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ABSTRACT

One hundred and sixty-two lodgepole pine (*Pinus contorta* var. *latifolia*) and 162 Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) seedlings were excavated in a clearcut north of Golden to ascertain the impact of skidroad construction and stump uprooting on the development and form of tree roots and the relationship of root morphology to tree growth. Equal numbers of trees were excavated from five disturbance categories in the skidroad plots and three disturbance categories in the stump uprooting plots. The size of the root systems were measured using a modified "root area" method.

Seedlings planted in excavated or gouged tracks generally develop root systems inferior to those in undisturbed ground or in deposits. Seedlings in tracks tended to concentrate root production in the upper 10 cm of mineral soil and there was a sharp reduction in rooting below this depth. For Douglas-fir, total root area of trees planted in the inner skidroad tracks was significantly lower than that of trees planted in undisturbed soil or in those skidroad categories with looser soil. Stump uprooting had less of an impact on root systems than skidroad construction and use; the inner track of skidroads had a particularly strong impact on root systems.

Poor root development and consequent low root area, as encountered in the inner track of skidroads and stump uprooting tracks, resulted in reduced tree growth. This was evidenced by positive correlations between root area and tree diameter, height and crown width. Lodgepole pine trees with J-shaped or L-shaped root systems had significantly reduced tree height on skidroads. Douglas-fir trees with well developed taproots had significantly greater tree diameter and tree volume on skidroads and greater tree height in the stump uprooting area than those without taproots.

On skidroads, the best planting spot for lodgepole pine was either the berm or the sidecast. The best planting spot for Douglas-fir on skidroads was the outer track followed by the berm. Using the Soil Conservation Guidelines maximum allowable area in skidroads (13%), unfavorable planting areas would comprise 6% and 3% of the harvested area for lodgepole pine and Douglas-fir, respectively.

In stump uprooting areas, the deposits were the best planting spots for both species. Based on the amount of stump uprooting disturbance with deposits and tracks on this site for both tree species, 34% of the clearcut was unsuitable for planting.

RÉSUMÉ

Cent-soixante-deux semis de pin tordu (*Pinus contorta* var. *latifolia*) et 162 semis de douglas taxifolié (*Pseudotsuga menziesii* var. *glauca*) ont été déterrés dans une zone de coupe à blanc située au nord de Golden. L'étude visait à déterminer l'impact de la construction de chemins de débardage ainsi que du dessouchage sur le développement et la morphologie des racines des arbres et à étudier la relation qui existe entre cette morphologie et la croissance de l'arbre. Un nombre égal de semis a été déterré dans chacun de 5 types de perturbation liés aux chemins de débardage et de 3 types de perturbation liés au dessouchage. La taille des systèmes racinaires a été mesurée par une méthode de «superficie rhizométrique» modifiée.

Les semis plantés sur une trace creusée produisent généralement des systèmes racinaires moins développés que les semis plantés sur un sol non perturbé ou sur des dépôts. La production de leurs racines tendait à se concentrer dans les premiers 10 cm du sol minéral et à diminuer brusquement à partir de cette profondeur. La superficie rhizométrique des douglas taxifoliés provenant de la trace côté montagne des chemins était significativement inférieure à celle des semis provenant d'un sol non perturbé ou de perturbations produisant un sol plus meuble. Le dessouchage avait moins d'impact sur le système racinaire que la construction et l'utilisation des chemins. L'impact était particulièrement important dans le cas des traces côté montagne.

Le développement médiocre des racines et la faible superficie rhizométrique qui en résulte, constatés chez les semis provenant de la trace côté montagne d'un chemin ou provenant d'une trace de dessouchage, ont entraîné une réduction de la croissance des arbres. Cette constatation s'appuie sur la corrélation positive qui existait entre d'une part la surperficie rhizométrique et d'autre part le diamètre du tronc, la hauteur de l'arbre et la largeur de la cime. Les pins tordus à système racinaire en forme J ou L qui provenaient d'un chemin de débardage avaient une hauteur totale significativement réduite. De même, par rapport aux douglas taxifoliés dépourvus de racine pivotante, les arbres de cette espèce qui avaient une racine pivotante bien développée possédaient un diamètre et un volume significativement plus grands, s'ils provenaient d'un chemin, et une hauteur significativement plus grande, s'ils provenaient d'un terrain dessouché.

Dans les chemins de débardage, les meilleurs endroits pour planter un pin tordu étaient l'accotement et le talus de remblai, tandis que les meilleurs endroits pour planter un douglas taxifolié étaient la trace côté vallée et, en deuxième lieu, l'accotement. En supposant que les chemins de débardage occupent 13 % de la zone exploitée, c'est-à-dire le maximum permis par les lignes directrices sur la conservation des sols, on peut estimer que la superficie ne convenant pas à la plantation des pins tordus ou des douglas taxifoliés représente respectivement 6 % ou 3 % de la zone exploitée.

En terrain dessouché, les dépôts constituaient le meilleur endroit pour planter les deux essences. En se fondant sur les taux de perturbation avec dépôts et avec traces associés au dessouchage, on peut évaluer à 34 % la portion de la zone de coupe à blanc qui ne convenait pas à la plantation des deux espèces.

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1.0 INTRODUCTION

The morphology of root systems of planted seedlings is influenced by seedling genetics, nursery practices, planting method, and soil characteristics such as texture, rock content, density, cementation, nature and content of organic materials, fertility, and moisture content (Harrington et al. 1989). Logging and site preparation practices can lead to changes in environmental and soil parameters. In British Columbia, yarding with ground-based systems occurs on 80% of the area harvested (Utzig and Walmsley 1988). In the Nelson Forest Region of British Columbia, an average of 32% of the area of sampled ground-skidded clearcuts yarded on bare ground (snow-free) consisted of skidroads and landings and 8% consisted of haul roads (Smith and Wass 1976). Recent progress has reduced this level of soil disturbance but the amount can still exceed 20% (B.C. Ministry of Forests 1992).

Construction and use of skidroads results in physical changes such as soil compaction, removal of organic material, mineral soil displacement, and chemical changes (Smith and Wass 1985). Smith and Wass (1979, 1980) reported reduced tree growth on the inner, gouged portion of skidroads. Mechanical site preparation may also degrade soils. Stump extraction to control root disease has been the focus of some concern. Smith and Wass (1991) found that stump uprooting was more detrimental to soil and tree growth in fine-textured, dense and moist soils than on soils with good drainage and low clay content.

The effects of soil disturbance on root system morphology are not well documented. Several studies have compared root system morphology of seeded-in-place and planted seedlings (Arnott 1978; Long 1978; Harrington et al. 1989), but studies comparing roots of planted seedlings on undisturbed mineral soil with those on adjacent disturbed sites are rare. Mason (1985) showed that for juvenile radiata pine (*Pinus radiata* D. Don) cultivation (ripping and disc treatments) increased toppling frequency. Four-year-old radiata pine trees on skidtrails toppled more frequently than off skidtrails (Firth and Murphy 1989). This result was attributed to planting tree seedlings in compacted soil. Also with radiata pine, Balneaves and De La Mare (1989) reported that deep ripping treatment in the presence of hardpan increased taproot penetration. By age five, slash pine (*Pinus elliottii* Engelm.) root and shoot biomass, and tree height and diameter were significantly increased by bedding (raised wide beds of soil for planting) compared to flat-harrowing (Schultz 1973; Sutton and Tinus 1983). McMinn (1978) reported that lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) bareroot seedlings five years after outplanting had greater root biomass in sites where duff had been mixed into the underlying mineral soil compared to blade scarified or untreated soil; however, no differences in root form were noted.

This study investigated (1) root development and form of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) and lodgepole pine seedlings growing on skidroads and on areas where stumps had been uprooted to control root rot, and (2) the relationship of root morphology to tree growth.

2.0 STUDY SITE

The experimental plantations were located at Marl Creek approximately 32 km north of Golden, British Columbia. This site is situated within the Golden Moist Warm variant of the Interior Cedar-Hemlock biogeoclimatic zone (ICHmw1) (Utzig et al. 1986; Braumandl and Curran 1992). It was logged in 1982 and skidded by crawler tractor. Stumps on approximately half of the cutblock were uprooted using a crawler tractor equipped with a brush blade. Part of the clearcut had no stump uprooting but was traversed by contour skidroads.

In 1985, three plots were established in the unstumped area to encompass portions of skidroads and surrounding undisturbed ground. In each plot a total of 160 seedlings each of Douglas-fir and lodgepole pine were planted in alternate rows across the skidroads with a 1-m spacing between rows. Spacing within rows varied from 1 to 2 m depending on disturbance size and pattern. In each plot, 20 trees of each species were planted on the inner track, outer track, berm, and sidecast, and 80 trees of each species were planted on undisturbed soil, for a total of 960 trees (Fig. 1).

