Heartwood and Sapwood Variation and Development in Chenshan Red-Heart Chinese Fir (*Cunninghamia lanceolata* (Lamb.) Hook)

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Abstract

Chenshan red-heart Chinese fir is a provenance of *Cunninghamia lanceolata*, with high-value red heartwood, which is widely used in high-quality furniture and construction. Yet, there is still little information on heartwood development of this tree for high-value decorative timber, which is essential to improve one's plantation management strategy. Here, we investigated the horizontal and vertical variation of heartwood and sapwood and simulated heartwood formation process using stem analysis method. We selected 15 sample trees from five plots of 20 m $\times$ 30 m in Chenshan red-heart Chinese fir plantations (9, 15, 26, 29, and 34 years old, respectively). The results showed that Chenshan red-heart Chinese fir stems began to form heartwood when the xylem diameter reached 4 to 8 cm. The heartwood diameter and area, as well as the sapwood area, all increased in the different-aged Chenshan red-heart Chinese firs with increasing xylem diameter and decreased with increasing tree height. As tree height increased, the red heartwood formation rate declined at all ages. Relationship analysis showed that xylem diameter was the most important factor influencing heartwood formation. Red heartwood rate at breast height could be modeled by logistic models. We concluded that heartwood formation began at about 7 years old, and the formation rate increased until peaking at 60 percent at 40 years old. In conclusion, it will be imperative to prolong the Chenshan red-heart Chinese fir rotation period from the currently common 25 years to about 40 years to achieve the maximum sustainable yield of high-value decorative timber.

In forest ecosystems, heartwood and sapwood are distributed in the xylem of most mature trees, and they can be visually distinguished from the rest of the wood (Jia et al. 2018, Wang et al. 2018). Heartwood is generally darker, denser, and stiffer than sapwood (Zhao et al. 2015, Naruna Felix de Almeida et al. 2020). The relative proportions of heartwood and sapwood affect the commercial use of the wood (Debell and Lachenbruch 2009). To understand heartwood and sapwood formation, it is important to comprehend the role of heartwood and sapwood in the context of the tree (Taylor et al. 2002). Sapwood, the outer zone of wood, is composed of physiologically active live cells and reserve substances. Here, the external rings transport water with minerals from roots to the cambium and assimilatory organs (Wang et al. 2018, Deng et al. 2019). Heartwood, the inner zone of the xylem, is physiologically inactive regarding water conduction (Pinto et al. 2004). As trees grow, parenchyma cells die. Consequently the wood becomes impregnated with complex organic compounds and contains a large amount of resinous and phenolic extractives (Wang and Zhang 1998). These substances (mostly polyphenols) are responsible for the natural stability of heartwood and its typically darker coloration (Knapic and Pereira 2005, Luo et al. 2008). Because heartwood and sapwood serve different functions

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in the tree, they are treated distinctly in timber processing and subsequently serve different commercial purposes (Morais and Pereira 2007). Sapwood is preferable for pulping because of the lower content of extractives (Naruna Felix de Almeida et al. 2020). Heartwood is generally more dense and stiff than sapwood (Zhao et al. 2021). Heartwood has better durability and aesthetic values and is often used to construct high-value wood products (Wen et al. 2018). Therefore, studies on heartwood formation and development can provide valuable insights into this industry. In particular, studies on the horizontal and vertical distribution of heartwood and sapwood in trees, as well as on the process of heartwood formation, are important for determining heartwood value accurately (Climent et al. 2003, Pinto et al. 2004, Zhao et al. 2015).

During recent decades, the relative variation of sapwood and heartwood had been reported for many tree species. For example, Morais and Pereira (2007) studied the variation of heartwood and sapwood in *Eucalyptus globulus* Labill. They found that the heartwood diameter (HD) and sapwood width (SW) were positively correlated with radial tree growth. The site and tree height were highly significant sources of variation for heartwood proportion and SW. Yang et al. (2020) reported that the heartwood and sapwood areas and the heartwood radius of *Tectona grandis* showed significant differences in horizontal and vertical directions among trees of different social status. In addition, researchers had also discussed heartwood formation and found that the diameter and area of heartwood were positively correlated with tree age and xylem width (Morais and Pereira 2007). Meanwhile, SW only changed slightly within and among trees, and the formation of heartwood was not affected by site conditions (Knapic et al. 2006, Zhao et al. 2015). The differences between these studies may be attributed to differences in tree species, stand density, and site, all of which are important factors to consider in forest management (Taylor et al. 2002).

Rotation age, which is the time span from forest regeneration and cultivation until harvesting to its final felling, is an important basis of forest management, and it is dictated by the requirements of a certain purpose for harvesting mature forests (Xie et al. 2020). Determining the optimal rotation age can make effective use of forest resources, achieve optimal production, and enable operators to obtain maximum economic benefits. Researchers had shown that shorter rotations led to lower forest carbon stocks (Ekholm 2020), and short rotations in plantations led to concerns about the ratio of juvenile trees to mature trees to make it unsuitable for higher-value products (Lowell et al. 2018). Rotation length also affected forest growth on soil quality (Zhao et al. 2019). For a long time, researchers had mainly used quantitative maturity age to determine the rotation age in production practice without considering the cultivation goal of high-value decorative wood to determine the rotation age (Liao et al. 2018, Wen et al. 2018). Therefore, to effectively use forest resources and harvest high-value decorative wood that meets the requirements of the market, it is very important to establish the optimal rotation age (Fahlvik et al. 2021).

