initial number of plants results in a lower growing stock. The stand's DBH exhibits greater variation as spacing increases, suggesting that high initial spacing leads to intense competition among individuals in the stand, hindering the formation of high-quality wood. At year 14, the variation in height among different spacings did not exceed 2 m. This indicates that once the *P.* × *euramericana* plantation in this region reached a specific age, the rate of height growth decelerated,

Table 6
Genetic gains of selected genotypes. Improvement rate is in parentheses.

ME	Low-density	High-density
Genotype	G4	G2
Survival rat%	35.31 (95 %)	23.44 (36 %)
Growing stock m^3 • ha^{-1}	311.91 (105 %)	119.91 (56 %)

Table7
Evaluation on efficiency of early selection of hybrid poplar.

Age	DBH		V	
	Correlation coefficient	Selection efficiency	Correlation coefficient	Selection efficiency
2	0.16	1.10	0.17	1.18
3	0.29*	1.37	0.33**	1.54
4	0.56**	1.96	0.53**	1.84
5	0.64**	1.80	0.73**	2.06
6	0.69**	1.60	0.73**	1.71
7	0.70**	1.41	0.75**	1.49
8	0.74**	1.29	0.79**	1.39
9	0.82**	1.27	0.87**	1.35
10	0.89**	1.24	0.91**	1.27
11	0.95**	1.21	0.95**	1.21
12	0.99**	1.14	0.98**	1.14
13	0.99**	1.07	0.99**	1.07

Table 8
Large diameter ouput. Sorted by Large diameter timber yield / (m^3 • ha^{-1}) in each spacing.

Design	Total timber yield /m^3 • ha^{-1}	Large diameter ratio /%	Large diameter timber yield /m^3 • ha^{-1}
D1×G2	513.66	56.17	288.52
D1×G4	414.07	55.66	230.47
D1×G1	241.77	64.88	156.86
D1×G10	276.49	34.03	94.09
D1×G11	208.12	0.00	0.00
D2×G4	293.16	67.77	198.67
D2×G2	253.22	59.98	151.88
D2×G11	243.28	40.19	97.77
D2×G1	212.58	45.54	96.81
D2×G10	212.19	40.09	85.07
D3×G4	276.61	77.30	213.82
D3×G2	244.43	72.48	177.16
D3×G1	176.14	87.67	154.42
D3×G10	184.07	64.10	117.99
D3×G11	193.02	52.33	101.01
D4×G4	236.26	85.66	202.38
D4×G2	178.20	83.24	148.33
D4×G11	192.05	60.27	115.75
D4×G10	157.30	66.71	104.93
D4×G1	119.76	82.43	98.72

and variations in V among individuals were primarily due to radial growth.

Generally, D1 can provide more growing stock, total timber yield, and large-diameter timber yield than lower spacings. However, D1 has a smaller DBH. We suggest using D3 to shorten the rotation period or harvest larger logs. The growth of D4 did not significantly surpass D3 despite the wider spacing. Conversely, the variation and minimum value of height, DBH, and V indicators exhibited poor results. This could be due to the fact that wider spacing amplifies the impact of local climate conditions characterized by low average temperatures and a short growing season. The lower growing stock of D4 compared to D3 is primarily due to the difference in the amount of trees. Although D4's growth performance is slightly higher than D3, after 14 years, 43 more trees survived per hectare for D3 than D4. This explains the higher growing stock of D3 per hectare, as the difference in individual tree volume between D3 and D4 is only 0.06 cubic meters per tree, but the additional 43 trees contribute to approximately 44 cubic meters in total.

4.2. Selection of genotypes and genetic parameters

The genotype × spacing interaction (G×E) in this study was evaluated based on rank changes and scale effects. The ranking of genotypes varied in response to environmental changes, forming the basis for selecting appropriate genotypes for specific environments (Yan et al., 2000). In our study, only the survival rate was not significantly influenced by the G×E effect, with high type-B correlation and heritability. The consistent survival rate rankings across various spacings suggest that survivability is primarily determined by genetic factors and stress tolerance. Previous studies have indicated that height and DBH are typically affected by G×E effects, with height often showing lower heritability compared to DBH (Li and Wu, 1997; Bian et al., 2014; Hodge and White, 1992). Our findings corroborate these results, with height demonstrating extremely low heritability, indicating predominant environmental influence. Higher heritability in DBH ensures consistency and supports effective management of large-diameter plantations.

