WOOD RESEARCH doi.org/10.37763/wr.1336-4561/67.2.187197
e-ISSN 2729-8906
67(2): 2022 187-197 pp.

SEASONAL DYNAMIC CHANGES OF SAPWOOD AND HEARTWOOD IN *LARIX GMELINII*

YINGZHI CHANG, CHUNLONG ZHENG, XUEJING SHAO, ZHIYI XIA, ENHUA XI
SHANDONG AGRICULTURAL UNIVERSITY
CHINA

(RECEIVED DECEMBER 2021)

ABSTRACT

This study describes the seasonal dynamic changes of heartwood transformation of *Larix gmelinii by* establishing the relationship between trunk radius, heartwood radius, sapwood width, trunk growth rings and heartwood growth rings in different heights during the growth season with regression analysis. The results showed that the initial age of heartwood formation was 7.25 years. Heartwood began to form when the trunk radius was greater than 2.6 cm, and then the heartwood radius grew 0.85 cm for every 1.00 cm growth of the trunk radius. It was also demonstrated that the significant change and growth rate of heartwood with month were higher than sapwood at the tree base and 1 m height, but lower than sapwood at 5 m and 9 m height. The absolute content of heartwood and sapwood area decreased with tree height, however, the relative content of sapwood area increased with the tree height.

KEYWORDS: *Larix gmelinii*, heartwood formation, dynamic change.

INTRODUCTION

Transformation from sapwood to heartwood is an important physiological process in tree growth. The growth and change of sapwood annual rings are also complicated. Some wood scientists have investigated that the uniqueness of heartwood material variously effect on trees, such as coloring (Calienno et al. 2014), antibacterial property (Chen et al. 2015), durability (Chen et al. 2014). Numerous experiments have also demonstrated that the heartwood play an important role in wood processing and utilization because its density, strength and natural durability (Pâques and Charpentier 2015) are all higher than sapwood. The location and content of heartwood (Miranda et al. 2014), the nature of heartwood and the extract (Morais and Pereira 2011, Davies et al. 2014) are important factors affecting the use of wood, including permeability (Scheiding et al. 2016), physical and chemical modification (Puntambekar et al. 2016, Bahmani et al. 2020), bonding, anti-corrosion and flame retardant treatment (Aguilera and Zamora 2009), wood product decoration performance (Baral et al. 2017). Because of the importance of heartwood, it is necessary to understand the formation mechanism of heartwood, so as to better control the properties of heartwood from the aspect of developmental biology and to better use of heartwood efficiently. In order to clarify the formation mechanism of heartwood, extensive studies have been carried out on the transformation process of heartwood, including the ratio of heartwood (Kokutse et al. 2010) and definition methods (Saito et al. 2008, Pfautsch et al. 2012), heartwood color characteristics (Lukmandaru et al. 2009, Moya et al. 2012), heartwood formation related gene expression (Huang et al.2010, Yoshida et al. 2012), water distribution during transformation (Kuroda et al. 2009), heartwood extract (Davies et al. 2014) and its application value (Chen et al. 2012, Li et al. 2012), heartwood durability. It has been proven that the heartwood transformation is a process controlled by genes (Huang et al. 2009), and is also a complex physiological process affected by climate, site conditions, temperature and other environmental factors. Therefore, the continuous process of heartwood formation, namely the seasonal dynamic change, is of great importance. Currently, few studies on the seasonal change of heartwood formation have been reported (Nakaba and Fukatsu 2012).

The purpose of this study was to describe the seasonal dynamic changes of heartwood formation during the growth season in order to analyze the growth mechanism and construct the growth model, which will provide scientific basis for the directional cultivation of artificial wood.

MATERIAL AND METHODS

Materials

Healthy plants of fast-growing 30 years old *Larix gmelinii* grown at a plantation in Genghis Khan Town (located at 47°75'N, 122°83'E, altitude 261 m, Zhalantun City, Inner Mongolia, China) with the same diameter at breast height were chosen and marked. Two trees of each month were harvested on 15 from March to December in 2018. The harvest dates are characterized in Tab. 1.

Tab. 1: Sampling date and the condition of sample trees.