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is one of the most important native tree species in China (Tian et al. 2011), and it has been widely planted in southern China for more than 2,000 years (Huang et al. 2019). Chinese fir is also an important commercial species, appreciated for its high-quality timber and fast growth (Wen et al. 2018). It plays an important role in leading wood production practices in all plantations (Li et al. 2019). Red-heart Chinese fir is a variant of *C. lanceolata*, which was originated from Jiangxi (Li et al. 2019). It is well-known for the beautiful color of its heartwood and the unique Chinese fir is called "red-heart Chinese fir" (Wen et al. 2018). Some studies have shown that red-heart Chinese fir has many special characteristics (Zhang et al. 2019; Wang et al. 2020). Compared with other varieties of *C. lanceolata* cultigens, red-heart Chinese fir has colored xylem that has great resistance, strong adaptability, excellent material quality, and a fast growth rate (Li et al. 2010). Red-heart Chinese fir is also resistant to decay, with a high red heartwood rate (RHR; Yan 2013). Since the RHR is more than 50.5 percent and the heartwood height can be as high as 80 percent (of tree height) in mature red-heart Chinese fir forests (Huang et al. 2006), the red-heart feature increases the value of this species (Li et al. 2019). In general, a high proportion of red heartwood and low proportion of sapwood make trees more valuable in the sawlog industry and market (Berrocal et al. 2020). Red-heart Chinese fir is regarded as one of the best timbers and is widely used for construction, railroad ties, mine timber, furniture, and other purposes, and its use has rapidly expanded in recent years (Zhang et al. 2019). Now it accounts for a large proportion of all Chinese fir plantations in China (Wen et al. 2018). In recent years, research on red-heart Chinese fir has been increasing gradually. However, few people have investigated the development of red heartwood and sapwood in the context of tree growth and determined the rotation age. To augment red-heart Chinese fir resources, it will be necessary to study the development of red heartwood and sapwood and determined the rotation age further.

In this study we investigated the development of heartwood and sapwood in Chenshan red-heart Chinese fir at different ages. Our objectives were: (1) to study the horizontal and vertical variation of heartwood and sapwood in Chenshan red-heart Chinese fir at different ages; (2) to analyze the main factors affecting heartwood formation; (3) to simulate the heartwood formation process of Chenshan red-heart Chinese fir at different ages; (4) to determine the rotation age of Chenshan red-heart Chinese fir to achieve maximum cultivation of this high-value decorative wood.

Materials and Methods

Experimental site

The research was conducted at the Chenshan Forestry Station in Jiangxi Province, China (27°04′ to 27°36′N, 114°01′ to 114°47′E) at an altitude of 140 to 450 m. The study region is characterized by a subtropical humid climate, with an average annual temperature of 17.7°C (average January and July temperatures are 5.9°C and 28.9°C, respectively); the average annual precipitation and rainfall days are 1663 mm and 166 days, respectively. Chenshan Forestry Station is famous for its red-heart Chinese fir. The Chenshan red-heart Chinese fir is widely distributed in an area across the forestry station, and the understory consists of *Sapium sebiferum*, *Vernicia fordii*, *Phyllostachys edulis*, and *Choerospondias axillaris* (Huang et al. 2019, Li et al. 2019, Wang et al. 2020).

Sample collection

We established five 20 m × 30 m plots in the Chenshan red-heart Chinese fir plantations. The stand ages were 9, 15,

*Table 1.—Growth factors of Chenshan red-heart Chinese fir (*Cunninghamia lanceolata*) at different ages, averaged within plots.*

Tree age	Stand density ($trees \cdot ha^{-1}$)	Height (m)	DBH[a] (cm)	Crown diameter (m)
9	4,500	7.94 ± 1.73	8.96 ± 2.32	2.49 ± 0.85
15	1,810	12.52 ± 2.81	14.54 ± 3.92	2.79 ± 0.49
26	2,279	13.15 ± 1.94	16.67 ± 3.82	2.81 ± 0.80
29	1,422	16.38 ± 3.78	18.57 ± 2.98	3.81 ± 0.75
34	1,176	17.81 ± 4.79	22.32 ± 5.50	3.89 ± 1.48

[a] DBH = diameter at breast height.

26, 29, and 34 years old, representing different stages of stand development. The stand information is shown in Table 1. Basic growth factors such as diameter at breast height (DBH), tree height, and crown diameter were measured for all trees in the study plots. Three healthy trees in each plot were selected and cut down for sampling.

Stem analysis

Before the sample trees were cut down, their trunks were marked in the east–west and north–south directions. After the sample trees were felled, we sawed discs of approximately 5 cm in thickness at 0, 1.3, 3.6, and 5.6 m and then every 2 m to the top (Fig. 1). A total of 157 discs was obtained. Each disc was numbered and then polished until the heartwood and sapwood could be clearly identified. HD and xylem diameter (XD) were measured (0.01 mm) in the four radial directions (east, south, west, and north) with a vernier caliper, and the mean observed diameters were calculated in each of the four directions.

