Root architecture and development in naturally regenerated and planted *Pinus densiflora* for. *erecta* in Korea

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Abstract: Containerized *Pinus densiflora* seedlings are regularly produced in South Korea. In this study, we identified differences between the root architecture and spatial development of naturally regenerated and artificially planted *P. densiflora* for. *erecta*. saplings at 2 sites in northeastern South Korea. The total taproot length was significantly longer in naturally regenerated stands than in planted stands (P < 0.01); the taproots of naturally regenerated saplings grew to a soil depth of 50 cm, but those of planted saplings grew to a soil depth of only 30 cm. The lateral roots of naturally regenerated saplings consistently developed straight and horizontally, tending to decrease in number and length as the soil depth increased; however, the lateral roots of planted trees developed irregularly, and most roots tended to spiral. The root characteristics of the saplings in planted stands were a factor causing deteriorating stability. Continuous monitoring of the root development of older planted *P. densiflora* for. *erecta* in various areas and advanced silvicultural techniques are required to ensure effective growth of these trees.
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1. Introduction

Korea’s forests were devastated during the colonization of Japan and the Korean War, by deforestation for forest products and fuels, and from illegal slash-and-burn activities until the early 1960s. Reforestation began in the 1960s, and the denuded mountains were reforested successfully through the first and second forestation projects that were conducted from 1973 to 1987. South Korea has succeeded in more reforestation than any other nation in the world (Brown, 2006). Now, 64% of South Korea is covered by forests (a total of 6,374,875 ha) including 42% softwood.

Pinus densiflora is one of the most common species of conifer in South Korea, accounting for 55.7% of the total softwoods. About 24,400 ha of *P. densiflora* were planted within the past 10 years (Korea Forest Service, 2010). The species is very important economically, ecologically, and culturally. *P. densiflora* was classified by Uyeki (1928) into 6 types on the basis of growth and development. *P.densiflora* for.*erecta* is one of these 6 types and grows near the Taebaek Mountain Range, where it is being protected as an important species because of its bole straightness, relatively narrow crown, high clear length, and superior wood quality.

Generally, forests are divided into 2 types based on the origin of regeneration: natural and artificial. Natural regeneration is the establishment of a plant from natural seeding, sprouting, or suckering. Artificial regeneration is the establishment of a group or stand of young trees by direct seeding or planting seedlings. In addition, 2 stock types, bare-rooted and containerized seedlings, are used for planting. Naturally regenerated seedlings that are germinated from seeds and directly seeded seedlings develop many roots at various soil depths (Plourde et al., 2009); however, directly seeded seedlings remain weak for a long time (Stanturf et al., 1998).

On a plantation, trees artificially regenerated from containerized seedlings had a much higher survival rate than those from bare-rooted seedlings (McDonald, 1991). However, producing seedlings in containers negatively affects the root system and development, and results in problems such as root spiraling (Rune, 2003), lower rooting depth (Danjon et al., 1999), a reduced number or no taproots (Burdett et al., 1986; Plourde et al., 2009), tree instability (Rune, 2003), and toppling of trees (Burdett et al., 1986). In South Korea, containerized seedlings were produced in the early 1960s and 1970s, and regular production began in 1996 by growing 1-0 containerized *P. densiflora* seedlings for the reforestation of forest fire sites.

Root system morphology influences the growth and stability of trees (Bergman and Haggstrom, 1976). In addition to their role in the natural processes related to evapotranspiration and the absorption of water and inorganic nutrients, well-developed roots are a good predictor of seedling quality, survival, and growth after planting in the field (Landis et al., 1990; Marler and Wilis, 1996).

Although many species have been artificially planted in many areas in South Korea, few studies have been conducted on the growth performance of trees as it relates to the origin of stands. In particular, there have been fewer studies of root development than of above-ground development because root studies require substantial time and effort. In this study, we aimed to identify those characteristics of root architecture and spatial development that differed between naturally regenerated and artificially planted *P. densiflora* for. *erecta*.