Seven plots were established in the area of stump uprooting. Three plots had undisturbed soil, three plots had deposits and tracks, and one plot had all three categories. The plots with only undisturbed soil were established as close as possible to plots with stumping disturbance. Two hundred seedlings of each tree species were planted in each disturbance category: deposit, track, and undisturbed. Tracks are generally characterized by gouging, and often by compaction due to vehicular traffic. Deposits result from soil displacement during root excavation or tractor movement.

In both operations, 2+0 bareroot Douglas-fir and 1+0 styroblock 211 plug lodgepole pine were planted with a shovel.

3.0 METHODS

Six trees for each skidroad plot (3), tree species (2), and disturbance category (5) were excavated in May 1990 for a total of 180 trees. Six trees for each paired plot (4 blocks) in the stump uprooted area, tree species (2), and disturbance category (3) were excavated for a total of 144 trees. Trees whose stem volumes were nearest to the mean tree volume of all trees for each species and disturbance category per plot were selected for excavation.

Tree height, and diameter at 2.0 cm above ground level, were taken in the fifth year (September 1989) after planting, and these growth measurements are reported elsewhere (Smith and Wass 1994a,1994b). Tree crown width was measured at the time of excavation. The ground level and the upper slope side of the stem was marked. Presence or absence of basal sweep and stem lean were noted. The stem was cut 5 cm above ground level and the trees excavated with mattocks and shovels to a depth required to collect the deepest roots with a diameter of 2 mm or more. Lateral roots were severed 15 cm out from the base of the tree. The type of soil substrate where the original seedling was planted was recorded (e.g., rotten wood, buried humus, mineral soil, bedrock).

Root systems were transported to Canadian Forest Service's Pacific Forestry Centre laboratory, Victoria, B.C., washed, then stored in a cold room set at 5°C. Stored roots were rehydrated prior to measurement by soaking in water for 48 hours. The roots were suspended from a cylindrical frame which was 10 cm in diameter and 40 cm deep, divided into four 10-cm-deep sections or layers (Fig. 2). Each layer was divided into four equal quadrants. The cut stump was centered in the cylinder with the ground line level with the top of the frame and the upper slope mark aligned with quadrant number one. The longitudinal axis of the main stem and root system were oriented in their original positions by using the cut plane as a horizontal reference.

The size of the root system was measured using a modification of the "root area" method devised by Lindgren and Orlander (1978). The diameter of each root greater than 2 mm passing through the walls and bottom of the cylinder were measured and the cross-sectional area calculated. The root area by 10 cm layer for each tree was determined by summing these areas. The total root-area for each tree is the sum of all root areas of roots passing through the walls plus root areas of roots passing through the bottom of the last cylinder where roots occur. The calculation of root areas of side roots is based only on roots passing through the walls of the cylinder by 10 cm layer and total side root area is the summing of the layers. Root systems were classified based on their general orientation (Table 1).

The length of the taproot was measured from the top of the cylinder (frame) to where it exited the cylinder. Taproots exiting the bottom of the cylinder were given the length of 400 mm. The solid wood depth and width were measured (Fig. 3). The depth and diameter of the first-order lateral root equal to or greater than 4.0 mm in diameter were measured and the quadrant of the root was recorded.

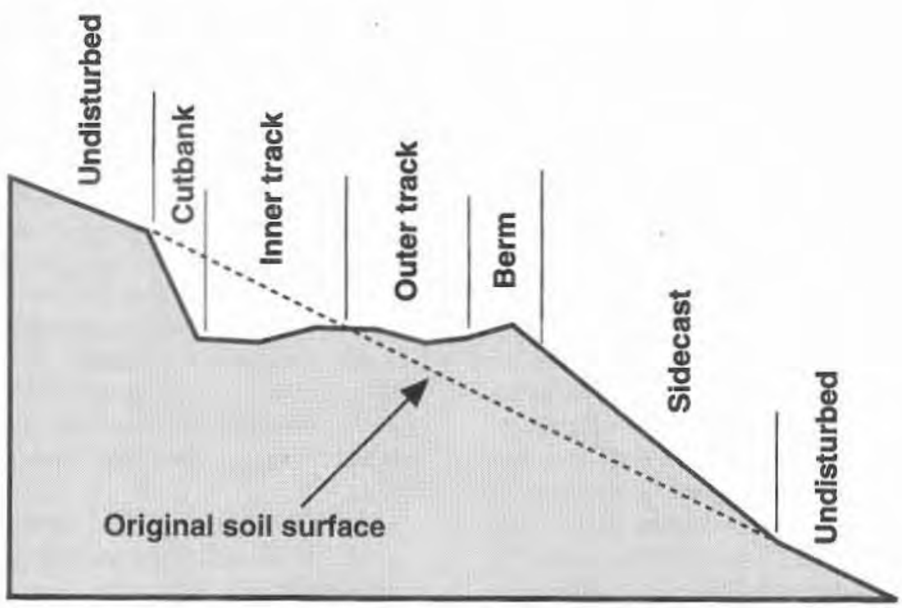


Figure 1. Skidroad disturbance classification system, and location of original soil surface

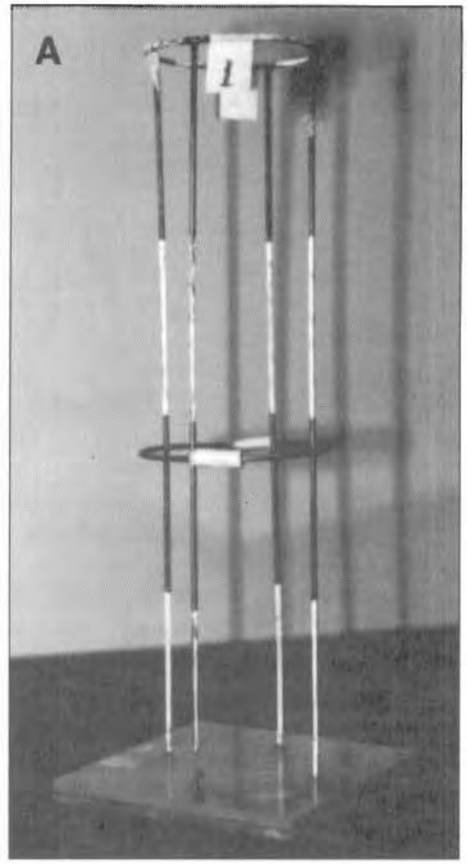
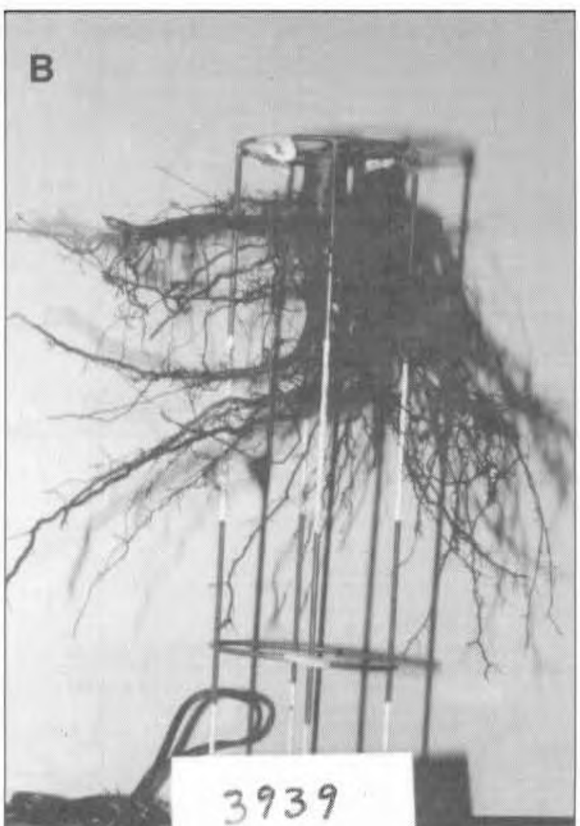
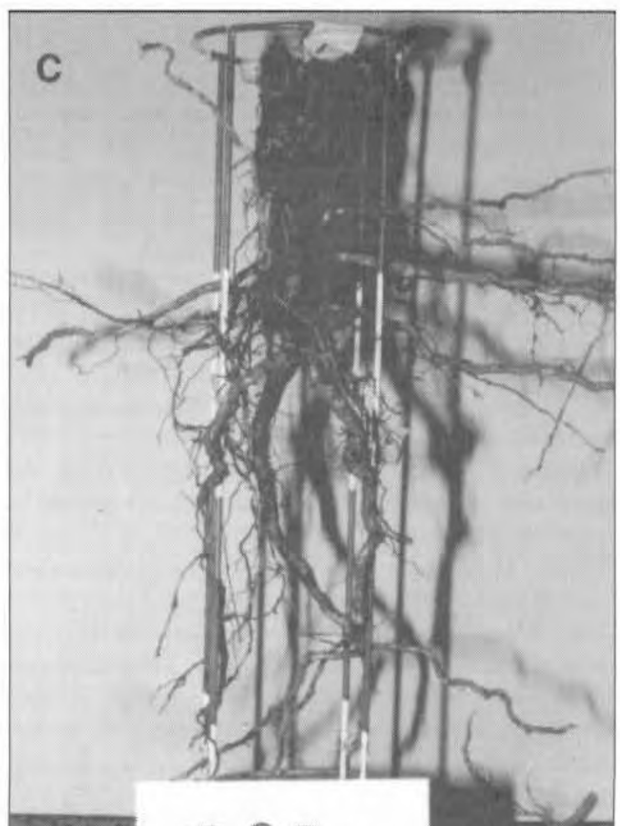


Figure 2. (A) Root measuring frame 10 cm in diameter, four longitudinal sections (each section 10 cm in depth) and four quadrants. (B) Douglas-fir suspended in the frame. (C) Lodgepole pine suspended in the frame.





