Relationship of H/D and crown ratio and tree growth for Chamaecyparis obtusa and Cryptomeria japonica in Korea

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ABSTRACT
This study was conducted to suggest the necessity of regulated stand density control in order to maintain the ratio of height to diameter at breast height (H/D ratio) of Hinoki cypress (Chamaecyparis obtusa) and Japanese cedar (Cryptomeria japonica) in South Korea. A total of 2,000 (1,000 each) Hinoki cypress and Japanese cedar were cut from various regions of South Korea, and their diameter at breast height (DBH), height and clear length were measured. The two species’ regional means of H/D ratio and crown ratio were then computed and compared to find the relationship with tree growth. The result of analyzing the relationship between the H/D ratio and tree growth by DBH class is as follows, 77.0% for small DBH class, 62.5% for medium DBH class, and 45.9% for large DBH class, with overall mean of 61.8%. The annual means of DBH growth were 4.6 mm, 7.4 mm, and 8.2 mm respectively for small, medium, and large DBH classes. As the DBH class went up, the H/D ratio decreased, showing a negative correlation ($p < 0.0001$) with the tree growth rate. However, the crown ratio showed a significant correlation with tree growth. Japanese cedar’s H/D ratios by DBH class were 100.5% for small, 74.9% for medium, and 53.6% for large, while its mean annual DBH growth were 5.1 mm, 7.6 mm, and 10.0 mm, from small to large DBH class respectively. Similar to that of Hinoki cypress, Japanese cedar’s H/D ratio showed a negative correlation with the growth rate ($p < 0.0001$), but no significant relationship could be established between the crown ratio and the tree growth. In both arboreal species, the correlation between the H/D ratio and growth rate is negative, and no significant correlation could be formulated between crown ratio and tree growth. In conclusion, both tree species tended to have a higher H/D ratio and a lower growth rate in small DBH class, while H/D ratio decreased and growth rate increased as DBH class got larger.

Introduction
Along with Japanese larch (Larix kaempferi) and Korean pine (Pinus koraiensis), Hinoki cypress (Chamaecyparis obtusa) and Japanese cedar (Cryptomeria japonica) are prominent species of South Korean man-made forests. Introduced from Japan, they initially have been planted in the southern region of South Korea since the early 20th Century, and then cultivated across the nation in the 1970s (Jin and Chon 1987). These species are highly valued for their commercial purposes, and are prominently seen in plantations in Japan and Taiwan due to their notable features such as dimensional stability, fast growth rate, and wood quality. Currently, Hinoki cypress and Japanese cedar occupy 52,423 ha and 16,326 ha of South Korean plantations, accounting for 3.9% of the total plantation area. Over 90% of Hinoki cypress are distributed across Jeolla and Gyeongsang provinces, namely in Jeongeup, Muju, Yeongam, Suncheon, and Geojje (Korea Forest Service 2016). The trees are mainly classified into the medium DBH class (18–28 cm in diameters) with age class IV (31–40 years) on average (Korea Forest Service 2016). Over 69.1% of Korean forests, whose age once belonged to class I or II, have reached class IV and are being actively logged. While majority of Korean forest over 40–50 years old is capable of producing high-quality timber, 67.1% of the forest is privately owned, and proper management and maintenance are currently lacking. Thus, it is urgent to establish a proper stand density control regime, such as thinning in opportune time, in order to expand the supply of domestic timber production.