Stand productivity, as indicated by growing stock, is closely related to genetic factors (Zhao and Zhou, 2005). Using GGE-Biplots, we assessed the productive potential of the genotypes under study (Yan and Hunt, 2002). Results showed a heritability of 0.79 for growing stock, largely controlled by genetics, with a significant yet not strong G×E effect. In the GGE-Biplots, two Mega-Environments (MEs) were identified based on correlation: high spacing (D1) and low spacing (D2, D3, and D4). The top five genotypes (G1, G2, G4, G10, and G11) were selected for their high productivity and stability. Genotype G4 performs best in low-density plantations, while genotype G2 excels in high-density plantations. Replacing other genotypes with G4 could increase survival rates by 35 % and growing stock by 312 m^3•ha^{-1} in low-density plantations. Similarly, replacing with G2 could lead to a 23 % increase in survival rate and a 120 m^3•ha^{-1} increase in growing stock in high-density plantations. It should be noted that genotype G11 in D1 did not meet the large-diameter material standard by the end of the study, highlighting significant differences among genotypes.

Given the single-site nature of this study, the performance of selected genotypes may not be universally applicable across regions with markedly different climates. Genotypes ranking lower in our study might perform better in warmer sites, emphasizing the need for site-specific evaluations when selecting genotypes for large-scale plantations.

4.3. Early selection, timber yield, and management suggestions

Early selection before maturity can significantly shorten the tree breeding cycle (Kumar and Singh, 2001). Our findings demonstrate a significant correlation of DBH and V from the third year onwards, with steadily increasing coefficients over time. The optimal early selection points identified were the 4th year for DBH and the 5th year for V, achieving maximum selection efficiencies of 1.96 and 2.06, respectively. Compared to the 14-year rotation period in our study, early selection could potentially save nearly ten years.

Regarding timber yield in the genotype × spacing design, D1 stands out for producing more timber and large-diameter timbers. Previous studies in China suggested an initial spacing range of 156–280 trees • ha^{-1} for large-diameter poplar plantations, not exceeding 400 trees • ha^{-1} (Fang, 2004; Miao et al., 2019). Research in Belgium suggested optimal spacings between 180 and 330 trees • ha^{-1} (Galinski et al., 1991), contrasting with our finding that D1 (1000 plants • ha^{-1}) performed best for large-diameter wood production. Genotype G2 exhibited the highest large-diameter productivity (288 m^3 • ha^{-1}) among all designs, leveraging advancements in log processing technology that have relaxed diameter standards. Additionally, superior genotypes thrive in high-density plantings, fully utilizing plantation potential. Among D2, D3, and D4, genotype G4 showed the highest total timber yield and large-diameter timber yield, with D1×G2 emerging as the top design for large diameter and total timber yield.

To optimize plantation management, suitable genotypes require specified spacings and rotation periods. Long rotations at high densities or short rotations at low densities cater to plywood versus bio-energy material needs, respectively. Future research will involve high-value-added plywood testing on the identified genotypes to refine their characteristics. For future spacing experiments, the Nelder systematic design (Nelder, 1962) is recommended to pinpoint optimal spacings and rotation ages, tailored for diverse forest management strategies (Galinski et al., 1991).

In summary, this study focuses on managing large-diameter poplar trees, selecting superior genotypes, and enhancing timber yield through early selection. Recommendations include carefully selecting spacings based on intended processing and product goals. D3 facilitates early harvesting of large-diameter wood and shortens rotation periods. When using genotypes G2 or G4 in a 14-year rotation, significant yields in both large-diameter and non-large-diameter crops were observed. Crucially, large-diameter genotypes should balance high survivability with rapid growth, emphasizing the importance of matching genotypes to environmental conditions before afforestation. Given the lengthy breeding process, poly-clonal and multi-environment trials, alongside early selection, are vital for achieving desirable genotypes.

Furthermore, to optimize productivity, adopting integrated agroforestry practices during establishment is strongly recommended. Poplar-crop intercropping optimally utilizes sunlight, space, and soil resources, thereby enhancing productivity beyond that of mono-agricultural or poplar plantation systems (Fang et al., 2005). Maintaining a minimum distance of 60 cm between intercropped crops and poplar seedlings is advised. Transitioning to composite management models like forest-livestock, forest-herbal medicine, and forest-fungi after 4 years can further boost income. Pruning poplars to the 8 m height at the 3rd, 5th and 7th year after planting is essential for knot reduction in this area. These measures collectively support sustainable and efficient management of large-diameter poplar plantations, ensuring optimal timber yield and economic viability.

