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Provenance variation in growth, stem-form, and wood basic density of 24-year-old *Liriodendron*

Variation von Wachstum, Stammform und Holzdichte von 24-jährigen *Liriodendron*-Provenienzen

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Schlagworte: Traits, Erntereife, Jahrringanalyse, Provenienzanalyse

Abstract

We studied phenotypic variation among provenances of *Liriodendron* at near-mature stage to identify those with the most desirable traits for production. To provide a scientific basis for the selection of superior provenances of *Liriodendron*, a provenance trial was established with five provenances of *Liriodendron tulipifera* and 15 provenances of Liriodendron chinense. This trial was established in 1992 at the Subtropical Experimental Center in the Chinese Academy of Forestry. The growth, stem-form qualities, and wood basic density of each provenance were investigated in December 2015. The findings indicated that the growth traits of *Liriodendron* possess signifi-

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cant genetic differences in terms of interaction between provenance and site. Analysis of growth related traits revealed that the choice of fast-growing provenances might improve trunk straightness but decrease the wood basic density. Ring width variance analysis showed that the variation coefficients increased for ring width of four 5-year ring segments between provenances, but the width decreased from pith to cambium, which suggested genetic improvement of wood productivity and density could be realized by provenance selection. Monan (MN) of Guizhou Province and Fuyang (FY) of Zhejiang Province were selected as two high-yield and high-quality provenances based on the analysis of radial variation patterns.

Zusammenfassung

In dieser Studie untersuchten wir die phänotypische Variation zwischen *Liriodendron*-Provenienzen kurz vor Erntereife um die am besten geeignete Provenienz zu identifizieren. Zu diesem Zweck wurden eine Auswahl viel versprechender Provenienzen von *Liriodendron* ein Provenienzversuch angelegt, wobei 5 *Liriodendron tulipifera* und 15 *Liriodendron chinense* verwendet wurden. Der Versuch wurde im Jahr 1992 im Subtropical Experimental Center der Chinese Academy of Forestry angelegt. Das Wachstum, die Stammform und die Holzdichte jeder Provenienz wurde im Dezember 2015 untersucht. Es zeigte sich, dass diese Wachstumstraits der untersuchten *Liriodendron*-Provenienzen deutliche genetische Unterschiede sowie Wechselwirkungen zwischen Provenienz und Standortsgüte aufweisen. Die Analyse der untersuchten Traits zeigte, dass die beste Provenienz eine bessere Stammform aber auch eine geringere Holzdichte aufweist. Ein Ergebnis der Varianzanalyse der Jahrringmessungen ist, dass der Variationskoeffizient in Radialrichtung zunimmt, während die Jahrringbreite abnimmt; dies lässt vermuten, dass eine genetische Verbesserung von Wachstum durch Selektion möglich ist. Die Ergebnisse dieser Studie lassen die Provenienzen „Monan“ aus der Guizhou Provinz sowie „Fuyang“ aus der Zhejiang Provenienz am besten geeignet erscheinen hinsichtlich hoher Stammqualität und Wachstum.

1. Introduction

Wood is a strategic renewable resource, and efficient wood production and regulation of wood traits are important foci of forestry research. However, large variation exists in wood traits among species, between provenances within species, among individuals within provenances, and within individuals themselves (Bamber et al., 1983; Megraw, 1985; Zobel and Van Buijtenen, 1989; Rozenberg and Cahalan, 1997). In turn, it is necessary to understand variation patterns, factors affecting wood traits, and their applications to effectively control and potentially optimize wood yield (Liu et al., 2009).

In 1856, De Vilmorin published his „Note on the Creation of a New Race of Beetroot and Considerations on Heredity in Plants", establishing the theoretical groundwork for the modern seed-breeding industry. After that, many studies were done by forestry breeding experts on provenance trials systems of species like Pinus sylvestris, P. taeda, P. massoniana or Cunninghamia lanceolata, which confirmed significant genetic differences in growth, material properties and adaptability of the seed sources from different places of origin, and made full use of this genetic variation (Tauer and Loo-Dinkins., 1990; Zhou et al., 1993; Hong et al., 1994; Blumenrother et al., 2001). One key result was that testing of the seed source and selection of good seed sources are most important for forest genetic improvement.

Liriodendron chinense and *Liriodendron tulipifera* are the two species in the genus *Liriodendron* of family *Magnoliaceae*, which are classified as a second-class endangered species (Schoenike, 1980; Harlow & Harrar, 1994; Wang, 2008), The former is distributed in the central and southern mountains of China and the northern part of Vietnam, while the latter is widely distributed from the eastern United States to southeastern Canada (Hao et al., 1997; Parks and Wendel, 1990). These rapidly growing species have straight trunks and leaves with a beautiful shape and colour, especially during the fall. The green-yellow flowers have a long flowering period, making them a desirable landscaping tree. The wood is white or reddish brown with a straight and clear grain and detailed texture and is light and strong, exhibiting moderate hardness and thus easy to process. (Wu, 1986; Gu, 1993; Wang, 2005).

