Root development of 18-year-old *Abies holophylla* under different densities of red pine overstories with different stand aspect

Do-Hyung Lee[1*]

[1]Department of Forest Resources, Yeungnam University, Gyungsan 712-749, Korea
dhlee@yu.ac.kr

Abstract: The aim of this study was to clarify the difference growth of underplanted *Abies holophylla*, which affected by overstory density and stand aspect. The overstory density needs to be considered as an interspecific competition factor that controls young *Abies* growth, not only by radiation limitation but also through root competition of the underground. In this study we clarify the differences in root system growth and architecture of underplanted *Abies holophylla* that is primarily influenced and controlled by the density of the overstory. Each research site represented a different overstory density class and also some differences in stand and slope aspects (valley plane with 500 trees/ha; east slope with 780 trees/ha and west slope with 1220 trees/ha). A total 15 firs, 5 representatives from each site were studied for their root shape, number of vertical and horizontal roots, root length, and root weight. The shape and growth increments of the roots in each stand were influenced by various environmental factors such as constitution, soil nutrients, gravel content, and slope angle. Roots of trees on the planes tended to be heart-shaped and grew around the gravel in a depth of 30-40 cm. The sample trees from the east-facing stand had the second largest growth increment; their roots were straight taproot with a deep and well-developed center. The samples from the west-facing stand showed the least growth and had straight taproots, but with a bent center and lesser tiny roots than those found in samples from other stands. This difference appeared to be important and indicates that light availability becomes limited with density and species of the overstory, and that other site conditions and stand factor conditions, particularly soil characteristics, need to be considered for obtaining stable secondary forests by underplantation. Therefore, when *A. holophylla* is used for afforestation, slope aspect and overstory density should be considered as important factors.

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1. Introduction

Korea initiated the fourth basic forest plan in 2011, which postulates not only the construction of sustainable healthy forest resources by afforestation but also species renewal after thinning, clear cutting, and selective lumber harvesting (Engelhard 2004; Lester 2006; Korea Forest Service 2010). In addition, vegetation, from shade-intolerant trees such as *Pinus densiflora*, *Pinus rigda*, *Robinia pseudoacacia*, and *Alnus japonica* to shade trees such as native *Carpinus*, *Quercus*, and *Acer* (Kwun et al. 2010), undergoes natural succession, and the population of red pine (*P. densiflora*) and pitch pine (*P. rigida*) decreased (Korean Forest Service 2010; Kwun et al. 2010) primarily because of light competition, insect problems, and forest fires. Therefore, for more stability, establishment of sustainable secondary forests or systematic exploration of forest renewal through underplanting unstable older forests with shade- and more fire-tolerant tree species (Szymura 2005; Korea National Arboretum 2009) is necessary.

Tree stability also depends on the geometry of the root system for anchorage to withstand storms and to support the whole plant and provide nutrition and water (Korea National Arboretum 2009). The direction of the aspect and intensity of solar radiation in that direction affects soil characteristics and tree growth (Stage 1976; Inderjit and Mallik 1997; Park and Seo 2001; Madan et al. 2003; Antonino et al. 2005; Green and Hawkins 2005; Jo et al. 2010). However, there is little literature on underplanting according to aspect direction. Thus far, studies have focused on determining the influence of soil properties on the development of roots and estimating the biomass of underplanted species (Atsushi 1993; Michael et al. 1997; Kristiina et al. 1998; Lee, 2000, 2004).

The Manchurian fir (*Abies holophylla* Max.) can grow in altitudes up to 1 600 m and is evenly distributed throughout South Korea (Wang and Wang 2004). It can reach a height of 40 m with 1 m diameter. This species grows on poor podzolic brown soils in areas with a humid-warm summer and dry-cold winter climate with annual precipitations between 600 mm and 1,340 mm (Wang and Wang 2004). *A. holophylla*, a flexible and shade-tolerant tree, has the ability to adopt to environmental changes and regenerate by proventitious shoots and secondary crown formation (traumatic and adaptive reiteration, regeneration) similar to *Abies alba* (compare Gruber 1994, 1995).

In this study, close observations were performed to study the various characteristics of the roots of 18-year-old *A. holophylla* underplanted on different facing aspects, such as growth condition, total length, total weight, and root shape within various categories. In addition, we established the difference in growth increments in the tree roots from 3 research stands, each of which has different environmental conditions. By comparing and analyzing the influence of the different environmental conditions, we were able to estimate the appropriate growing environment of *A. holophylla* for establishing secondary growth forests.

The main hypotheses tested in this research were as follows: 1) *Abies holophylla* is a flexible shade-tolerant tree and is therefore suitable for underplanting older red pine (*Pinus densiflora*) stands with good growth results in youth, which form the basis of sustainability and physical and morphological stability. 2) The root growth characteristics of underplanted *Abies holophylla* depend on the density of the overstory as well as soil characteristics.