Currently, the stand density of Hinoki cypress and Japanese cedar in South Korea is expected to have a high H/D ratio due to the high stand density of both species, with Hinoki cypress of age class IV at 1,037/ha, and Japanese cedar of age class IV at 1,232/ha respectively (Korea Forest Service 2016). With such high stand density, stand structure is expected to be weak and unstable, especially from natural disasters such as typhoons and heavy snow (van Gelder et al. 2006). Both H/D ratio and crown ratio are suggested as important factors that are indicative of the stand’s stability, growth, and biomass characteristics (van Laar 2006).
and Akca 1997; Wonn and O’Hara 2001; Picard et al. 2012). The H/D ratio in particular is a good measure of a stand’s vulnerability, and a stand could be damaged by typhoon or snow (Cremer and Borough 1982). Many studies investigating the relationship between the two have been conducted in Europe and North America in the past (Cremer et al. 1983; Lohmander and Helles 1987; Nykänen et al. 1997). These studies have suggested that the H/D ratio and the amount of damage on trees dealt by snow or typhoon are strongly correlated (Brunig 1974; Faber 1975; Vospernik et al. 2010). Wonn and O’Hara (2001) investigated the H/D ratio to predict the stability against wind and snow damage for decades, and reported that such damage increased with H/D ratio across four different types of trees such as pine and larch. The H/D ratio and crown ratio have a strong correlation with stand density as well (Lanner 1985), and the past studies on stand density have reported that the increase in stand density intensifies the wind and snow damage (Reukema 1970; Cremer and Borough 1982; Oliver 1997). Generally speaking, H/D ratio under 70% is considered to be adequate while over 80% is deemed to be susceptible (van Laar and Akca 1997, 2007; Oda 1992; Harada and Kawata 2005; Forestry and Forest Products Research Institute (Japan) 2011; Kim et al. 2015; National Institute of Forest Science 2015; Kunisaki 2005). Once crown ratio gets smaller, growth also slows down, and this shifts the center of the tree upwards, making it more susceptible to wind and snow damage (Cremer et al. 1983; Japan Forest Technology Association 1998; Kato 2009).

The H/D ratio shows a strong correlation with stand density and is used as an important index to determine the timing of thinning (Pretzsch 1996; Abetz and Klädtké 2002). Burschel and Huss (1997) categorized H/D ratio, which represents the degree of stability of coniferous trees, into Very unstable (>100), Unstable (80–100), Stable (<80), and Open grown tree (<45). The forest management that involves density control is crucial for sustainable production and preservation in man-made forests. In particular, since stand density has a close relationship with H/D ratio and crown ratio, which are considered good criteria for the stability and growth of the stand, properly planned stand density treatment is absolutely necessary (Pretzsch 1996; Wonn and O’Hara 2001; Abetz and Klädtké 2002; Park et al. 2009; Kim et al. 2015). Since stand density affects not only the number of trees died of natural cause, but also the spread of various pests and diseases, the control of the stand density through an effective system is essential. To accomplish such task, thinning is a crucial step that aids in maximizing the harvest and maintaining the forest healthy. Crown ratio of stand varies largely from stand density of species, and is associated with growth and stability of the trees in a man-made forest. As density grows, the stem gets thinner while the ratio of a tree’s height to diameter at breast height (H/D ratio) rises, and a tree with H/D ratio of 70% or higher may be more susceptible to damages (National Institute of Forest Science 2015).

The ratio of live crown length to total height (crown ratio) is not only an influential factor in DBH growth, (Assmann 1970; Spurr and Barnes 1980; Abetz 1987; Valentine et al. 1994; Hasenauer and Monserrud 1996) but also in assessing the timber quality and its commercial value (Abetz and Unfried 1983; Kleine 1986; Abetz 1987; Kershaw et al. 1990). Schütz (2001) suggests that crown ratio is an index that indicates of the stability of trees and classified them as Very unstable (<0.30), Unstable (0.30 < c/h ≤ 0.50), Stable (>50), Open grown tree (>0.62). A low crown ratio has a negative impact not only on the height growth but also on the development of a root system, determining whether a tree is likely to be broken or withstand a strong wind or heavy snow. Such cases were more frequently observed in high density forests. As a result, in these stands, it can be observed that damages from wind, snow, and disease and pest are growing due to a rapid reduction in the crown ratio and a resultant increase in the H/D ratio. Based on these characteristics, the importance of a tree’s H/D and crown ratio cannot be overemphasized in terms of the development of forest resources for a healthy stand (Kim et al. 2015; Park et al. 2017).

