Growth pattern analysis of major coniferous tree species in South Korea

Yeongwan Seoa, Daesung Leeb and Jungkee Choisb

abDepartment of Forest Management, College of Forest and Environmental Sciences, Kangwon National University, Chuncheon 24345, Republic of Korea.

aInstitute of Forest Science, College of Forest and Environmental Sciences, Kangwon National University, Chuncheon 24345, Republic of Korea.

ABSTRACT

The size growth patterns of major coniferous trees species Pinus densiflora (Pd), Pinus koraiensis (Pk), and Larix kaempferi (Lk) in South Korea were found and compared using stem analysis. A dominant or co-dominant tree selected from each of 131 sites (39 sites for Pd, 47 sites for Pk, and 45 sites for Lk) was stemmed and analyzed for the study. Total increment (TI), periodic annual increments (PAI), mean annual increments (MAI), and growth percentage of diameter at breast height (DBH), height, and volume were numerically and statistically compared among the three tree species. As the trees age the total DBH growths of Pk and Lk were similar to each other but higher than that of Pd. A noticeable difference of total height growth was shown among the trees and the total height increment was Lk > Pk > Pd. Like the total height growth, the volume difference was noticeably different among the trees and the growth was Lk > Pk > Pd. Given no difference of DBH between Lk and Pk, the volume difference between the two species was due to height. Unlike DBH and height, MAI and PAI of volume did not meet together. This inferred that the volume growth was still vigorous to reach the rotation age. Growth percentages of DBH, height, and volume tended to decrease with age and no difference was shown among the tree species. The growth percentage of volume was higher than that of DBH and height, while there was no difference between DBH and height.

Introduction

The principle reason for analyzing the past growth of trees is to establish a pattern for predicting future growth (Avery and Burkhart 2002). For sustainable forest management the growth patterns for individual trees with information on the size increment are very important factors to predict the growth and conserve trees, to estimate cutting cycles and climatic effects, and to prescribe silvicultural treatments (da Silva et al. 2002; Brienen and Zuidema 2006; Dang et al. 2010; Soliz-Gamboa et al. 2010). Complete stem analysis is the most accurate method to obtain the growth information including accumulated tree volume growth through a record of the past size growth of individual trees (Husch et al. 2003). Also, a relationship between size (diameter, height, or volume) and age of trees can infer age structures and enable assessment of the population dynamics of forests through establishing size class frequency distributions (Harcoumb and Marks 1978; Lorimer 1980; Stewart 1986; Bergeron 2000; Baker et al. 2005; Xing et al. 2012).

In South Korea many studies using stem analysis have been carried out on modeling growth parameters of diameter, height, stem volume, site index, or stand density (Ma 1997; Park and Chung 1999; Lee 2002; Lee 2003; Choi and Yoo 2006; Jeon et al. 2007; Lee et al. 2009), while, even with limited stem data, there have been only a few studies (Seo et al. 2014, 2015) conducted on the size growth patterns of diameter, height, and volume for trees.

Meanwhile coniferous tree species, especially Pinus densiflora (Pd), Pinus koraiensis (Pk), and Larix kaempferi (Lk), have been intensively planted as they are grow fast and are used commercially for lumber in South Korea. Of the total forest land in 2015 coniferous species covered about 37% (2,339,022 ha), of which Pd, Pk, and Lk occupied, respectively, about 67% (1,562,843 ha), 7.3% (170,905 ha), and 12% (272,800 ha) (Korea Forest Service 2016). As the importance of domestic wood supply and utilization increases, there are greater concerns over how to grow and manage these tree species as well as on how much timber to supply in the future.

Therefore this study aimed to find the size growth patterns of Pd, Pk, and Lk in South Korea. Specifically the study questions were: (1) what kind of size growth patterns exist in the tree species in this study; and (2) whether there is any difference between the growth patterns among the tree species focusing on diameter at breast height (DBH), height, and volume growth.

Materials and methods

Study area

This study was conducted in Pd, Pk, and Lk plantations of the national forest of Gangwon-do, Gyeonggi-do, and Gyeongsangbuk-do in South Korea. During 2012–2015 a total of 131 permanent monitoring plots (20 m × 20 m) in 16 cities and counties were installed: 39 plots for Pd, 47 plots for Pk, and 45 plots for Lk (Figure 1).