2. Material and Methods

2.1. Study stands

This study was undertaken to compare root growth patterns between naturally regenerated and planted saplings of *P. densiflora* for. *erecta* in areas within Dae-gi (Site 1: 37° 36′ N, 128° 45′ E) and Bo-gwang (Site 2: 37° 46–53′ N, 128° 42–45′ E), Kangwon Province, South Korea. At each site, naturally regenerated saplings (NRS) and planted saplings (PS) were selected that were geographically close to one another in order to minimize the effects of any environmental differences on growth performance. The stands were supposed to have been disturbed either not at all or very little from either natural or artificial sources. Ten healthy individual saplings were selected from a 10 m x 10 m plot established in each stand. Trees that were overtopped, wolf-damaged, and top-shoot damaged were excluded. Forty saplings were investigated for this study.

The NRS from site 1 was established by seeds that fell from the mother trees, and their age ranged from 2 to 10 years. The mean age of the selected 10 saplings was 7.3 years and the mean height and root-collar diameter was 146.2 cm and 2.6 mm, respectively. The NRS from site 2 was also established by seeds that fell from *P. densiflora*, and the mean age, height, and root-collar diameter of the selected 10 saplings was 7.9 years, 199.0 cm, and 4.7 mm, respectively. The PS from sites 1 (3.1 ha) and 2 (2.0 ha) were established in 2003 using 2-year-old containerized seedlings. The mean ages of the saplings, stand density, and geographical characteristics of each studied stand are shown in Table 1.

Table 1. Geographical characteristics of *Pinus densiflora* for. *erecta* sapling stands, stand density, mean sapling age, height and root-collar diameter (RCD)

Sites	Stands	Location	Altitude (m)	Slope (°)	Aspect	Stand density (tree/ha)	Age	Height (cm)	RCD (mm)
Site 1	NRS	37° 36′60″ N 128° 45′22″ S	865	20	S	2,600	7.3±0.5	146.2±7.5	2.6±0.1
	PS	37° 36′50″ N 128° 45′12″ S	893	25	SW	2,200	7.0±0.0	83.9±3.9	2.5±0.2
Site 2	NRS	37° 53′19″ N 128° 42′44″ S	496	20	S	2,800	7.9±0.3	199.0±9.5	4.7±0.2
	PS	37° 46′13″ N 128° 45′14″ S	485	15	S	2,200	7.0±0.0	93.1±4.2	2.6±0.2

NRS: naturally regenerated saplings, PS: planted saplings. ± Standard error of mean (n = 10)

2.2. Characteristics of the soil in each stand

Soil samples were collected from a depth of 10-50 cm using a portable soil core sampler (400 cc) from within a 10 cm x 10 cm plot in each stand. In each plot, 3 areas were selected in which the litter layer and soil surface were not disturbed, and the soil was collected before digging out selected saplings in order to minimize soil disturbance.

The collected soils were air dried after removing roots and fallen leaf debris. The chemical composition of the soil, such as pH, electrical conductivity (EC), and cation exchange capacity (CEC), was measured (Carter, 1993). In addition, gravel content larger than 2 mm that affected tree-root development and gravel bulk density (g/cm^3) was measured. Gravel bulk density was calculated as: Bulk density (g/cm^3) = Soil dry weight (g) (<2 mm)/Volume of soil sample (cm^3)

2.3. Analysis of root development

The entire root system of the selected saplings was excavated with the soil over a radius of 50 cm from the stem to prevent and/or minimize any damage to the roots. The soils attached to the roots were removed by gentle shaking. Taproot and lateral roots cut during collection were collected separately (Figure 1).

The depth of the soil was divided into 5 levels at 10-cm intervals. The length and number of taproots and the length and weight of lateral roots at each interval were measured. The ground distance to the right and left of the stem was also divided into 5 distance ranges at 10 cm intervals, and the number and length of lateral roots at each interval were measured. The results were analyzed using Duncan's multiple range test (P > 0.05) included in the Statistical Analysis System (SAS Institute, 1999).