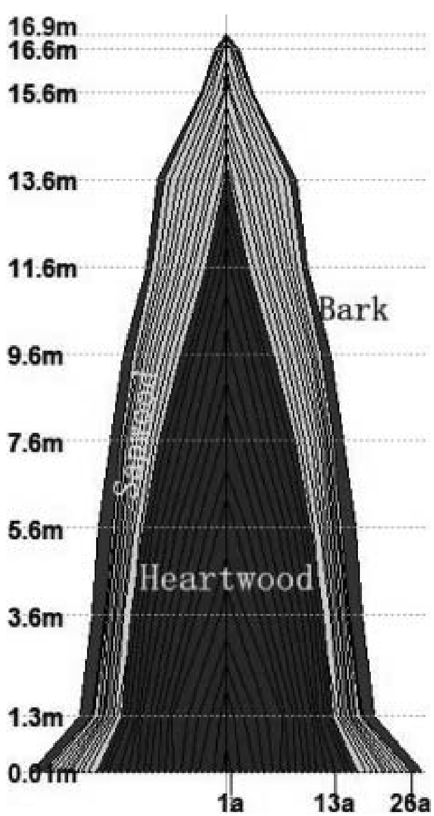

Figure 1.—Vertical profile of stem.

Data processing

HD and XD of each disc were calculated as the mean of the four directional diameters. Heartwood area (HA) and heartwood volume (HV) were estimated with a mean sectional area approximate quadrature method. The RHR, SW, HA, sapwood area (SA), and HV were calculated as follows:

$$\mathrm{RHR} = \left(\frac{\overline{\mathrm{HD}}}{\overline{\mathrm{XD}}}\right)^2 \tag{1}$$

$$\mathrm{SW} = \overline{\mathrm{XD} - \mathrm{HD}} \tag{2}$$

$$\mathrm{HA} = \pi \times \left(\frac{\overline{\mathrm{HD}}}{2}\right)^2 \tag{3}$$

$$\mathrm{SA} = \pi \times \left(\frac{\overline{\mathrm{XD}}}{2} - \frac{\overline{\mathrm{HD}}}{2}\right)^2 \tag{4}$$

$$\mathrm{HV} = \sum\left(\frac{1}{2} \times (g_n + g_{n+1}) \times L_n\right) \tag{5}$$

where $\overline{\mathrm{HD}}$ and $\overline{\mathrm{XD}}$ are the mean diameters for heartwood and xylem of each disc, respectively; g_n is the cross-sectional area of the base heartwood and g_{n+1} is the cross-sectional area of the top heartwood for a stem section; and L_n is the length of the section.

To better explore the relationship between tree age and RHR, the logistic model was used (Xu and Qiao 2015, Qiu 2020). The model we selected was:

$$Y = \frac{K}{1 + e^{a^* t + b}} \tag{6}$$

where Y is the RHR; K is the upper limit of RHR in the measured stand, which means the growth saturation; a and b are equation parameters obtained by using a logistic curve regression analysis method, taking RHR as the dependent variable and time as the independent variable to estimate the saturation value k of the RHR; t is tree age.

Pearson correlation analysis was performed to determine the influence factors of heartwood formation. Regression analysis was used to estimate the parameters of heartwood formation relative to the growth equation. All analyses were performed using Excel and R 4.0.3 software (R Development Core Team 2020).

Results

Heartwood and sapwood variation

Horizontal variation.—The relationship between HD and XD at different ages (Fig. 2a) indicated that when the XD

