Radial variations to wood anatomical and chemical properties in eight poplar clones

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2020-0465.R4
Manuscript Type:	Article
Date Submitted by the Author:	10-Jun-2021
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Keyword:	poplar, clone, anatomical properties, radial variation, chemical properties
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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1 **Radial variation of wood anatomical and chemical**
2 **properties in eight poplar clones**

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14

15 **Competing interests statement**

16 The authors declare there are no competing interests

17

Abstract: Wood properties are crucial for the development and application of poplar clones. Here, the effects of clone and age on anatomical and chemical properties were analyzed in eight poplar clones (clone 50, Zhonglin46, 108, 36, N179, Danhong, Sangju, and Nanyang) from Henan province, China. The results showed that the effects of clone and age were both significant for these wood properties. Eight clones were grouped into three clusters according to their annual ring width, fiber quality, and chemical properties. For some properties including annual ring width, fiber length, and microfibril angle, all clones displayed the same radial variation trends. Whereas, for other ones, such as holocellulose content, the radial variation trends were different depending on clones. The culmination of the mean annual increment corresponded to the turning ages of wood properties such as annual ring width in eight clones and holocellulose content in partial clones except for fiber length, microfibril angle, and vessel length. The rotation age of the poplar clones could be determined as 7-8 years based on the fiber quality and chemical components. These results indicated strong genetic and age control of the wood properties and highlighted the rich source of variation for poplar clone selection.

Keywords: poplar, clone, anatomical properties, chemical properties, radial variation, rotation age.

1. Introduction

Poplars (family *Salicaceae*; *Populus* sp.) are primarily distributed in the temperate forests of the northern hemisphere (Fang and Yang 2003). Since the 1940s, the favorable properties of poplars, such as short life, fast growth, wide distribution,

40 considerable genetic variation, and relative ease of hybridization have placed them as
41 the principal tree species in plantation forestry across central and northern China (Guo
42 and Zhang 2010; Gong et al. 2011). Several poplar species and new interspecific
43 hybrids are commonly used in the plywood, wood-composite, and paper industry (Li et
44 al. 2004; Ahmed et al. 2020).

45 Wood quality is crucial for the application and development of clones (Yin et al.
46 2017). For example, the cell size, proportion, and arrangement of elements, as well as
47 the wood chemical components (cellulose and lignin contents) have a direct impact on
48 the timber quality and final products (Bos and Caligari 2008; Sousa et al. 2015).
49 Furthermore, increasingly competitive market pressure is pushing forest industries to
50 shift their focus from the growth to the quality of wood (Wei et al. 2013). The properties
51 of wood are closely related to numerous internal and external factors affecting tree
52 growth, such as genetic origin, cambial age, and silvicultural practices (Zobel and Jett
53 1995). Thus, investigating the impact of clone and age on the wood properties is
54 essential in tree improvement programs to understand the variability trends for different
55 wood traits in species with long harvest periods. Poplar clones have generally been
56 observed to exhibit intra- and inter-clonal variability in wood traits (Peszlen 1994;
57 Koubaa et al. 1998; Jiang et al. 2003; Wu et al. 2013). Currently, a large amount of
58 newly bred poplar clones (e.g., Danhong and Nanyang) were selected and planted to
59 possess different properties of fast-growing, disease resistance, and waterlogging
60 tolerance at the early stage (Meng et al. 1989; Su et al. 1990; Zhao et al. 2006; Zhang
61 et al. 2008; Hu et al. 2013). However, studies on the variation of wood properties of

62 middle-aged poplar clones (9–10 years) are limited. It is beneficial to explore the
63 difference of wood properties among different clones and analyze the rotation ages of
64 middle-aged samples for further breeding and economical wood utilization of poplar
65 clones.

66 Hence, we systematically investigated the following anatomical and chemical
67 properties among eight poplar clones: microfibril angle, dimensions of fibers, vessels,
68 and ray, tissue proportions, holocellulose content, lignin content, and extractive content.
69 Furthermore, different radial variation patterns were deduced, and the parameters of
70 clones were summarized. The objectives of this study were: (1) to evaluate the impact
71 of the genetic origin on wood properties; (2) to explore the radial variations of wood
72 properties; and (3) to suggest the rotation age of poplar clones.