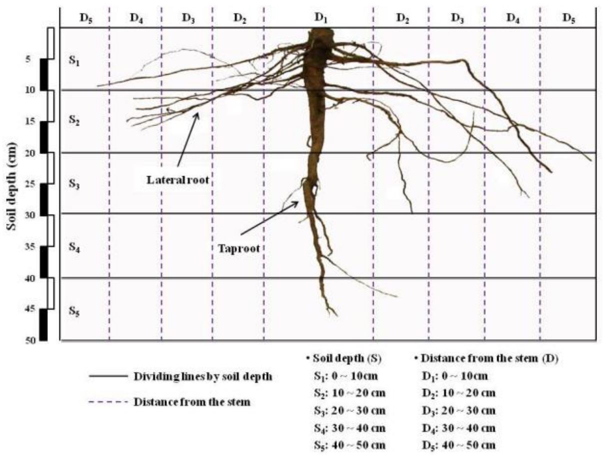

Figure 1. A practical method of differentiating between vertical and horizontal sapling roots

3. Results

3.1. Soil characteristics

The soil pH of NRS and PS at site 1 was 5.5 and 5.7, respectively. At site 2, the soil pH of NRS was nearly the same as that of PS at 5.4 (Table 2). The mean EC in all stands was 0.1. The Na^+ content of both stands at site 1 was 0.18, but the K^+, Mg^{2+}, and Ca^{2+} content of the soil was larger in the NRS than in the PS. At site 2, there was a greater concentration of all cations in soil samples from PS than in those from NRS.

The gravel content in PS at both sites was slightly higher than that in NRS (8.2% and 5.6% at site 1, 7.9% and 7.2% at site 2, respectively); however, soil bulk density was slightly higher in NRS at both sites than in PS.

Table 2. Characteristics of the soil at 2 sites covered by *Pinus densiflora* for. *erecta*

		pH	EC (ds/m)	Major cations (cmol+/kg)				Gravel contents		
				K^+	Mg^{2+}	Na^+	Ca^{2+}	2mm > (%)	2mm < (%)	Bulk density (g/cm^3)
Site 1	NRS	5.5	0.1	0.25	0.51	0.18	0.86	502.2 (94.4)	29.8 (5.6)	1.33
	PS	5.7	0.1	0.22	0.34	0.18	0.66	447.0 (91.8)	40.2 (8.2)	1.21
Site 2	NRS	5.4	0.1	0.24	0.44	0.20	0.76	465.2 (92.8)	36.0 (7.2)	1.25
	PS	5.4	0.1	0.25	0.46	0.25	0.78	446.2 (92.1)	38.0 (7.9)	1.20

NRS: naturally regenerated saplings, PS: planted saplings.

3.2. Root development

Taproot length was significantly different between NRS and PS at each soil depth at each site (Table 3; $P < 0.01$ for both sites). The total taproot length in NRS and PS at site 1 was 43.3 cm and 21.5 cm, respectively, and that at site 2 was 47.8 cm and 26.1 cm, respectively.

Six of the 10 saplings sampled from NRS at site 1 had taproots that grew to a depth of 50 cm, 3 had taproots that grew to a depth of 40 cm, and 1 taproot only grew to a depth of 30 cm. In contrast, only 3 of the 10 saplings sampled from PS at site 1 had taproot growth to a depth of 30 cm, while 3 grew to a depth of 20–30 cm, 1 to a depth of 10–20 cm, and the remaining 3 stopped growth at a depth of 10 cm. Nine of 10 saplings sampled from NRS at site 2 had taproot growth to a depth of 50 cm and the taproot of the remaining sapling grew to a depth of 40 cm. However, only 1 of the 10 saplings sampled from PS at site 2 had taproot growth to a depth of 40 cm, while 5 grew to a depth of 30 cm and 4 grew to a depth of 20 cm.