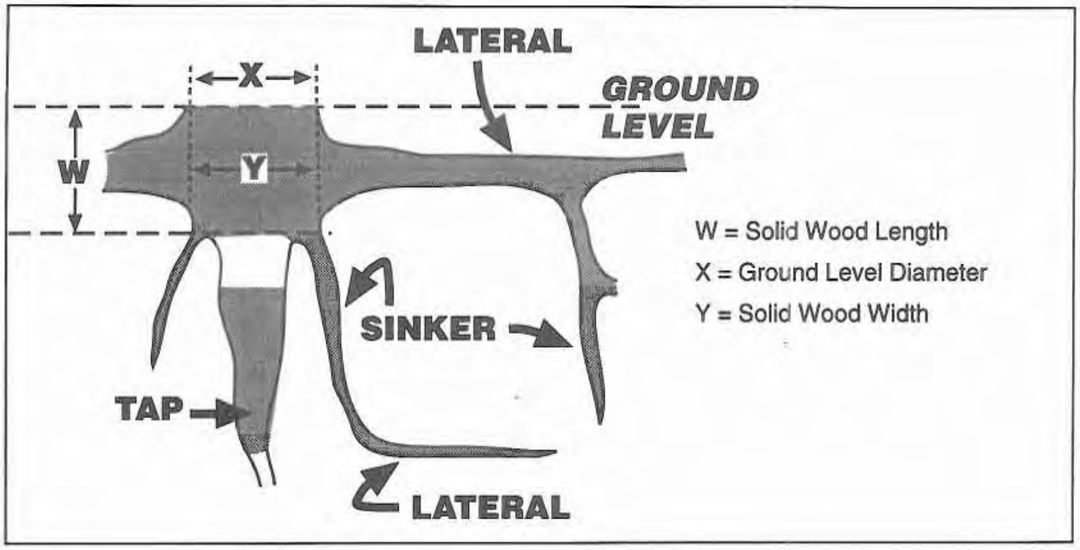


Figure 3. Root dimension classification

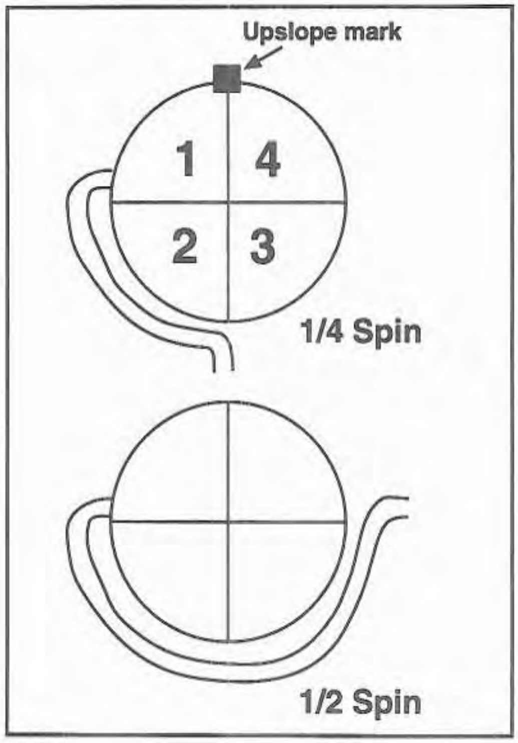


Figure 4. Horizontal root spin

For individual roots greater than 2.0 mm in diameter at the edge of the cylinder, parameters recorded in addition to root diameter were the layer and quadrant at which the root exited the cylinder and the root type (taproot, lateral [0-45 degrees from horizontal] or sinker [45-90 degrees from horizontal]). For lateral roots, the degree of horizontal spin was recorded. Horizontal spin was measured by quarter spins, i.e, the difference between the point where the lateral root emerged from the primary root and the point through which it passed the cylinder "wall" (Fig. 4).

A tree topples when it leans by pivoting about a point below the ground (Lines 1980). A toppling tree is restored to the vertical by geotropic curvature in the lower part of the stem, creating "basal sweep." A number of ratios that are useful in determining the susceptibility of trees to toppling may be calculated . The imbalance created by rapid early height growth and slow root growth can make trees more susceptible to toppling (Chavasse 1978; Van Eerden 1978). Top-root length (TRL) and top-root volume (TRV) ratios indicate the tree's susceptibility to toppling. Smaller TRL and TRV ratios indicate greater expected stability. The ratio of seedling stem height to root collar diameter (SR), also called the Sturdiness Quotient, indicates tree sturdiness (Thompson 1985; Winter and Low 1990). Trees "with a smaller ratio may be more sturdy and better able to withstand vegetation or snow press" (Winter and Low 1990). TRV, TRL, and SR ratios were calculated as follows:

$$TRV = \frac{\text{Stem volume}}{\text{Root volume}}$$

$$= \frac{0.261799 \times (\text{dia}^2) \times \text{tree height}}{0.3333 \times \text{root area} \times \text{root depth}}$$

$$TRL = \frac{\text{Tree height}}{\text{Root depth}}$$

$$SR = \frac{\text{Tree height}}{\text{Root collar diameter}}$$

Recognizing that the categories of disturbed soil vary in their capability to support growth of planted trees, a rating system was devised to rank those from most to least likely to support acceptable rates of survival and tree growth. Eighteen tree and non-tree parameters were used. For skidroads, the rating was from 1 to 5, with 1 the least likely and 5 the most likely site for that parameter. The parameters used and their relation to best site conditions are shown in Table 2. Once the individual parameters were ranked for each disturbance category the number of each ranking was totaled (number of 5, 4, 3, 2, 1 ratings). The total of each ranking was multiplied by its value (e.g., 5 ratings of 4= 20 points). The best planting site with a top ranking of 5 per parameter and with 18 parameters would have 90 points. The total points possible for a site from the stump uprooting treatment was 54 points.

Soil bulk density was measured by soil displacement and estimation of the volume of excavated holes with a sand-cone apparatus (Blake 1965). In the stump uprooted area three samples were taken at each of two depths (0-10 cm and 10-20 cm) in each of three categories (undisturbed, track, and deposit) in each of four plots (i.e., 12 samples per depth and disturbance category combination). For the skidroad area two samples were taken at each of two depths (0-10 cm and 10-20 cm) in each of three disturbance categories (inner track, outer track and berm) in each of three plots. Three samples were taken at each depth in undisturbed mineral soil in an adjacent plot. Bulk densities were calculated for the total soil (TBD) and for the fine fraction (FBD), i.e., particles less than 2 mm in diameter. The soil disturbance effects on soil bulk density have been reported previously (Smith and Wass 1994a, 1994b); thus, only relationships of bulk density and root area are reported in this study.

The clearcut block contained both stump uprooting and skidroad treatments. To determine if the undisturbed trees from both treatment areas could be pooled, the total root area of trees from the undisturbed soil from both treatments was compared. Douglas-fir was significantly different ($p=0.0030$ t test (LSD)) while lodgepole pine was not ($p=0.0544$) (significance was achieved when $p<0.05$). This analysis plus slight differences in site characteristics (soil type, percent free carbonate, and soil density) confirmed that a separate analysis of the two treatments was warranted.

Analysis of variance (ANOVA), using a general linear model procedure for unbalanced designs, was used to determine significant differences between disturbance categories.

A. Skidroad treatment ANOVA table.

Source of variation	df	Error
Plot, P	p-1= 2	-
Dist. category, D	d-1= 4	P×D
P×D	(p-1)(d-1)= 8	-
Trees, R(PD)	(r-1)pd= 75	-
Total	(pdr)-1= 89	

B. Stump uprooting treatment ANOVA table.

Source of variation	df	Error
Block, B	b-1=3	-
Dist. category, D	d-1=2	B×D
B×D	(b-1)(d-1)=6	-
Trees, R(BD)	(r-1)bd=60	-
Total	(bdr)-1=71	

Appendices 1-4 present the mean square (MS), F values, and probabilities for parameters that were analyzed by disturbance category. The Student Newman Keul multiple range test ($p=0.05$) was used to separate disturbance category means. Regression analysis and Pearson correlation coefficients were also used to elucidate relationships among parameters. Statistical comparisons were also made using ψ^2. Percentage data were transformed to the arcsine before ANOVA. All statistical analyses were performed with SAS computer programs (SAS Institute Inc. 1985).