Stand density varies drastically by region. In particular, the stand density of Hinoki cypress and Japanese cedar, which are representative species found in Korean artificial forests, fluctuated greatly depending on their management entity or the purpose of the stands in each region. Some of these stands are particularly in danger due to improper density management. Therefore, it is necessary to identify the vulnerability of stand through regional HD ratio and crown ratio analysis to examine the need of proper density management. Among the timbers currently distributed in the domestic market, Hinoki cypress is one of the highly sought-after species along with pin trees. They are both commonly found in Korean artificial forests, as they provide great source of leisure and therapeutic qualities to forests. Therefore, this study aims to analyze the vulnerability of the stand structure by examining the growth relationship with between Hinoki cypress and Japanese cedar, and suggest the need for proper forest management in order to restore the stability and maximize the productivity.

**Material and methodology**

**Sample species**

For the field survey of HD ratio of Hinoki cypress and Japanese cedar across the country, the distribution area of two species nationwide was extracted by region. A forest type map with a scale of 1:5,000 was used. The data for total coverage area across the country was collected for these two species in order to determine the number of sample trees which were to be cut according to the data (National Institute of Forest Science 2013b). As noted in Figure 1, Hinoki cypress and Japanese cedar take up 52,423 ha (3.1%) and 16,362 ha.
(0.95%) of man-made forest (Korea Forest Service 2017).

**Material and data collection**

A total of 1,000 sample trees of each species (Hinoki cypress and Japanese cedar) from South Korea’s southwestern coast and Jeju island were cut. In order to minimize the regional bias, samples from different regions were selected with even distribution among different DBH classes (6–16 cm for small, 18–28 cm for medium, 30 cm or over for large). Their characteristics, including the height, the DBH, and the clear length were then measured.

**Subject analysis**

In this paper, the H/D ratio was calculated as the ratio of the whole height to the DBH of a tree (H/D) (Equation 1, Mitchell 2000; Pommerening and Grabarnik 2019), and the crown ratio was estimated as the ratio of the whole height to the length of the crown of a tree (CL/H) (Equation 2, van Laar and Akca 2007; Pommerening and Grabarnik 2019) (Figure 2).

The H/D ratio (%) = (Height, m)/

Diameter at breast height, cm) × 100

The Crown ratio (%) = (Crown length, m)/

Tree height, m) × 100

**Statistical analysis**

Statistical analysis was conducted by comparing DBH class, H/D ratio, and crown ratio based on the data for growth characteristics such as stand age, height, DBH, and clear length were utilized for an empirical assessment. Once the data was organized from the stem

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Figure 1. Spatial distribution maps of C. obtusa and C. japonica stands in Korea.

Figure 2. Collection of shape form and crown data from trees.
Table 1 shows the stem analysis summary data of Chamaecyparis obtusa and Cryptomeria japonica used in this study.

| Species       | Diameter class | Felled tree (Tree No.) | Age (yr) Min. Max. Mean | DBH (cm) Min. Max. Mean | Height (m) Min. Max. Mean | Stand density (trees/ha) Site Index |
|---------------|----------------|------------------------|-------------------------|-------------------------|----------------------------|-----------------------------------|
| C. obtusa     | Small          | 1,000                  | 11.3 57.3 32.8          | 6.0 32.0 22.4           | 4.5 19.8 12.9                | 1,187 12                           |
|               | Medium         | 309                    | 8.0 47.0 25.4           | 6.0 16.0 11.1           | 2.7 15.6 8.3                 | 1,428 10                           |
|               | Large          | 417                    | 10.0 59.0 31.5          | 6.0 28.0 22.1           | 5.1 19.9 14.2                | 1,164 14                           |
| C. japonica   | Small          | 274                    | 16.0 60.0 41.6          | 6.0 52.0 34.0           | 5.6 24.0 16.1                | 949 16                             |
|               | Medium         | 1,000                  | 12.7 49.7 32.1          | 18.0 35.0 24.0          | 9.5 24.5 15.8                | 870 14                             |
|               | Large          | 347                    | 8.0 46.0 26.0           | 6.0 16.0 11.6           | 2.5 25.5 11.4                | 1,265 12                           |

Note: Small: DBH < 16 cm, Middle: 16 cm ≤ DBH < 30 cm, Large: 30 cm ≤ DBH. Site Index: based age = 30 years.