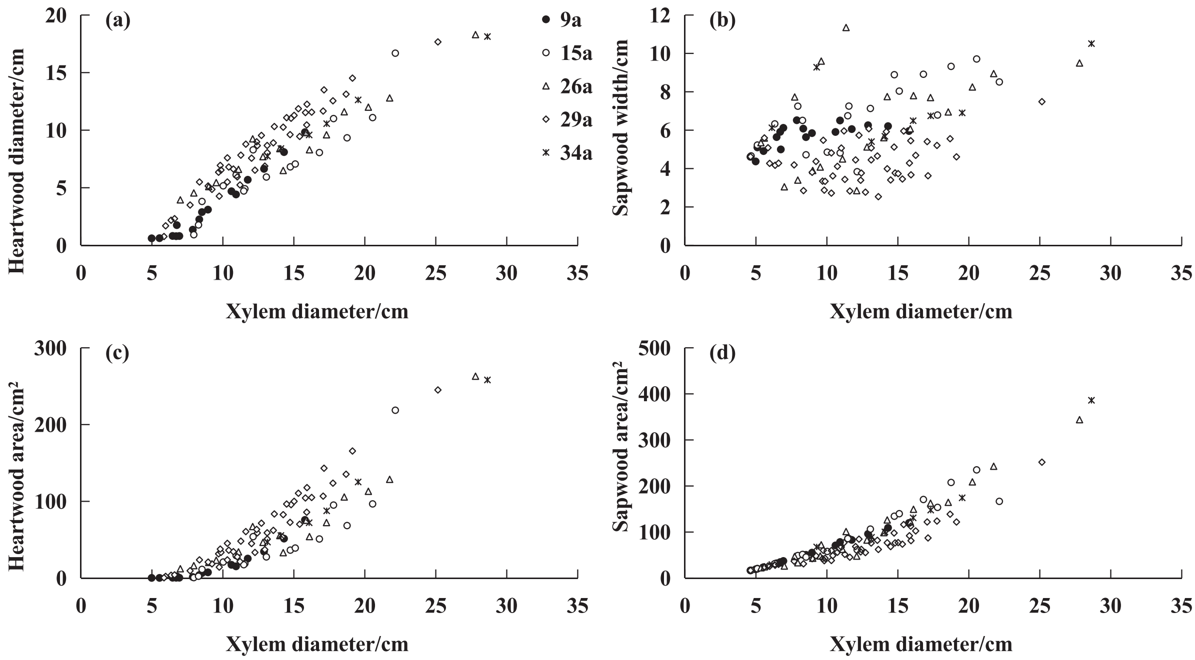

Figure 2.—Relationship between xylem diameter and heartwood diameter (a), sapwood width (b), heartwood area (c), and sapwood area (d).

reached 4 to 8 cm, the heartwood of Chenshan red-heart Chinese fir began to form, after which the HD increased rapidly with increasing XD. Similarly, the HA increased significantly with increasing XD (Fig. 2c). In contrast, the SW showed no close relationship with XD for Chenshan red-heart Chinese fir at different ages (Fig. 2b). The SA also increased with increasing XD (Fig. 2d), which was distinct from the SW.

Vertical variation.—From the vertical variation of heartwood and sapwood, we saw that (Fig. 3) regardless of tree age, the HDs of Chenshan red-heart Chinese fir all decreased with increasing tree height (Fig. 3a). The SW was much greater at the base of the trunk (0% to 10%), relatively stable at the middle part of the trunk (10% to 60%), and then decreased sharply toward the top (Fig. 3b). Last, the HA and SA both decreased with increasing tree height (Figs. 3c and

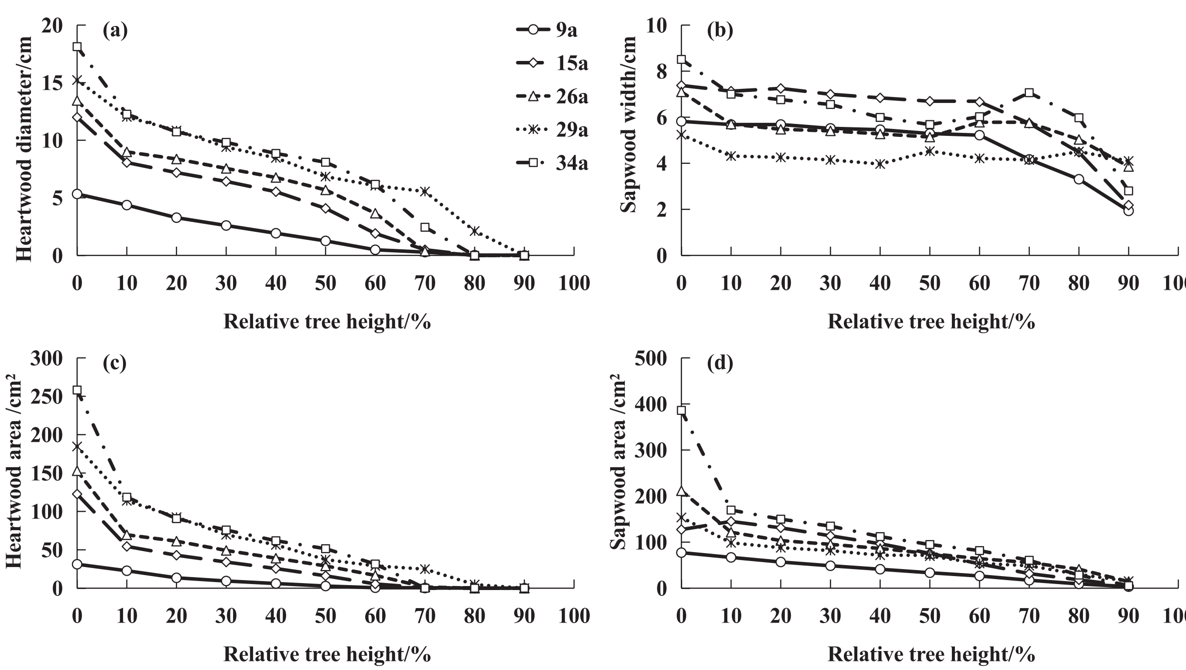

Figure 3.—Relationship between relative tree height and heartwood diameter (a), sapwood width (b), heartwood area (c), and sapwood area (d).

Table 2.—Correlation between heartwood/sapwood parameters and tree growth factors.

Item	Heartwood diameter	Red heartwood ratio	Max. heartwood height	Sapwood width	Sapwood area	Heartwood area	Heartwood volume
Tree age	0.392[b]	0.475[b]	0.524[b]	−0.052	0.199[c]	0.344[b]	0.323[b]
Xylem radius	0.943[b]	0.756[b]	0.329[b]	0.593[b]	0.923[b]	0.892[b]	0.884[b]
DBH[a]	0.400[b]	0.285[b]	0.579[b]	0.388[b]	0.475[b]	0.379[b]	0.419[b]
Tree height	0.471[b]	0.519[b]	0.761[b]	0.082	0.298[b]	0.401[b]	0.369[b]
Crown width	0.386[b]	0.398[b]	0.755[b]	0.112	0.269[c]	0.328[b]	0.266[c]
Stand density	−0.410[b]	−0.447[b]	−0.675[b]	−0.106	−0.281[b]	−0.338[b]	−0.324[b]

[a] DBH = diameter at breast height.
[b] Significant at $P < 0.001$.
[c] Significant at $P < 0.01$.