The summery statistics of the 131 permanent plots for the tree species were shown in Table 1. The mean DBHs were 30.5 cm for Pd, 29.8 cm for Pk, and 27.8 cm for Lk, and
mean heights were 17.0 m for Pd, 17.2 m for Pk, and 22.8 m for Lk. The mean numbers of trees were 843 trees/ha for Pd, 871 trees/ha for Pk, and 782 trees/ha for Lk, the mean basal areas were 36.3 m²/ha for Pd, 36.9 m²/ha for Pk, and 30.6 m²/ha for Lk, and the mean site indices 14.2 m for Pd, 15.3 m for Pk, and 21.4 m for Lk.

Data collection and analysis

For collecting stem profile data, a dominant or co-dominant tree was felled from each of 131 sites where a plot was installed and the stem sectioned at 2 m intervals beginning at 20 cm with last disc at 1 m or 2 m intervals (Seo et al. 2014, 2015). After sanding all discs every fifth ring was marked and cross checked between radii for identifying errors in ring counting. Using a tree ring measuring system with a stereo-microscope, two diameters outside bark (dob) and two diameters inside bark (dib) perpendicular to each other were measured to the nearest 0.001 mm and averaged for all discs. Smalian’s formula was used to compute the volume of each section and the volume of a cone was calculated for the portion from the last cut to the tip of the tree.

The summery statistics of the 131 sample trees species in this study are shown in Table 2. For each Pd, Pk, and Lk the mean ages were 47, 40, and 38 years old, the mean DBH were 30.4 cm, 29.9 cm, and 27.6 cm, and the mean heights were 17.7 m, 17.3 m, and 22.6 m, respectively. The mean stem volume inside bark and outside bark were 0.6074 m³ and 0.6634 m³ for Pd, 0.6509 m³ and 0.6939 m³ for Pk, and 0.6663 m³ and 0.7498 m³ for Lk.

Total increment (TI), mean annual increment (MAI), periodic annual increment (PAI), and growth percentage (GP) of DBH, height, and stem volume were analyzed every 5 years. They were numerically compared among the tree species to calculate the growth patterns of individual tree in terms of age. The analysis of variance (ANOVA) was carried out to statistically verify the growth difference of DBH, height, and volume among the tree species, and Duncan’s multiple range test was used to analyze the size growth differences.

Table 1. Summary statistics of 131 permanent plots for the study.

| Species          | No. of plots | Slope aspect (°) | Slope gradient (°) | Trees (n/ha) | Mean DBH (cm) | Mean height (m) | Basal area (m²/ha) | Site index |
|------------------|--------------|------------------|--------------------|--------------|---------------|-----------------|---------------------|------------|
| **Pinus densiflora** | 39           | 22.6 ± 8.3 (7–37) | 217.1 ± 83.9 (30–350) | 843 ± 445 (204–2168) | 25.7 ± 10.2 (2.6–47.8) | 14.5 ± 4.5 (2.1–21.8) | 36.3 ± 11.8 (4.8–57.5) | 14.2 ± 2.2 (10–18) |
| **Pinus koraiensis** | 47           | 22.3 ± 9.2 (3–42) | 171.6 ± 113.1 (0–350) | 871 ± 433 (295–2247) | 26.3 ± 10.9 (7.4–55.9) | 15.7 ± 4.7 (5.6–24.3) | 36.9 ± 13.6 (9.6–73.8) | 15.3 ± 1.6 (12–18) |
| **Larix kaempferi** | 45           | 24.7 ± 9.3 (4–43) | 180 ± 103.8 (20–354) | 782 ± 326 (233–1478) | 23.7 ± 9.3 (7.1–45.3) | 19.8 ± 6.1 (5–33.2) | 30.6 ± 9.2 (11.3–54.3) | 21.4 ± 2.8 (12–26) |

Notes: Mean ± SD; base age of site index is 30 years (Korea Forest Research Institute 2012).
Result and discussion

**DBH growth pattern**

Total DBH growths of Pk and Lk were similar to each other and higher than that of Pd (Figure 2). The total DBH growth curves of Pk and Lk showed quite similarly increasing patterns with each other and were located upper than the total DBH growth curves of Pd at each age. There was a significant difference in total DBH increment among the tree species \((p < 0.05)\). By Duncan’s multiple range test \((\alpha = 0.05)\) the difference was not found to be significant between total DBH increments of Pk and Lk, but was definitely significant between Pk (or Lk) and Pd. The DBHs of Pk and Lk grew to 4.7 cm and 6.8 cm at age 10, 22.6 cm and 21.7 cm at age 30, and 32.1 cm and 34.3 cm at age 50, respectively, while DBH of Pd grew to 4.5 cm at age 10, 18.8 cm at age 30, and 28.8 cm at age 50.