Results and discussions

Growth characteristics by species

Table 1 shows the stem analysis summary data of Chamaecyparis obtusa and Cryptomeria japonica used in this study. The data was sorted age, DBH, and height by species and diameter class.

Upon measuring the cut sample wood, Hinoki cypress stand’s average age came out to be 32.8 years (age class V), and average DBH and average height were gauge at 22.4 cm and 12.9 m respectively. These values are higher than national averages (32.0 years, 19.4 cm, and 11.4 m). Similar trend could be observed for Japanese cedar, where all three values came up slightly above national average (Korea Forest Service 2016). Majority of these two species have grown to slightly above national average (Korea Forest Service 2016). The average Hinoki cypress’s average age came out to be 32.8 years in Korea. The average Hinoki cypress was found to be 65.3%, and its average H/D ratios based on DBH class were 49.3% for large, 63.6% for medium, and 83.1% for small, presenting a negative relationship between the H/D ratio and DBH class (p < 0.0001, Figure 3). Generally speaking, it has been previously noted that as a stand matures, and as its DBH increases, the HD ratio tends to decrease (Pommerening and Grabarnik 2019). A stable stand structure that maintains a tree’s HD ratio under 70% can withstand wind and snow damage, (Brunig 1974; Faber 1975; Burschel and Huss 1997; Vospernik et al. 2010), and since this study’s sample Hinoki cypress’s H/D ratio did not surpass 46.3%, 63.6%, and 70% for each DBH class, it could be deduced that proper stand density management has been performed. Burschel and Huss (1997) stipulates HD, the indicator of coniferous trees’ stability, as Very unstable (>100), Unstable (80–100), Stable (<80), and Open grown tree (<45). Japanese cedar’s average H/D ratio was estimated to be 75.8%, a number higher than that of Hinoki cypress, and its H/D ratios corresponding to DBH classes were 54.1%, 74.9%, and 98.3% for large, medium, and small, showing once again a trend of inverse correlation between H/D ratio and DBH class (p < 0.0001). Contrary to that of Hinoki cypress, the H/D ratios of Japanese cedar belonging to small and medium classes exceeded 70% (with small DBH class going over 80%).
With such ratios, the stands belonging to these classes would be more vulnerable to wind and snow damage, and a proper stand density treatment is needed (Cremer and Borough 1982; van Laar and Akca 1997; Oda 1992; Wonn and O’Hara 2001; Harada and Kawata 2005; van Gelder et al. 2006; Forestry and Forest Products Research Institute (Japan) 2011; Kim et al. 2015; National Institute of Forest Science 2015; Kunisaki 2005). Wonn and O’Hara (2001) has used the H/D ratio to predict the tree’s stability from wind and snow damage over the past several decades, and the four species (pine, larch, etc) in the research became more vulnerable to these damages as their H/D ratio increased. The increase in H/D ratio begets decrease in crown ratio, and since the amount of crown deals with a tree’s photosynthesis, once crown ratio lowers growth of the tree gets stunted as well (Wykoff et al. 1982; Burkhart et al. 1987; Monserud and Sterba 1996). Wykoff (1990) reported that crown ratio is a good indicator for the increase in a tree’s DBH growth, Daniels and Burkhart (1975) has utilized crown ratio for predicting the height and DBH growth, and crown length of loblolly pines in Southwestern United States. Shifley (1987) reported that 19 out of 22 trees have shown growth in DBH with the increase in crown ratio. As these studies suggests, crown ratio is closely related to with a tree’s growth, making it a suitable growth indicator that predict the outcome (Daniels and Burkhart 1975; Wykoff et al. 1982; Wykoff 1990; Monserud and Sterba 1996; van Laar and Akca 1997; Schütz 2001).