5. Conclusion

Increasing spacing promotes the diameter growth of individual trees, but lower initial spacing produces more large-diameter wood per hectare. Genetic factors significantly affect DBH and survival rate performance, while tree height has lower heritability. Early selection can effectively shorten the breeding cycle, with the optimal time points being the 4th year for DBH and the 5th year for V. The D1×G2 planting design offers the highest yield in this study. Genotype G2 is best suited for high-density planting, while genotype G4 excels in low-density conditions. Both genotypes can significantly improve survival rates and timber yields. Future research should focus on evaluating genotype performance under diverse climatic conditions and implementing integrated management practices to optimize wood production.

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CRediT authorship contribution statement

Fenfen Liu: Investigation, Data curation. **Chengcheng Gao:** Investigation, Data curation. **Jan Van den Bulcke:** Writing – review & editing. **Joris Van Acker:** Writing – review & editing. **Chenggong Liu:** Validation, Project administration, Conceptualization. **Qinjun Huang:** Supervision, Funding acquisition, Conceptualization. **Jinjin Yu:** Investigation, Data curation. **Xiaohua Su:** Project administration, Funding acquisition. **Ning Liu:** Writing – original draft, Methodology, Formal analysis.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ning Liu reports financial support was provided by China Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

References

Benomar, L., DesRochers, A., Larocque, G.R., 2012. The effects of spacing on growth, morphology and biomass production and allocation in two hybrid poplar clones growing in the boreal region of Canada. Trees 26, 939–949. https://doi.org/10.1007/s00468-011-0671-6.

Bian, L., Shi, J., Zheng, R., Chen, J., Wu, H.X., 2014. Genetic parameters and genotype–environment interactions of Chinese fir (Cunninghamia lanceolata) in Fujian Province. Can. J. For. Res. 44 (6), 582–592. https://doi.org/10.1139/cjfr-2013-0427.

Bisaria, A.K., Solanki, K.R., Ajit, A., Newaj, R., Tiwari, R., 1999. Effect of tree densities and environmental factors on Hardwickia binata and companion crops in agrisilviculture. J. Trop. For. 15 (2), 93–102. 〈https://www.cabidigitallibrary.org/doi/full/10.5555/19990612678〉.

Bo, H., Zhu, J., Zhang, R., Nie, L., Song, L., 2020. Effects of planting density and clone type on growth and wood volume of Populus tomentosa stands. J. For. Res. 25 (6), 444–449. https://doi.org/10.1080/13416979.2020.1809761.

Ceulemans, R., Deraedt, W., 1999. Production physiology and growth potential of poplars under short-rotation forestry culture. For. Ecol. Manag. 121 (1-2), 9–23. https://doi.org/10.1016/S0378-1127(98)00564-7.

Cooke, J.E., Rood, S.B., 2007. Trees of the people. Grow. Sci. poplars Can. Worldw. Bot. 85 (12), 1103–1110. https://doi.org/10.1139/B07-125.

Dickmann D.I., Isenbrands J.G., J.E. Eckenwalder, J. Richardson (Eds.), Poplar culture in North America. Part A, NRC Research Press, National Research Council of Canada, Ottawa, ON (2001), pp. 1-42.

DeBell, D.S., Clendenen, G.W., Zasada, J.C., 1993. Growing *Populus* biomass: comparison of woodgrass versus wider-spaced short-rotation systems. Biomass. Bioenergy 4 (5), 305–313. https://doi.org/10.1016/0961-9534(93)90046-7.

Fang, S., 2004. Poplar directional cultivation technology and industrialization in the southern region. China For. Ind. 5, 8–10. DOI:CNKI:SUN:LYCY.0.2004-05-005.

Fang, S., Liu, Y., Yue, J., Tian, Y., Xu, X., 2021. Assessments of growth performance, crown structure, stem form and wood property of introduced poplar clones: results from a long-term field experiment at a lowland site. For. Ecol. Manag. 479, 118586. https://doi.org/10.1016/j.foreco.2020.118586.

Fang, S., Xu, X., Lu, S., Tang, L., 1999. Growth dynamics and biomass production in short-rotation poplar plantations: 6-year results for three clones at four spacings. Biomass. Bioenergy 17 (5), 415–425. https://doi.org/10.1016/S0961-9534(99)00060-4.