Sampling time	Temperature (°C)	Phenology	Phase of cambium
Mar. 15, 2018	-17～6	Defoliation	Dormant phase
Apr. 15, 2018	2～12	Leaf growing	Active phase
May 15, 2018	11～21	Full foliage	Active phase
Jun. 15, 2018	11～19	Full foliage	Active phase
Jul. 15, 2018	19～29	Full foliage	Active phase
Aug. 15, 2018	12～24	Full foliage	Active phase
Sep. 15, 2018	9～17	Full foliage	Active phase
Oct. 15, 2018	0～8	Yellow leaf	Dormant phase
Nov. 15, 2018	-13～4	Defoliation	Dormant phase
Dec. 15, 2018	-16～9	Defoliation	Dormant phase

Disks with thickness of 10 cm were cut by a chain saw from the stem of sample tree base, 1 m, 5 m and 9 m (Fig. 1). In the disc, the three types of sapwood (SW), transition zone (TW) and heartwood (HW) differ in color. Heartwood is the darkest, reddish brown. Sapwood is yellowish-white, much lighter than heartwood, but darker than transition wood, which is the lightest or whitest. The heartwood and transition zone were defined according to the color observed by naked eye. The boundary between sapwood and transition zone and between transition zone and heartwood is usually easy to distinguish. The transition zone surrounds the heartwood. Transition area wood generally extends tangentially along the growth ring boundary (Fig. 2).

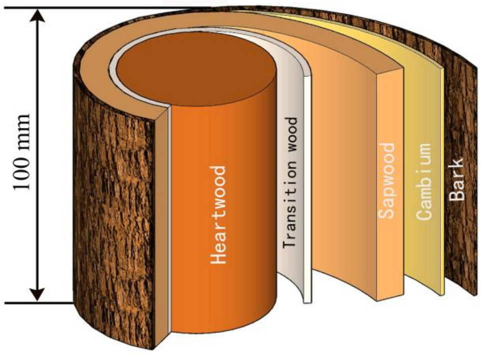


Fig. 1: Sampling discs of sapwood, transition wood and heartwood.

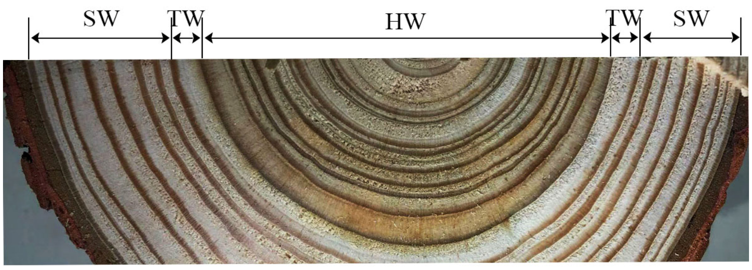


Fig. 2: The colors on samples distinguish of sapwood (SW), transition wood (TW) and heartwood (HW).

Methods

On each occasion, the disk was planed and the number of disk rings, sapwood, heartwood and transition zone were recorded according to the color difference. The diameter of the disk, sapwood, heartwood and the width of the transition zone were measured by vernier calipers.

RESULTS AND DISCUSSION

The initial age of the heartwood

A linear model was used to estimate the heartwood's initial age. As shown in the Fig. 3, the number of heartwood annual rings and disk rings at each height of the trunk were distributed on the coordinate axis. The formation velocity of heartwood was represented by the slope of the fitting regression line. The initial age of heartwood was indicated by the intersection of line extrapolation and abscissa. The number of heartwood rings were generally increased as the number of disk rings increased, which indicating that the growth of heartwood was gradually transformed from sapwood with the increase of tree age. The average heartwood formation rate was 0.91 rounds per year and the starting age of heartwood was 7.25 according to the slope of the regression curve. The initial age of heartwood in Coast pine (Pinto et al. 2004) and Norway spruce (Longuetaud et al. 2006) was 10 years or so which belongs to the species with earlier heartwood formation.

There is a significant positive quadratic function between the number of tree rings and cambium age. The latter is the main control factor of the former variation can explain 97.9% of the former variation. A high correlation between these two variables has been confirmed by other studies (Bjorklund 1999). In general, each cambium age corresponds to a definite heartwood growth rate. For example, the cambium age of *Pinus sylvestris* is 45 years and 115 years, the growth rates of heartwood ring numbers were 0.5 and 0.9, respectively (Bjorklund 1999).