In accordance with stand density, the H/D ratio and the crown ratio generally establish a negative correlation (Park et al. 2019). While HD density lowered, increase in volume growth was observed, a significant trend with crown ratio was not seen in Hinoki cypress forests (Figure 4). In relation to Hinoki cypress, H/D ratios and crown ratios were 49.3% and 62.8% for large DBH class, 63.6% and 62.7% for medium DBH class, and 83.1% and 59.4% for small DBH class. As DBH class goes from small to large, the H/D ratio decreased and the crown ratio increased (p < 0.0001). However, crown ratio did not present any significant pattern. A similar tendency between H/D ratio and crown ratio was observed in Japanese cedar, and no particular pattern with crown ratio could be established either once again (Figure 4). Broadly speaking, in a high stand density environment, increase in H/D ratio results in decrease in crown ratio, which contributes to reduction in stem biomass. Such reduction causes to lower photosynthetic activity, slowing down the tree growth. The crown ratio is an important growth indicator for evaluating the vitality, wood quality, and commercial value of a tree (Assmann 1970; Spurr and Barnes 1980; Abetz and Unfried 1983; Kleine 1986; Abetz 1987; Kershaw et al. 1990; Valentine et al. 1994), so it is an important to perform stand density management and with the crown ratio around at 50% (National Institute of Forest Science 2015; Son et al. 2015; Park et al. 2019). Despite H/D ratio showing clear changes in accordance with DBH class, crown ratio appeared to show no particular correlation with DBH class. Thus, it could be stated that stand density directly influences the H/D ratio of the tree.

The correlations between the H/D ratio, crown ratio and three growth were analyzed. In regards to Hinoki cypress, the H/D ratio, crown ratio, and annual DBH growth were 83.1%, 59.4%, 4.6 mm for small DBH class; 63.6%, 62.7% 7.4 mm for medium DBH class; 49.3%, 62.8, 8.2 mm for large DBH class respectively (p < 0.0001). The H/D ratio decreased while the diameter growth increased as the stand density went from high to low. In a meantime, crown ratio showed a positive correlation as the growth rate and the DBH class increased (p < 0.0001). The H/D ratio, crown ratio, and annual DBH growth of Japanese cedar in varying DBH classes were 98.3%, 59.4%, 5.1 mm for small, 74.9%, 59.5%, 7.6 mm for medium, 54.2% 61.2%, 10.0 mm for large DBH classes, displaying a similar trend found in Hinoki cypress (p < 0.0001). Reflecting on these results, it could be stated that stand density management affects the both HD and crown ratios, which determine a tree’s growth (Figures 4 and 5). In the case of even-aged stands with the same species, as the stand density increases, the lower branches wither away, leading to the decrease in crown ratio. Once the crown ratio decreases, the tree growth declines as well, leading to an upward shift in the center of crown, making the tree more vulnerable to wind hazard and snowstorm (Brunig 1974; Faber 1975; Cremer et al. 1983; Japan Forest Technology Association 1998; Kato 2009; Vospernik et al. 2010). The crown ratio should not be under 30% in the young mature stand and is suitable around 50–60% in the old stand (National...
Institute of Forest Science 2015). If the crown ratio is escalated, the stem becomes thinner. While the stand becomes prone to wind and snow damage at the crown ratio of 80% or higher, the ratio below 70% displays excellent stand stability (Oda 1992; Wonn and O’Hara 2001; Harada and Kawata 2005; Forestry and Forest Products Research Institute (Japan) 2011; Kim et al. 2015; National Institute of Forest Science 2015; Kunisaki 2005). Therefore, in the superior timber production management perspective, density control that affects the HD and the crown ratios through thinning at an opportune time is the most important forest management activity in the forest with high crown ratio. However, growth from the change in crown ratio does not always produce the definite correlations. Since the crown ratio, which is about branches of crown or quantity of leaves, can be affected by outer influences or artificial forest-working, figuring out the specific correlation between the crown ratio and the volume growth is highly challenging. In this study, the crown ratio is calculated by the rate of crown length for the height, which leads to the less rigorous representation of the exact amount of crown. In other words, the more specific correlation between the ratio and growth would be revealed when the value of the crown biomass calculated with width and length of the crown is presented. Due to the advancement in LiDAR technology, it is possible to obtain the numerical amount of crown biomass by the 3D scanning tree as a whole. Thus, it is expected that the correlation of the crown ratio with growth could be brought to light more clearly.