4.0 RESULTS

4.1 Skidroad Treatment

4.1.1 Ground level diameter and solid wood dimensions

The mean ground level diameter of lodgepole pine growing on undisturbed soil (29.8 mm) and sidecast disturbance (27.6 mm) was significantly greater than that of trees growing on the inner track (21.9 mm). There were no significant differences among disturbance categories in solid wood length (range 38.8-61.8 mm), width (range 31.6-42.8 mm), or area (range 1503-2632 mm^2).

The mean ground level diameter of Douglas-fir on the inner track (15.9 mm) was significantly less than that of trees from all other disturbance categories (range 19.3-21.7 mm). There were no significant differences among disturbance categories in solid wood length (range 23.9-33.2 mm). The solid wood widths of roots from the inner track (15.7 mm) and sidecast (13.0 mm) categories were significantly less than those of roots from the other disturbance categories (range

21.4-25.9 mm). The solid wood area (stump) of trees on the inner track (427 mm^2) was significantly less than that of trees growing on other disturbance categories (range 740-921 mm^2) except sidecast (531 mm^2).

4.1.2 Root depth and stem/root ratios

Root depth of lodgepole pine was significantly less on the inner track (141 mm) than on other disturbance categories. Root depth of trees on the outer track (179 mm) was significantly less than that of trees growing on the undisturbed soil (225 mm), berm (271 mm), or sidecast (251 mm).

Douglas-fir roots on the inner track were significantly shallower (126 mm) than on other disturbance categories (range 166-184 mm).

Lodgepole pine root depth was significantly related to total bulk density (TBD2) and fine bulk density (FBD2) in the 10-20 cm layer. The regressions yielded the following equations:

$$\textit{Root depth}\ (\text{mm}) = 396.3\text{-}131.9 \times \textit{TBD}2\ (\text{Mg/m}^3)$$
$$(r^2=0.74;\ p=.0002)$$

$$\textit{Root depth}\ (\text{mm}) = 371.9\text{-}149.5 \times \textit{FBD}2\ (\text{Mg/m}^3)$$
$$(r^2=0.69;\ p=.0005)$$

There was no significant relationship between root depth and bulk density for Douglas-fir trees.

The TRL ratio of lodgepole pine trees on the berm (4.3) was significantly smaller than that of trees on the inner track (5.9) and outer track (6.0). There were no significant differences among disturbance categories in SR ratio (range 36-39) or TRV ratio (range 8.0-13.9).

For Douglas-fir trees there were no significant differences among disturbance categories in TRL ratio (range 4.0-4.8) or SR ratio (range 32-37). Trees growing on the inner track had a significantly larger TRV ratio (20.7) than trees growing on other disturbance categories (range 8.5-11.4).

4.1.3 Tree lean, basal sweep, and crown width

There were no significant differences among lodgepole pine growing on different disturbance categories in tree lean (range 6-28%; p=0.340) or basal sweep (range 6-22%; p=0.3630), or among Douglas-fir in lean (range 17-44%; p=0.3350) or basal sweep (range 11-42%; p=0.256). In total, 10.8% more Douglas-fir than lodgepole pine had lean, and 16.4% more Douglas fir than lodgepole pine had basal sweep.

Lodgepole pine trees on the inner and outer tracks had significantly less crown width (55 and 61 cm, respectively) than trees on other disturbance categories (range 73-75 cm). Crown width was significantly correlated with root area in the 0-10 cm (r=0.63; p=0.0001), 10-20 cm (r=0.49; p=0.0001) and 20-30 cm (r=0.32; p=0.0025) layers, and with total root area (r=0.42; p=0.0001).

Douglas-fir trees on the inner track had significantly less crown width (43 cm) than trees on other disturbance categories (range 53-58 cm). Crown width was significantly correlated with root area in the 0-10 cm (r=0.50; p=0.0001) and 10-20 cm (r=0.36; p=0.0005) layers, and with total root area (r=0.42; p=0.0001).

4.1.4 Root system orientation

On the berms, 72% of lodgepole pine roots were directed downward (classes 1 and 3). Trees growing on the undisturbed soil and the sidecast had 55% and 50% of their roots directed downward, respectively. Only 33% of root systems on the inner track and 23% on the outer track were directed downward. Trees from the outer track and sidecast had a high percentage (39% and 28%, respectively) of J or L roots. There was no significant difference among root form classes in the diameter (range 22-24 mm; p=0.3180) of the lodgepole pine trees, but those with J or L root systems were significantly shorter (91 mm) than trees with other root systems (range 99-103 mm; p=0.0432). There were no significant differences in height, diameter, or volume between lodgepole pine with root systems directed downward and those with root systems directed outward.

Of all the Douglas-fir trees examined, 59% had roots conforming to the shape of the planting shovel with the taproot bent upward or not present (classes 3 and 4), 24% had roots conforming to the planting shovel but with a taproot, 3% had well distributed roots but no taproot, and 14% had well distributed root systems and a taproot present. The percentage of taproots present (classes 1 and 3) ranged from 28% for inner track to 50% for outer track. There were no significant differences among Douglas-fir root form classes in tree height (range 65-74 cm) . Douglas-fir with well distributed root systems and no taproot had significantly greater mean diameter (23 mm) than those without well distributed root systems and a taproot (17 mm). Trees with taproots had significantly greater diameter (19 mm) and volume (67 cm^3) than those without taproots (17 mm and 54 cm^3). There were no significant differences in height, diameter, or volume between trees with well distributed roots and those with poorly distributed roots.

4.1.5 First large lateral root

For lodgepole pine, the first lateral root greater than or equal to 4.0 mm was significantly deeper on the berm

(88 mm) and sidecast (91 mm) than on the inner track (30 mm) and outer track (41 mm) or the undisturbed soil (55 mm). There were no significant differences in the mean diameter of the first lateral root among the different disturbance categories (range 5.8-7.2 mm). Seventy-two percent of the first large lateral roots in the undisturbed soil were directed upslope. Roots in the inner track were directed equally upslope and downslope, whereas 55% of lateral roots in the outer track and berm were directed upslope, and 65% of first lateral roots in sidecast were oriented downslope. For all trees, 54% of the first large lateral roots were directed up-slope.

There were no significant differences among disturbance categories in depth (range 60-81 mm) and diameter (range 5.7-6.8 mm) of the first lateral root of Douglas-fir. The percentages of these lateral roots oriented upslope in the different disturbance categories were as follows: inner track 40%; undisturbed soil 48%; berm 57%; sidecast 64%; and outer track 65%. For all trees, 57% of the first large lateral roots were directed upslope.

4.1.6 Root area

In the 10-20 cm layer, root area of lodgepole pine was significantly greater on the sidecast than on the inner track (Table 3). In the 20-30 cm layer, root area of trees on the sidecast was significantly greater than that of trees on the undisturbed soil or on the inner track. Trees growing on undisturbed soil had significantly greater total root area than trees on the inner track (Table 3).

For Douglas-fir, the root area in the 0-10 cm layer and total root area were significantly greater on undisturbed soil than on other disturbance categories (Table 3). Trees from the inner track had significantly less root area than trees growing on the other disturbance categories in the 0-10 cm and 10-20 cm layers; they also had significantly less total root area (Table 3).

Lodgepole pine trees on the inner track had significantly greater root area of side roots in the 0-10 cm layer than trees on the sidecast (Table 4). In the 10-20 cm layer, trees growing on the inner track had significantly lower root area than trees growing in either undisturbed soil, the outer track, or the sidecast (Table 4). There were no significant differences among trees from different disturbance categories in total root area of side roots. There were no significant differences among quadrants in total root area of side roots (range 50.1 -58.1 mm^2). Trees on the inner track had significantly fewer side roots (6.7) than trees on other disturbance categories (range 9.7 - 11.0).

Douglas-fir trees on the inner track had significantly less root area of side roots in the 10-20 cm layer than trees on the undisturbed soil and on the sidecast (Table 4). Trees on the inner track had significantly less total root area of side roots than trees on other disturbance categories (Table 4). In Douglas-fir, there were no significant differences among quadrants in total root area of side roots (range 24.3-36.2 mm^2). Trees on the inner track and sidecast had significantly fewer side roots (4.1 and 6.1, respectively) than trees on other disturbance categories (range 6.9-8.8).

There were no significant differences in total root area between lodgepole pine growing in a soil mix (soil mixed with either buried humus or rotten wood) and those growing in mineral soil (258 and 312 mm^2, respectively; p=0.25) or between Douglas-fir growing in a soil mix and those growing in mineral soil (148 and 156 mm^2, respectively; p=0.88).