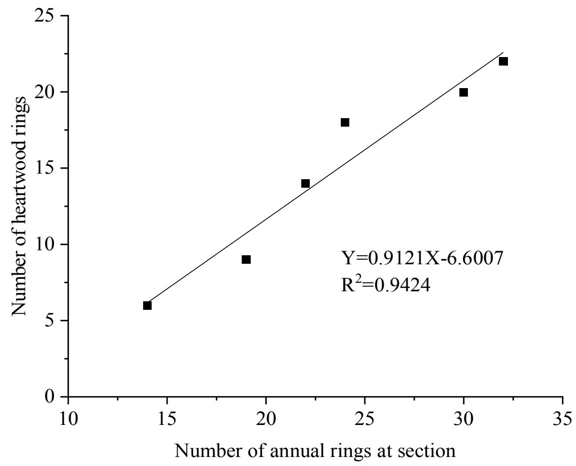


Fig. 3: Variation of heartwood rings number with disk rings number.

The seasonal change of heartwood and sapwood width

The variation of heartwood and sapwood in the annual growth cycle is helpful to understand the growth process of trees and evaluate the wood yield and quality of wood. The regression equation of heartwood radius and trunk radius was Y = 0.8513X - 2.2162, and the correlation coefficient was R^2 = 0.9849, as shown in Fig. 4.

It can be seen from the Fig. 4 that when the cross section radius was larger than 2.6 cm, the heartwood was began to form. After that, the heartwood radius grew 0.85 cm for every 1 cm growth of the trunk radius. The growth index of heartwood radius showed a significant linear relationship with the radius of the trunk. The regression equation between the radius of sapwood and the trunk was Y= 0.1742X + 2.1302, and the correlation coefficient R^2 = 0.6862, indicating that after the heartwood was formed, both heartwood and sapwood were existed on the section. The ratio change of sapwood width was not significantly, and the difference was 2.74 - 4.13 cm. When the radius of trunk was 6.42 cm, the width of heartwood and sapwood was equal. The radius of heartwood was smaller than that of sapwood when the trunk radius was less than 6.42 cm. The heartwood radius was larger than sapwood’s when the radius of trunk was greater than 6.42 cm. Therefore, the growth rate of heartwood was greater than sapwood.