Table 3. Distribution of taproot length for naturally regenerated and planted stands of *Pinus densiflora* for. *erecta* saplings (n=10) at soil depths of 0–50 cm

Soil depth (cm)	Stands	Site 1	Site 2
0~10	NRS	10.0±0.0	10.0±0.0
	PS	10.0±0.0	10.0±0.0
10~20	NRS	10.0±0.0	10.0±0.0
	PS	6.7±1.5	9.6±0.4
20~30	NRS	9.9±0.1	10.0±0.0
	PS	4.8±1.4	5.5±1.6
30~40	NRS	8.7±1.0	10.0±0.0
	PS	-	1.0±1.0
40~50	NRS	4.8±1.5	7.8±1.2
	PS	-	-
Total	NRS	43.3±2.2	47.8±1.2
	PS	21.5±2.7	26.1±2.3
	T-test	**	**

NRS: naturally regenerated saplings, PS: planted saplings. Different letters on the columns indicate statistical differences at the 5% levels by Duncan's multiple-range test. **indicates significance at 1% level.

There was a distinct difference in the overall shape of NRS and PS roots (Fig. 2). The taproots of naturally regenerated saplings grew straight down to a depth of 50 cm, and it was easy to distinguish taproots from lateral roots. In contrast, the taproots of planted saplings grew only to a depth of 30 cm, and some grew horizontally, bending like horizontal roots. It was not easy to distinguish between tap and lateral roots in PS.

The lateral roots in naturally regenerated saplings were stretched out horizontally, and most roots were distributed around the surface soil, tending to reduce in number as the soil deepened. However, the total amount of roots was greater in the PS than in the NRS. The lateral roots in planted saplings were irregularly shaped and spiraled mostly around the surface soil.

The taproot in the first 10 cm of soil in NRS was well developed and straight, and the lateral roots that diverged from the taproot were developed evenly in all directions (Figure 2). The taproots at the same level in PS were poorly developed and grew horizontally or toward the surface. In addition, 2-3 diverged roots were tangled, resulting in inferior growth.

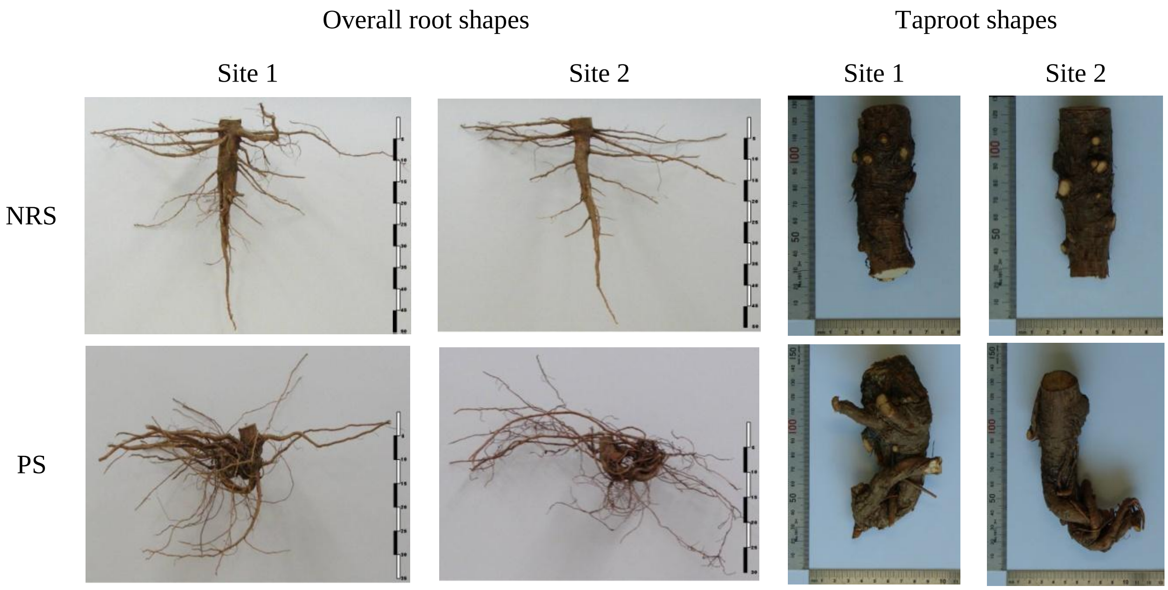

Figure 2. Overall shapes of *Pinus densiflora* for. *erecta* sapling root development and shapes of taproots at a soil depth of 0–10 cm (NRS: naturally regenerated saplings, PS: planted saplings)