It was shown in all the tree species that the PAI of DBH culminated at early ages and then slowly decreased. The culmination of PAI was Lk > Pk > Pd in order; PAIs of Lk, Pk, and Pd peaked at 1.15 cm at age 10, 1.07 cm at age 15, and 0.83 cm at age 15, respectively. The MAI culmination was smaller than the PAI but had a similar pattern; MAI of Lk, Pk, and Pd peaked at 0.79 cm at age 20, 0.75 cm at age 30 and 0.63 cm at age 35, respectively, where MAI and PAI came together. There was a significant difference among the tree species in both PAI and MAI of DBH \((p < 0.0001)\). By Duncan’s multiple range test PAI and MAI of DBH were found not to be significantly different between Pk and Lk, but were significantly different between Pk (or Lk) and Pd.

**Height growth pattern**

Unlike total DBH growth a noticeable difference was shown among total height growths of Pd, Pk, and Lk \((p < 0.0001)\) and the total increment of height was Lk > Pk > Pd as the trees age (Figure 3). By Duncan’s multiple range test \((\alpha = 0.05)\) the difference was found to be significant among the tree species. The total heights of Pd, Pk, and Lk were 3.3 m, 4.0 m, 7.3 m at age 10, 12.5 m, 14.5 m, 20.2 m at age 30, and 17.0 m, 19.2 m, 26.4 m at age 50, respectively.

**Table 2.** Summary statistics of stemmed trees for this study.

| Species       | No. of trees | Age | DBH (cm) | Height (m) | Volume (ob) \( (m^3) \) | Volume (ib) \( (m^3) \) |
|---------------|--------------|-----|----------|------------|--------------------------|--------------------------|
| *Pinus densiflora* | 39           | 47 ± 16 | 30.5 ± 8.4 | 17.0 ± 4.0 | 0.6707 ± 0.3940 | 0.6147 ± 0.3715 |
| *Pinus koraiensis* | 47           | 40 ± 16 | 29.8 ± 7.9 | 17.2 ± 4.4 | 0.6935 ± 0.4743 | 0.6505 ± 0.4477 |
| *Larix kaempferi* | 45           | 38 ± 12 | 27.8 ± 9.7 | 22.8 ± 4.4 | 0.7480 ± 0.5160 | 0.6688 ± 0.4653 |

Notes: Mean ± SD; ob = outside bark; ib = inside bark.

Figure 2. Comparing DBH growth patterns by species as the trees age.

Figure 3. Comparing height growth patterns by species as trees age.
It was shown in all the tree species that the PAI of height culminated at early ages and then slowly decreased, as did DBH. There was a significant difference in PAI of height among the tree species. The culmination of PAI was in the order of $Lk > Pk > Pd$, getting closer after age 40; PAIs of $Lk$, $Pk$, and $Pd$ peaked to 0.98 cm at age 10, 0.59 cm at age 15, and 0.48 cm at age 15, respectively.

The MAI of height pattern was similar to the PAI, but it was more clearly $Lk > Pk > Pd$. There was a significant difference in MAI of height among the tree species. MAI of $Lk$, $Pk$, and $Pd$ peaked at 0.78 cm at age 15, 0.49 cm at age 25, and 0.42 cm at age 30, respectively, where MAI and PAI came together.

**Volume growth pattern**

DBH and height growth normally presented a concave curve (Liao et al. 2003; Kwak et al. 2004; Son et al. 2004; Perez 2008; Zuidema et al. 2011), while volume growth presented a convex curve (Chiba Y and Shinozaki 1994; Brienen and Zuidema 2006; Jeon et al. 2007; Castagneri et al. 2013). Our study also showed that DBH and height growth curves were slightly concave while volume growth curves were convex (Figure 4).

Total volume growth was similar to total height growth and the volume difference was noticeably shown among the trees: $Lk > Pk > Pd$ (Figure 5). There was a significant difference among the total volumes of the tree species ($\alpha = 0.05$). The total volumes for $Pd$, $Pk$, and $Lk$ grew to 0.0053 m$^3$, 0.0056 m$^3$, 0.0150 m$^3$ at age 10, 0.1930 m$^3$, 0.3144 m$^3$,
The study was carried out to find and compare the growth patterns of diameter, height, and stem volume for three major coniferous tree species (Pinus koraiensis, Pinus densiflora, and Larix kaempferi) in South Korea using stem analysis data. TI, PAI, MAI, and growth percentage of DBH, height, and volume were compared numerically and statistically among the three tree species.