73 **2. Materials and Methods**

74 **2.1. Study Site**

75 The experimental site is in a plantation in Jiaozuo City, Henan province, China
76 (34°48′–35°29′ N, 112°32′–113°39′ E). The climate is characterized by a distinct
77 medium latitude climate with a monsoon influence. The average yearly temperature is
78 between 12.8 °C and 14.8 °C, and rainfall ranges between 600 and 700 mm. Peak rainfall
79 occurs from May to September; the dry season is between November and March, and
80 April and October are the transition months. Trees were spaced with a 3 × 3 m
81 configuration. The plantation was a monoculture planted on flat land and surrounded
82 by farmlands.

83 **2.2. Plant Material and Data Collection**

Wood discs were collected from the following eight poplar clones: clone 50 (*P. deltoids* CL.'55/65'), clone Zhonglin46 (*P. euramericana* 'Zhonglin46'), clone 108 (*P. euramericana* 'Guariento'), clone 36 (*P. deltoides* CL. '2KEN8'), clone N179 (*P. nigra* CL. 'N179'), clone Danhong (*P. deltoides* CL. 'Danhong'), clone Sangju (*P. euramericana* CL. 'Sangju'), and clone Nanyang (*P. deltoides* CL. 'Nanyang'). The age of clone 50, Zhonglin46, 108, N179, Sangju, and Nanyang was 10 years, while the age of clone 36 and Danhong was 9 years (Table 1, Fig. 1). Five trees were selected for each clone.

The selection of the sample trees was based on the mean stem diameter at breast height (DBH) and the mean height (H) of all trees in the plots with stems that showed no apparent defects. At the time of harvesting, the H (m) and DBH (cm) of the trees were measured and tree volume (V, m³) was determined as follows (Xu 1988):

$$V = 0.5134H^{0.826956}\left(\frac{DBH}{100}\right)^{1.995375} \quad (1)$$

The north direction was also marked. The average H, DBH, and V were listed in Table 1.

Each sample tree was cut at ground level. The discs from each tree were sampled at breast height (at 1.3 m) for further analyses of the wood anatomical and chemical properties. The annual ring widths (ARW) were measured from four directions (east, west, south, and north) of each disc, and the total mean ring widths of the eight clones were applied as the current annual increment. The mean annual increment was calculated using the total ring widths and years. The culmination of the mean annual increment (CMAI) was determined through the intersection point of the current annual

increment curve and the mean annual increment curve (Huang et al. 2020).

2.3. Anatomical Characteristic Measurement

The samples employed for the analysis of anatomical properties (fiber length (FL), fiber diameter (FD), microfibril angle (MFA), double wall thickness (2WT), ray height (RH), ray width (RW), vessel element length (VL), vessel element width (VD), vessel frequency (VF), proportion of fiber (PF), proportion of vessel (PV), and proportion of ray (PR)) were taken from the north side of each trunk to ensure that the growth conditions of the wood were as similar as possible. Measurements were performed for each annual ring from the pith to the bark. For FL and VL measurements, wood macerations were conducted using glacial acetic acid and 30% hydrogen peroxide (1:1 ratio) at 80 °C for 4 h. Fifty fiber and 30 vessel element measurements were taken using a depth of field microscope (Keyence VHX-600E, Keyence Corporation, Tokyo, Japan).

The wood blocks (2 cm³) were softened by boiling in water with a microwave for approximately 15-20 min, and transverse and tangential sections (approximately 25-30 µm thick) were prepared with a rotary microtome (Leica RM 2265, Wetzlar, Germany). Sections were observed using a light microscope (Nikon ECLIPSE Ni, Nikon Corporation, Tokyo, Japan) with a DS-Ri2 camera and Image NIS 5.10 software. Fifty measurements of FD, 2WT, and VD were taken in transverse sections, and 30 measurements of RH and RW were taken in tangential sections. In addition, 10 measurements of VF were taken per mm². A 25-points grid was placed over each image of the transverse section. Fiber, vessel, and ray were counted on 30 randomly selected areas. Their proportions were then calculated.