3d). The relative tree height is the percentage of different heights to total tree height in a tree (Yang et al. 2020).

Influencing factors of heartwood formation

The correlation analysis of sapwood and heartwood parameters with tree parameters (Table 2) showed that HD, RHR, maximum heartwood height, and HA were all significantly positively correlated with tree age, XD, tree height, DBH, and crown width ($P < 0.001$). Maximum heartwood height is the maximum height of the heartwood (Fernández-Sólis et al. 2018). Miranda et al. (2015) carried out some estimations for predicting HD and maximum heartwood height in *E. globulus* trees. HV was also significantly positively correlated with tree age, XD, tree height, and DBH ($P < 0.001$) and significantly positively correlated with crown width ($P < 0.01$). HD, RHR, maximum heartwood height, HA, and HV were all significantly negatively correlated with stand density ($P < 0.001$). SA was significantly positively correlated with XD, DBH, and tree height ($P < 0.001$) and significantly positively correlated with tree age and crown width ($P < 0.01$); it was significantly negatively correlated with stand density ($P < 0.001$). However, SW was significantly positively correlated with XD and DBH ($P < 0.001$), but not with tree age, tree height, crown width, or stand density ($P > 0.05$).

Therefore, we concluded that HD, maximum heartwood height, HA, and HV were directly affected by tree age, XD, DBH, tree height, and crown width. In addition, stand density was also important in affecting the formation of heartwood. Adjusting the stand density to a reasonable concentration will help promote heartwood formation and obtain more red heartwood.

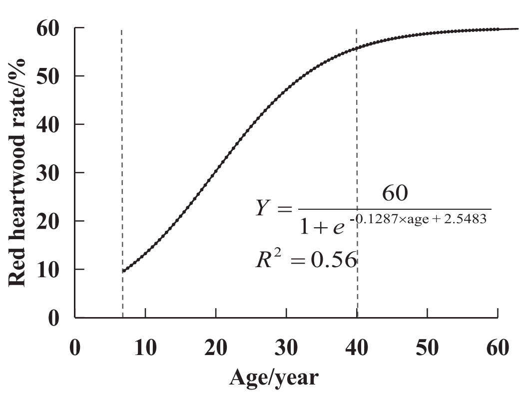

Figure 4.—Logistic model curve of tree age and red heartwood rate at breast height in Chenshan red-heart Chinese fir (Cunninghamia lanceolata).

Simulation of heartwood growth process

RHR at breast height.—We selected the logistic model to simulate and predict RHR at breast height in Chenshan red-heart Chinese fir (Fig. 4), and we found that there were two inflection points in the curve, the 7th and the 40th years ($R^2 = 0.56$). The heartwood began to form in the Chenshan red-heart Chinese fir at around 7 years old, and the RHR peaked at 60 percent at 40 years old and reached the goal of our research, which is to get the largest ratio of high-quality heartwood in a rotation as possible to achieve the maximum sustainable yield of high-value decorative wood. Therefore, 40 years is a key age for red heartwood growth processes and is also an important age for technical rotation in Chenshan red-heart Chinese fir. Therefore, we concluded that plantation specimens should be harvested after reaching at least 40 years of rotation length.

RHR at different heights of the trunk.—In this study, we analyzed the RHR in Chenshan red-heart Chinese fir at different heights of the trunk at different ages (Fig. 5). The results showed that the RHR declined with increased trunk height at all ages.

The RHR at the base of the 9-year-old tree was about 10 percent to 30 percent and the heartwood height reached 70.71 percent of the total tree height at a maximum; this model only explained 40.13 percent of the RHR change ($P = 0.001$). The RHR at the base of the 15-year-old tree was about 30 percent to 50 percent and the heartwood height reached 67.84 percent of the total tree height at a maximum; the model explained 80.91 percent of the RHR change ($P < 0.001$). The RHR at the base of the 26-year-old tree was about 40 percent to 50 percent and the heartwood height reached 60 percent of the total tree height at a maximum; this model explained only 76.22 percent of the RHR change ($P < 0.001$). The RHR at the base of the 29-year-old tree was about 50 percent to 60 percent and the heartwood height reached 81.97 percent of the total tree height at a maximum; the model explained 91.35 percent of the RHR variation ($P < 0.001$). Last, the RHR of the 34-year-old tree was also about 40 percent to 60 percent and the heartwood height reached 56.14 percent of the tree height at a maximum; the model explained 73.74 percent of the RHR change ($P < 0.001$). Because the heartwood formation of the 9-year-old tree was unstable, in this model $R^2 = 0.4013$. The heartwood formation of the 15-, 26-, 29-, and 34 -year-old trees was relatively stable, and in this model $R^2 > 0.70$.