2. Material and Methods

2.1. Selection of the investigation areas and trees

This research was conducted on 18-year-old *A. holophylla* planted in Bakdal-li Ne-Nam Myun Gyeong-ju city, Gyeongsangbuk-do (35°43′24″N, 129°6′7″E; 225 m; Table 1). The superstratum of the research site consisted of an average diameter at breast height (DBH) of 25 cm and average height of 30 m. The dominant overstory tree species were 40-50-year-old red pine trees (*Pinus densiflora*) with a DBH of up to 23 cm and heights of up to 21 m. The chosen 3 slopes (west slope, east slope, and valley plane) had different overstory tree densities of between 500 and 1 220 trees/ha (Table 1).

In 1995, 3-year-old seedlings (approx. 2 500-3 000) of *Abies holophylla* were underplanted on each stand to start secondary forest renewal. *A. holophylla* had an average height and root diameter of 1.7 m and 11 cm, respectively. In addition, short plant species such as *Rhus trichocarpa*, *Lindera obtusiloba*, and *Pueraria thunbergiana* appeared frequently.

The forest of the east-facing stand, west-facing stand, and planes had an incline of 10-20°, 20-40°, and 0-5°, respectively, and the density of forestation in the west-facing stand was the thickest. The variation in tree growth characteristics were investigated using 5 sample trees (except suppressed, wolf, and dead trees) that represented the average growth of trees at each facing aspect.

The radiation from February 7th to the 26th between the hours of 09:00 and 15:00 was recorded using a digital data logger (HOBO-H8-003, USA). In addition, the intensity of illumination was measured 10 times using a digital light meter (DER EE DE-3351, Taiwan). The study was conducted from February 7th to the 26th between the hours of 12:00 and 13:00. Relative intensity of illumination (%) was calculated in comparison to that in an open area (86 560 Lux).

Table 1. General description of the study areas

Facing	Location	Altitude (m)	Mean tempera ture (℃)	Annual precipitation (mm)	Stand density (trees/ha)	Overstory average DBH (cm)	Overstory average height (m)	Intensity of illumination (lux)	Relative intensity of illumination (%)
West (20-140°)					1 220	18	17	4 954	5.7
East (180-340°)	35°43'24"N 129°6'7"E	225-250	14.0	1037	780	20	19	7431	8,6
Plane					500	23	21	30 970	35.7
Open area								86 560	100

2.2. Survey of soil properties

The physical and chemical characteristics of the stands were investigated by measuring soil pH, percentage water content, gravel content, and degree of cation (K^+, Na^+, Ca^{2+}, and Mg^{2+}) and anion (PO_4^{3-}, SO_4^{2-}, NO_3^-, and Cl^-) substitution. A soil sample, representing the forestry of each aspect, was collected without disturbing the surface layer. In addition, 3 soil samples were collected using sampling machines (400 mL) and cans (100 mL) located 1 m from the selected spot. A pH meter was used to test soil pH by using 100 mL of soil dissolved in distilled water for 2 h. The percentage water content was obtained by recording the original can weight and that after drying the contents for 72 h at 104℃. In addition, a 9-mesh-size standard screen was used to determine gravel content, followed by analysis of degree of cation and anion substitution by using the method developed by the Korea Rural Development Administration (2000).

2.3. Investigation of root growth characteristics

The destruction of roots was minimized by collecting roots from sample trees from soil within a radius of 1.50 m horizontally around the stem (Figure. 1). The underground base diameter was divided into 4 categories: root stock, vertical root, horizontal root, and tiny roots. The root diameter was ≤2 mm (Kristiina *et al.* 1983; Kurt *et al.* 2002; Peter and Stuart 1982).

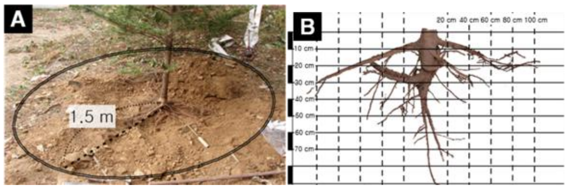

Figure 1. A studied tree (A) and distinct layers of the vertical and horizontal root systems (B)

With the exception of the root collar, all characteristics of root systems, such as number of roots, root length, and root weight, were measured 10 cm vertically and horizontally. The lengths and weights were calculated to the nearest 0.1 cm and 0.1 g, respectively. The total biomass was calculated by drying the separated root categories in each layer per sample to obtain the dry weight (Peter and Stuart 1982). To determine the distribution of the root parts in the different soil layers, we investigated the proportions of the vertical and horizontal root growth.

2.4. Statistical analysis

Data were collected to analyze the influence of each stand factor on root development. The obtained differences were verified by multiplying the growth of thick and tiny roots in every 10-cm thick vertical and 20-cm broad horizontal layers. The growth characteristics of 18-year old under planted *A. holophylla* in each stand was verified using statistical software (SPSS 18.0), Microsoft Excel 2010, and the LSD Fisher multiple-range test ($p < 0.05$).