Fang, S., Xu, X., Yu, X., Li, Z., 2005. Poplar in wetland agroforestry: a case study of ecological benefits, site productivity, and economics. Wetl. Ecol. Manag. 13, 93–104. https://doi.org/10.1007/s11273-003-3104-5.

FAO, 2016. Abstracts of Submitted Papers prepared for the 25 th Session of the International Poplar Commission, jointly hosted by FAO and the German Federal Ministry of Food and Agriculture, Berlin, Germany, 13-16 September 2016. International Poplar Commission Working Paper IPC/14. Forestry Policy and Resources Division, FAO, Rome. Published at 〈http://www.fao.org/forestry/ipc/69946/en/〉.

FAO, Last update: 2023. Forestry Production and Trade. License: CC BY-NC-SA 3.0 IGO. Extracted from: 〈https://www.fao.org/faostat/en/#data/FO〉. Data of Access: 27-01-2024.

Galinski, W., Goossens, R., Ceulemans, R., Impens, I., 1991. The wood productivity of two poplar clones (Populus trichocarpa × Populus deltoides) as affected by stocking and age. Biomass. Bioenergy 1 (4), 233–239. https://doi.org/10.1016/0961-9534(91)90008-Z.

Hodge, G.R., White, T.L., 1992. Genetic parameter estimates for growth traits at different ages in slash pine and some implications for breeding. Silvae Genet. 41, 252–262.

Jiang, Z.H., Wang, X.Q., Fei, B.H., Ren, H.Q., Liu, X.E., 2007. Effect of stand and tree attributes on growth and wood quality characteristics from a spacing trial with Populus xiaohei. Ann. For. Sci. 64 (8), 807–814. https://doi.org/10.1051/forest:2007063.

Khan, G.S., Chaudhry, A.K., 2007. Effect of spacing and plant density on the growth of poplar (Populus deltoides) trees under agro-forestry system. Pak. J. Agric. Sci. 44 (2), 321–327.

Kumar, D., Singh, N.B., 2001. Age-age correlation for early selection of clones of Populus in India. Silvae Genet 50 (3-4), 103–108.