At present, both China's domestic and international forest research of *Liriodendron* mainly concentrates on the seedling and middle-aged growth stages of *Liriodendron*, studying growth patterns and characteristics of forest stands, as well as the effect of provenances from different locations, site conditions, soil preparation, fertilization, and mixed planting on *Liriodendron* plantation growth and wood traits (Hao et al., 1997; Liao et al., 2005; Cai et al., 2011; Tong et al., 2013; Peng et al., 2013, Liu, 2013; Hao et al., 2017; Zhang et al., 2018; Gao et al., 2018). Compared to the growth adaptability of different provenances of *Liriodendron* seedlings, the early-stage wood traits of *L. tulipifera* during the early 1980s have been well studied (Taylor, 1979; Harold and William, 1980). Some experts have previously studied on seedling stage, middle and young age of *Liriodendron* geographical provenances. For example, the characters of seed germination and seedling growth of different geographical provenances were studied of *L. chinensis* (Li et al., 1997); Breeding and young stand experiment of *L. chinensis*, *L. tulipifera* and *Liriodendron* hybrids were carried out by Dong et al. (1999). Li et al. (2001a, 2001b) and Li et al. (2000) reported on the performance of young plantation stage of *L. chinensis* provenance trials and Li et al. (2005) examined a case study on provenance testing of *Liriodendron*. In turn, rather little is known about the wood traits of *Liriodendron* at the near-mature age. To address this issue, we investigated four 24-year-old *Liriodendron* provenance trials including 20 seed sources located at Nianzhu Forestry Center and Shangcun Forestry Center of the Subtropical

Experimental Center, Chinese Academy of Forestry, to select the optimal regional high-quality *Liriodendron* provenances.

2. Materials and method

2.1 Experimental site and materials

20 *Liriodendron* provenances collected were used as test materials, including 15 *L. chinense* provenances from the eight provinces covering the whole distribution range—Xuyong (XY) and Youyang (YY) of Sichuan; Ezhou (EZ) of Hubei; Huangshan (HS) and Dabieshan (DBS) of Anhui; Monan (MN) and Liping (LP) of Guizhou; Liuyang (LY), Sangzhi (SZ), and Suining (SN) of Hunan; Fuyang (FY) and Songyang (SY) of Zhejiang; Lushan (LS) and Wuyishan (WYS) of Jiangxi; and Mengla of Yunan (YN) and five *L. tulipifera* provenances were from Missouri (MSL), Anna Lewis (LYS), North Carolina (BK), South Carolina (NK), and Georgia (ZZY) of the United States (Table 1; Figure 1).

Seeds were sown in 1991, four provenance trials were planted in the spring of 1992, two provenance trials in the Nianzhu Forestry Center (114°33‘47“ E, 27°34‘41“ N, elevation 200 m), and the other two provenance trials in Shangcun Forestry Center (114°35‘67“ E, 27°39‘43“ N, elevation 226 m) of the Subtropical Experimental Center, Chinese Academy of Forestry (Fenyi, Jiangxi Province, China, Figure 1). This region is located on Wugong Mountain, which is the northern branch of the Luoxiaoshan Mountains in Jiangxi. This region is characterized by a humid subtropical monsoon climate. The average annual temperature and average annual rainfall are 16.8°C and 1910 mm, respectively. The used site index system utilizes the relationship between average dominant tree height and base age as an index to quantify site production potential (Nanos et al., 2002; Harry et al., 1997). Provenance trials were planted in a randomized block design with four replications, The growth conditions correspond to the four replications, differentiate according to the growth of previously planted Cunninghamia lanceolata and soil fertility (Duan and Zhang, 2017). In each replicate plot, each provenance is planted in three rows with eight trees in each row, which result in total 24 plants at a spacing of 4 by 2 m (Figure 2).

2.2 Test forest evaluation and wood trait determination

In December 2015, we chose three optimal trees of each provenance in every plot as samples for this study. They were evaluated by tree height, height of the first branch, diameter-at-breast-height at 1.3 m (DBH), diameter at half of trunk height, diameter at 4 m trunk height, trunk straightness (on a five-point scale from straight, relatively straight, medium, mildly bent to bent, with a higher score signifying a straighter trunk). We also extracted a whole and intact wood core from the bark to the pith at breast height at the uphill side with a 6 mm diameter increment borer. From the pith outward, every five rings were cut into one segment respectively to measure the ring width (Wi) to explore the radial variation in wood growth. In addition, basic wood density (Di) for every ring segment were measured with the national standard method for determining wood density (GB/T1933-2009), which definers basic wood density as dry sample mass divided by its water saturated volume. We also analyzed snow break rate following a heavy snow event of 2008, by the number of trees damaged divided by the original total number of trees within each provenance

2.3 Data analysis

The width of each ring segment was used to estimate the ring segment area (Ai), from which the weighted average basic density of the wood core was calculated as follows: Db=∑AiDi/Ai (Liu et al., 2009). The volume of individual trees was calculated with the binary standing volume formula for broad-leaved trees, published by the Ministry for Main Tree Species (Li, 2005). For data analysis and comparison, a cubic polynomial ($y=ax^3+bx^2+cx+d$) was selected to fit the relationship between radial growth and wood basic density of *Liriodendron* provenances with cambial age to understand the effect of age. In this model, y is the average ring width or wood basic density for each ring segment, x is the average annual rings number of rings between the ring segment and pith, and a, b, c, and d are regression constants. Using the measured values for individual trees in the plots the GLM program in SAS software was used for the variance analysis in the traits of *Liriodendron*. A bi-factorial ANOVA was employed to test the effects of provenance, site and their interaction. The analyzed traits include growth traits, stem-form qualities, and wood basic density. We computed the I value to represent the uniformity of the radial variation of basic density as the ratio of young wood basic density to that of mature wood. An I value close to 1 implies a more uniform radial variation of wood density.