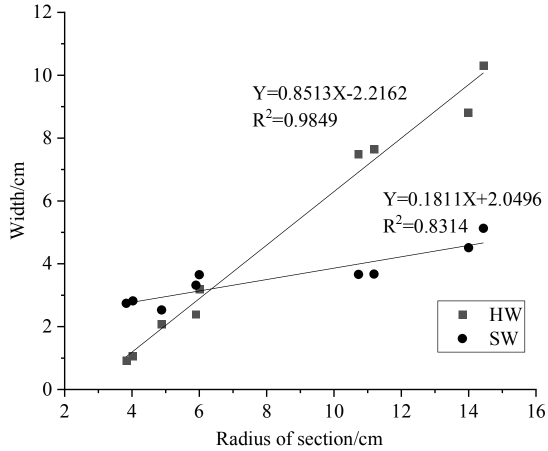
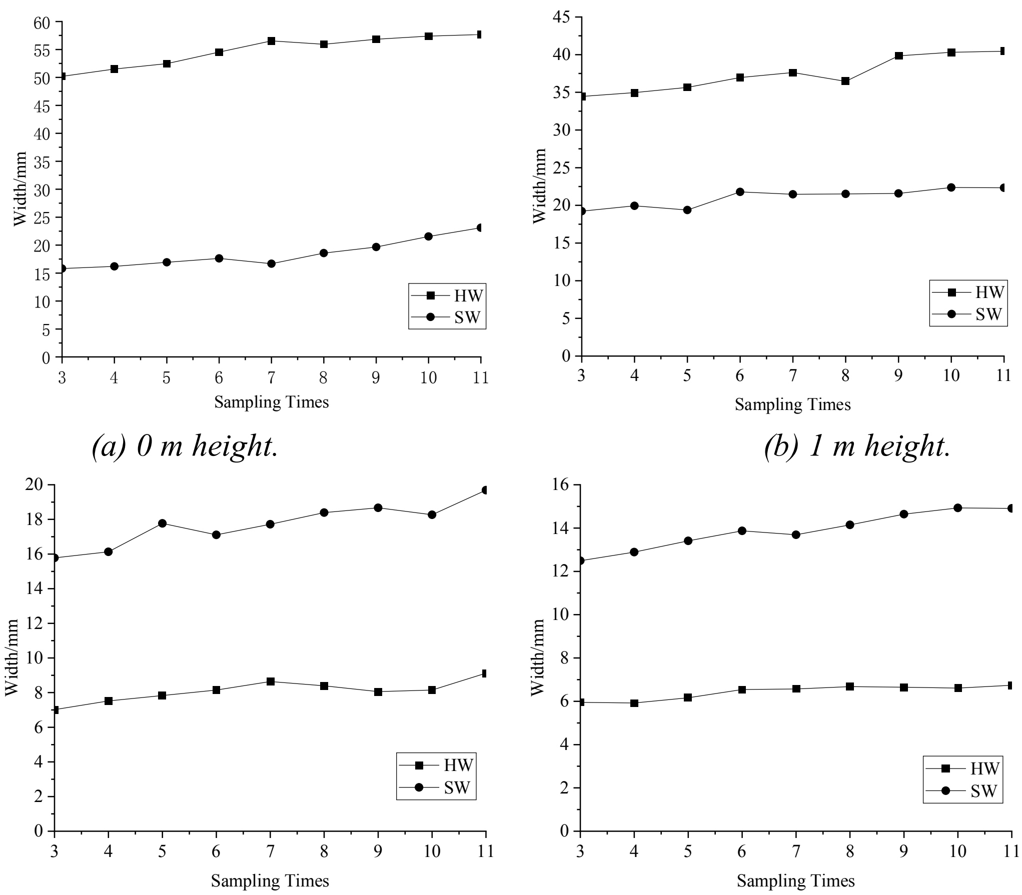


Fig. 4: The relationship between the diameter of heartwood and sapwood.

The relationship between heartwood and sapwood widths changing with time at different heights is shown in Fig. 5. It can be seen from Fig. 5a that the heartwood radius was always larger than the sapwood width at the base of the tree.



(a) 0 m height. *(b) 1 m height.*

(c) 5 m height. *(d) 9 m height.*

Fig. 5: Variation of sapwood width and heartwood radius with time at different heights.

It was observed that the heartwood radius increased by 3.69% and the sapwood width decreased by 5.39% in July. The change at 1m tree height is shown in Fig. 5b. It can be seen from the figure that the maximum increase of heartwood radius occurred in September with a growth rate of 9.3%. However, the maximum growth rate of sapwood width was 12.44% in June. The change at 5m tree height is shown in Fig. 5c. The width of sapwood was greater than the heartwood as shown in the figure. The sapwood width showed an obvious increasing trend in May and November, with a growth rate of 10.17% and 7.77%, resp. The heartwood radius showed an increasing trend before July, and then a slight decrease. The maximum growth rate of heartwood was 11.9% in November. The width of sapwood was larger than heartwood at 9 m height. The heartwood radius showed a trend of slow increase without great fluctuation, while the sapwood width showed a trend of decrease in July, with a decrease rate of 1.3%. The heartwood width of most tree species were first increased and then decreased in the axial direction until the heartwood disappeared (Pinto et al. 2004), but the heartwood of some trees presented a vertebral distribution in the axial direction (Gominho et al. 2005).