In order to provide growth characteristics information of stand for stable and efficient forest management throughout the country, regional forest management offices and local governments regionally analyzed HD ratio and crown ratio, both of which are closely related to a tree’s susceptibility to wind and snow damage. The following are the H/D ratio and the mean annual increment (MAI) of Hinoki cypress by region: 77.1%, 0.0061 m³ in Boryeong, 75.0%, 0.0087 m³ in Gangjin, 71.7%, 0.0078 m³ in Geoje, 70.2%, 0.0081 m³ in Muju, 70.2%, 0.0081 m³ in Gochang, 55.2%, 0.0084 m³ in Ulju, 50.6%, 0.0098 m³ in Suncheon, 49.9%, and 0.0087 m³ in Jeju (p < 0.0001) (Figure 6). During the time when both H/D ratio and growth in volume increased (p < 0.0001), no definite pattern was observed between growths in volume and diameter and crown ratio. For Boryeong, Gangjin, Geoje, and Muju, where H/D ratio surpassed 70% for the trees with medium DBH class or higher, an appropriate density management is highly suggested. This management needs to be performed to trees before they enter medium DBH class, and if the thinning was carried out in a stand with over 80% of the H/D ratio due to missing the most opportune time for density management, the H/D ratio of the forest trees in remaining stands after afforestation would be still high, leading to damages such as broken stems from a typhoon, or snowstorm. The H/D ratio of the forest trees is used as a vitality indicator of the stands in forest management (Kim et al. 2015; Park et al. 2019). As the density increases, the H/D ratio also goes up (Son et al. 2015). As the density goes up in the same stand age, stem volume also increases. Small trees die out from withering above a certain density in same stand age (Son et al. 2015). Fish et al. (2006) asserted that crown oppression appears when the H/D ratio goes up and soon an amount of overtopped tree in stand will increase. Park et al. (2016) indicate a possible rise in damage from wind and snow damage in this phase, even if the thinning would be carried out owing to the late timing of it.

Park et al. (2019) also described that the H/D ratio was 92.0% in treatment plots of extremely heavy thinning intensity and 94.3% in control treatment plots (non-thinned treatment plot) in 2000. On the other hand, it was 77.1% in treatment plots of extremely heavy thinning intensity and 120.6% in control treatment plots (non-thinned treatment plot) in 2018. It showed that the H/D ratio of the heavily thinned plots drastically decreased, but a ratio of the non-thinned plots rapidly rose. Compared to 65.3% of the mean H/D ratio of Hinoki cypress in this study, it was noted to be 77.1% in extremely thinned plots and 95.7% in heavily thinned plots in the research by Park et al. (2019). As mentioned in their study, after the afforestation in 1978 the H/D ratio of extremely thinned plots was 92% at the first treatment in 2000. Even though several thinning had been carried out since then, due to the overdue thinning timing, there has been no significant effect of variation in the H/D ratio, nor significant difference in stand volume by different levels of thinning intensity. It was reported that in case of extreme thinning, the H/D ratio was over 90% at that time of thinning and after several thinning since then, there has been a lot of damage caused by wind hazard or typhoon. When the thinning is applied to stands with high crown ratio and H/D ratio, the damage can be greatly intensified (Valinger and Pettersson 1996; National Institute of Forest Science 2015). In the case of Hinoki cypress in this study, the stand age was 32.8, DBH was 22.4, and the site index was 12. The average number of trees in actual stand per hectare was 1,187, which was slightly higher than 950, the proper number of trees in the stand after thinning which was suggested by Korea Forest Service (National Institute of
Forest Science 2012). Thus, in order to maintain optimal remaining tree number, it is urged to carry out forest management such as thinning to sustain the proper H/D ratio, leading to minimizing the damage caused by snowstorm or wind hazard and to produce the useful and quality wood. In the final analysis, it is considered that the appropriate time for thinning and stand density control in forest management can be the basic of important forest management, not only maximizing the tree growth by maintaining the stabilized H/D ratio, but also minimizing the damage by wind hazard and snowstorm. Accordingly, when it comes to Hinoki cypress forest practices like thinning need to be implemented in appropriate time so that the density of the stand can be timely controlled, which minimizes various kinds of natural disaster damages after thinning and maximizes diameter growth. Through that process, a stable stand structure can be secured, by which superior quality of wood can be produced.