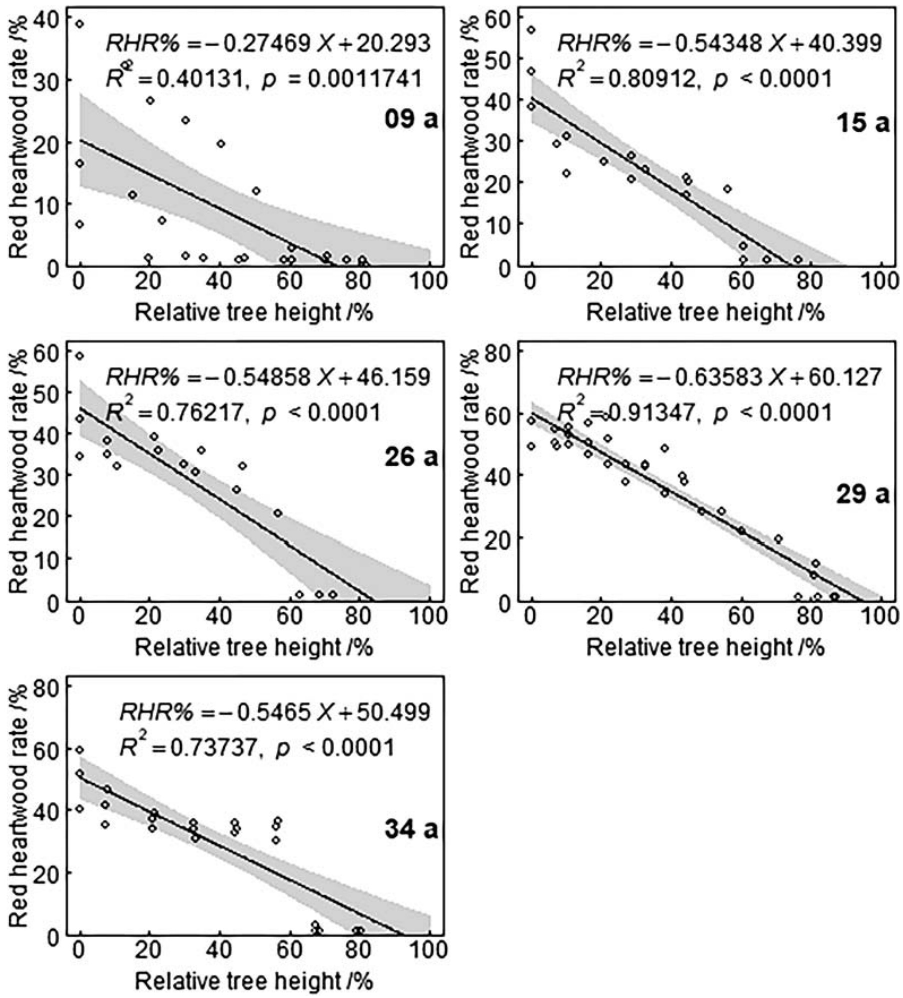

Figure 5.—Relationship between red heartwood ratio and relative tree height at different tree ages. Shaded area represents confidence interval at 95% significance level.

Discussion

Heartwood and sapwood variation

Horizontal variation.—In our study, the HD and HA in Chenshan red-heart Chinese fir basically increased with increasing XD at each age (Figs. 2a and 2c). It was also indicated that heartwood content increased with increasing XD, which agreed with results for *T. grandis* in Costa Rica (Pérez and Kanninen 2003) and teak trees in India (Vindhya and Mariswamy 2013). The consistent and extremely significant positive correlation between HD and the radial growth of the trunk seemed to be a general rule of trees. Many authors had also reported that heartwood is formed at a constant annual ring rate after a certain starting age in other species (Hazenberg and Yang 1991, Wilkes 1991, Sellin 1994). Furthermore, the XD was the best predictor of HD (Miranda et al. 2009). This has further been reported for other tree species, such as *T. grandis* (Kokutse et al. 2004), *Acacia melanoxylon* (Knapic et al. 2006), *E. globulus* (Gominho and Pereira 2000), and *Pinus sylvestris* (Björklund 1999).

In contrast, the variation in SW was not explained well by XD in our study (Fig. 2b). This had also previously been reported in *E. grandis* (Wilkes 1991) and in other species, particularly conifers (Sellin 1994, Pinto et al. 2004, Morais and Pereira 2007). The SA increased with increasing XD in our study (Fig. 2d), which agreed with the pipe model theory of Shinozaki et al. (1964). In their opinion, a certain number of pipes is required in the trunk to support the crown and it might be that sapwood enhances fluid flow, supports the tree, and serves as nutrient storage. The increasing XD required more nutrients and water, which could explain why the SA increased with XD (Hazenberg and Yang 1991). However, this is not certain because abnormal phenomena have also been observed. For example, Long and Smith (1988) found a poor correlation between SA at breast height and crown area of *Pinus contorta*. Björklund (1999) also reported that the DBH of *P. sylvestris* could only explain 24 percent and 23 percent of the variation of heartwood and sapwood, respectively. From this it can be concluded that the relationship between tree characteristics and the amount of heartwood and sapwood might vary depending on the tree species (Gominho and Pereira 2000). In addition, sapwood might be affected by heartwood. If the amount of sapwood has satisfied the tree's transport and mechanical support systems, any excess sapwood could be transformed into heartwood by the tree (Zhao et al. 2015). According to one physiological explanation put forward by Bamber (1976), heartwood formation may help regulate the amount of sapwood to a physiologically optimal level, thereby affecting the growth of trees.