3. Results

3.1 Provenance variation in growth, stem-form qualities, and wood basic trait

Significant provenance effects existed for the eight main economic traits of *Liriodendron*, including growth, stem-form qualities, and wood basic density (Table 2). Comparing all provenances regarding average DBH growth reveals that the largest value (provenance XY) was 1.97 times higher than the lowest value (provenance DBS). Four provenances (XY, MSL, FY, and MN) had an average DBH larger 27 cm with a variation coefficient of 23.18%. In terms of average height, the height of largest provenance (XY) was 2.08 times larger than of the smallest provenance (DBS). The volume growth exhibited with 56.74% the largest variation by provenance among the studied growth traits. The highest volume growth (provenance XY) was 7.20 times higher than that of the lowest (provenance DBS). Comparing good performing provenances such as XY, FY, MSL, and MN reveals a range in volume growth of 0.6 m^3 per tree. Overall, the stem straightness by provenance ranged from 3.22 to 5.00. With the exception of BK and NK with a straightness score lower 4, all other provenances scored higher 4 for straightness. Therefore, *Liriodendron* had good stem straightness overall. Provenance variation in basic density ranged from 0.37 to 0.46 g per cm^3. The highest density (provenance HS) was 1.24 times that of the least (provenance YN). Provenances such as HS, DBS, and FY had average basic density lower 0.45 g per cm^3, with a variation coefficient of 10.16%. Variation among sites in *Liriodendron* in terms of the eight examined traits studied was significant accounting for 1.10% to 18.00% of total variance (Table 2). Variation among *Liriodendron* provenance in terms of the eight traits was significant, accounting for 5.95% to 26.81% of total variation. The interaction effect of site and provenance had significant effects on all of the traits except for wood basic density, accounting for 21.25% to 36.05% of total variation. Therefore, it was suggested that besides making full use of provenance variation, site and selection of individuals within the provenance should be emphasized.

3.2 Effects of microsite conditions on growth, stem-form qualities, and wood basic density of provenances

Site environment had significant effects on all eight studied traits (Table 2). With improved site conditions, height and DBH of *Liriodendron* increased significantly (Figure 3). The average height and DBH were 21.84 m and 24.96 cm, respectively, for the 24-year-old provenances growing in nutrient rich sites, which were 1.20 and 1.09 times of those growing on poor sites. However, stem straightness and basic density did not show any significant difference in site environment gradients. Therefore, microsite conditions have minimal effects on stem straightness and basic density, although they affect the height and DBH to some extent.

3.3 Pearson's correlation of growth traits with basic density or straightness for provenances

Pearson's correlation coefficients were calculated pairwise between straightness and basic density, on the one hand, and between height, DBH, diameter at half of trunk height, stem volume, diameter a 4 m trunk height and height of the first branch, on the other. The CORR program in SAS software was used for correlation analysis in the statistical test. Pearson's correlation between growth traits and straightness and basic density for the 20 provenances is shown in Table 3. The results show that there is a significant or extremely significant negative correlation among six traits and basic density ($r = -0.5948 \sim -0.2681$), but a significant or extremely significant positive correlation between basic density and straightness ($r = 0.4016 \sim 0.5927$).

3.4 Analysis of ring width and basic density for *Liriodendron* of different ages

Ring width for rings 1–5, 6–10, 11–15, and 16–20 displayed significant provenance variation with a variation coefficient larger 25% (Table 4). This implied that a relatively large variation exists in the radial growth of the 20 *Liriodendron* provenances, from young stand stage until mature age, and that this provenance effect on radial growth lasts through the entire growth period. Provenance selection is thus important for improving the productivity of *Liriodendron*. Furthermore, the coefficient of provenance variation for the four 5-year ring widths showed an increasing trend, indicating an enhanced provenance effect on the radial growth of *Liriodendron* with an increase in cambial age. Provenance effect on basic density was significant for all four 5-year ring segments, and the coefficient of provenance variation was relatively constant at approximately 11%, which was not significantly affected by ring growth, repeated testing, and the interaction with provenance.

3.5 Radial variation patterns and selection of superior provenances

The 20 provenances were divided into *L. chinense* and *L. tulipifera*. Figure 4 shows the radial variation trend lines for the average ring width and average wood basic density, fitted with cubic polynomial, for provenances of the Chinese and North American regions. The R2 value ranged from 0.981 to 0.998, indicating a good fit.

Radial variation in ring width across ring segments showed a similar trend for provenances in the two regions, i.e., a rapid decrease was observed after the first 5 years, which implied that ring width narrowed gradually, with an average width of the 16–20 rings constituting only 33.38% of the rings 1–5 (Figure 4). In addition, *L. chinense* in general has wider rings than *L. tulipifera*. The difference in average ring width was less evident for the 16–20 ring segments of provenances from *L. chinense* and *L. tulipifera*. For both species, the radial variation in wood basic density for the ring segments decreased, increased, then decreased slightly again. The measured basic density was higher for rings 1–5 of *L. chinense*, and lower for the next 3 five-year segments.

Table 5 shows an average I value of 0.95 for the *L. chinense* provenances with a range from 0.90 to 0.98 and a coefficient of variation of 2.46%. The average I value for *L. tulipifera* provenances was 0.93 ranging from 0.89 to 0.97 with a coefficient of variation of 3.75%. This suggests that overall the radial uniformity for provenances of the genus *Liriodendron* was good with the highest average I values of 0.98 found for YN and DBS.

LS was selected as standard control based on the comprehensive analysis of LS and WYS provenances of Jiangxi. Provenances XY, MN, FY, and MSL were chosen as four high-volume provenances, as their volume is 10% above that of LS. Considering high diameter increment, I value close to 1 and good stem form, MN and FY were chosen as two superior provenances (Table 5).