4.1.7 Root area relationships

For lodgepole pine, there was a significant negative relationship between total bulk density (TBD2) in the 10-20 cm layer and root area in the 0-10 cm and 30-40 cm layers, and significant negative correlations between the fine fraction bulk density (FBD2) in the 10-20 cm layer and root area in the 20-30 cm and 30-40 cm layers. The regressions yielded the following equations:

$$\textit{Root area}\ (0\text{-}10\ \text{cm}) = 673.3 - 199.2 \times \textit{TBD2} \quad (r^2 = 0.33;\ p = 0.0299)$$

$$\textit{Root area}\ (30\text{-}40\ \text{cm}) = 6.877 - 3.883 \times \textit{TBD2} \quad (r^2 = 0.42;\ p = 0.0141)$$

$$\textit{Root area}\ (20\text{-}30\ \text{cm}) = 22.995 - 13.97 \times \textit{FBD2} \quad (r^2 = 0.28;\ p = 0.0444)$$

$$\textit{Root-area}\ (30\text{-}40\ \text{cm}) = 7.386 - 5.48 \times \textit{FBD2} \quad (r^2 = 0.65;\ p = 0.0009)$$

Tree height, diameter, and volume of lodgepole pine were positively correlated with root areas in the 0-10 cm, 10-20 cm, and 20-30 cm layers, and with total root area (Table 5). Tree height was also positively correlated with root area in the 30-40 cm layer.

There were no significant relationships between bulk density parameters and Douglas-fir root area in different layers or total root area.

For Douglas-fir, height was significantly and positively correlated with root area in the 0-10 cm layer and with total root area, and diameter and volume were signficantly and positively correlated with root area in the 0-10 cm and 10-20 cm layers and with total root area (Table 6).

4.1.8 Root spin

Twenty-nine percent of all lodgepole pine side roots examined had some horizontal spin. There were no significant differences among disturbance categories in total horizontal spin (range 21-45%). In terms of layers, there were no significant differences among disturbance categories in horizontal spin in the 0-10 cm layer (range 29-46%), but in the 10-20 cm layer, significantly more roots on the outer track had horizontal spin (43%) than on other disturbance categories (range 13-25%). Of the side roots with horizontal spin, 87% had quarter spin, 11% had half spin, and 2% had three-quarter spin.

Nineteen percent of all Douglas-fir side roots examined had some horizontal spin. There were no significant differences among disturbance categories in horizontal spin in any of the layers or in total (range 10-23%). Of the side roots with horizontal spin, 74% had quarter spin and 26% had half spin.

4.2 Stump Uprooting Treatment

4.2.1 Ground level diameter and solid wood dimensions

For lodgepole pine, there were no significant differences among disturbance categories in ground level diameter (range 25.2-25.9 mm), solid wood length (range 45-55 mm), solid wood width (range 37-39 mm), or solid wood area (range 1721-2082 mm^2).

For Douglas-fir, there were no significant differences among disturbance categories in ground level diameter (range 16.8-17.3 mm), solid wood length (range 20.5-24.8 mm), solid wood width (range 13.2-17.6 mm), or solid wood area (range 445-604 mm^2).

4.2.2 Root depth and stem/root ratios

Root depth of lodgepole pine was significantly greater on the deposit (252 mm) than on undisturbed soil (195 mm) or on the track (172 mm). Root depth was significantly related to bulk density of the fine fraction in the 10-20 cm layer. The regression yielded the following equation:

$$\textit{Root depth}\text{ (mm)} = 330.65-127.055 \times \textit{FBD2}\text{ (Mg/m}^3\text{)}$$
$$(r^2 = 0.27;\ p = 0.0473)$$

Douglas-fir roots on tracks were significantly shallower (126 mm) than on the deposit (183 mm) or on undisturbed soil (159 mm). Root depth was significantly related to total bulk density (TBD2) and fine bulk density (FBD2) in the 10-20 cm layer. The regressions yielded the following equations:

$$\textit{Root depth}\text{ (mm)} = 314.25-122.27 \times \textit{TBD2}\text{ (Mg/m}^3\text{)}$$
$$(r^2=0.3918;\ p=0.0174)$$

$$\textit{Root depth}\text{ (mm)}=268.37-114.84 \times \textit{FBD2}\text{(Mg/m}^3\text{)}$$
$$(r^2=0.4071;\ p=0.0152)$$

Lodgepole pine growing on the deposit had a significantly smaller TRL ratio (4.3) than those on the track (5.6) or on undisturbed soil (5.6). There were no significant differences among disturbance categories in either the SR ratio (range 37-40) or TRV ratio (range 7.4-9.6).

For Douglas-fir, there were no significant differences among disturbance categories in the TRL ratio (range 4.3-5.2) or the SR ratio (range 37-42). Seedlings growing on the deposit had a significantly smaller TRV ratio (14.1) than those growing on the track (23.0); the TRV ratio was 18.6 on undisturbed soil.

4.2.3 Tree lean, basal sweep, and crown width

Significantly fewer lodgepole pine trees (17%) had stem lean in the undisturbed soil than in other disturbance categories (58% each; p=0.002). There were no significant differences among disturbance categories in the basal sweep of lodgepole pine trees (range 4-8%; p=0.779). Significantly more Douglas-fir trees on tracks had tree lean (83%) than on the deposit (42%) or on undisturbed soil (50%; p=0.006). There were no significant differences among disturbance categories in the basal sweep of trees (range 17-42%; p=0.145).

For lodgepole pine, there were no significant differences among disturbance categories in crown width (range 58-64 cm). Crown width was significantly correlated with root area in the 0-10 cm layer (r=0.30; p=0.0105). Douglas-fir crown widths were all significantly different among disturbance categories; those on the track had the smallest crown width (48 cm), followed by those on the undisturbed soil (52 cm), and the deposit (56 cm). Crown width was significantly and positively correlated with root area in the 0-10 cm layer (r=0.33; p=0.0043) and the 10-20 cm layer (r=0.43; p=0.0002), and with total root area (r=0.31; p=0.0072).

4.2.4 Root system orientation

Thirty-seven percent of the lodgepole pine root systems in the undisturbed soil, 58% in tracks, and 63% in deposits were directed downward (classes 1 and 3). The lower percentage of systems directed downward in the undisturbed soil was mainly the result of a low percentage of root systems in the major sinker root class (class 3) and a high frequency (17%) of J or L roots. There were no significant differences among lodgepole pine trees of different root form classes in tree diameter (range 21-22 mm) or tree height (range 93-101 cm).

There were no significant differences in height or diameter between lodgepole pine with the root system directed downward and those with the root system directed outward.

Forty-two percent of the Douglas-fir tree roots in the undisturbed category, 55% in deposits, and only 25% in tracks had taproots. There were no significant differences among Douglas-fir trees of different root form classes in tree diameter (range 14-16 mm) or height (range 64-75 cm). Douglas-fir trees with a taproot directed downward were significantly taller (71 cm) than those that either had no taproot or had a taproot bent upward (64 cm). Trees with well distributed roots were taller (73 cm) than trees with poorly distributed roots (66 cm), but the difference was not significant.

4.2.5 First large lateral root

For lodgepole pine, there were no significant differences among disturbance categories in either average depth (range 36.1-46.3 mm) or average diameter (range 6.3-7.4 mm) of the first lateral root greater than 4.0 mm in diameter. In all disturbance categories, a higher percentage of the first large lateral roots were directed upslope than downslope: differences in favor of the upslope orientation were 8% on undisturbed soil, 25% on deposits, and 22% on tracks.

There were no significant differences among disturbance categories in depth (range 69.5-88.6 mm) or diameter (range 5.1-5.8 mm) of the first Douglas-fir lateral root greater than 4.0 mm. Of all Douglas-fir roots examined that had a lateral root greater than 4.0 mm, 55% were directed downslope (ranging from 53% on deposits to 57% on undisturbed soil and tracks).

4.2.6 Root area

In the 10-20 cm layer, root area of lodgepole pine was significantly greater on the deposit (101 mm^2) than on the track (29 mm^2); root area of lodgepole pine in undisturbed soil was 66 mm^2. There were no significant differences among disturbance categories in root area in any of the other layers or in total root area. Total root area ranged from 256 to 299 mm^2.

For Douglas-fir, there were no significant differences among disturbance categories in root area in any of the layers or in total root area. Total root area ranged from 83 to 103 mm^2.

For lodgepole pine, there were no significant differences among disturbance categories in root area of side roots in any of the layers or in the total root area. Total root area of side roots in the different disturbance categories ranged from 139 to 164 mm^2. There were no significant differences among quadrants in the total root area of side roots (range 39.4-51.0 mm^2). Lodgepole pine on tracks had significantly fewer side roots in the 10-20 cm layer (2.1) and a significantly lower total number of side roots (7.8) than those on other disturbance categories (ranges 4.8-5.5 and 10.3-10.8, respectively).