3.3. Root development

The number and length of lateral roots at each soil depth differed between NRS and PS (Table 4). The number of lateral roots at a depth of 0–10 cm in NRS at sites 1 and 2 was 60.2 and 76.1, respectively, but that in PS was 81.2 and 62.4, respectively. The percentage of total lateral roots that were at a depth of 0–10 cm in NRS at sites 1 and 2 were 78.2 and 71.7, respectively, and those at sites 1 and 2 in PS were 94.0 and 93.0, respectively. The number of lateral roots at a depth of 10–20 cm (site 1 - NRS: 9.6; PS: 3.6; site 2 - NRS: 18.2; PS: 4.9) and 20–30 cm (site 1 - NRS: 4.3; PS: 1.1; site 2 - NRS: 8.5; PS: 0.2) was higher at both sites in NRS than in PS. At a depth of 30–40 cm, the lateral roots existed only in NRS at both sites 1 and 2. At a depth of 40–50 cm, the lateral roots existed only in NRS at site 2.

The length of lateral roots at different soil depths was also different between NRS and PS (Table 4). Lateral roots at a depth of 0–10 cm in PS at site 1 were significantly longer ($P < 0.05$) than those in NRS (894.5 cm and 492.3 cm, respectively), but the difference was not statistically significant at site 2. The percentage of total lateral root length that was found at a depth of 0–10 cm was significantly greater at both sites in PS compared to that in NRS ($P < 0.01$). However, at depths of 10–20 cm and 20–30 cm, total lateral root length was much greater in NRS than in PS at both sites.

3.4. Lateral root distribution by distance from stem

There were distinct differences between NRS and PS in the number and length of lateral roots at the surface of the soil (Table 5). The number of lateral roots at 0–10 cm from the stem was greater for PS than for NRS ($P < 0.05$) at site 1; however, there was no statistical difference in the number of lateral roots between PS and NRS at 10–20 cm and 20–30 cm at site 1. At lateral distances of 30–40 cm and 40-50 cm, NRS had more lateral roots than PS at both sites ($P < 0.05$). At site 2, there was no difference between NRS and PS in the number of roots at a lateral distance of 0–10 cm, but the differences were significant at other intervals ($P < 0.05$) at site 2.

The PS lateral roots at a distance of 0–10 cm were significantly longer than those of NRS at both site 1 and site 2 ($P < 0.01$ and $P < 0.05$, respectively). In addition, the lateral roots of PS were also significantly longer than those of NRS at a distance of 10–20 cm at site 1 ($P < 0.01$), but no difference was found between stand types at a distance of 20–30 cm. At site 1, at lateral distances of 30–40 cm and 40–50 cm, NRS root length was significantly longer than PS root length (P < 0.01, and P < 0.05, respectively). At site 2, the lateral roots of NRS were significantly longer than those of PS at distances of 10–20 cm, 20–30 cm, and 30–40 cm.

At both sites, a significantly greater percentage of the number of lateral roots, root length, and root weight was found at a distance of 0–10 cm in PS than in NRS (P < 0.01). However, PS and NRS did not differ in these percentages at a distance of 10–20 cm, with the exception of root weight at site 2. At lateral distances greater than 20 cm from the stem, the percentage of the number of lateral roots, root length, and root weight was significantly higher in NRS than in PS, with the exception of weight at site 2 (P < 0.05).