Wood slices with 1 (radial direction) $\times$ 10 (tangential direction) $\times$ 30 mm (longitudinal direction) were prepared, and five MFA measurements were taken using X-ray diffraction (XD-3, Beijing Persee Instrument Co., Ltd., Beijing, China). The data were then computed using the 0.6 T method (Cave 1966) using Origin 2020b software (USA).

2.4. Chemical Component Measurements

The samples used for chemical components (holocellulose content (HOC), lignin content (LC), extractive content (EC)) measurements were collected from the rings around the disc (1-4, 5, 6, 7, 8, and 9–10th growth rings). The 1-4th year included the first four years owing to small increments from the pith till the 4th year, and the 9–10th year included the 9th and 10th years for the same reason. The components were determined based on the national standard for chemical analysis, including GB/T 2677.10-1995, GB/T 35818-2018, GB/T 35816-2018.

2.5. Statistical Analyses

Data was analyzed using SPSS 19.0 IBM (USA). We performed descriptive statistical analysis to determine the mean values and standard deviations of wood properties, considering all clones. An analysis of variance (ANOVA) was carried out to determine significant differences between clone variants and ages with Tukey's multiple range test as a post hoc test. Hierarchical cluster analysis was performed using SPSS 19.0 for ARW, anatomical properties, and chemical properties combined with the "Squared Euclidean Distance" method. The hierarchical grouping developed a relationship between clones that are similar for specified traits. However, the extent of

difference might vary to a certain degree. Thus, during clustering, the number of clones might vary from one to the total number of clones used. To optimize the number of clusters, a cut line on the dendrogram was close to 1/3 of the value. Three clusters were developed based on an information (Pande et al. 2014). The variation in traits with cambial age per clone was fitted with a multiple linear regression equation using Origin 2020 (USA). R^2 values were calculated to assess the degree of the correlations. Radial variations of FL and MFA determined the demarcations of the juvenile and mature wood regions, as recommended by Bao and Jiang (1998).

3. Results

3.1. Variation in Wood Properties among Clones

Table 2 exhibits the means and standard deviations of the wood properties at breast height from the eight poplar clones. These tested wood properties presented significant differences among the eight poplar clones.

3.2. Cluster Analysis

We grouped the eight clones into three clusters (Fig. 2). Table 3 displays the components and the mean values of different wood traits of these clusters. Cluster 1 exhibited the highest values for ARW, FL, 2WT, and PF and lowest values for MFA, RW, VD, PV, and HOC and EC. Cluster 2 demonstrated the highest values for FD, MFA, RH, RW, VL, PV and HOC and lowest values for 2WT, VF, PF, PR, LC and EC. Cluster 3 showed the highest values of VD, VF, PR, and LC and EC and lowest values for ARW, FL, FD, MFA, RH, and VL.

3.3. Radial Variation in Wood Properties

The same trend was observed for ARW of the eight clones (Fig. 3) with cambial age. In particular, the ARW increased rapidly from the pith and subsequently decreased to the periphery. The smallest and largest ring widths were observed in the 9–10 and 5–6 growth rings, respectively. ARW increased with cambial age from pith until the 5–6th year and then rapidly decreased, with the minimum value in the last year. A polynomial function well described this relationship, with an R^2 of 0.61–0.82. There were significant differences in ARW among the rings ($p < 0.001$).

The intersection points of the current annual increment and mean annual increment curves ranged from 6.3 (Danhong) to 7.8 (Zhonglin46 and Nanyang), with a mean value of 7.4 (Fig. 3). The mean annual increment exceeded the current annual increment. The CMAI was estimated as 6–8 years for the eight clones.