3.6 Effect of snow load and variation of break rate

Evaluation and analysis of the high-mountain *Liriodendron* provenance test forest (Shangcun Forestry Center) after the heavy snow coverage of 2008 showed that the rate of snowbreak of *L. chinense* provenances have a negative correlation with the longitude and latitude of sites of origin (Table 5). The correlation coefficients were -0.1969 and -0.4246, respectively. The average rate of snowbreak is 54.25% for *L. chinense* provenances and 71.43% for *L. tulipifera* provenances.

4. Discussion

Provenance variation in growth, stem-form qualities and wood basic density was investigated in four 24-year-old *Liriodendron* provenance trials including 20 seed sources. We found significant variation among sites for the eight traits studied (accounting for 1.10%–18.00% of total variation). Provenance variation for the eight traits was also significant for *Liriodendron* (accounting for 5.95%–26.81% of total variation). Moreover, site × provenance interaction had significant effects on all of the traits except for wood basic density, which accounts for 21.25%–36.05% of the total variation. This suggest that site, site × provenance interaction (Zobel and Kellison, 1981), and selection of individuals within the provenance should be emphasized while making full use of the variation among provenances. This conclusion is consistent with the results of many other tree provenance trials (Liu et al.,2009), but not with the results of investigation 12-year-old *Liriodendron* provenances (Li et al., 2005). Perhaps because young and middle-aged *Liriodendron* do not show this difference or it may be related to the origin of these provenances. Therefore out study suggests that molecular methods should be used to investigate provenance affinity and classification studies.

The results of Table 3 show that the fast-growing provenances have reduced wood basic density but improved trunk straightness. It was further confirmed that the straightness of fast-growing provenances under high productivity conditions was better, but the wood basic density was significantly reduced (Zhou et al.,1990; 1993; Liu et al.,2009). Therefore, the selection of related provenances should be carried out according to the different cultivation objectives.

Analysis of ring width and wood basic density for ring segments showed that the variation coefficient among provenances increased gradually for the four 5-year ring segments and that provenance effect on radial growth was more prominent as cambial age increased. This is probably due to the genetic differences among provenances, as well as the enhanced difference among provenances caused by the fierce competition of growing in small test plots (Zhou et al., 1993). Provenance effect on basic density is significant for all the four 5-year ring segments, the coefficient of variation among provenances is constant at approximately 11%, and it is not much affected by the growth and development of the ring, test repetition, and interaction with provenance. We can conclude that provenance selection can contribute to genetic improvements in wood basic density.

Radial variation trend lines for average ring width and average wood basic density of ring segments were fitted for provenances of the Chinese and North American regions. The radial variation in ring width across ring segments showed similar trends for provenances in the two regions, i.e., a rapid decrease after the first 5 years. This implies that ring width decreases gradually, with the average width of rings 16–20 being only 33.38% of that of rings 1–5. In general, *L. chinense* had wider rings than *L. tulipifera* .This difference in average ring width was less distinct for the 16–20 ring segments of provenances from these two origins. For both regions, the radial variation in wood basic density for the ring segments decreased, increased, and then decreased slightly again. The basic density was higher in rings 1–5 of *L. chinense* and lower for the next three 5-year segments. These results show that genetic improvement on wood basic density during the seedling stage of *L. chinense* is of particular importance.

Radial uniformity of wood basic density is an important criterion for judging the quality of the provenance, because unevenness in basic density seriously affects the quality of the final product (Schoenike, 1980). Improving the juvenile wood density could reduce the decline in wood quality due to short rotation age (Rozenberg and Cahalan, 1997). Analysis of the results in Fig. 3 and Table 5 show that genetic improvement of wood basic density during the seedling stage of *L. chinense* is of particular importance.

The analysis of snowbreak showed that *L. chinensis* was more stable than *L. tulipifera*. This finding is consistent with working on research sites in Fujian, but different from that of working in Jiangsu. One explanation of the observed pattern can be the natural distribution of *L. chinensis*, which is more common in subalpine regions with precipitation of 600 to 1500 mm, high air humidity, mild summer, deep soil layer and fertile soil (Fang, 1994). Both our test sites and the Fujian test site of Li et al. (2001) are suitable for the growth of *L. chinensis*, but the natural conditions of Jiangsu test site (Li et al. 2005) are quite different from the original distribution of *L. chinensis*, which may explain its poor growth. Site condition had minimum influence on stem straightness and basic density but affected height and DBH to some extent. Site selection seems important for growing productive forests with high wood volume. This conclusion is consistent with the results of a previous study on 7-year-old *Liriodendron* provenances (Li et al 2001a; 2001b).

5. Conclusions

The results of this investigation showed that four provenances (XY, MN, FY, and MSL) were least 18% higher than LS (Standard controls) in volume growth. Two of them (MN and FY) had not only high yield, but also high quality, uniform radial growth, high wood basic density, and good stem form. This conclusion somewhat contradicts studies on the seedling stage, young and middle age of *Liriodendron* geographical provenances (Hao et al., 1997; Dong et al., 1999; Li et al., 2001; Li et al., 2005). Explanations may involve enhanced provenance effects on rings with changes with cambial age and/or growth competition both among provenances and among individuals within provenances in the test plots. We like to advocate to repeat similar studies in the mature forest stage of *Liriodendron* provenances.

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Availability of data and materials

After acceptance, data will be made publicly available as an additional file.

Authors' contributions

YQL, WTP, and XX conceived and designed the experiments. WTP analyzed the data. JJS contributed with analytical tools. WTP, JJS, and YQL wrote the paper, RL and XYW performed the experiments and fieldwork. All the authors read and approved the final manuscript.

References

Bamber P, Burley J (1983) The wood properties of radiate pine. Commonwealth Agricultural Bureau, Slough, England, pp 1-84.