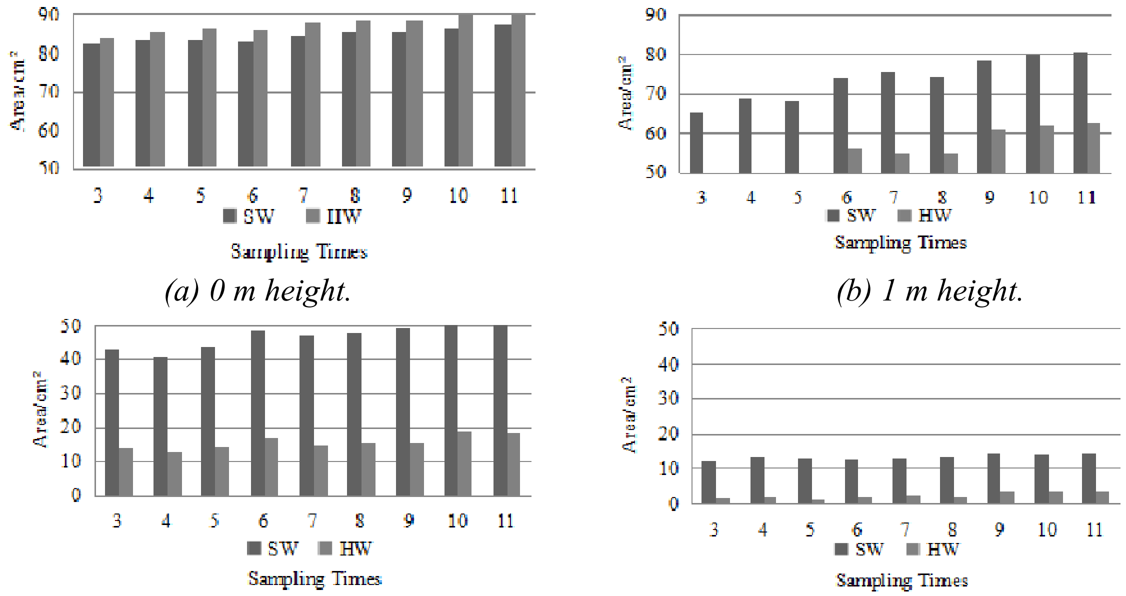
The correlation analysis between heartwood and sapwood width with time is shown in Tab. 2. It was observed that the heartwood radius and sapwood width at all heights were positively correlated with time. It can be seen from the Tab. 2 that the growth rate of heartwood was greater than that of sapwood at the base and 1 m height of the tree. The correlation coefficient of heartwood radius was greater than that of sapwood, so the growth of heartwood at the base and 1m height of the tree was more significantly affected by the season. In contrast, the growth rate of sapwood was higher than that of heartwood at 5 m and 9 m of the tree. The correlation coefficient of sapwood width was larger than that of heartwood, so sapwood growth was more significantly affected by seasons at 5 m and 9 m height.

Tab. 2: Regression analysis of sapwood and heartwood with time at different heights.

Heights (m)	Part	Regression analysis	Determination coefficient
0	SW	$y = 0.8625x + 14.142$	$R^2 = 0.8729$
	HW	$y = 0.9633x + 49.966$	$R^2 = 0.9101$
1	SW	$y = 0.397x + 19.083$	$R^2 = 0.7922$
	HW	$y = 0.7985x + 33.421$	$R^2 = 0.8983$
5	SW	$y = 0.419x + 15.631$	$R^2 = 0.8634$
	HW	$y = 0.1832x + 7.1819$	$R^2 = 0.6714$
9	SW	$y = 0.309x + 12.342$	$R^2 = 0.9576$
	HW	$y = 0.1058x + 5.8953$	$R^2 = 0.8056$

The seasonal change of heartwood and sapwood area

Since the heartwood radius and sapwood width vary a little in a year, the heartwood radius and sapwood width were used to approximate the disk as a circle and calculate the area of heartwood and sapwood. It was more intuitive to explain the change rule by analyzing the seasonal variation of heartwood and sapwood area.