3. Results

3.1. Soil characteristics

The east-facing stand had an incline of 10-20° and brown forest soil, with an average pH of 5.6; water content, 4.5%; and gravel, 24% for more than 2 mm. The west-facing stand had an incline of 22-36° and brown soil, with an average pH of 5.3; water content, 3.5%; and gravel, 35% for more than 2 mm. The valley plane stand had an incline of 0-5° and sandy soil with rocks; the average soil pH was 5.9; water content, 3.5%; and gravel content, 73%.

In addition, the section below 30 cm of the surface soil mainly consisted of gravel. Gravel content at the west-facing stand was higher than that at the east-facing stand, while the moisture content was similar in both; however, as the slope increased, the water content decreased (Andrew *et al.* 1998; Yun *et al.* 1993). The major cations were Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} and the anions were Cl^{-}, SO_4^{2-}, PO_4^{3-}, and NO_3^{-} in that order, which is similar to those in the average forest soil of Korea (Lee 1981).

Table 2. Physical and chemical properties of the study stands

Facing	Depth (cm)	Slope (°)	Moisture Content (%)	Gravel Content (%)	pH	Major cations				Major anions			
						K^{+}	Mg^{2+}	Na^{+}	Ca^{2+}	PO_4^{3-}	SO_4^{2-}	NO_3^{-}	Cl^{-}
East	0-20	10~20	3.5	20	5.6	0.38	0.51	0.21	1.07	0.28	13.11	0.38	25.51
	20-40		4.4	22		0.22	0.57	0.20	0.69	0.16	12.95	0.19	15.74
	40-60		5.6	30		0.20	0.17	0.18	0.51	0.09	11.76	0.11	10.11
	Mean		4.5	24		0.27	0.42	0.20	0.76	0.18	12.61	0.23	17.12
West	0-20	22~36	2.7	27	5.3	0.34	0.55	0.19	1.11	0.25	13.88	0.27	27.99
	20-40		3.5	35		0.21	0.48	0.18	0.73	0.11	11.54	0.17	15.41
	40-60		4.3	43		0.22	0.22	0.17	0.68	0.06	10.97	0.10	11.38
	Mean		3.5	35		0.26	0.42	0.18	0.84	0.14	12.13	0.18	18.26
Plane	0-20	0~5	3.0	40	5.9	0.39	0.61	0.26	0.98	0.31	11.71	0.17	14.41
	20-40		3.8	80		0.32	0.57	0.19	0.88	0.27	10.11	0.16	13.26
	40-60		-	100		-	-	-	-	-	-	-	-
	Mean		3.4	73		0.36	0.59	0.23	0.93	0.29	10.91	0.17	13.84

3. 2. Root characteristics

Each aspect differed greatly in terms of root structure (Figure 2). On the east-facing stand, a taproot system was found, having a relatively deep and straight center and equally balanced left and right sides. The west-facing stand showed roots that were bent and more asymmetrically developed on the east side. On the planes, the central part of the root was usually heart-shaped.