There was a highly significant effect of the annual ring position from the pith on the FL ($p < 0.001$). The FL was observed to be shorter close to the pith and subsequently increased to the bark ($R^2 = 0.96–0.99$; Fig. 4). The FD increased with distance from the pith until the 6–7th year, then decreased or remained constant in clones 50, Zhonglin46, N179, Danhong, Sangju, and Nanyang ($R^2 = 0.69–0.85$), but FD increased from the pith to the bark in clones 108 and 36 ($R^2 = 0.51–0.80$). A significant difference in FD was observed between the growth rings ($p < 0.001$). Thus, 2WT was significant ($p < 0.001$), showing thickness increasing with cambial age in clones 50, 36, Danhong, Sangju, and Nanyang ($R^2 = 0.50–0.90$). In contrast, it exhibited a decreasing trend first until the 5–6th year and then increased toward bark in clones Zhonglin46, 108, and N179 ($R^2 = 0.25–0.50$). MFA exhibited a pith-to-bark decreasing trend for all clones ($R^2 =$

0.84–0.97). This result contradicts the observed variations of FL. There were significant differences in MFA among the rings ($p < 0.001$). RH increased from the pith to 6–8th year and remained constant or decreased in clones 50, Zhonglin 46, 108, 36, Danhong, and Nanyang ($R^2 = 0.60–0.89$). However, it increased from the pith to the bark in clones N179 and Sangju ($R^2 = 0.82–0.90$). RW increased with distance from the pith until the 6–7th year and then decreased in clones 50 and Zhonglin46 ($R^2 = 0.67–0.73$). Opposite patterns were found from pith to bark in clones 108, 36, N179, Danhong, Sangju, and Nanyang ($R^2 = 0.20–0.74$). These results illustrate that the influence of age on RH and RW was significant ($p < 0.001$).

The vessel element characteristics varied significantly from the pith to the bark ($p < 0.001$; Fig. 5). Specifically, the VL increased rapidly from the pith to the bark, followed by a reduction in the increment speed. The multiple linear regression exhibited a linear relationship with an R^2 from 0.93 to 0.99. VD increased until the 6–7th year and then decreased ($R^2 = 0.62–0.94$). The opposite was observed for the VF ($R^2 = 0.45–0.94$). There was a significant influence of age on tissue proportion ($p < 0.001$). PF changed differently by cambial age among clones: it increased from the pith to the 5th year, followed by a minor decrease and a slight curvature in clones Zhonglin46, Sangju, and Nanyang ($R^2 = 0.21–0.57$); it decreased from the pith to the bark in clones 50, 36, and Danghong ($R^2 = 0.22–0.73$); and it increased from the pith to the bark in clone 108 ($R^2 = 0.76$), but it was independent in clone N179 ($R^2 = 0.003$). PV exhibited an increasing pattern from the pith to the bark ($R^2 = 0.52–0.91$) except for clones 108 and 36 which reached the maximum at 7th year ($R^2 = 0.58–0.79$). PR decreased from the

216 pith until the 6-8th year and increased or remained constant to the bark in clones
 217 Zhonglin46, 108, N179, Danhong, and Sangju ($R^2 = 0.75\text{--}0.90$). For clone Nangyang
 218 ($R^2 = 0.78$), the PR decreased from the pith to the bark. For clones 50 and 36 ($R^2 =$
 219 $0.09\text{--}0.23$), it changed little.

220 There were significant differences in the chemical properties among the rings ($p <$
 221 0.05 or $p < 0.01$) (Fig. 6). HOC increased from the 1-4th to the 6-7th year and
 222 subsequently decreased, with the lowest value observed in the first four growth rings in
 223 clones 50, Zhonglin46, 108, 36, Danhong, and Sangju ($R^2 = 0.66\text{--}0.94$). Whereas it
 224 decreased from the pith to 6-7th year and then increased slightly in clones N179 and
 225 Nanyang ($R^2 = 0.30\text{--}0.62$). LC demonstrated a declining trend with cambial age, and
 226 the maximum value occurred in the first four growth rings in clones 50, 108, 36, N179
 227 and Danhong ($R^2 = 0.50\text{--}0.96$). Whereas it decreased until 6-7th year and then increased
 228 in clones Sangju and Nanyang ($R^2 = 0.39\text{--}0.86$). Thus, it increased from the pith to the
 229 bark in clone Zhonglin46 ($R^2 = 0.32$). Our results showed variations in EC along with
 230 the cambial age, with a parabolic model in clones Zhonglin46, 108, Danhong, and
 231 Sangju ($R^2 = 0.65\text{--}0.86$), and the maximum value occurred in the 6-7th year, a
 232 decreasing pattern in clones 50, 36, and N179 ($R^2 = 0.23\text{--}0.64$), and no noticeable
 233 change in clone Nanyang ($R^2 = 0.02$).