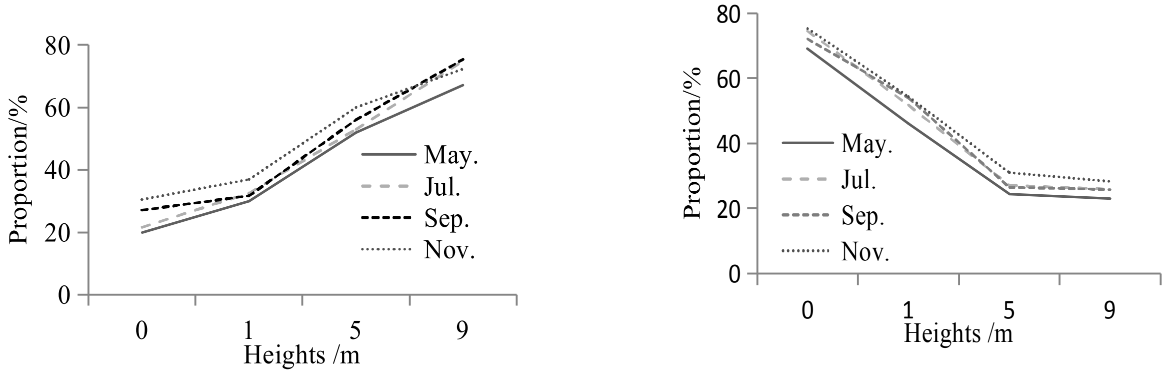


(a) 0 m height. *(b) 1 m height.*

(c) 5 m height. *(d) 9 m height.*

Fig. 6: Variation of heartwood and sapwood area with time at different heights.

The seasonal change of area at the tree base is shown in Fig. 6a. It can be seen intuitively that the area of sapwood and heartwood fluctuated little during the active period and showed a slow increasing trend, mainly because the activity of wood cells at the tree base was low and basically tended to be stable. It can be seen that the area of sapwood and heartwood showed a significant increasing trend as a whole at 1 m height. The area of sapwood was larger than that of heartwood on the whole. The sapwood area decreased slightly in April to May and July to August, with the decreasing rate being 0.93% and 1.98%, resp. The growth rate was 7.62% and 5.92% in May to June and August to September, resp. The area of heartwood was lower than 50 cm² from March to May, and the largest growth rate was 13.54% from May to June. The growth rate of May to June and August to September was 7.62% and 5.92%, respectively. The area of heartwood was lower than 50 cm² from March to May, and the largest growth rate was 13.54% from May to June. It can be seen from Fig. 6c that the sapwood area changed greatly from March to July and decreased with a rate of 4.81% in April. In addition, the growth rate was 10.65% from May to June and decreased slightly in July, and then maintained a slow and stable growth trend. However, heartwood area increased from May to June and from September to October by 17.54% and 19.7%, resp. The seasonal change at 9 m of tree height is shown in Fig. 6d. The area of sapwood and heartwood both decreased from May to June, with a decrease rate of 3.23% and 8.48%, resp. The maximum growth rates of sapwood and heartwood area were 8.46% and 64.15% from August to September, resp.



(a) Sapwood. *(b) Heartwood.*

Fig. 7: Variation of area ratio at different month.

In order to more intuitively analyze whether the changes in the proportions of sapwood and heartwood area in the cross section are consistent with the changes in area, sapwood and heartwood in March, May, July and September were selected to calculate the proportions of sapwood and heartwood in the cross section area and a broken line graph was draw, as shown in Fig. 7. The proportion change of sapwood area in different months is shown in Fig. 7a. As can be seen in the figure, the trend of the sapwood area proportion was towards an increasing with the height, which was contrary to the change trend of pure sapwood area. The proportion change of heartwood area in different months is shown in Fig. 7b. The proportion of heartwood area decreased generally with the height, which was consistent with the change trend of heartwood area in height. These results are consist with Oaks by Diaz et al. (2017) which showed that the proportion of heartwood was positively proportional to the age of the tree.

The sapwood area of most tree species was decreased with increasing height (Longuetaud et al. 2006), but unlike absolute content, the relative sapwood area (the percentage of sapwood area in trunk cross-sectional area) was generally increased with increasing height (Pérez et al. 2003). The texture and proportion of heartwood and sapwood of different tree species and different provenances were different, which was related to plant genetic characteristics (Zhao et al. 2015). Tree growth and site conditions can also cause difference in the amount of heartwood and sapwood (Bektas et al. 2003).

CONCLUSIONS

The results reveal that the initial age of heartwood formation was 7.25 years. When the trunk radius was greater than 2.6 cm, the heartwood began to be transformed. When the radius of trunk was 6.42 cm, the width of heartwood and sapwood was equal. The heartwood radius was larger than sapwood's when the radius of trunk was greater than 6.42 cm. Furthermore, the significant change and growth rate of heartwood with month were higher than sapwood at the tree base and 1 m height, but lower than sapwood at 5 m and 9 m height. It also can be pointed out that the absolute content of heartwood and sapwood area decreased with tree height, however, the relative content of sapwood area increased with the tree height.