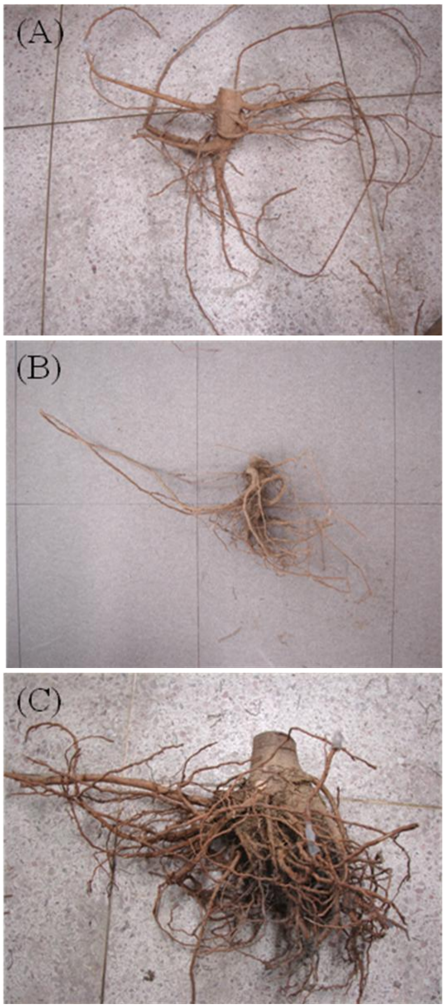

Figure 2. Overall external shapes of roots on different facing aspects

3. 3. Developmental characteristics of the vertical center root

The vertical root length and weight of roots in each aspect are shown in Figs. 3 and 4. The average development of the vertical central root in the east-facing stand, west-facing stand, and plane was 60.3 ± 3.8, 50.1 ± 5.0, 33.4 ± 1.0 cm, respectively. With respect to the frequency of the vertical central root, the east-facing stand had 4 trees with roots covering more than 50 cm, while the west-facing stand had only 1 tree with roots covering more than 50 cm. The sample trees from the planes had no roots that had grown for more than 40 cm, but most of them had a side-shaped form. The average biomass of the root collar (in descending order) was 547.8 ± 94.1, 242.3 ± 21.1, and 60.5 ± 2.0 g, respectively, for the plane > east-facing stand > west-facing stand. The roots of trees from the planes were 9.05 times heavier than those from the west-facing stand and 2.26 times heavier than those from the east-facing stand. This result was expected considering the better growth condition of young *Abies holophylla* due to the lower overstory competition of less dense *Pinus densiflora* stands.

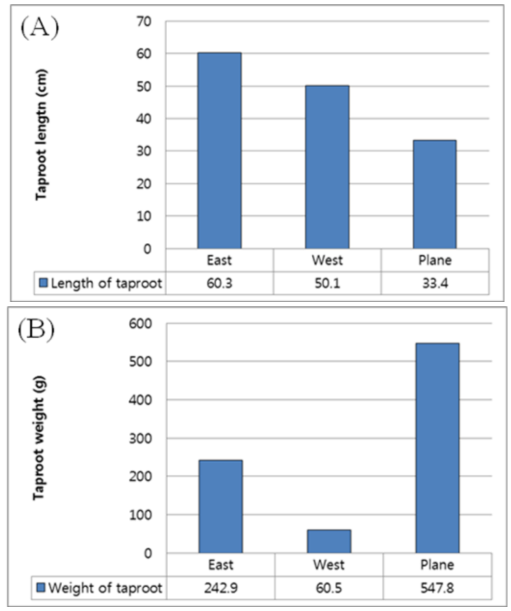

Figure 3. The taproot length (A) and weight (B) of the different facing aspects

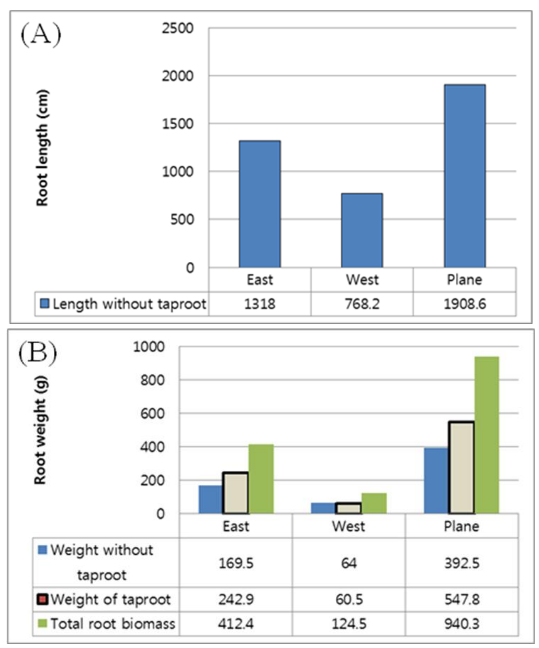

Figure 4. The length (A) and weight of roots (B) without taproot of the different facing aspects

3. 4. Vertical root growth characteristics

The distribution of vertical roots in each aspect is shown in Table 3, and the distribution ratio of the entire root biomass is shown in Figure 5. The total number of roots in the planes was 1.6 times greater than that in the east-facing stand and 2.4 times greater than that in the west-facing stand, with a 95% confidence level. The lengths of the roots in the east-facing, west-facing, and plain stands were 1318.0 ± 235.9, 768.2 ± 103.9, and 1908.6 ± 467.5 cm, respectively. Root weights (except rootstock) in the east-facing stand, west-facing stand, and planes were 169.4 ± 19.3, 64.0 ± 13.4, 392.5 ± 99.6 g, respectively, with a 95% confidence level.

The distribution ratio, which is relevant to biomass, at a depth of 10-20 cm was 43.8% ± 9.8% of the total number of roots, 43.2% ± 6.1% of the total length, and 42.7% ± 6.7% of the total weight in the east-facing stand. In the west-facing stand, it was 51.3% ± 5.1% of the total number of roots, 46.7% ± 6.1% of the total length, and 47.7% ± 8.6% of the total weight. In contrast, in the planes, the ratio was 41.8% ± 5.6% of the total number of roots, 42.0% ± 7.1% of the total length, and 41.5% ± 6.8% of the total weight at a depth of 20-30 cm. The ratios tended to decrease sharply after a depth of 30 cm in every aspect.