Cai W J, Dou X, Gao H D, et al. (2011) Effect of combined fertilization of NPK on initial growth of young L.chinese × L.tulipifera plantation. Journal of Nanjing Forestry University (Natural Science Edition) 04:27-33.

Dong C, Tan D L, Wang C J, et al. (1999) Research report on the geographical provenance test result of *Liriodendron*. Hubei Forestry Science and Technology (01):3-10.

Duan A G, Zhang J G (2004) Modeling of Dominant Height Growth and Building of Polymorphic Site Index Equations of Chinese Fir Plantation. Scientia Silvae Sinicae 40(6):13-19.

Fang Y M (1994) Geographical distribution and spatial pattern of *Liriodendron chinense*. Journal of Nanjing Forestry University (Natural Science Edition) 18(2):13-18.

Gao C L, Song B Y, He X G (2017) Techniques for *Liriodendron chinense* Breeding. Shanxi Forest Science and Technology (03):85-86.

Gu W C (1993) Fast growing and high yield technology of major broad leaved tree species. Chinese Forestry Press, Beijing, pp 64-78.

Hao R M, He S A, Tang S J, et al. (1997) Geographical distribution of *Liriodendron chinense* in China and its significance. Journal of Plant Resources and Environment (01):1-6.

Hao R M, Liu Y L, Cai X L, et al. (1997) Adaptability comparison of seedling growth of *Liriodendron chinense* provenances. Journal of Jiangsu Forestry Science & Technology (01):37-38+50.

Hao Z Y, Li H G, Kang H, et al. (2017) Growth Pattern and Early Selection of *Liriodendron tulipifera*. Forest Research 30(05):878-885.

Harlow WM, Harrar ES (1994) Textbook of dendrology. McGrau-Hill Book Company: 397-400.

Harold C, William M (1980) Some anatomical characteristics of yellow poplar branch wood. Wood science 13(2):99-101.

Eriksson H, Johansson U, Kiviste A (1997) A site-index model for pure and mixed stands of Betula pendula and Betula pubescens in Sweden. Scandinavian Journal of Forest Research, 12(2):149-156.

Hong J S, C Y X (1994) Special Journal of provenance trials of Chinese fir (Cunninghamia lanceolata). Forest Research 7 (Special Issue):1-15.

Li B, Gu W C, Xia L F, et al. (2001a) Study on genetic variation and selection of main wood characteristics among provenances of *Liriodendron*. Scientia Silvae Sinicae 37(2):43-51.

Li B,Gu W C, Xia L F,et al. (2001b) Genetic variation and selection of Provenances of Liriodendron evaluation research. Forestry Research 14(3):237-244.

Li B K (2005) The method for determining the standing volume by illegal & excessive logging. Forest inventory and planing 30(6):25-28.

Li H G, Chen L, Liang C Y, et al. (2005) A Case Study on Provenance Testing of Tulip Tree (Liriodendron). China Forestry Science and Technology (05):13-16.

Li J M, Feng J W, Xie F (2000) Growth Characteristics of *Liriodendron chinense* Plantation. Forestry Research 13(6):622-627.

Li W Q, Luo D H, Dong C Y, et al. (1997) Preliminary Study on the Seedling Stage of Geographical Provenance Test of *Liriodendron chinense*. Journal of Hunan Forestry Science and Technology (01):4-7.

Liao M, Wei X L,Zhu Z R, et al. (2005) Study on Growth Regularity and cultivation technology of *Liriodendron chinese* seedlings. Guizhou Forestry Science and Technology 01:20-23.

Liu H T (2013) 20-Year-Old *Liriodendron tulipifera* Productivity and Carbon and Nitrogen Accumulation Evaluation. Fujian Forestry Science and Technology 01:26-28.

Liu Q H, Jin G Q, Zhang R, et al. (2009) Provenance Variation in Growth, Stem-Form and

Wood Density of Masson Pine at 24-Year-Old and the Provenance Division. Scientia Silvae Sinicae 45(10):55-61.

Megraw R A (1985) Wood quality factors in loblolly pine. TAPPI Press Atlanta, Georgia, 68(7):1-88.

Nanos N, Calama R, Cañadas N, et al. (2002) Spatial stochastic modelling of cone production from stone pine (Pinus pinea L.) stands in the Spanish Northern Plateau[C]// Modelling forest systems. Workshop on the interface between reality, modelling and the parameter estimation processes, Sesimbra, Portugal, 2-5

Parks CR, Wendel JF (1990) Molecular divergence between Asian and North American species of *Liriodendron* (*Magnoliaceae*) with implication for interpretation of fossil floras. Amer J Bot 77(10):1243-1256.

Peng X, Geng Y H, Li X Z, et al. (2013) Study on Container Seedling Cultural Techniques of Light Media for *Liriodendron chinense*. Hubei forestry science and technology 01:5-8.

Rozenberg P, Cahalan C (1997) Spruce and wood quality:geneticaspects (a review). Silvae Genetica 46(5):270-279.

Schoenike RE (1980) Yellow poplar an annotated bibliography. Entry, 1013, Department of Forestry, Clemson University, Clemson, SC, 200-300.

Blumenrother M, Bachmann M, Muller-Starck G (2001) Genetic characters and diameter growth of provenances of Scots Pine (Pinus sylvestris L.). Silvae Genetica, 50(6): 212- 222.

Tauer C G, Loo-Dinkins J A (1990) Seed source variation in specific gravity of loblolly pine grown in a common environment in Arkansas. Forest Science, 36(4): 1133-1145.

Taylor F W (1979) Property variation within stems of selected hardwoods growing in the mid-south. Wood science, Mississippi. USA 11(3):193-199.