Table 4. The number, length, and weight of the lateral roots of naturally regenerated and planted *Pinus densiflora* for. *erecta* saplings at soil depths of 0-50 cm

		Root number (n)				Root length (cm)			
		site 1		site 2		site 1		site 2	
		Means	%	Means	%	Means	%	Means	%
0~10	NRS	60.2±5.6	78.2±3.0	76.1±7.3	71.7±5.1	492.3±39.0	82.8±2.2	670.5±53.6	73.7±4.8
	PS	81.2±7.6	94.0±1.9	62.4±4.5	93.0±2.1	894.5±84.0	95.4±1.6	710.2±46.1	94.1±1.6
	T-test	*	**	ns	**	**	**	ns	**
10~20	NRS	9.6±1.9	12.9±2.2	18.2±2.9	17.2±2.8	64.9±10.2	11.5±1.9	148.6±25.6	16.2±2.9
	PS	3.6±1.1	4.5±1.3	4.9±1.8	6.6±2.1	29.1±9.1	3.4±1.0	45.8±14.4	5.6±1.6
	T-test	*	**	**	**	*	**	**	**
20~30	NRS	4.3±0.7	6.0±1.0	8.5±2.8	7.3±2.2	24.2±3.6	4.2±0.6	70.4±22.8	7.3±2.2
	PS	1.1±0.6	1.5±0.8	0.2±0.1	0.4±0.2	9.6±6.7	1.2±0.8	2.2±1.6	0.3±0.2
	T-test	**	**	*	**	ns	**	*	**
30~40	NRS	2.0±0.4	2.9±0.7	3.1±0.9	3.0±1.0	8.0±2.1	1.5±0.4	20.0±6.7	2.4±0.8
	PS								
	T-test								
40~50	NRS			0.9±0.2	0.1±0.1			4.4±3.2	0.5±0.3
	PS								
	T-test								
Total	NRS	76.1±5.8	100	106.8±8.0	100	589.5±39.6	100	913.8±49.9	100
	PS	85.9±7.1	100	67.6±5.2	100	933.2±79.3	100	758.3±158.8	100
	T-test	ns		**		**		*	

NRS: naturally regenerated saplings, PS: planted saplings. ±Standard error of mean (n = 10)
Different letters on the columns indicate statistical differences at the 5% levels by Duncan's multiple-range test.
*and ** indicate significance at 5% and 1% levels, respectively. ns, non-significant.

Table 5. The number, length, and weight of the lateral roots of naturally regenerated and planted *Pinus densiflora* for. *erecta* saplings at distances of 0–50 cm from the stem

			Means					%				
			0~10	10~20	20~30	30~40	40~50	0~10	10~20	20~30	30~40	40~50
Root number (n)	Site 1	NRS	32.0±3.2	20.4±2.3	14.1±1.3	6.2±1.0	3.4±0.8	41.9±1.8	26.3±1.6	18.6±0.8	8.5±1.4	4.7±1.1
		PS	46.2±3.8	24.7±2.9	12.2±1.6	2.2±0.8	0.5±0.5	54.6±3.2	28.3±1.9	14.2±1.4	2.5±0.8	0.5±0.5
		T-test	*	ns	ns	**	*	**	ns	*	**	**
	Site 2	NRS	38.6±3.4	29.2±3.5	22.3±1.9	12.3±1.7	4.4±1.0	36.3±1.9	26.9±1.4	20.9±1.1	11.7±1.5	4.3±1.0
		PS	38.4±3.7	18.6±1.8	7.5±1.0	2.1±0.9	0.9±0.4	57.5±4.3	27.3±2.1	11.0±1.5	3.0±1.2	1.2±0.5
		T-test	ns	*	**	**	**	**	ns	**	**	*
Root length (cm)	Site 1	NRS	266.5±23.1	152.8±12.9	103.9±8.2	49.4±9.1	16.9±3.5	45.0±1.8	25.9±1.2	17.6±0.6	8.5±1.5	3.0±0.6
		PS	560.9±60.8	254.2±25.6	101.4±12.9	13.5±5.9	3.3±3.3	59.9±3.3	27.6±2.3	10.9±1.1	1.3±0.5	0.2±0.2
		T-test	**	**	ns	**	*	**	ns	**	**	**
	Site 2	NRS	347.3±22.7	255.6±19.4	176.8±11.9	94.3±12.9	39.9±12.5	38.3±2.0	28.0±1.3	19.4±0.9	10.2±1.1	4.2±1.1
		PS	473.3±38.9	190.2±21.0	61.9±13.8	21.8±8.3	11.0±4.8	63.3±4.0	24.9±2.5	7.8±1.5	2.7±1.0	1.3±0.5
		T-test	*	*	**	**	ns	**	ns	**	**	*

NRS: naturally regenerated saplings, PS: planted saplings. ±Standard error of mean (n = 10)
Different letters on the columns indicate statistical differences at the 5% levels by Duncan's multiple-range test.
*and ** indicate significance at 5% and 1% levels, respectively. ns, non-significant.