Table 3. Distribution of root number, length, and weight depending on vertical soil layer

Soil depth (cm)	Facing	Root Number (n) (Mean ± CI)	Root Length (cm) (Mean ± CI)	Root weight (g) (Mean ± CI)
0~10	East	25.4 ± 9.4	230.5 ± 100.3	39.7 ± 22.0^{a}
	West	14.2 ± 7.1	99.6 ± 45.6	11.9 ± 5.3^{b}
	Plane	19.4 ± 8.2	117.9 ± 62.7	69.3 ± 45.8^{ab}
10~20	East	71.2 ± 22.2	561.7 ± 180.4^{ab}	59.3 ± 23.8^{ab}
	West	51.5 ± 10.3	358.4 ± 97.9^{a}	36.6 ± 9.8^{b}
	Plane	87.6 ± 29.1	712.6 ± 238.0^{b}	112.6 ± 44.4^{a}
20~30	East	32.2 ± 15.6^{a}	295.9 ± 158.8^{c}	43.7 ± 18.4^{b}
	West	24.3 ± 5.4^{a}	226.7 ± 49.4^{b}	12.6 ± 5.3^{c}
	Plane	101.4 ± 28.9^{b}	796.9 ± 262.0^{a}	141.9 ± 43.7^{a}
30~40	East	13.8 ± 4.3^{a}	144.5 ± 53.0^{a}	15.4 ± 6.0^{a}
	West	8.8 ± 2.9^{b}	66.7 ± 22.6^{b}	2.2 ± 0.2^{b}
	Plane	27.8 ± 14.6^{ab}	215.9 ± 164.8	51.2 ± 35.8^{a}
40~50	East	8.8.0 ± 6.0^{a}	74.0 ± 53.9^{a}	10.2 ± 8.8^{a}
	West	2.0 ± 1.4^{b}	16.7 ± 11.8^{b}	0.7 ± 0.6^{b}
	Plane	6.0 ± 8.0^{a}	55.9 ± 67.1^{ab}	3.9 ± 9.8^{ab}
50~60	East	1.2 ± 0.5	10.2 ± 2.1	0.98 ± 1.1
	West	-	-	-
	Plane	1.4 ± 1.9	9.4 ± 14.4	13.5 ± 25.3
60~70	East	0.2 ± 0.25	2.0 ± 2.1	0.1 ± 0.3
	West	-	-	-
	Plane	0.2 ± 0.4	1.4 ± 2.7	0.1 ± 0.2
Total (except rootstock)	East (+taproot)	152.8 ± 22.2*	1 318 ± 235.9*	169.5 ± 19.3* (+242.9 = 412.4)
	West (+taproot)	100.71 ± 9.7*	768.16 ± 103.9*	64.0 ± 13.4* (+60.5 = 124.5)
	Plane (+taproot)	244.2 ± 45.2*	1908.6 ± 467.5*	392.5 ± 99.6* (+547.8 = 940.3)

Note : CI: confidence interval, a = 0.05, *difference between the 3 stands,
Subscript letters *a*, *b*, and *c* indicate significance of east-facing stand, west-facing stand, and plane at 5% levels, respectively, by the LSD multiple test.

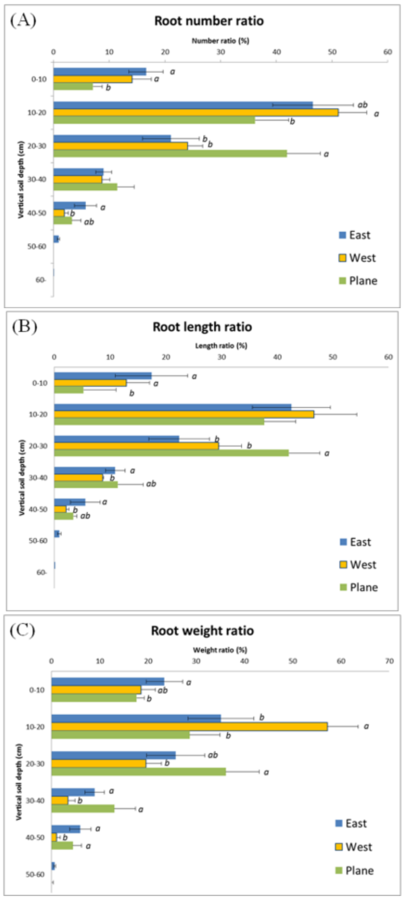

Figure 5. Root distribution according to root number ratio (A), length ratio (B), and weight ratio (C) depending on the vertical soil layer. The bar chart fits the mean ± confidence interval. Subscript letters *a*, *b*, and *c* indicate significance of east-facing stand, west-facing stand, and planes at 5% levels, respectively, by least square difference (LSD) multiple test

3. 5. Horizontal root growth characteristics

The distribution of horizontal roots in each aspect is shown in Table 4, and the distribution ratio of the entire root biomass is shown in Figure 6. The total numbers of horizontal roots in the east-facing stand, west-facing stand, and planes were 152.8 ± 22.8, 100.2 ± 9.7, 244.2 ± 46.3, respectively. The lengths were 1 318.7 ± 235.9 cm, 768.2 ± 103.9 cm, and 1 908.6 cm ± 480 cm, respectively, and the weights were 169.4 ± 19.3 g, 64.0 ± 13.4 g, and 392.5 ± 99.1 g, respectively.