Tong B Q, Lu Y Z, Li W Q (2013) Different woven bag types on growth of *L. tulipifera* after bagged cultivation. Shandong forestry science and technology 03:45-47.

Wang Z R (2005) With the use of *Liriodendron* hybrids breeding. Chinese Forestry Press, Beijing.

Wang Z R (2008) Achievements and Strategies of Cross breeding of *Liriodendron*. China Forestry Science and Technology (05):1-4.

Wu D C (1986) Excellent Alpine timber ornamental rare species *Liriodendron*. Research of Agricultural Modernization 3:42-46.

Zhang X L (2018) Seedling raising and afforestation techniques of *Liriodendron chinense*. Forestry of Shanxi (03):36-37.

Zhou Z C, Fu Y S, Wu T L (1993) Geographic variation in growth and wood properties and determination of the optimum provenance region for paper-pulp wood of Masson pine. Forest Research (05):556-564.

Zhou Z C, Jin G Q, Qin G F (1990) Geographical variation and correlation in specific gravity and tracheid length of juvenile wood of Masson pine. Forest Research 3(4):393-397.

Zobel B J, Kellison C (1981) Significance of genotype and environment interaction in forest management. Selected papers of the Eighth World Conference on forestry. China Forestry Publishing House, Beijing, pp 162-167.

Zobel B J, van Buijtenen J P (1989) Wood variation: its causes and control. Springer-Verlag, Berlin, pp 72-131.

Appendix

able 1: Description of 20 Liriodendron seed stands, of which seeds were used in this study

Tabelle 1: Beschreibung der 20 *Liriodendron*-Bestände, deren Samen in dieser Studie verwendet wurden.

Nr.	Country	Province/State	Provenance region	Latitude	Longitude	Elevation (m)
XY	China	Sichuan	Xuyong	28.2°N	105.5°E	700-900
YY	China	Sichuan	Youyang	28.82°N	108.8°E	800-1000
EZ	China	Hubei	Ezhou	30.3°N	109°E	1100-1300
HS	China	Anhui	Huangshan	30.17°N	116.1°E	1150-1350
MN	China	Guizhou	Monan	26.8°N	109.5°E	950-1150
LP	China	Guizhou	Liping	26.5°N	108.6°E	1000-1200
LY	China	Hunan	Liuyang	28.05°N	113.9°E	1000-1200
SZ	China	Hunan	Sangzhi	29.16°N	110.2°E	1100-1300
SN	China	Hunan	Suining	26.22°N	110.2°E	1400-1600
FY	China	Zhejiang	Fuyang	29.13°N	119.9°E	0-100
SY	China	Zhejiang	Songyang	28.5°N	119.6°E	100-200
LS	China	Jiangxi	Lushan	29.53°N	116°E	1000-1200
WYS	China	Jiangxi	Wuyishan	27.92°N	117.8°E	900-1100
YN	China	Yunnan	Mengla	21.4°N	101.6°E	600-800
DBS	China	Anhui	Dabieshan	31.13°N	118.2°E	1350-1550
MSL	USA	Missouri	Doss	37.6°N	91.5°W	600-800
LYS	USA	Louisiana	Deridder	31°N	93.6°W	0-100
BK	USA	North Carolina	Ansonville	35.13°N	80.09°W	1000-1200
NK	USA	South Carolina	Collinton	34.5°N	81.8°W	100-300
ZZY	USA	Georgia	Morganton	34.73°N	84.15°W	350-700

Table 2: Variance analysis of examined traits

Tabelle 2: Varianzanalyse der untersuchten Traits

Traits		Height (m)	DBH (cm)	Diameter at 50% height (cm)	Straightness	Diameter at 4m height (cm)	Height first branch (m)	Basic density ($g\cdot cm^{-3}$)	Volume (m^3)
Source of variation	Site	183.5856**	80.0798**	84.8602**	1.2023**	200.4797**	85.7977**	0.0222**	0.3987**
		(17.71)	(1.10)	(9.21)	(1.20)	(9.18)	(13.58)	(18.00)	(7.16)
	Provenance	72.1830**	115.7262*	41.8586**	1.5071**	108.5104**	23.3287**	0.0051**	0.2345**
		(26.81)	(22.64)	(19.01)	(18.52)	(19.66)	(5.95)	(16.00)	(16.24)
	Interaction	14.3757 **	40.6213**	14.6086**	0.6521**	35.8279**	12.0872**	0.0014	0.0990**
		(25.52)	(32.89)	(21.25)	(27.25)	(29.07)	(26.84)	(5.50)	(36.05)
	Error	5.1410	13.2702	6.8119	0.2576	13.0859	5.5475	0.0012	0.0293
		(29.96)	(43.37)	(50.53)	(53.03)	(42.09)	(53.63)	(60.50)	(40.55)
Mean		20.35±4.04	23.76±5.51	14.56±3.62	4.46±0.69	20.89±5.50	10.36±3.16	0.43±0.04	0.47±0.27
CV (%)		19.84	23.18	24.86	15.57	26.32	30.47	10.16	56.74

Notes: Percentage of total phenotypic variance explained by variance component is provided within parentheses. DF of site, provenance, site × provenance, and error is 3, 19, 57, and 80, respectively. * and ** indicate significance at 0.05 and 0.01 probability levels, respectively.

Table 3: Genetic correlation between growth traits and straightness, basic density for 20 provenances.

Tabelle 3: Genetische Korrelation zwischen Wachstumstraits, Stammform und Holzdichte der 20 Provenienzen.