4. Discussions

The formation of a taproot increases the ability of trees to explore deep soil horizons; therefore, those species that have a strong taproot have an advantage in dry areas (Strong and La Roi, 1983; Kodrik, 1995). Poor taproot development in planted trees will negatively affect the growth of those trees. A taproot does not continue to develop on every tree, but it is most obvious on seedlings and is often found on *Pinus* and trees grown from large seeds, such as *Quercus* spp. and *Juglans* spp. (Philipson, 1978).

In the present study, the most significant differences in root morphology between naturally regenerated and planted saplings of *P. densiflora* for. *erecta* were the presence or absence of a taproot and differences in the soil depth to which a taproot grew. Taproots of naturally regenerated saplings grew perpendicular to the soil and developed straight at a depth > 40 cm, but taproots in planted saplings did not grow perpendicular to the soil. These roots therefore do not function as taproots. Taproots of planted *P. densiflora* for. *erecta* that grew to a depth of <10 cm were very small in diameter compared to those of naturally regenerated trees and had no branching lateral roots. Natural rooting depth is significantly influenced by environmental and cultural conditions (Atkinson, 1980).

The results of the present study are similar to those of a study of the development of the root system of *P. banksiana* in natural and planted stands by Plourde et al. (2009). Plourde et al. (2009) reported that trees from the natural stand developed 70% of their main roots, which had origins in the taproot, at depths between 0 and 10 cm and the number of main roots gradually decreased with increasing depth. In the plantation, root development was concentrated near the surface; therefore, 97% of main roots were distributed within the first 20 cm of soil.

In this study, the lateral roots of naturally regenerated saplings consistently developed straight and horizontally, tending to decrease in number and length as the soil depth increased; however, the lateral roots of planted trees developed irregularly, and most roots tended to spiral. Lindström and Rune (1999) reported that the young planted trees displayed a high proportion of severely spiraled root systems, whereas only a few of the older trees showed this trait. Environmental factors, such as soil density and slope, affect root formation and direction of growth. However, abnormal root development in planted *P. densiflora* for *erecta*, such as the absence of a taproot, the lack of much in-depth rooting, and deformed roots (including root spiraling) is a complicated problem caused by the planting of containerized seedlings using incorrect planting methods. Planted trees are affected by artificial as well as environmental factors from planting to rooting.

In general, containerized seedlings are more likely to have spiral roots than naturally regenerated seedlings. In addition, the main and lateral roots of containerized seedlings are trimmed before moving the trees to planting sites in order to save transportation costs. After arriving at planting sites, the seedlings are planted in holes regardless of the size of their roots, and the roots must often be bent to fit into small holes. These artificial planting processes are likely to affect root formation in planted *P. densiflora* for. *erecta*.

Our study showed that the taproot length and, at many soil depths and distances from the stem, the number, length, and weight of lateral roots varied more in naturally regenerated saplings than in planted saplings. At site 1, 46.2% of the total NRS taproot length was distributed within the first 20 cm of soil and this percentage was slightly less at both sites 1 and 2 for PS. Root density near the soil surface was reduced by competition with turf and other vegetation (Watson, 1988). However, most of the roots of planted saplings in the current study were distributed within a 10-cm lateral distance and soil depth.

Woody plants respond to compaction by producing a shallow root system (Pan and Bassuk, 1985). In addition, roots in compacted soil are redirected up toward the soil surface (Gilman et al., 1987); however, in the current study, naturally regenerated saplings, which have higher soil bulk density than planted saplings, showed a wide distribution of the roots.