The numbers of horizontal roots within a depth of 0-20 cm in the east-facing stand, west-facing stand, and planes were 88.0 ± 8.9, 76.6 ± 4.4, and 147.6 ± 11.8, respectively; therefore, there was no significant difference at the 5% significance level between the east-facing and west-facing stands. In contrast, the numbers of roots within a depth of 20-40 cm in the east-facing stand, west-facing stand, and planes were 38.8 ± 7.2, 17.0 ± 2.3, and 61.6 ± 11.3, respectively. The number of roots in the east-facing stand was 2.2 times greater than that in the west-facing stand, and that in the planes was 1.5 times greater than that in the east-facing stand ($p < 0.05$).

Horizontal root length distribution within a depth of 0-60 cm was in the order of planes, east-, and west-side stands, but at a depth of more than 60 cm, the order changed to east-, west-side, and plane stands. The roots in the planes tended to divide with root collar as the center.

The average weights of the roots within a depth of 0-20 cm in the descending order were 275.8 ± 57.2, 128.1 ± 16.3, and 55.9 ± 4.9 g, respectively, for planes > east facing > west facing stands ($p < 0.05$). This order was unchanged at a depth of 0-80 cm, but changed at a depth of more than 80 cm to east facing > west facing > planes, with the average weights of 2.12 ± 1.2, 0.6 ± 0.3, and 0.3 ± 0.3 g, respectively. Roots of trees in the planes and west-facing stand had more biomass than those of trees in the east-facing stand.

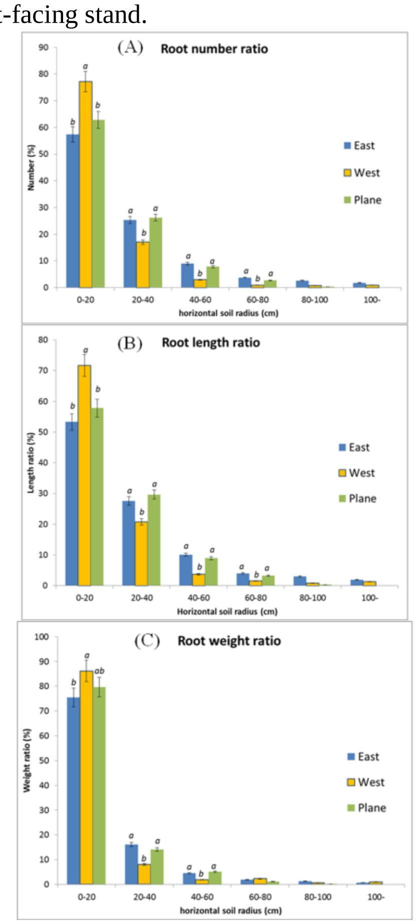

Figure 6. Root distribution according to root number (A), length (B), and weight (C) depending on horizontal soil radius. The bar chart fits the mean ± confidence interval. Subscript letters *a*, *b*, and *c* indicates significance at the east-facing stand, west-facing stand, and planes at 5% levels, respectively, by the LSD multiple test

Table 4. Distribution of root number, length, and weight depending on horizontal soil radius

Soil radius (cm)	Facing	0-20	20-40	40-60	60-80	80-100	100-	Total
Root Number (n)	East	88.0 ± 8.9^{b}	38.8 ± 7.2^{b}	13.8 ± 2.3^{b}	5.8 ± 2.3	4.0 ± 2.6^{a}	2.8 ± 1.5^{a}	152.8 ± 22.2^{b}
	West	76.6 ± 4.4^{b}	17.0 ± 2.3^{c}	2.8 ± 1.3^{c}	1.2 ± 0.5	1.0 ± 0.4^{b}	1.6 ± 1.0^{b}	100.7 ± 9.7^{c}
	Plane	147.6 ± 11.8^{a}	61.6 ± 11.3^{a}	18.4 ± 11.7^{a}	6.4 ± 5.4	0.8 ± 0.8^{ab}	-	244.2 ± 46.3^{a}
Root Length (cm)	East	705.48 ± 102.3^{b}	364.8 ± 70.8^{b}	133.7 ± 21.4^{a}	53.6 ± 19.0^{a}	39.8 ± 22.7^{a}	25.4 ± 11.2^{a}	1318.8 ± 235.9^{b}
	West	531.9 ± 34.4^{c}	157.8 ± 23.6^{c}	27.0 ± 12.9^{b}	15.3 ± 6.2^{b}	9.8 ± 5.0^{b}	13.0 ± 9.9^{b}	768.2 ± 103.9^{c}
	Plane	$1\,080.0 \pm 100.3^{a}$	554.7 ± 107.5^{a}	167.1 ± 110.5^{a}	61.5 ± 56.0^{a}	5.9 ± 5.8^{b}	-	$1\,908.6 \pm 480^{a}$
Root weight (g)	East	128.1 ± 16.3^{b}	27.2 ± 4.8^{b}	7.6 ± 1.7^{a}	3.3 ± 1.5	2.12 ± 1.2^{a}	1.2 ± 0.7	169.4 ± 19.3^{b}
	West	55.9 ± 4.9^{c}	5.6 ± 0.9^{c}	1.4 ± 0.4^{b}	1.7 ± 0.7	0.6 ± 0.3^{b}	1.0 ± 0.6	64.0 ± 13.4^{c}
	Plane	275.8 ± 57.2^{a}	48.6 ± 16.6^{a}	17.7 ± 12.1^{a}	3.9 ± 3.6	0.3 ± 0.3^{b}	-	392.5 ± 99.1^{a}