234 4. Discussion

235 The effects of clone and age on anatomical and chemical properties were discussed
 236 in this present study. Anatomical and chemical properties varied between clones (Table
 237 2), indicating a strong genetic control of the wood properties from the eight clones and

highlighted the rich source of variation for clone selection (Xie et al. 2008). In general, the effects of the clones on the wood properties of the selected trees agreed with previous descriptions for the species (Pande et al. 2012; Pande et al. 2014). However, our observations were contrast to those of Fang and Yang (2003) and Šefc et al. (2009), who reported non-significant differences in fiber length among tested clones. Furthermore, Yang (2003) concluded that there was no significant difference in microfibril angles and fiber length at breast height among seven mature poplar clones. These differences may be attributed to the regulation of the wood traits by environmental factors (e.g., temperature, drought, and wind speed) that alter the final gene expression (Lasserre et al. 2009). The site could have a moderate or significant effect on wood traits (Zhang et al. 2012; Wu et al. 2013). However, our study was performed on a single site and based on five trees per clone. For suitable clone improvement purposes, estimation of quantitative parameters should be performed in more samples from different test locations.

Ring width, which is reflected in cumulative stem volume production, is also considered a crucial wood quality trait by the commercial forest products industry (Downes et al. 2009). The tearing strength of paper and wood strength increase with fiber length (Panshin and de Zeeuw 1980; Song et al. 1997). Cell walls are microscopic indicators that reflect the physical and mechanical properties of wood (Hu et al. 2019). MFA can have an impact on the mechanical properties of wood, such as the tensile strength and stretch properties of pulp fibers, with small microfibril angles resulting in increased tensile strength, and large microfibril angles enhancing elasticity (Mark and

Gillis 1973; Ruelle 2014). Large vessel diameter and high vessel percentage can be problematic in refining and printing processes as well as in the finishing of solid wood. A high ray proportion may affect the shrinkage anisotropy and increase the fine component in the pulp, subsequently slowing down the pulping process (Lei et al. 1997; Leal et al. 2003). The cellulose content determines the value of the raw material and pulping yield (Wang 2010). Whereas, the LC determines the chemical consumption and contamination, and the EC affects the organic solvent consumption (Wang et al. 2004).

In the current study, cluster 1 demonstrated wide ARW, long FL, thick 2WT, high PF, and small MFA, which are preferred for high-quality paper making, wood-composite, plywood, and solid wood products. The high values of HOC and low values for VF, PR, LC, and EC in cluster 2 are suitable for the high-yield and low-consumption paper industry. Cluster 3 was associated with a small ARW, FL, and MFA, whereas the LC and EC were high. Therefore, cluster 3 has fewer application areas than their counterparts in the study. Moreover, cluster 1 exhibited higher H, DBH, and V (Table 1).

A major issue for the genetic selection of wood traits is that most wood properties change with cambial age and stabilize only with cambial maturity (Lenz et al. 2010). Age had a significant effect on all the anatomical and chemical characteristics. In particular, the FL and VL exhibited a significant increase trend from the pith to the outer layer (Jiang and Jiang 2008; Luo et al. 2015; Longui et al. 2017). In contrast, MFA gradually decreased and subsequently remained relatively constant (Jiang et al. 2003; Vega et al. 2020). The transition between juvenile and mature wood was recorded

about 12 years in clone “Zhonglin Sanbei-1” (Bao and Jiang 1998). Here, the wood of eight clones was considered almost juvenile wood, although the radial variation of FL and MFA approached stability at nearly 10 years. Radial variations of other properties, such as PF, HOC, and PR were observed to be different depending on the clones.