ACKNOWLEDGEMENTS

The study was funded by the National Natural Science Foundation of China (grant number: 31700485).

REFERENCES

1. Aguilera, A., Zamora, R., 2009: Surface roughness in sapwood and heartwood of Blackwood (*Acacia melanoxylon* R. Br.) machined in 90-0 direction. European Journal of Wood and Wood Products 67(3): 297-301.
2. Bahmani, M., Fathi, L., Koch, G., Kool, F., Aghajani, H., Humar, M., 2020: Heartwood and sapwood features of *Sorbus torminalis* grown in Iranian forests. Wood Research 65(2): 195-204.
3. Baral, S.K., Berninger, F., Schneider, R., Pothier, D., 2017: Effects of heartwood formation on sugar maple (*Acer saccharum* Marshall) discoloured wood proportion. Trees-structure and function 31(1): 105-114.
4. Bektas, I., Alma, M.H., Goker, Y., 2003: Influence of site on sapwood and heartwood ratios of *Turkish calabrian* pine. Forest Products Journal 53(4):48-50.
5. Björklund, L., 1999: Identifying heartwood-rich stands or stems of *Pinus sylvestris* by using inventory data. Silva Fennica 33(2):119-129.
6. Calienno, L., Monaco, A.L., Pelosi, C., Picchio, R., 2014: Colour and chemical changes on photo degraded beech wood with or without red heartwood. Wood Science and Technology 48(6): 1167-1180.
7. Chen, C., Bock, C.H., Hotchkiss, M.W., Garbelotto, M.M., Cottrell, T.E., 2015: Observation and identification of wood decay fungi from the heartwood of peach tree limbs in central Georgia, USA. European Journal of Plant Pathology 143(1): 11-23.
8. Chen, H., Li, J., Wu, Q., Niu, X.T., Tang, M.T., Guan, X.L., Li, J., Yang, R.Y., Deng, S.P., Su, X.J., 2012: Anti-HBV activities of *Streblus asper* and constituents of its roots. Fitoterapia 83(4): 643-649.
9. Chen, P.S., Chen, Y.H., Yeh, T.F., Chang, S.T., 2014: Mechanism of decay resistance of heartwood extracts from *Acacia confusa* against the brown-rot fungus *Laetiporus sulphureus*. Wood Science and Technology 48(3): 451-465.
10. Davies, N.T., Wu, H.F., Altaner, C.M., 2014: The chemistry and bioactivity of various heartwood extracts from redwood *(Sequoia sempervirens)* against two species of fungi. New Zealand Journal of Forestry Science 44(1): 1-7.
11. Diaz, M.I.J., Vila, L.p., Tahir, S., 2017: Assessment of anatomical characteristics of wood-bark, sapwood and heartwood-in hardwoods species of Galician oaks by image processing: relationship with age. Wood Research 62(5): 763-772.
12. Gominho, J., Pereira, H., 2005: The influence of tree spacing in heartwood content in *Eucalyptus Globulus* Labill. Wood and Fiber Science 37(4): 582-590.