Note: CI: confidence interval, a = 0.05, Subscript letters *a*, *b*, and *c* indicate significance of the east-facing stand, west-facing stand, and plane at 5% levels, respectively, by the LSD multiple test.

The horizontal root distribution shown in Figure 6 suggests that, at a depth of 0-20 cm, more than 50% of the number, length, and weight of roots were formed in each aspect, and this rapidly decreased in zones farther from the stump. In the case of the west-facing stand, in particular, the roots were distributed close to the stump, followed by that in the planes and the east-facing stand. In the east-facing stand, at a depth of 0-20 cm, the number of roots was 57.6% of the whole, the length was 53.4% of the entire length, and the weight was 75.6% of the total.

In the west-facing stand, at a depth of 0-20 cm, the total number of roots was 76%, the total length was 69.2%, and total weight was 87.3%. Similarly, in the planes, the total number of roots was 60.9%, the total length was 57.1%, and the total weight was 72.3%. Therefore, 62.2%, 77.6%, and 63.5% of the area in the east-facing stand, west-facing stand, and planes were covered by roots.

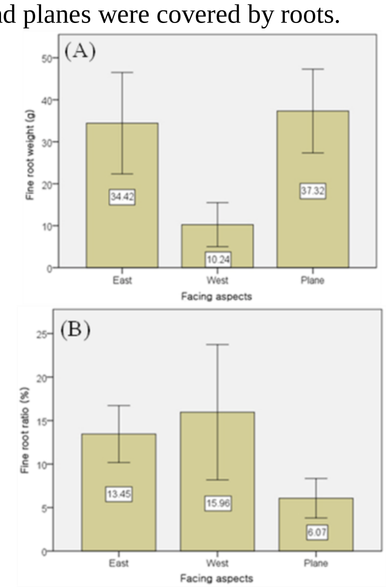

Figure 7. Fine root weight (A) and ratio (B) per below biomass

3. 6. Distribution of tiny roots

The weight and ratio of tiny roots in each aspect are shown in Figure 7. The average root distribution in the east-facing stand and planes were 34.42 ± 12.1 g and 37.32 ± 11.1 g, respectively, at a 95% confidence level without any significant difference. In contrast, the west-facing stand showed a wide variance in the average number of tiny roots of 10.24 ± 8.3 g compared with the east-facing stand and planes. At the 95% level of confidence, the ratio of tiny roots was 22.3% in the east-facing stand and 28.1% in the west-facing stand; the west-facing stand had a higher ratio, although this was statistically insignificant. The planes had half the number of tiny roots compared with those found in the east-facing and west-facing stands.

4. Discussions

4. 1. Morphological characteristics of the roots on the different facing aspects

In this research, the trees of the east-facing stand had a taproot structure that was straight and deep. The sample trees from the west-facing stand had a well-developed vertical root; however, the entire form was bent because of the steep underground slant. Biomass and base diameter were greater in the planes than in the east- and west-facing stands, and this is believed to be because of overstory growth. A previous study (Kurt *et al.* 1998) reported that, because of gravel content, biomass and base diameter increase, soil condition deteriorates, and roots develop a heart-shaped structure instead of being straight. Accordingly, the sample trees from the planes had a greater number of tiny and side heart-shaped roots.

Generally, if the soil conditions are poor and the gravel content is high, the central root region cannot grow properly and develops only on one side with a steep slant (Alder *et al.* 1996). In addition, pine and fir species ideally show vigorous straight, tap roots; however, in poor soil conditions, the roots tend to develop a large number of side and tiny roots (Howard *et al*. 1966; Lee 2004; Matteo 2007). On a steep slope, the roots grow only in one direction or the central part bends (Alex *et al.* 1999; Fan and Chen 2010; Frederic *et al.* 2008; Madan *et al.* 2003; Sun *et al.* 2008).