In this study, the CMAI was estimated as 6–8 years, and meanwhile, the turning ages of 6–8 years were observed in the variation curves of some anatomical properties such as ARW, VD, and VF in eight poplar clones. In addition, turning ages in variation curves of other anatomical and chemical properties such as PF, HOC, and LC corresponded to CMAI in partial clones. However, the FL, MFA, and VL changed sharply from the pith to 8-9th year, and subsequently gently regardless of CMAI. Considering wood quality, 8-9 years could be defined as the suitable rotation age for middle-aged poplar clones, showing long FL, small MFA, thick 2WT, high HOC, and low LC, which are preferred for paper making and solid wood products. The rotation ages were agreeing well with the results presented by Tang et al. (2004) and Huang et al. (2020).

5. Conclusions

In this study, it was found that the genetic origin and cambial age can significantly affect the anatomical and chemical properties of poplar clones. Eight clones were grouped into three clusters according to their annual ring width, fiber quality, and chemical properties. It was found that FL and VL tend to exhibit a pith-to-bark increasing. Whereas, MFA exhibited a pith-to-bark decreasing trend. The ARW and VD displayed increase and subsequent decrease trends from the pith to the bark, while

VF had a fully inverse trend compared to ARW and VD. In addition, radial variation of other properties, such as PF, RH, and HOC were different depending on the clones. The CMAI was related to the turning ages of anatomical and chemical properties such as ARW in all clones and HOC in partial clones except for FL, MFA, and VL. The rotation age for middle-aged poplar clones could be determined as 8-9 years based on the fiber quality and chemical components. These significant differences observed among clones and the radial variations in the anatomical and chemical properties suggest that breeding programs should focus on improving wood properties and select a suitable rotation age. Additional studies are required to evaluate economic and ecological factors for the appropriate selection of the rotation period of poplar clones. Thus, different locations and increased sample size are needed to develop suitable selection strategies.

Acknowledgments

We are grateful to Xiao Wu, Ning Pei, and Jingliang Zhang of Anhui Agricultural University for the technical assistance regarding the microstructural observation and some data analysis.

Funding

This research was supported by the National Key Research and Development Project of China (grant No. 2017YFD0600201), the Scientific Research Fund of Anhui Education Department (grant No. KJ2017A138), the International Science and Technology Cooperation Program of Anhui Province (grant No. 1704e1002226), and the Natural Science Foundation of Anhui Province (grant No. 2008085MC99).

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Table 1. General characteristics of the poplar clone plantations.

Clones	Stand Age, years	Tree height, m (Mean ±SD)	DBH, cm (Mean ±SD)	Tree Volume, m ³ (Mean ±SD)
50	10	16.8±2.5	19.6±3.3	0.215±0.08
Zhonglin46	10	17.7±0.6	21.2±1.6	0.253±0.04
108	10	18.0±1.3	22.7±1.3	0.294±0.05
36	9	16.7±1.3	17.2±1.8	0.160±0.04
N179	10	17.7±0.8	20.9±2.4	0.246±0.06
Danhong	9	19.8±0.4	20.7±1.4	0.265±0.03
Sangju	10	18.6±0.7	21.7±0.7	0.273±0.02
Nanyang	10	17.4±1.6	20.6±0.9	0.235±0.04

Notes: Mean ±SD indicates mean value and standard deviation.

Table 2. Means and standard deviations of measured wood characteristics in the eight poplar clones.