For Douglas-fir, there were no significant differences among disturbance categories in root area of side roots in any of the layers or in total root area. Total root area of side roots in the different disturbance categories ranged from 35 to 59 mm^2. There were no significant differences among quadrants in the total root area of side roots (range 17.0-22.7 mm^2). Douglas-fir on the undisturbed soil had the lowest total number of side roots (3.8), significantly fewer than those on the deposits (5.9).

There were no significant differences in total root area between lodgepole pine growing in mineral soil or in soil mix (307 and 264 mm^2, respectively; $p = 0.33$) or between Douglas-fir growing in mineral soil or in soil mix (87 and 95 mm^2, respectively; $p = 0.63$).

4.2.7 Root area relationships

For lodgepole pine, there was a significant negative relationship between total bulk density in the 0-10 cm layer (TBD1) and root area in the 0-10 cm layer. The regression yielded the following equation:

$$\textit{Root area}\ (0\text{-}10\ \text{cm}) = 785.9 - 369.9 \times \textit{TBD}1$$
$$(r^2{=}0.46;\ p{=}0.0095)$$

Tree diameter was positively correlated with root area in the 0-10 cm and 10-20 cm layers and with total root area (Table 7). Likewise, tree volume was correlated with root area in the 0-10 cm and 10-20 cm layers, and with total root area.

For Douglas-fir, there was a significant negative relationship between total bulk density in the 0-10 cm layer (TBD1) and root area in the 0-10 cm layer. There was also a negative relationship between bulk density of fines in the 0-10 cm layer (FBD1) and total root area. The regressions yielded the following equations:

$$\textit{Root area}\ (0\text{-}10\ \text{cm}) = 231.89 - 114.62 \times \text{TBD1}$$
$$(r^2{=}0.28;\ p{=}0.0438)$$

$$\textit{Root area}\ (\text{total}) = 209.11 - 139.2 \times \text{FBD1}$$
$$(r^2 = 0.34;\ p = 0.0277)$$

Douglas-fir tree height was significantly correlated with root area in the 0-10 cm layer (Table 8). Tree diameter was significantly correlated with root areas in the 0-10 cm and 10-20 cm layers and with total root area (Table 8). Likewise, tree volume was significantly correlated with root area at depths 0-10 cm and 10-20 cm, and with total root area.

4.2.8 Root spin

Thirty-one percent of lodgepole pine side roots examined had some horizontal spin. There were no significant differences among disturbance categories in root spin in any of the layers or in total root spin (range 27-35%). Of the side roots with horizontal spin, 89% had quarter spin, 10% had half spin, 0.5% had three-quarter spin, and 0.5% had full spin.

Thirteen percent of all Douglas-fir side roots examined had some horizontal spin. There were no significant differences among disturbance categories in the amount of horizontal spin in any of the layers or in total root spin (range 6-14%). Of the side roots with horizontal spin, 70% had quarter spin and 30% had half spin.

5.0 DISCUSSION

This comparative study of root systems of trees planted in undisturbed and disturbed soil shows that lodgepole pine and Douglas-fir root growth and morphology is affected by the type and degree of soil disturbance, particularly if this disturbance has changed surface soil density. In addition, the study supports the conclusion of Grene (1978) that root area provides a practical and precise method of comparing root development of different species in different site conditions.

The study indicated that seedlings planted in excavated or gouged tracks generally develop root systems inferior to those developing in undisturbed ground or in deposits. Root development is limited in tracks by high soil density and, when excavation is deep, by high pH and carbonate levels characteristic of the lower soil horizons of the site (Smith and Wass 1994*a*). In this situation, taproots are less likely to develop and depth of root penetration is significantly less than in undisturbed soil or deposits. Root depth of lodgepole pine was significantly restricted in soils with an average density of 1.69 Mg/m^3. Douglas-fir root depth was restricted in tracks with an average density of 1.47 Mg/m^3 on the stump uprooting site, but on skidroads significant restriction occurred only on the inner track where the average density was 1.81 Mg/m^3. The negative, linear relationship between root depth and soil bulk density found in our study is in agreement with the literature (Foil and Ralston 1967; Heilman 1981). Seedlings on tracks tend to concentrate root production in the upper 10 cm of mineral soil and there is a sharp reduction in rooting below this depth. For Douglas-fir, total root area was significantly lower in trees planted on the inner skidroad tracks than in those trees planted in undisturbed soil or in those skidroad categories with looser soil. The scanty, shallow root systems associated with the inner skidroad track contribute to instability and increased toppling. Lindgren and Orlander (1978) found a strong correlation between stability of Scots pine (*Pinus sylvestris* L.) and root area. Also, shallow root systems would reduce contact with water at depth, which might predispose trees to moisture stress.

Stump uprooting had a less extreme impact on root systems than some results (particularly the inner track) of skidroad construction and use. Negative correlations of root area with bulk density indicated that this difference is at least partially due to the more moderate soil densities resulting from stump uprooting (up to 1.47 Mg/m^3) compared with those resulting from skidroads (up to 1.81 Mg/m^3).

Poor root development and consequent low root area, as encountered in the inner track of skidroads and stump uprooting tracks, reduce tree growth. Evidence for this can be found in the positive correlations between root area and tree diameter, height, and crown width. Lindgren and Orlander (1978) found similar correlations between total root area and plant size.

Lodgepole pine trees with J or L root systems were significantly shorter in the skidroad treatment. Douglas-fir trees with well developed taproots had significantly greater tree diameter and tree volume on skidroads, and they had greater tree height in the stump uprooting area. These results differ from the literature on the subject. Long (1978) found that J or L root system deformation did not affect tree growth of either lodgepole pine or Douglas-fir 4 to 7 years after outplanting. When comparing Douglas-fir J or L root forms with "correctly" planted controls 10 years after outplanting, Haase et al. (1993) found no significant differences in tree growth. They do mention that on a harsher site than the one they used differences between root forms may be more dramatic. Newton and Cole (1991) and Preisig et al. (1979) found that root deformation was not correlated with growth of Douglas-fir. Growth of Douglas-fir with poorly distributed roots (single plane) in our study did not differ significantly from that of trees with well distributed roots. In contrast, Rudolf (1939) found a 20% reduction in height of pines with roots in a single plane compared to those with better root distribution. For other species, Harrington et al. (1987), using the same classification system as in this study, reported that loblolly pine (*Pinus taeda* L.) and shortleaf pine (*Pinus echinata* Mill.) trees with root systems oriented downward had better growth than trees with surface-oriented roots. However, Schultz (1973) found no difference in growth between 12-year-old slash pine (*Pinus elliottii*

Engelm.) with straight taproots and those with bent taproots.

Lateral roots of lodgepole pine had almost twice as much horizontal spin (30%) as those of Douglas-fir (17%). Lodgepole pine on the skidroad sidecast had significantly less spin than trees of both species on the other disturbance categories. This could be due to the looser soil found in the sidecast. Van Eerden (1978) reported that, 5 years after planting in undisturbed soil with lodgepole pine stock similar to that used in our study (styro-plug 2, 1+0 and 2+0), 67% of lateral roots had some spiraling. Douglas-fir in the above study (styro-plug 2, 1+0, and 2+0) had only 31% lateral root spiraling. These results were similar in proportion to those of our study, but about twice as high. The seedlings used in Van Eerden's trial were grown in non-ribbed styroblocks, whereas the seedlings used in this study were grown in ribbed wall containers, which reduce root spin (Arnott 1978; Persson 1978). The degree of spin shows no evidence of root strangulation for either tree species.

Root area in the 0-10 cm layer appeared to be greater in a soil mix (mineral soil plus buried humus or rotten wood) than in mineral soil. This could be due to a greater supply of organic carbon, but it is more likely the result of the lower soil density in the soil mix.

The best planting spot for lodgepole pine on skidroads is either the berm or the sidecast (Fig. 5). The outer track and especially the inner track should be avoided. The best planting spots for Douglas-fir on skidroads are on the outer track followed by the berm (Fig. 6). Again, the inner track should be avoided. Using the maximum allowable area in skidroads (13%) given in the Soil Conservation Guidelines (British Columbia Ministry of Forests, 1992), unfavorable planting areas would account for 6% and 3% for lodgepole pine and Douglas-fir, respectively.