Larocque, G.R., 1999. Performance and morphological response of the hybrid poplar DN-74 (Populus deltoides x nigra) under different spacings on a 4-year rotation. Ann. For. Sci. 56 (4), 275–287. https://doi.org/10.1051/forest:19990402.
Li, B., Wu, R., 1997. Heterosis and genotype× environment interactions of juvenile aspens in two contrasting sites. Can. J. For. Res. 27 (10), 1525–1537. https://doi.org/10.1139/97-110.
Liu, N., Ding, C., Li, B., Ding, M., Su, X., Huang, Q., 2021. Analysis of the genotype interaction of four-year-old Populus euramericana using the BLUP-GGE technique. Forests 12 (12), 1759. https://doi.org/10.3390/f12121759.
Miao, T., Wu, Z., Liu, J., Sun, H., Cao, Z., 2019. Key techniques for cultivation of large-size log of populus plantation. Anhui Agric. Sci. Bull. 25 (07), 96–98. https://doi.org/10.16377/j.cnki.issn1007-7731.2019.07.039.
Miller, R.O., 2018. Growth variation among hybrid poplar varieties in Michigan, USA and the implications for commercial biomass production. BioEnergy Res. 11 (4), 816–825. https://doi.org/10.1007/s12155-018-9937-9.
Nelder, J.A., 1962. New kinds of systematic designs for spacing experiments. Biometrics 283–307. https://doi.org/10.2307/2527473.
Nelson, N.D., Berguson, W.E., McMahon, B.G., Cai, M., Buchman, D.J., 2018. Growth performance and stability of hybrid poplar clones in simultaneous tests on six sites. Biomass. Bioenergy 118, 115–125. https://doi.org/10.1016/j.biombioe.2018.08.007.
Norhazaedawati, B., SaifulAzry, S.O.A., Lee, S.H., Ilyas, R.A., 2022. Wood-based panel industries. In Oil Palm Biomass for Composite Panels. Elsevier, pp. 69–86. https://doi.org/10.1016/B978-0-12-823852-3.00018-0.
Qian, Z., Ge, X., Bai, Y., Tian, Y., Zhuang, S., Fang, S., Tang, L., 2022. Effects of different planting configurations and clones on biomass and carbon storage of a 12-year-old poplar ecosystem in southern China. Can. J. For. Res. 52 (1), 70–78. https://doi.org/10.1139/cjfr-2021-0041.
Sedjo,R.A. 2001. From foraging to cropping: the transition to plantation forestry, and implications for wood supply and demand. Unasylva. In: Perlis A (ed) Unasylva - No. 204 - Looking forward, pp 24–27.
Sixto, H., Cañellas, I., van Arendonk, J., Ciria, P., Camps, F., Sánchez, M., Sánchez-González, M., 2015. Growth potential of different species and genotypes for biomass production in short rotation in Mediterranean environments. For. Ecol. Manag. 354, 291–299. https://doi.org/10.1016/j.foreco.2015.05.038.
State Forestry Bureau of China. 2013. Forestry Industry Standards of the People's Republic of China: Guidelines for lare-size timber cultivation(LY/T 2118-2013).
State Forestry Bureau of China. 2019. National forestry and grassland development statistical bullet in 2018.
Steenackers, J., Steenackers, M., Steenackers, V., Stevens, M., 1996. Poplar diseases, consequences on growth and wood quality. Biomass. Bioenergy 10 (5-6), 267–274. https://doi.org/10.1016/0961-9534(95)00121-2.
Strong, T., Hansen, E., 1993. Hybrid poplar spacing/productivity relations in short rotation intensive culture plantations. Biomass. Bioenergy 4 (4), 255–261. https://doi.org/10.1016/0961-9534(93)90083-G.
Van Acker, J., Defoirdt, N., Van den Bulcke, J. 2016. Enhanced potential of poplar and willow for engineered wood products. Proceedings of the 2nd Conference on Engineered Wood Products based on Poplar/willow Wood. León, Spain.
Wang, H., Jiang, L., Zhang, F., Zhao, X., 2024. Effects of planting density and nitrogen fertilization on growth traits and leaf and wood characteristics of three poplar clones. Sustainability 16 (19), 8561.
White, T.L., Adams, W.T., Neale, D.B., 2007. Forest Genetics. CSIRO-CABI Publishing, New York, NY.
Wu, H.X., 2019. Benefits and risks of using clones in forestry–a review. Scand. J. For. Res. 34 (5), 352–359. https://doi.org/10.1080/02827581.2018.1487579.
Yan, W., Hunt, L.A., 2002. Biplot analysis of diallel data. Crop Sci. 42 (1), 21–30. https://doi.org/10.2135/cropsci2002.0021.
Yan, W., Hunt, L.A., Sheng, Q., Szlavnics, Z., 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Sci. 40 (3), 597–605. https://doi.org/10.2135/cropsci2000.403597x.
Yan, W., Tinker, N.A., 2006. Biplot analysis of multi-environment trial data: principles and applications. Can. J. Plant Sci. 86 (3), 623–645. https://doi.org/10.4141/P05-169.
Yu, Q., Pulkkinen, P., 2003. Genotype–environment interaction and stability in growth of aspen hybrid clones. For. Ecol. Manag. 173, 25–35. https://doi.org/10.1016/S0378-1127(01)00819-2.
Yu, W., Zhongtao, Z., Qi, W., 2022. Achievements of high-quality development of china wood-based panels industry. China Wood-Based Panels 29 (5), 1–6.
Zhao, M., Zhou, G.S., 2005. Estimation of biomass and net primary productivity of major planted forests in China based on forest inventory data. For. Ecol. Manag. 207 (3), 295–313. https://doi.org/10.1016/j.foreco.2004.10.049.
Zhao, T., Cheng, Z., 1994. The Poplar Intensive Cultivation in China. Forestry Publishing House, p. 673 pp:516-523.
Zhu, W., Wang, Y., Qu, G., Xi, B., Jia, L., 2024a. Cultivar and tree size, but not climate, are principal factors affecting stem quality of Populus tomentosa plantations in the North China Plain, 122348,ISSN 0378-1127 For. Ecol. Manag. 573, 2024. https://doi.org/10.1016/j.foreco.2024.122348.
Zhu, W., Wang, Y., Qu, G., Xi, B., Jia, L., 2024b. Cultivar and tree size, but not climate, are principal factors affecting stem quality of Populus tomentosa plantations in the North China Plain. For. Ecol. Manag. 573, 122348. https://doi.org/10.1016/j.foreco.2024.122348.
Zhu, W., Wu, X., Jia, L., Xi, B., 2022. Effects of key forest management practices and climatic factors on the growth of *Populus tomentosa* plantations in the North China Plain. For. Ecol. Manag. 521, 120444.