With regard to the DBH growth pattern, a noticeable difference in total DBH growth was not shown between Pk and Lk, but was seen between Pk (or Lk) and Pd. The total DBH growth curves of Pk and Lk showed similarly increasing patterns with each other and were located above the total DBH growth curves of Pd at each age. PAI of DBH culminated at the early ages and then slowly decreased. The culmination of MAI was Lk > Pk > Pd in order; MAIs peaked at 0.79 cm at age 20, 0.75 cm at age 30, and 0.63 cm at age 35, respectively, for Lk, Pk, and Pd. The PAI difference was not significant between Pk and Lk, but was significantly different between Pk (or Lk) and Pd.

A noticeable difference of total height growth was shown among Pd, Pk, and Lk and the total height increment was Lk > Pk > Pd as the trees age. The total heights of Pd, Pk, and Lk grew to 3.3 cm, 4.0 cm, 7.3 cm at age 10, 12.5 cm, 14.5 cm, 20.2 cm at age 30, and 17.0 cm, 19.2 cm, 26.4 cm at age 50, respectively. PAI of height culminated at the early ages and then slowly decreased in the same way as DBH. There was a significant difference in MAI of height among the tree species and the MAI peaked at 0.78 cm at age 15, 0.49 cm at age 25, and 0.42 cm at age 30, respectively, for Lk, Pk, and Pd.

Total volume growth was similar to total height growth and the volume difference was noticeably different among the trees; Lk > Pk > Pd. Given no difference of DBH between Lk and Pk the volume difference was due to the difference of height between the two trees. The difference was significant among the volumes of the trees. The total volume grew to 0.0053 m$^3$, 0.0056 m$^3$, 0.0150 m$^3$ at age 10, 0.1930 m$^3$, 0.3144 m$^3$, 0.3707 m$^3$ at age 30, and 0.5803 m$^3$, 0.8010 m$^3$, 1.1402 m$^3$ at age 50, respectively. MAI and PAI of volume were differentiated from those of DBH and height in that MAI and PAI of volume did not meet together. This inferred that the volume growth was still vigorous to reach the rotation age.

Growth percentages of DBH, height, and volume were compared numerically and statistically among the three tree species. While there was no clear difference between the growth percentages of DBH and height, the growth percentage of volume was higher than those of DBH or height in all the tree species. The difference was found to be significant between DBH or height and volume by Duncan’s multiple range test ($\alpha = 0.05$). For all the trees, the growth percentages of DBH and height fell rapidly down to 5% at age 25 and slowly decreased after that, while volume growth percentage was down to 6% at age 40.

**Conclusion**

0.3707 m$^3$ at age 30, and 0.5803 m$^3$, 0.8010 m$^3$, 1.1402 m$^3$ at age 50, respectively.

There was a significant difference in PAI and MAI of the volumes among the tree species. Also PAI and MAI of the volumes were differentiated from those of DBH and height in terms of shape and they did not meet together. In the production function its maximum is achieved at the age when MAI is equal to PAI and decides the rotation age. Therefore the growth in our study is inferred to be still vigorous to reach the rotation age (Figure 5). This was consistent with the results from other studies; the PAI of the volume of Japanese cedar (Cryptomeria japonica) increased up to age 150 (Sawata et al. 2007) and aging did not reduce PAI of basal area of Norway spruce (Picea abies) over age 150 (Pretzsch et al. 2002; Castagneri et al. 2013).

**Growth percentage**

Using Pressler’s formula the growth percentages were calculated of DBH, height, and volume for all the tree species. It was found that all the percentages tended to decrease with age in all three tree species (Figure 6) and no significant difference was found between them. While there was no clear difference between the growth percentages of DBH and height, the growth percentage of volume was higher than those of DBH or height in all the tree species. The difference was found to be significant between DBH or height and volume by Duncan’s multiple range test ($\alpha = 0.05$). For all the trees, the growth percentages of DBH and height fell rapidly down to 5% at age 25 and slowly decreased after that, while volume growth percentage was down to 6% at age 40.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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