The difference in the root shapes of the trees sampled from the east- and west-facing stands was influenced by slope and direction, and the difference in the root shapes between the trees samples from the plane and those samples from the other 2 stands is the result of the difference in the physical and chemical properties of soil and the amount of sunlight received. Therefore, roots from the east-facing stand are considered to be ideal compared to those from the planes and the west-facing stand.

4. 2. Growth characteristics of the root stock on the different facing aspects

Because the planes consist of gravel below 30 cm of soil, the central root develops sideways. The roots from the west-facing stand were less developed than those from the east-facing stand. This finding is in agreement with those reported by previous studies, which suggest that an east-facing stand is superior to a west-facing stand in terms of growth, and that the central part of the root shows stunted growth in highly inclined slopes (Alex *et al.* 1999; Howard *et al.* 1966; Juan and Josέ 1978).

The descending order in terms of biomass of the central part of the root was plane > east-facing stand > west-facing stand; the trees from the planes had better solar condition than did those from the other stands. This is in agreement with the findings of previous research indicating that shade trees grow better when they are exposed to sunlight and are grown in the east- and south-facing stands rather than in the north- and west-facing stands (Atsushi *et al.* 1993; Cho *et al.* 2008; Lee 1992).

Other studies (Burroughs and Thomas 1977; Lee *et al.* 2005) stated that, in general, the deeper the root system, the higher the lodging resistance. Trees without a deep root system are vulnerable to flooding and wind damage. The sample trees from the east-facing stand grew well vertically and were more resistant to natural damage than those from the other 2 stands.

4. 3. Horizontal and vertical development characteristics on the different facing aspects

As shown in Figure 5, 0-60% of the entire biomass was distributed within a depth of 0-30 cm in each aspect and showed a sharp decrease below that depth (>30 cm). In particular, the roots from the east- and west-facing stands showed the highest biomass distribution within a depth of 10-20 cm, and those from the planes showed the highest distribution within a depth of 20-30 cm. This result agrees with those of previous research suggesting that 35-80% of the roots grow below a depth of 30 cm (Dexter 2004; Marler and Discekici 1997).

In particular, despite the fact that the planes have the most biomass, roots in this region barely develop at depths under 35 cm. These results are consistent with those of root form and soil gravel content reported by previous studies on root growth and soil conditions (Dexter 2004; Fan and Chen 2010; Knute and James 1992; Munns 1993; Sun *et al*. 2008).

In addition, roots from the west-facing stand bent to one side because of the steeper slope; this was not the case in roots from the east-facing stand, which contained more biomass and showed better root development than those from the west-facing stand. The west-facing stand had a steeper slope than the east-facing stand, and a large number of roots grew to support the root collar but did not spread widely from the center (Figure 5 and 6). This agreed with the report stating that root growth and total root concentrate on the root collar part are better on steeper slants (Alex *et al.* 1999; Antonino *et al.* 2005).

In addition, it agrees with another report suggesting that the underground parts grow well in the east- and south-facing stands because of more exposure to sunlight than in the north- and west-facing stands (Alex *et al.* 1999; Atsushi *et al.* 1993; Heljä *et al.* 2007). Previous research shows that horizontal and vertical root development is highly related to the health of trees and, if the biomass ratio of the root collar is high, the tree is vulnerable to environmental conditions such as high winds and water-related disasters (Borroughs and Thomas 1977; Gale and Grigal 1987; Tamasi *et al.* 2005).

Thus, a large number of tiny roots develop when soil conditions are poor, and this was the case in the roots from the west-facing stand. The biomass content was the highest in the planes because of the solar radiation intensity, and the plane land has the most advantage. The reasons for the east-facing stand showing better root growth than the west-facing stand are because of superior soil and gloss conditions, which provide a more conducive growth environment. Overall, the sample trees from the east-facing stand were the most superior in terms of root form, vertical and horizontal root growth, and distribution of tiny roots.

The roots of trees from the valley plane were heart-shaped, those from the east-facing stand had a straight taproot system and were the most ideal, and those from the west-facing stand had the lowest growth. This difference appeared to be important and indicates that light availability becomes limited with density and species of the overstory, and that other site conditions and stand factor conditions, particularly soil characteristics, need to be considered for obtaining stable secondary forests by underplantation.

Our study found that aspect and overstory density should be considered when deciding on a location for planting and growth of secondary-forest trees. These results can provide necessary information on the composition of artificial and natural afforestation. Overall, the study provides valuable information for an important tree species that is widely distributed throughout North and South Korea, northeastern China, and far southeastern Russia. Additionally, the concept that environmental effects can vary so widely in a relatively small geographic area is intriguing. Thus, this work should be of interest to the international community of researchers specializing in forest ecology.

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Corresponding Author:
Dr. Do-Hyung Lee,
Department of Forest Resources,
Yeungnam University,
280 Daehak-ro, Gyeongsan-si, Gyeongsangbuk-do, South Korea.
E-mail address: dhlee@yu.ac.kr .

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