Vertical variation.—The HD and HA, as well as the SA, of Chenshan red-heart Chinese fir basically decreased with increasing tree height at all ages (Figs. 3a, 3c, and 3d), which was similar to most other tree species, including *Pinus pinaster* Ait (Knapic and Pereira 2005), *Picea abies* (Longuetaud et al. 2006), and *Pinus tabulaeformis* (Chang et al. 2009). However, SW in Chenshan red-heart Chinese fir varied less with increasing tree height than did HW (Fig. 3b). SW was greater at the base of the trunk (0% to 10%), remained relatively constant in the middle of the trunk (10% to 60%), and decreased significantly near the top of the trunk, which was consistent with Knapic's investigation of *A. melanoxylon* R.Br (Knapic et al. 2006) and might be attributed to the observation that the radial growth of heartwood and xylem were similar within this certain tree height range. Vindhya and Mariswamy (2013) believed that sapwood should increase with the growth of the tree crown and that its proportion could only be maintained at an optimal level via heartwood formation. Although SW of red-heart Chinese fir did not change significantly at different tree heights, SA decreased with increasing tree height, possibly due to the change in trunk taper (Cardoso and Pereira 2017).

Main factors affecting heartwood formation

Tree parameters of Chenshan red-heart Chinese fir had a certain influence on the formation of heartwood and sapwood. Tree age, XD, DBH, tree height, crown width, and stand density all had significant effects on HD, maximum heartwood height, HA, and HV (Table 2). The results were consistent with the study by Zhao et al. (2015), which reported that the HD and HA of *Erythrophleum fordii* correlated very significantly and positively with tree age and XD. HV of Chenshan red-heart Chinese fir was greatly influenced by DBH and tree height, which is in agreement with results for *E. fordii* in China (Zhao et al. 2021). Climent et al. (2003) also found that tree height and DBH are the best predictors for the HV in *Pinus canariensis*. Further, crown width had a significant effect on SA, in accordance with the pipe model theory (Shinozaki et al. 1964). In practical terms, our results confirmed that heartwood formation depends on diameter growth. For example, larger trees have more heartwood, which corresponds to a greater proportion of the tree's diameter (Miranda et al. 2009). In addition, Gominho and Pereira (2005) found that spacing affected the amount of heartwood and sapwood; the wider the spacing, the higher the ratio of heartwood. This was consistent with our result that stand density significantly affected heartwood formation. Pérez and Kanninen (2003) believed that low-density plantations (150 to 800 trees ha^{-1}) had a higher heartwood ratio than high-density plantations (1,600 trees ha^{-1}). Arce (2001) reported that in *T. grandis* L.F. plantations, the heartwood rate in a stand density of 830 trees ha^{-1} accounted for a higher value than that in a stand density of 1,111 trees ha^{-1}.

Some authors also concluded that tree age and tree height were the main factors controlling heartwood and sapwood (Harrison 1974, Searle 2000, Bradbury 2006). Moya and Marín (2011) showed a relationship of HD with respect to tree height and tree age. Fernández-Sólis et al. (2018) obtained a strong correlation of maximum heartwood height in a study on *T. grandis* with DBH and tree height. Sellin (1994) obtained similar results for *Picea abies*. However, others found that among trees of similar ages, the diameter and area of heartwood were quite different, possibly due to the influence of tree genes and environmental factors. Climent et al. (2003) studied the heartwood of *Pinus canariensis* Sm. in the direction of tree height and found irregular results that were mainly influenced by the local windy climate, which caused the trees to shake violently during the growth process and affected the formation rate of heartwood at different tree heights. In addition to the influence of these factors, variation in heartwood and sapwood might also be influenced and restricted by single or comprehensive factors such as tree species, genetic inheritance, site conditions, forest growth quality, growth rate, and so on (Zobel and Jett 1995, Ogle and Pacala 2009, Bradbury et al. 2011). Because the environmental conditions for all trees sampled at our research site were generally similar, heartwood formation in our study might have been genetically regulated rather than environmentally regulated. This suggests that a breeding program could be implemented to produce more heartwood (Taylor et al. 2002, Zhao et al. 2015).

Simulation of heartwood growth process

Using the logistic model to simulate the initial age of the heartwood in Chenshan red-heart Chinese fir, we found that heartwood formation begins around the 7th year (Fig. 4). According to the research of Cardoso and Pereira (2017), the initial age of heartwood formation of Douglas-fir was estimated to be 8 to 9 years. The initial age of heartwood growth also differed among other species, such as *Pinus pinaster* at about 13 or 18 years old (Esteves et al. 2005), *P. sylvestris* at 15 to 25 years old (Mörling and Valinger 1999), and *P. canariensis* at 30 years old (Climent et al. 2003). If comparing the age of heartwood formation in Chenshan red-heart Chinese fir with that of other species, the initial age of heartwood formation of Chenshan red-heart Chinese fir is earlier. This indicated that the rapid growth conditions of Chenshan red-heart Chinese fir accelerated the physiological process that transforms sapwood into heartwood, which resulted in earlier heartwood formation (Taylor et al. 2002). These results also indicate that the initial age of heartwood was specific to tree species.