Roots have a variety of functions for tree growth, such as absorption of water and nutrients, respiration, storage, and support (Fitter, 1985). The importance of an evenly spread and undisturbed root system is essential for anchoring a young tree (Lindström and Håkansson, 1994). The results of this study showed that root development that is concentrated at the soil surface would negatively affect the fundamental functions of roots, such as support and water absorption, resulting in growth differences between planted and natural trees. The insufficient absorption of nutrients and water by planted tree roots is another weak point of planted trees.

Water and nutrient absorption by roots are negatively affected when trees are artificially planted because of the lack of sufficient root-development space, which limits root expansion. Height is one of the big differences in growth performance between naturally regenerated and artificially planted trees. In a previous report (Na et al., 2010), we found that, after 7 years in the field, naturally regenerated saplings grew much taller than artificially planted saplings. Halter and Chanway (1993) also reported that the height of naturally regenerated saplings of Douglas fir and lodgepole pine was greater than that of artificially planted saplings, but the diameters were similar.

The form of the root system is well known to be an important determinant of tree stability. The root characteristics in PS in this study were a factor that may lead to deteriorating stability. The lack of a taproot, which contributes to tree stability and water absorption, and lateral roots that mainly developed along the soil surface decreases the ability of trees to cope with environmental changes, such as drought and increased instability (Khuder et al., 2007; Doi et al., 2008; Kalliokoski et al., 2008). The planted trees had a small root area (Lindström and Rune, 1999) and non-uniform root distribution (Langerud et al., 1988) compared to naturally regenerated trees, which are usually associated with instability.

Tree instability in planted stands is also caused by the use of containerized seedlings, which have unstable root shapes (Halter and Chanway, 1993). Uprooting and root breakage have been observed in young plantations of container-grown Scots pine (Lindström and Håkansson, 1995) and lodgepole pine (Rosvall, 1994). In addition, tensile strength in stump-wood samples is substantially lower for planted trees than for naturally regenerated trees (Lindström and Rune, 1999). The soil-hold ability of roots is closely related to the stability of trees and it is well known that root depth increases resistance to overthrow (Danjon et al., 2005; Dupuy et al., 2005).

The minimum adaptation period of root development to different soil environments in seedling production and planting is a 2 years and depends on the species (Nieuwenhuis and Wills, 2002). Artificially regenerated trees showed growth deterioration for 5 years after planting, resulting in significant loss of water and nutrient absorption ability (Sundström and Keane, 1999).

However, the growth pattern of naturally regenerated and artificially planted trees changes with time. It has been reported that the effects of containerization on root morphology are not severe enough to cause further growth reduction of trees in studies of Douglas-fir and Sitka spruce seedling performance within the first decades after outplanting (Preisig et al., 1979; Carlson et al., 1980), although structural abnormalities were observed in the root system of paper-pot-grown Scots pine trees 19–21 years after planting (Lindström and Rune, 1999).

In the current study, the main differences in root development between naturally regenerated and artificially planted *P. densiflora* were: 1) a clear division between taproots and lateral roots in naturally regenerated trees, but not in planted trees; 2) the depth of taproot development, and 3) the spiraling of taproots and lateral roots. In root distribution in different depth classes, naturally regenerated saplings showed good root development at various depths, but planted saplings had roots that were distributed only around the stump.

The higher risk of instability of planted saplings relative that that of naturally regenerated saplings in the current study may result from: (1) differences between naturally regenerated saplings and planted saplings in initial rooting characteristics; (2) deformation of roots from artificial planting, and (3) incorrect planting methods, in which all these negative factors may contribute to the absence of taproot development and the presence of dense roots around the soil surface.

The maximum rooting depth of seeded trees is primarily established during the seedling or early sapling stage, and that of transplanted trees is established within the first several years after planting. A natural root system is largely determined by the environment early in root development. In the present study, the abnormal root development of *P. densiflora* for. *erecta* 7 years after artificial planting was still unfavorably affecting tree growth, deteriorating the soundness of stands and slope stability. To resolve the problem, continuous monitoring of root development of older planted *P. densiflora* for. *erecta* in various areas is necessary, and correct silvicultural practices that may ensure a better and effective growth of planted trees are required.

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