The relationship between regional H/D ratio and MAI in Japanese cedar showed 87.3%, 0.0110 m³ for Gangjin, 85.7%, 0.0075 m³ for Ulju, 80.2%, 0.0116 m³ for Pohang, 76.5%, 0.0094 m³ for Seogwipo, 75.5%, 0.0099 m³ for Suncheon, 71.5%, 0.0124 m³ for Jeju, 70.6%, and 0.0088 m³ for Geoje, 64.4%, 0.0153 m³ for Gochang in order (p < 0.0001) (Figure 7).

A negative correlation was displayed in the Figure 7 in which the MAI increased in broad outlines, as the H/D ratio decreased. Yet, no significant correlation was found between the crown ratio and the MAI. A similar trend was observed in Japanese cedar. When it comes to the volume growth by the regional H/D ratio, there is a tendency that the volume increased as the regional H/D ratio decreased. Yet, no significant correlation was found between the crown ratio and the MAI in which the MAI increased in broad outlines, as the H/D ratio decreased. However, it showed no significant correlation with the crown ratio and tree volume (Figure 7).

It appears that in Hinoki cypress and Japanese cedar, there is a significant difference in the H/D ratio by the variation of DBH classes. Also, there is a significant difference in the specie comparison as the H/D ratio was 65.3% and 75.8% respectively (p < 0.0001). The H/D ratio of a large DBH class in both of the species was 49.3% and 54.2% respectively, which is a stable ratio. However, it showed 63.6% and 74.9% for medium DBH class and 83.1% and 98.3% for small DBH class respectively. It means that it is more urgent to manage stand density through forest practices like thinning in Japanese cedar more than Hinoki cypress. In stand density of Japanese cedar, the mean stand age is 49.7, DBH is 24.0 cm, average site index is 14, and the average number of trees in stand per hectare is 870 (Korea Forest Service 2016), which is slightly higher than the proper number of a remaining tree, 950 (National Institute of Forest Science 2012), after thinning in Hinoki cypress. Park et al. (2018) developed and applied Relative yield index (RY) of Stand density management diagram for Hinoki cypress in order to analyze the appropriate time intensity of thinning. As a result of analyzing the relationship between RY and tree volume at different thinning intensities, unless the thinning is carried out in most optimal timeframe, it is hardly possible to maintain 0.8 of RY, the reference level, because RY of most of the cases in which the density management intensity of thinning was intensified exceeded over 0.90 close to 1, which is the maximum value of RY. The proper Relative yield index (RY) varies by species but is generally between 0.6 and 0.8. Ry more than 0.8 indicates overcrowding (National Institute of Forest Science 2015). In case of Korean red pine stand, Ry more than 0.8 is defined as heavy density stand (Ando 1962) and it is the appropriate time for density management when Relative Yield index (RY) reaches between 0.75 and 0.8 (Forestry and Forest Products Research Institute Japan 2011). This H/D ratio of three is greatly affected by stand density and its value can be an indicator of how much the stand is safe from wind hazard, snowstorm, and harmful insects and a standard for density management. The H/D ratio of Japanese larch, one of the most typical afforestation tree species along with Japanese cedar and Hinoki cypress, was 73.4% for large DBH class and 92.7% for medium DBH class, which was far higher than Japanese cedar and Hinoki cypress. It means that the density of the two was better managed by thinning than Japanese larch. As mentioned above, if the H/D ratio is over 70% for large DBH class, thinning does not bring the significant result in the H/D ratio control and rather triggers the stand structure to be at risk from wind and snow hazard. In a European case of stands damaged from natural elements, there has been a report that the H/D ratio of stands damaged from wind and snow in a spruce-fir forest in Germany was over 80% while nondamaged ones were accounted for 63% (Korea Forest Service 2000). In domestic cases, it appears that for forest trees damaged from artificial disturbance, wind hazard, wildfire, or insects were low levels of DBH classes with the high H/D ratio (National Institute of Forest Science 2013a). The H/D ratio of three is greatly affected by stand density and its value can be an indicator of how much the stand is safe from wind hazard, snowstorm, and harmful insects and a standard for density management. The H/D ratio of Japanese larch, one of the most typical afforestation tree species along with Japanese cedar and Hinoki cypress, was 73.4% for large DBH class and 92.7% for medium DBH class,