Clone	ARW, mm	FL, μm	FD, μm	MFA, $^{\circ}$	2WT, μm	RH, μm	RW, μm	VL, μm	VD, μm	VF, n/mm ²	PF, %	PV, %	PR, %	HOC, %	LC, %	EC, %
50	7.8 $\pm$ 4.0cd	1086 $\pm$ 274bc	17.1 $\pm$ 3.2c	16.3 $\pm$ 5.3c	3.6 $\pm$ 0.9d	307 $\pm$ 75.6a	8.2 $\pm$ 1.7a	462 $\pm$ 135b	60.4 $\pm$ 9.8c	47.0 $\pm$ 10.9b	60.5 $\pm$ 11.6e	30.3 $\pm$ 10.1a	10.2 $\pm$ 5.4d	83.2 $\pm$ 1.2a	22.0 $\pm$ 2.1de	1.4 $\pm$ 0.2de
Zhonglin46	8.8 $\pm$ 3.7abc	1102 $\pm$ 272b	19.8 $\pm$ 3.9a	19.2 $\pm$ 5.1a	3.9 $\pm$ 0.9c	293 $\pm$ 75.1b	7.8 $\pm$ 1.5b	492 $\pm$ 136a	61.7 $\pm$ 11.5b	44.3 $\pm$ 12.3c	66.6 $\pm$ 10.0c	24.1 $\pm$ 8.3cd	10.2 $\pm$ 5.6d	81.4 $\pm$ 1.3cd	20.7 $\pm$ 1.8e	1.6 $\pm$ 0.2bc
108	9.6 $\pm$ 4.8a	1145 $\pm$ 269a	17.8 $\pm$ 3.2b	18.3 $\pm$ 7.2ab	4.1 $\pm$ 1.0b	272 $\pm$ 61.2c	7.5 $\pm$ 1.5cd	446 $\pm$ 138c	59.4 $\pm$ 11.2c	47.9 $\pm$ 9.1b	65.7 $\pm$ 15.5cd	24.7 $\pm$ 10.1c	12.4 $\pm$ 6.1c	80.0 $\pm$ 2.0ef	24.0 $\pm$ 1.7abc	1.7 $\pm$ 0.2b
36	7.4 $\pm$ 3.4d	1027 $\pm$ 266d	15.9 $\pm$ 3.6d	16.6 $\pm$ 4.8c	4.4 $\pm$ 1.1a	268 $\pm$ 58.4cd	7.6 $\pm$ 1.5c	410 $\pm$ 121e	63.2 $\pm$ 11.8a	51.8 $\pm$ 8.7a	69.7 $\pm$ 12.9b	21.6 $\pm$ 9.7e	14.8 $\pm$ 6.4a	82.7 $\pm$ 1.8ab	24.5 $\pm$ 1.4ab	1.4 $\pm$ 0.2de
N179	8.7 $\pm$ 3.9abc	1077 $\pm$ 256c	17.8 $\pm$ 3.7b	17.8 $\pm$ 5.9abc	3.6 $\pm$ 1.0d	290 $\pm$ 69.8bc	7.1 $\pm$ 1.4e	429 $\pm$ 120d	59.5 $\pm$ 11.2c	48.1 $\pm$ 7.9b	64.2 $\pm$ 9.7d	23.0 $\pm$ 9.0d	12.8 $\pm$ 5.2bc	81.9 $\pm$ 1.1bc	24.7 $\pm$ 1.3a	1.5 $\pm$ 0.1cd
Danhong	9.2 $\pm$ 4.1ab	1137 $\pm$ 299a	16.9 $\pm$ 3.7c	16.7 $\pm$ 3.9bc	3.5 $\pm$ 0.8e	272 $\pm$ 55.8c	7.2 $\pm$ 1.5e	450 $\pm$ 119bc	59.8 $\pm$ 10.3c	46.0 $\pm$ 9.3bc	74.0 $\pm$ 13.8a	21.4 $\pm$ 8.8e	10.9 $\pm$ 5.8d	80.6 $\pm$ 1.5de	23.0 $\pm$ 1.6cd	1.6 $\pm$ 0.2bc
Sangju	8.8 $\pm$ 4.0abc	977 $\pm$ 253e	16.1 $\pm$ 4.4d	18.7 $\pm$ 6.2a	3.2 $\pm$ 0.9f	261 $\pm$ 53.1d	7.4 $\pm$ 1.4d	449 $\pm$ 119bc	59.4 $\pm$ 12.4c	50.5 $\pm$ 9.7a	61.0 $\pm$ 13.5e	27.2 $\pm$ 11.0b	13.4 $\pm$ 5.4b	79.2 $\pm$ 1.2f	23.2 $\pm$ 2.0bcd	2.2 $\pm$ 0.2a
Nanyang	8.3 $\pm$ 3.5bcd	1153 $\pm$ 262a	15.4 $\pm$ 3.4e	17.7 $\pm$ 3.7abc	4.2 $\pm$ 1.0b	283 $\pm$ 66.2c	7.2 $\pm$ 1.4e	439 $\pm$ 108cd	61.7 $\pm$ 11.7b	51.0 $\pm$ 13.4a	68.9 $\pm$ 15.3b	23.8 $\pm$ 9.4cd	13.3 $\pm$ 5.8b	81.3 $\pm$ 1.9cd	23.9 $\pm$ 2.2abc	1.3 $\pm$ 0.2e