However, it should be noted that most estimates of the initial age of heartwood in these studies were inferred on the basis of fitted models, rather than from the observations of young trees generally; the age of heartwood formation was usually lower when estimated by fitted models than by observation of wood discs (Pinto et al. 2004). There are models that relate the diameter and percentage of heartwood with tree age using DBH as a reference (Pérez and Kanninen 2003). Models for the formation of heartwood at different tree heights have also been developed (Berrocal et al. 2020). In addition, our results were also obtained though models. Therefore, it should also be worth noting in our study. In the future, we need more data on the very early phases of heartwood formation to strengthen most models of heartwood initiation age (Li et al. 2019).

This study found that the heartwood height of the Chenshan red-heart Chinese fir could reach 81.97 percent of the total tree height at a maximum and the RHR could reach 58.52 percent at a maximum. This result was consistent with Huang et al. (2006) who showed that the red-heart Chinese fir is considered outstanding because of its proportion of red-heart wood ratio being uniquely high, generally up to 50.5 percent, and can reach 80 percent of tree height in mature forests. Compared with other tree species such as *Eucalyptus globulus* (Gominho and Pereira, 2000) and *Pinus pinaster* Ait. (Knapic et al. 2014), Chenshan red-heart Chinese fir has a higher red heartwood height. Gominho and Pereira (2005) found that the maximum heartwood height of the 9-year-old *E. globulus* only reached 65 percent to 70 percent of the total tree height. In this study, the maximum heartwood height of the 9-year-old Chenshan red-heart Chinese fir reached 70.71 percent of the total tree height. Other research also showed that the maximum heartwood height was found to be 17.6 m (70% of the total tree height) in a sample of mature *Pinus radiata* (Wilkes 1991). In the 42- to 83-year-old *P. pinaster* Ait., heartwood was found at a height of 20 m (69% of the total tree height) and in some of the branches (Pinto et al. 2004). In this study, maximum heartwood height was significantly and positively correlated with tree age and tree height (Table 2). For Chenshan red-heart Chinese fir, the maximum heartwood height was expected to increase as tree age and tree height increase, and heartwood might even be observed in some branches. This is especially useful for plantation managers who aim to cultivate high-quality trees and high-value decorative wood with a high RHR.

Suitable trees are cultivated and harvested in rotations. Determining a reasonable rotation age is the primary task of stand management (Peng et al. 2002). This rotation age is often based on the economic benefits, carbon sink value, and other forest indicators in fast-growing plantations (Asante et al. 2010). In the past, the rotation age in Chinese fir plantations has mainly been determined by tree maturity, which occurs at about 25 to 30 years, though harvesting is now common in the range of 20 to 25 years because of increasing demand for timber (Zhao et al. 2018). For Chenshan red-heart Chinese fir, the quantitative maturity age was about 25 years (Liao et al. 2018).

In our study, the result indicated that 40 years is the technical rotation age for Chenshan red-heart Chinese fir, which may explain why there have been shortages of high-value decorative wood of red-heart Chinese fir lately. The traditional rotation generally only considered the quantitative maturity and did not consider high-value decorative wood required by the market. In addition to this, the rotation age not only affects the restoration process of artificial stands, but also affects the influence of the rotation on the soil fertility of Chinese fir plantations (Qian et al. 2006, Chen et al. 2017). Because of the short rotation length, the heartwood of red-heart Chinese fir cannot meet the market's demand for high-value decorative wood. Ma et al. (2000) showed that extending the rotation length increases the proportion of heartwood and decreases the proportion of sapwood. Thus, the ratio of heartwood and sapwood increases year after year. This further indicates that as the rotation length increases, high-value decorative wood can be harvested. Yang et al. (2010) also showed that short rotation length leads to nutrient loss. In fact, the shorter the rotation, the more nutrients are removed per unit biomass during harvesting (Xu et al. 2020). Several studies have also suggested prolonging the rotation length to maintain soil nutrient levels for successive plantings (Ma et al. 2007; Chen et al. 2017). Miao et al. (2019) also recommended that the rotation period be prolonged beyond 25 years to achieve a balance between ecological and economic benefits.

Therefore, red-heart Chinese fir plantation managers should choose a reasonable rotation age. For Chenshan red-heart Chinese fir, a 40-year technical rotation age meets the requirements for high-value decorative wood, which will help optimize cultivation of highly valuable red-heart Chinese fir decorative wood in the long run. Optimal rotation age is of great significance to the sustainable management of red-heart Chinese fir plantations.

Conclusions

In this paper, the variation of heartwood and sapwood was studied in Chenshan red-heart Chinese fir of different ages. We observed contrasting variation patterns of heartwood and sapwood of Chenshan red-heart Chinese fir in the horizontal and vertical directions. Heartwood began to appear when the xylem radius was 4 to 8 cm, after which the HD increased rapidly with increasing XD. HD and HA decreased with increasing height. Heartwood formation was closely correlated with tree age and stand density. The model simulation of heartwood formation in Chenshan red-heart Chinese fir showed that heartwood formation begins at around 7 years and that RHR stabilizes (about 60%) after 40 years, so that is when the wood is most valuable. To achieve cultivation goals for this high-value decorative wood, we recommend prolonging the rotation age from 25 (quantitative maturity age) to about 40 years (technical maturity age).

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