Table 4: Variance analysis of width and wood basic density of different ring segments of Liriodendron provenances

Tabelle 4: Varianzanalyse der Jahrringbreite und Holzdichte verschiedener Jahrringsegmente der *Liriodendron*-Provenienzen

Trait	Ring segment	Source of variation				Mean	Range	CV (%)
		Site	Provenance	Site × Provenance	Error			
Ring width (mm)	1-5	552.5344**	369.8858**	217.1480**	88.3058	47.82	10.35-90.32	25.71
	6-10	47.3180	202.7954**	121.3153*	73.6562	26.20	6.39-58.02	37.47
	11-15	191.4111**	140.0961**	73.3466*	44.6243	20.28	5.02-49.33	38.84
	16-20	16.8796	99.4132**	62.6903**	34.1327	15.96	4.10-45.51	42.85
Basic density ($g\ cm^{-3}$)	1-5	0.0253**	0.0053**	0.0017	0.0016	0.43	0.32-0.56	11.26
	6-10	0.0209**	0.0061**	0.0020	0.0016	0.42	0.31-0.58	11.65
	11-15	0.0235**	0.0077**	0.0018	0.0017	0.43	0.31-0.65	11.68
	16-20	0.0222**	0.0055**	0.0028**	0.0016	0.45	0.32-0.69	11.33

Table 5: Summary of trait und properties of 20 provenances in this study showing mean ± standard deviation

Tabelle 5: Zusammenfassung der untersuchten Traits und Eigenschaften der 20 *Liriodendron*-Provenienzen dieser Studie mit Mittelwert ± Standardabweichung

Nr.	Height (m)	DBH (cm)	Basic density (g·cm-3)	Volume (m^3)	Wood dry matter (kg)	I value	Straightness	Snow damage rate (%)
XY	24.32±2.91	28.00±4.32	0.41±0.04	0.72±0.27	293.77±74.23	0.91±0.04	4.75+0.39	37.93
YY	21.32±3.11	23.79±5.75	0.43±0.04	0.48±0.26	204.39±68.63	0.95±0.02	4.71+0.45	50.00
EZ	20.35±2.59	24.38±3.18	0.41±0.05	0.46±0.16	189.48±64.25	0.96±0.02	4.25+0.69	50.00
HS	20.65±3.26	22.68±3.86	0.46±0.04	0.42±0.21	190.87±67.89	0.94±0.02	4.00+0.71	75.00
MN	21.66±3.85	27.33±5.84	0.41±0.03	0.64±0.37	265.89±72.51	0.96±0.02	4.54+0.66	80.00
LP	21.95±2.10	25.53±3.74	0.43±0.03	0.53±0.15	228.61±69.34	0.92±0.03	4.88+0.31	33.33
LY	21.15±2.22	22.93±2.83	0.43±0.04	0.42±0.13	177.79±66.20	0.95±0.02	4.38+0.86	14.29
SZ	19.31±4.10	20.73±3.72	0.42±0.05	0.33±0.15	134.90±67.67	0.97±0.03	4.54+0.58	70.00
SN	21.08±3.42	20.86±4.78	0.44±0.05	0.37±0.19	152.61±72.38	0.96±0.03	4.94+0.18	60.00
FY	21.17±4.47	27.83±6.37	0.45±0.03	0.66±0.37	291.29±74.02	0.96±0.02	4.61+0.33	63.64
SY	21.23±3.31	25.06±4.84	0.41±0.05	0.52±0.23	211.42±69.46	0.90±0.04	4.58+0.36	54.55
LS	21.39±3.92	25.38±6.33	0.46±0.02	0.56±0.35	242.32±70.86	0.95±0.02	4.50+0.39	64.71
WYS	19.50±3.88	22.83±4.99	0.44±0.04	0.41±0.20	181.55±66.94	0.96±0.03	4.61+0.49	71.43
YN	22.19±2.95	24.78±3.39	0.37±0.03	0.64±0.26	191.49±68.59	0.98±0.03	4.75+0.34	88.89
DBS	11.68±1.92	20.30±2.84	0.46±0.04	0.46±0.21	144.53±74.49	0.98±0.02	4.05+0.88	0.00
MSL	21.61±3.81	27.96±4.73	0.42±0.03	0.42±0.09	268.37±78.75	0.90±0.03	4.67+0.33	57.14
LYS	19.93±2.75	24.35±5.36	0.45±0.03	0.35±0.19	203.96±69.85	0.96±0.03	4.08+0.58	91.67
BK	17.31±2.01	20.18±3.00	0.43±0.04	0.36±0.16	105.12±74.23	0.95±0.02	3.22+0.92	75.00
NK	15.93±2.99	17.24±4.82	0.44±0.04	0.64±0.16	107.83±72.31	0.89±0.03	3.39+1.36	60.00
ZZY	16.22±3.09	19.45±5.44	0.43±0.05	0.20±0.04	85.55±78.71	0.97±0.03	4.59+0.48	71.43