Figure 7. Relationship of H/D ratio, crown ratio and tree volume by regions in C. japonica of Korea. Note. KJ: Kangjin; UJ: Ulju; PH: Pohang; SP: Seogwipo; SC: Sunchun; JJ: Jeju; GJ: Geoje, GC: Gochang.
which was far higher than Japanese cedar and Hinoki cypress. It means that the density of the two was better managed by thinning than Japanese larch. As mentioned above, if the H/D ratio is over 70% for large DBH class, thinning does not bring the significant result in a H/D ratio control and rather triggers the stand structure to be at risk from wind hazard and snow damage. In a European case of stands damaged from wind hazard and snow damage, there has been a report that the H/D ratio of stands damaged from wind and snow in a spruce-fir forest in Germany was over 80% and the non-damaged stand was 63% (Korea Forest Service 2000). In domestic cases, it appears that for forest trees damaged from artificial disturbance, wind hazard, wildfire, or insects were low levels of DBH classes with the high H/D ratio (Wonn and O’Hara 2001).

Conclusion

This study has shown the relationship of H/D and crown ratio of Hinoki cypress and Japanese cedar. Based on the analysis of the H/D and crown ratio, both of which are affected by stand density, a total of 2,000 trees, 1,000 for each species, were cut. To obtain accurate information on each tree, the analysis based on the regional H/D ratio, the crown ratio and the tree’s DBH class, which were used as the criteria of a stand density management. This study examined the correlation of tree growth with these criteria. A negative correlation was revealed between the H/D ratio of forest tree and tree growth, as its DBH class climbed to a larger one. However, tendency of the crown ratio decreasing when the H/D ratio increases was not found in this research. As the H/D ratio increased By DBH class and region, the tree growth was disposed to decrease, but a significant correlation of tree growth with the crown ratio was not observed. As a result, stand density is considered to be clearly correlated with the H/D ratio and the H/D ratio is negatively correlated with tree growth. It is feasible to use this result as a standard for future stand density management with forest practices like thinning for artificial forestation species in Korea like Korean red pine, Japanese larch, Korean pine, and Hinoki cypress, all of which are typical afforestation species in Korea. Along with Japanese larch, Hinoki cypress is surging in demand. The recent development in domestic policy in wood utilization, the use of laminated wood as a building material has been steadily increasing. Due to its unique scent and phytoncide, Hinoki cypress is also used for leisure purposes such as cosmetic items and in recreational forests as well, and the afforestation area of Hinoki cypress is projected to continue expanding. Therefore, it is required to establish the criteria of stand density management based on scientific data regarding artificial forestation species of trees which are in increasing demand and highly utilized for timber. It is time to introduce the precise forest management system to maximize stand stability and productivity through maintaining stand H/D ratio and crown ratio by controlling stand density in proper timing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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