Notes: Statistical differences between clones are denoted using lowercase letters. Different letters correspond to significant differences ($p < 0.01$), ANOVAs were followed by Tukey's tests at the 5% significance level to compare means using SPSS 19.0. ARW annual ring width, FL fiber length, FD fiber diameter, MFA microfibril angle, 2WT double wall thickness, RH ray height, RW ray width, VL vessel element length, VD vessel element diameter, VF vessel element frequency, PF proportion of fiber, PV proportion of vessel, PR proportion of ray, HOC holocellulose content, LC lignin content, and EC extractive content.

Table 3. Mean value of wood properties for the three clusters.

Cluster number	Clones	ARW, mm	FL, μm	FD, μm	MFA, $^{\circ}$	2WT, μm	RH, μm	RW, μm	VL, μm	VD, μm	VF, n/mm ²	PF, %	PV, %	PR, %	HOC, %	LC, %	EC, %
1	108, Danhong, Nanyang	9.3	1145	16.7	17.6	3.9	275.8	7.3	445.2	60.3	48.3	69.5	23.3	12.2	80.6	23.6	1.5
2	50, Zhonglin46, N179	8.4	1089	18.2	17.8	3.7	296.6	7.7	460.8	60.5	46.5	63.8	25.7	11.1	82.2	22.5	1.5
3	36, Sangju	8.1	1002	16.0	17.6	3.8	264.3	7.5	429.3	61.3	51.2	65.3	24.4	14.1	81.0	23.9	1.8

Note: ARW annual ring width, FL fiber length, FD fiber diameter, MFA microfibril angle, 2WT double wall thickness, RH ray height, RW ray width, VL vessel element length, VD vessel element diameter, VF vessel element frequency, PF proportion of fiber, PV proportion of vessel, PR proportion of ray, HOC holocellulose content, LC lignin content, and EC extractive content.

Fig. 1. Xylem observations of disk in clone Sangju and wood strip in clone Nanyang. The cross-sectional surface was photographed under air-dried conditions

Fig. 2. Dendrogram using average linkage (between groups)

Fig. 3. Average wood ring width in the eight poplar clones versus cambial age. The culmination of mean annual increment is equal to the intersection point of the current annual increment and mean annual increment curves. ARW = annual ring width. The curves and equations were fitted by multiple linear regression per clone: (1) 50, (2) Zhonglin 46, (3) 108, (4) 36, (5) N179, (6) Danhong, (7) Sangju, (8) Nanyang.

Fig. 4. Average fiber and ray characteristic in the eight poplar clones versus cambial age. FL=fiber length, FD=fiber diameter, 2WT= double wall thickness, MFA=microfibril angle, RH=ray height, and RW=ray width. The curves and equations were fitted by multiple linear regression per clone: (1) 50, (2) Zhonglin 46, (3) 108, (4) 36, (5) N179, (6) Danhong, (7) Sangju, (8) Nanyang.

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17 **Fig. 5.** Average vessel characteristics and tissue proportions in the eight poplar clones versus
18 cambial age. VL=vessel element length, VD=vessel element diameter, VF=vessel element
19 frequency, PF=proportion of fiber, PV=proportion of vessel, and PR=proportion of ray. The curves
20 and equations were fitted by multiple linear regression per clone: (1) 50, (2) Zhonglin 46, (3) 108,
21 (4) 36, (5) N179, (6) Danhong, (7) Sangju, (8) Nanyang.

Fig. 6. Average chemical components in the eight poplar clones versus cambial age. HOC= holocellulose content, LC=lignin content, and EC=extractive content. The curves and equations were fitted by multiple linear regression per clone: (1) 50, (2) Zhonglin 46, (3) 108, (4) 36, (5) N179, (6) Danhong, (7) Sangju, (8) Nanyang.