13. Huang, Z., Meilan, R., Woeste, K., 2009: *A KNAT3-like* homeobox gene from *Juglans nigra* L., *JnKNAT3-like*, highly expressed during heartwood formation. Plant Cell Reports 28(11): 1717-1724.
14. Huang, Z., Tsai, C.J., Harding, S., Meilan, R., Woeste, K., 2010: A cross-species transcriptional profile analysis of heartwood formation in Black walnut. Plant Molecular Biology Reporter 28(2): 222-230.
15. Kokutse, A.D., Stokes, A., Kokutse, N.K., Kokou, K., 2010: Which factors most influence heartwood distribution and radial growth in plantation teak? Annals of Forest Science 67(4): 407-407.
16. Kuroda, K., Yamashita, K., Fujiwara, T., 2009: Cellular level observation of water loss and the refilling of tracheids in the xylem of *Cryptomeria japonica* during heartwood formation. Trees 23(6): 1163-1172.
17. Li, L.Q., Li, L., Huang, Y., Wu, Q., Deng, S.P., Su, X.J., Yang, R.Y., Huang, J.G., Chen, Z.Z., Li, S., 2012: Lignans from the heartwood of *Streblus asper* and their inhibiting activities to Hepatitis B virus. Fitoterapia 83(2): 303-309.
18. Longuetaud, F., Mothe, F., Leban, J.M., Annikki, M., 2006: *Picea abies* sapwood width: Variations within and between trees. Scandinavian Journal of Forest Research 21(1): 41-53.
19. Lukmandaru, G., Ashitani, T., Takahashi, K., 2009: Color and chemical characterization of partially black-streaked heart-wood in teak (*Tectona grandis*). Journal of Forestry Research 20(4): 377-384.
20. Miranda, I., Gominho, J., Arújo, C., Pereira, H., 2014: Family effects in heartwood content of *Eucalyptus globulus* L. European Journal of Forest Research 133(1): 81-87.
21. Morais, M.C., Pereira, H., 2011: Variation of extractives content in heartwood and sapwood of *Eucalyptus globulus* trees. Wood Science and Technology 46(4): 709-719.
22. Moya, R., Fallas, R.S., Bonilla, P.J., Tenorio, C., 2012: Relationship between wood color parameters measured by the CIELab system and extractive and phenol content in *Acacia mangium* and *Vochysia guatemalensis* from fast-growth plantations. Molecules 17(4): 36-39.
23. Nakada, R., Fukatsu, E., 2012: Seasonal variation of heartwood formation in *Larix kaempferi*. Tree Physiology 32(12): 1497-1508.
24. Pâques, L.E., Charpentier, J.P., 2015: Perspectives for genetic improvement in heartwood size and extractive content in relation to natural durability and aesthetics in *interspecific hybrid larch (Larix × eurolepis)*. European Journal of Forest Research 134(5): 857-868.
25. Pérez, L.D., Kanninen, M., 2003: Heartwood, sapwood and bark content, and wood dry density of young and mature teak (*Tectona grandis*) trees grown in Costa Rica. Silva Fennica 37(1): 45-54.
26. Pfautsch, S., Macfarlane, C., Ebdon, N., Meder, R., 2012: Assessing sapwood depth and wood properties in *Eucalyptus* and *Corymbia* spp. using visual methods and near infrared spectroscopy (NIR). Trees 26(3): 963-974.
27. Pinto, I., Pereira, H., Usenius, A., 2004: Heartwood and sapwood development within maritime pine (*Pinus pinaster Ait.*) stems. Trees 18(3): 284-294.

28. Puntambekar, R., Pydimalla, M., Dinda, S., Adusumalli, R.B., 2016: Characterization of Eucalyptus heartwood and sapwood pulp after kraft cooking. Journal of the Indian Academy of Wood Science 13(1): 8-15.
29. Saito, K., Mitsutani, T., Imai, T., Matsushita, Y., Yamamoto, A., Fukushima, K., 2008: Chemical differences between sapwood and heartwood of *Chamaecyparis obtusa* detected by ToF-SIMS. Applied Surface Science 255(4): 1088-1091.
30. Scheiding, W., Direske, M., Zauer, M., 2016: Water absorption of untreated and thermally modified sapwood and heartwood of *Pinus sylvestris L*. European Journal of Wood and Wood Products 74(4): 585-589.
31. Yoshida, K., Futamura, N., Nishiguchi, M., 2012: Collection of expressed genes from the transition zone of *Cryptomeria japonica* in the dormant season. Journal of Wood Science 58(2): 89-103.
32. Zhao, Z.G., Guo, J.J., Wang, C.S., Zeng, J., 2015: Simulating the heartwood formation process of *Erythrophleum fordii* in South China. Journal of Forestry Research 26(04): 1049-1055.

YINGZHI CHANG, CHUNLONG ZHENG, XUEJING SHAO, ZHIYI XIA, ENHUA XI*
SHANDONG AGRICULTURAL UNIVERSITY
COLLEGE OF FORESTRY
TAI'AN 271018
CHINA
*Corresponding author: xienhua@126.com