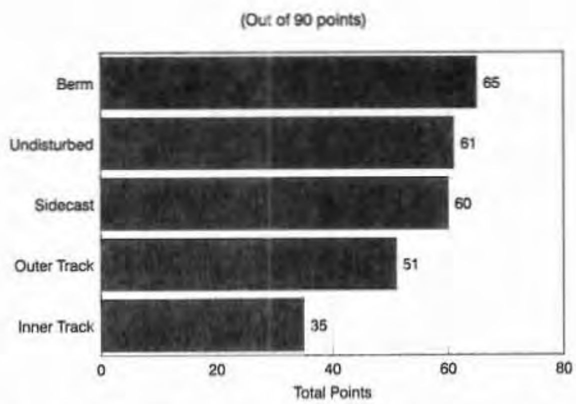


Figure 5. Ranking of planting spots for lodgepole pine on skidroads

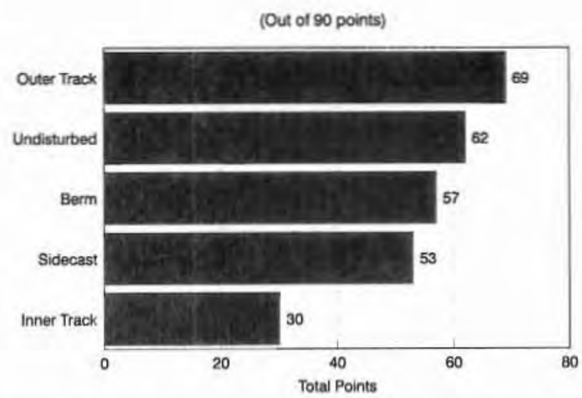


Figure 6. Ranking of planting spots for Douglas-fir on skidroads

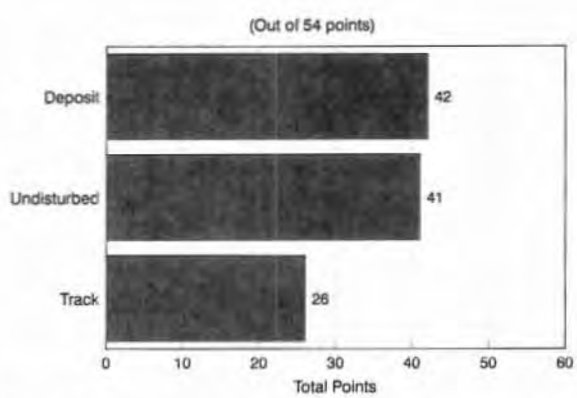


Figure 7. Ranking of planting spots for lodgepole pine in areas where stumps have been uprooted

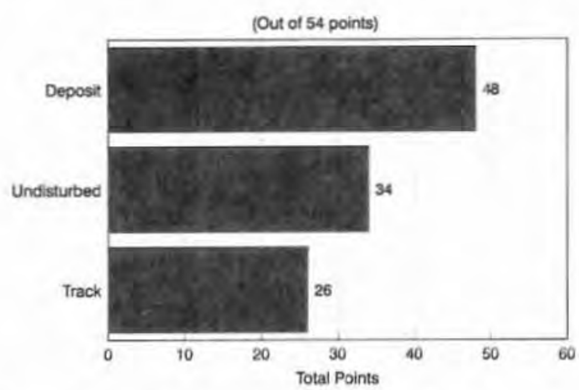


Figure 8. Ranking of planting spots for Douglas-fir in areas where stumps have been uprooted

In areas where stumps have been uprooted, planting of either species should be avoided on the track (Figs. 7 and 8). Deposits were better planting spots than undisturbed soil. Smith and Wass (1991) also found that tracks in moist soils with a relatively high clay content should be avoided on stump uprooting sites. Based on the amount of stump uprooting disturbance with deposits and tracks on this site (Smith and Wass 1994b), 34% of the clearcut was unfavorable for planting either tree species.

6.0 IMPLICATIONS FOR MANAGEMENT

1. Seedlings of either lodgepole pine or Douglas-fir planted in excavated or gouged tracks generally develop root systems inferior to those developing in undisturbed soil or in deposits. Root development is limited in tracks by high soil density and, when excavation is deep, by high pH and carbonate levels.

2. Seedlings planted on tracks tend to concentrate root production in the upper 10 cm of mineral soil and there is a sharp reduction in rooting below this depth.

3. Low root volume and reduced tree growth is found particularly in seedlings growing on the inner track of skidroads and on stump uprooting tracks.

4. On excavated skidroads, lodgepole pine should be planted either on the berm or sidecast, and Douglas- fir should be planted on the berm or outer track. For both species, the inner track should be avoided.

5. On stump uprooting areas, both lodgepole pine and Douglas-fir should be planted on deposits and intervening undisturbed ground.

6. Although detrimental impacts on root development are greatest when seedlings are planted on the inner track of skidroads, a greater percentage of area treated is detrimentally affected by stump uprooting. Not including landings and haul roads, 11% of the skidroad area studied (based on actual skidroad cover of 23%) is considered unsuitable for planting, and 34% of the stumped area is considered unsuitable for planting. However, obtaining uniform spacing of satisfactory planting spots in the skidroad site should be more difficult since the whole skidroad surface may be unsuitable.

7. The area unsuitable for planting can be minimized by reducing the number of skidroads. Had the cover of skidroads in our study area met current guidelines, the percentage of unsuitable planting sites would be halved. Other ways to reduce the incidence of unsuitable planting sites include the use of cable systems for harvesting, using backhoes rather than bulldozers for uprooting stumps, and uprooting only those stumps that are known to be infected with disease.

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Table 1. Root system orientation classification

Tree species	Class	Description
	1	One major root oriented downward.
	2	One major root but root system not directed downward ("L" and "J" roots).
Lodgepole pine*	3	Root system with downward orientation but with more than two to four large "sinker" roots.
	4	Root systems without a major root and with the orientation outward rather than downward.
	1	Root system well distributed in most directions and taproot present.
Douglas-fir**	2	Roots well distributed but no taproot present.
	3	Roots poorly distributed and conforming to the shape of the planting shovel, but taproot present.
	4	Root system conforming to the shape of the planting shovel and taproot bent upward or not present.

* Classification based on Harrington et al. (1987).

** Classification based on Segaran et al. (1978).

Table 2. Parameters and relationships used in the ranking of sites for suitability for planting

Parameter	Best condition
Root depth	Deep
TRL ratio	Small
SR ratio	Small
TRV ratio	Small
Lean	Low
Sweep	Low
Crown width	Great
All roots: Root area	
0-10 cm layer	Large
10-20 cm layer	Large
Total	Large
Side roots: Root area	
0-10 cm layer	Large
10-20 cm layer	Large
Total	Large
First lateral root (>4.00 mm dia.) depth	Deep
Total bulk density*	
0-10 cm layer	Low
10-20 cm layer	Low
Tree height*	Great
Tree survival*	High

* Data from Smith and Wass 1994a, 1994b.

Table 3. Mean root areas (mm^2) for excavated trees from skidroads

Tree species	Layer	Disturbance category: Undisturbed soil	Inner track	Outer track	Berm	Sidecast
Lodgepole pine	0-10 cm	467 a*	250 a	386 a	429 a	443 a
	10-20 cm	111 ab	31 b	115 ab	100 ab	172 a
	20-30 cm	4 b	1 b	9 ab	16 ab	32 a
	30-40 cm	0 a	0 a	1 a	5 a	8 a
	Total**	438 a	213 b	326 ab	269 ab	266 ab
Douglas-fir	0-10 cm	241 a	60 c	184 b	153 b	162 b
	10-20 cm	39 a	6 b	32 a	23 a	40 a
	20-30 cm	1 a	0 a	6 a	1 a	2 a
	30-40 cm	0	0	0	0	0
	Total	263 a	61 c	163 b	152 b	136 b

* Means within rows followed by the same letter are not significantly different at the 0.05 level.

** The total root-area for each tree is the sum of all root-areas of roots passing through the walls plus root-areas of roots passing through the bottom of the last cylinder where roots occur.

Table 4. Mean root areas (mm^2) of side roots for excavated trees from skidroads

Tree species	Layer	Disturbance category: Undisturbed soil	Inner track	Outer track	Berm	Sidecast
Lodgepole pine	0-10 cm	75.2 ab*	133.8 a	115.7 ab	91.5 ab	63.3 b
	10-20 cm	100.9 a	29.9 b	109.1 a	69.5 ab	106.1 a
	20-30 cm	3.1 a	1.5 a	7.4 a	8.5 a	16.2 a
	30-40 cm	0.0 a	0.0 a	0.4 a	0.9 a	0.8 a
	Total	179.2 a	165.2 a	232.6 a	170.4 a	186.4 a
Douglas-fir	0-10 cm	80.3 a	32.2 a	73.3 a	74.5 a	43.5 a
	10-20 cm	37.7 a	4.3 b	20.3 ab	20.4 ab	36.8 a
	20-30 cm	0.7 a	0.0 a	6.1 a	0.9 a	1.5 a
	30-40 cm	0	0	0	0	0
	Total	118.7 a	36.5 b	99.7 a	95.8 a	81.8 a

*Means within rows followed by the same letter are not significantly different at the 0.05 level.