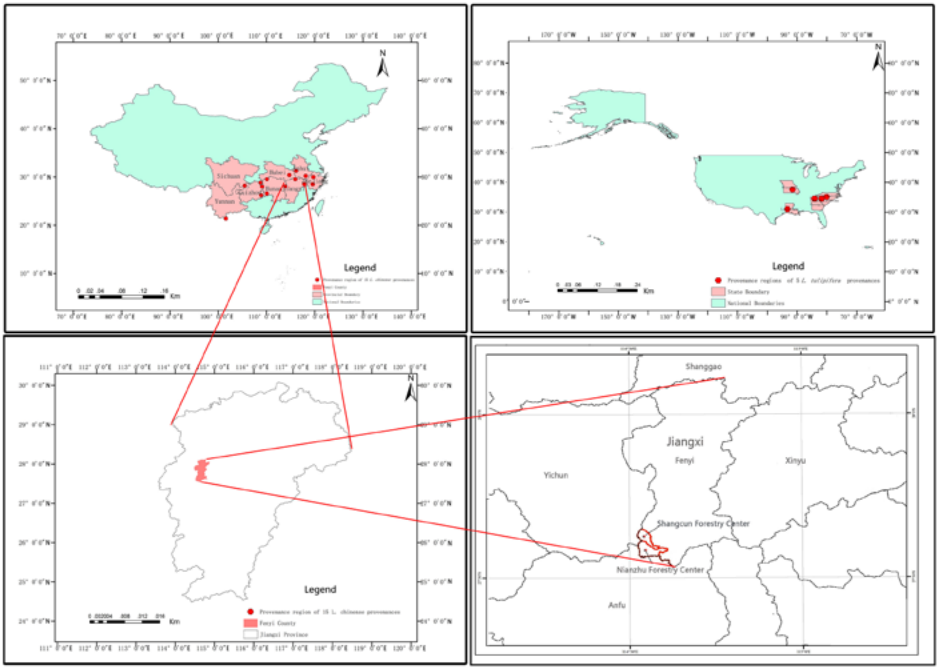


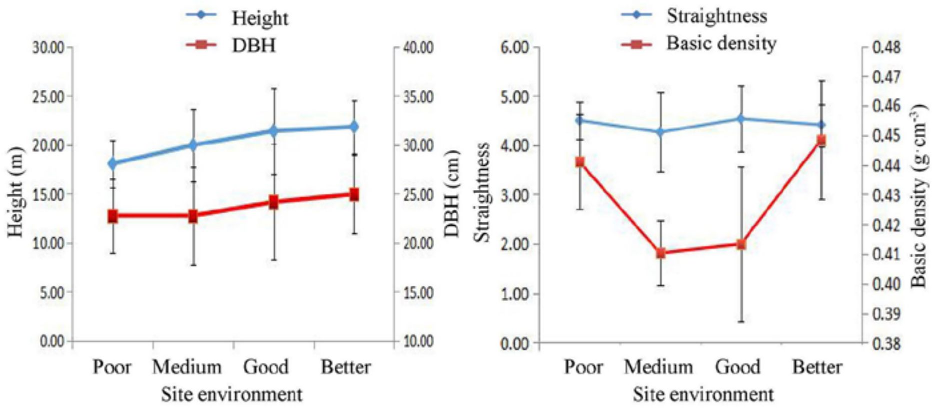
Figure 1: Collection regions of 15 Liriodendron chinense provenances in China and 5 L. tulipifera provenances in USA (top) and location of provenance trials (bottom)

Abbildung 1: Lage der Samenbestände der 15 *Liriodendron chinense*-Provenienzen in China und 5 *L. tulipifera* Provenienzen in den USA (oben) und Lage der Provenienzversuchsflächen (unten)

I	WYS	MN	NK	BK	EZ	ZZY	YN	LS	DBS	SZ	SN	SY	LY	HS	FY	LYS	YY	MSL	XY	LP
II	LS	XY	ZZY	SY	SZ	SN	YY	NK	FY	BK	MSL	YN	LP	DBS	EZ	LY	WYS	LYS	MN	HS
III	XY	DBS	MSL	SZ	WYS	YN	SN	LYS	NK	FY	ZZY	MN	LY	LS	LP	BK	YY	SY	EZ	HS
IV	LYS	DBS	BK	FY	NK	ZZY	LS	SY	SN	YN	XY	SZ	EZ	MSL	LY	MN	HS	WYS	YY	LP

Figure 2: The layout of the four repetitions in this study. The abbreviations refer to the used provenances.

Abbildung 2: Versuchslayout der vier Wiederholungen dieser Studie. Die Abkürzungen beziehen sich auf die verwendetetn Provenienzen.



F igure 3: Trait mean and standard deviation across a site environment gradient

Abbildung 3: Traitmittelwerte und deren Standardabweichung entlang eines Standortsgütegradienten

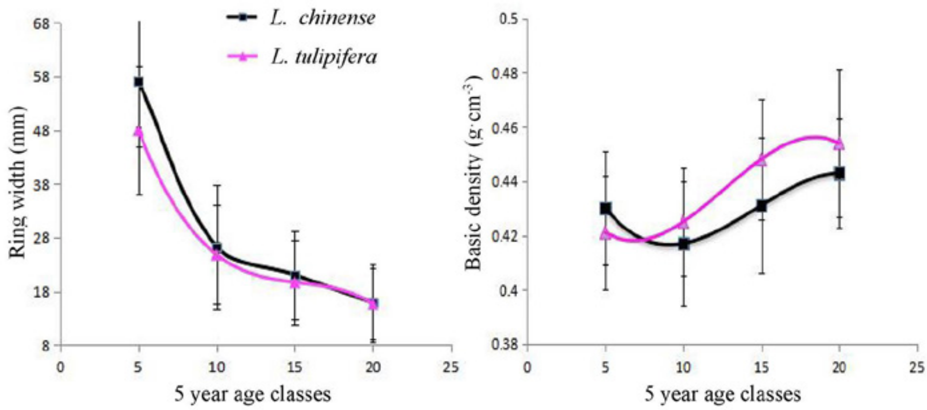


Figure 4: Radial change in average ring width and wood basic density analyzed for 5-year age class segments for Liriodendron provenances from two provenance zones.

Abbildung 4: Radielle Änderung der Jahrringbreite und Holzdichte analysiert in 5-Jahres Segmenten für zwei Provenienzzonen