Table 5. Pearson's correlation coefficients for root areas of lodgepole pine on skidroads

Layer		Tree height	Tree diameter	Tree volume
0-10 cm	correlation coefficient	0.603	0.622	0.6541
	probability	0.0001	0.0001	0.0001
10-20 cm	correlation coefficient	0.469	0.456	0.516
	probability	0.0001	0.0001	0.0001
20-30 cm	correlation coefficient	0.284	0.227	0.295
	probability	0.0067	0.0316	0.0048
30-40 cm	correlation coefficient	0.262	-	-
	probability	0.0125	-	-
Total	correlation coefficient	0.404	0.468	0.455
	probability	0.0001	0.0001	0.0001

Dash indicates no significant correlation at p=0.05.

Table 6. Pearson's correlation coefficients for root areas of Douglas-fir on skidroads

Layer		Tree height	Tree diameter	Tree volume
0-10 cm	correlation coefficient	0.349	0.679	0.660
	probability	0.0007	0.0001	0.0001
10-20 cm	correlation coefficient	-	0.572	0.515
	probability	-	0.0001	0.0001
Total	correlation coefficient	0.333	0.603	0.567
	probability	0.0013	0.0001	0.0001

Dash indicates no significant correlation at p=0.05.

Table 7. Pearson's correlation coefficients for root areas of lodgepole pine in stump uprooting areas

Layer		Tree height	Tree diameter	Tree volume
0-10 cm	correlation coefficient	-	0.516	0.524
	probability	-	0.0001	0.0001
10-20 cm	correlation coefficient	-	0.369	0.357
	probability		0.0014	0.0021
Total	correlation coefficient	-	0.372	0.283
	probability	-	0.0013	0.0161

Dash indicates no significant correlation at p=0.05.

Table 8. Pearson's correlation coefficients for root areas of Douglas-fir in stump uprooting areas

Layer		Tree height	Tree diameter	Tree volume
0-10 cm	correlation coefficient	0.326	0.409	0.566
	probability	0.0052	0.0004	0.0001
10-20 cm	correlation coefficient	-	0.339	0.433
	probability	-	0.0036	0.0001
Total	correlation coefficient	-	0.392	0.419
	probability	-	0.0007	0.0003

Dash indicates no significant correlation at p = 0.05.

APPENDIX 1. Analysis of variance for parameters measured for lodgepole pine on skidroads by disturbance category (df=4)

Parameter	MS	F	PR>F
Ground level diameter	155	6.55	0.0121
Solid wood length	1641	3.74	0.0531
Solid wood width	348	2.04	0.1809
Solid wood area	3 594 887	1.93	0.1983
Root depth	51 159	31.53	0.0001
Crown width	1401	9.36	0.0041
Stem/root ratios			
TRL	10.08	5.17	0.0235
SR	45.57	1.56	0.2752
TRV	131.77	2.22	0.1561
Lateral root diameter	4.97	0.88	0.5156
Lateral root depth	12 473	13.85	0.0011
Root area (all roots)			
0-10 cm	134 193	3.31	0.0701
10-20 cm	45 569	4.16	0.0412
20-30 cm	2648	4.23	0.0396
30-40 cm	221	2.44	0.1316
Total	131 878	3.86	0.0492
Root area (side roots)			
0-10 cm	14 845	4.21	0.0399
10-20 cm	19 411	5.19	0.0233
20-30 cm	578	2.83	0.0986
30-40 cm	3	0.62	0.6589
Total	12 657	1.87	0.2091
Number of side roots			
0-10 cm	41	4.00	0.0451
10-20 cm	71	10.54	0.0028
20-30 cm	3	4.66	0.0308
30-40 cm	$8x10^{-2}$	1.43	0.3088
Total	54	4.98	0.0259
Horizontal spin			
0-10 cm	$14x10^{-2}$	0.58	0.6858
10-20 cm	$56x10^{-2}$	5.62	0.0188
Total	3x10-1	3.49	0.0626

MS = mean square
F = MS (treatment)/MS (error)
PR>F = probability value of F-ratio

APPENDIX 2. Analysis of variance for parameters measured for Douglas-fir on skidroads by disturbance category (df=4)

Parameter	MS	F	PR>F
Ground level diameter	89	10.39	0.0030
Solid wood length	508	2.05	0.1794
Solid wood width	535	11.21	0.0023
Solid wood area	742 250	9.24	0.0043
Root depth	9268	10.56	0.0028
Crown width	811	9.73	0.0037
Stem/root ratios			
TRL	2	1.06	0.4362
SR	67	1.65	0.2540
TRV	451	9.08	0.0045
Lateral root diameter	3	1.99	0.1894
Lateral root depth	1021	2.29	0.1486
Root area (all roots)			
0-10 cm	76 971	15.02	0.0009
10-20 cm	3809	7.30	0.0089
20-30 cm	106	3.77	0.0521
30-40 cm	-		-
Total	93 749	10.46	0.0029
Root area (side roots)			
0-10 cm	8175	3.09	0.0817
10-20 cm	3458	7.47	0.0083
20-30 cm	106	3.77	0.0521
30-40 cm	-		-
Total	17 108	8.18	0.0063
Number of side roots			
0-10 cm	22	4.16	0.0412
10-20 cm	22	4.37	0.0363
20-30 cm	$2x10^{-1}$	1.92	0.2007
30-40 cm	-		-
Total	60	7.35	0.0087
Horizontal spin			
0-10 cm	$13x10^{-2}$	1.46	0.2997
10-20 cm	$15x10^{-2}$	0.22	0.9210
Total	$18x10^{-2}$	1.42	0.3124

MS = mean square
F = MS (treatment)/MS (error)
PR>F = probability value of F-ratio

APPENDIX 3. Analysis of variance for parameters measured for lodgepole pine on stump uprooting areas by disturbance category (df=2)

Parameter	MS	F	PR>F
Ground level diameter	4	1.39	0.3200
Solid wood length	760	2.03	0.2118
Solid wood width	23	0.69	0.5391
Solid wood area	881 668	0.96	0.4336
Root depth	40 809	17.41	0.0032
Crown width	306	1.81	0.2425
Stem/root ratios			
TRL	17	25.74	0.0011
SR	35	1.45	0.3057
TRV	30	0.89	0.4579
Lateral root diameter	9	3.74	0.0882
Lateral root depth	660	0.52	0.6192
Root area (all roots)			
0-10 cm	83 688	3.00	0.1249
10-20 cm	31 174	6.81	0.0286
20-30 cm	2101	2.85	0.1352
30-40 cm	12	4.59	0.0618
Total	14 247	0.43	0.6687
Root area (side roots)			
0-10 cm	6120	3.34	0.1058
10-20 cm	12 237	3.91	0.0818
20-30 cm	1365	2.37	0.1748
30-40 cm	2	1.00	0.4219
Total	4019	1.18	0.3688
Number of side roots			
0-10 cm	11	1.11	0.3879
10-20 cm	82	13.44	0.0061
20-30 cm	7	3.17	0.1151
30-40 cm	6×10^{-2}	1.00	0.4219
Total	63	5.33	0.0467
Horizontal spin			
0-10 cm	8×10^{-2}	0.62	0.5706
10-20 cm	38×10^{-2}	1.21	0.3623
Total	1×10^{-1}	1.77	0.2492

MS = mean square
F = MS (treatment)/MS (error)
PR>F = probability value of F-ratio

APPENDIX 4. Analysis of variance for parameters measured for Douglas-fir on stump uprooting treatment by disturbance category (df=2)

Parameter	MS	F	PR>F
Ground level diameter	2	0.57	0.5958
Solid wood length	111	0.32	0.7349
Solid wood width	124	1.21	0.3621
Solid wood area	168 150	0.71	0.5278
Root depth	20 157	5.99	0.0372
Crown width	431	15.66	0.0042
Stem/root ratios			
TRL	5	1.78	0.2478
SR	134	2.64	0.1508
TRV	475	5.26	0.0479
Lateral root diameter	67×10^{-2}	0.52	0.6241
Lateral root depth	2950	1.70	0.2738
Root-area (all roots)			
0-10 cm	4437	1.13	0.3838
10-20 cm	1196	2.33	0.1780
20-30 cm	14	4.45	0.0654
30-40 cm	6×10^{-1}	1.00	0.4219
Total	2918	0.84	0.4777
Root-area (side roots)			
0-10 cm	1141	1.10	0.3908
10-20 cm	860	1.80	0.2447
20-30 cm	5	0.86	0.4711
30-40 cm	58×10^{-2}	0.99	0.4243
Total	3257	2.96	0.1275
Number of side roots			
0-10 cm	10	3.40	0.1029
10-20 cm	13	3.12	0.1176
20-30 cm	17×10^{-2}	1.00	0.4219
30-40 cm	14×10^{-3}	1.00	0.4219
Total	26	11.82	0.0083
Horizontal spin			
0-10 cm	6×10^{-2}	1.05	0.4053
10-20 cm	58×10^{-2}	2.27	0.1990
Total	15×10^{-2}	2.53	0.1595

MS = mean square
F = MS (treatment)/MS (error)
PR>F = probability value of F-ratio