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Impacts of stump uprooting on a gravelly sandy loam soil and planted Douglas-fir seedlings in south-coastal British Columbia

E.F. Wass and R.B. Smith

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Pacific Forestry Centre, Victoria, B.C.

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Abstract

Studies to determine levels and impacts of soil disturbance caused during root-disease control by stump removal were initiated on a cutover on southern Vancouver Island immediately prior to the control operation and the establishment of a plantation of Douglas-fir (*Pseudotsuga menziesii*). Soil surface condition was assessed on the stumped area. Soil disturbance was measured at 699 planting spots. Vegetation development was assessed at 10% of the spots. Of all planting spots, 180 were undisturbed soil, 277 deposits and 242 gouges.

The soil, a gravelly sandy loam, increased naturally in soil density with depth from 1.05 Mg/m^3 at the surface to over 1.60 Mg/m^3 at depths more than 40 cm. Disturbance did not significantly increase soil density. Unlike previous studies of this nature, ease of soil penetrability was increased by the stump uprooting disturbance and vegetation development was not greatly dissimilar between disturbed and undisturbed soil. The relatively low soil impacts were attributed to the ability of the excavator to pile stumps without pushing topsoil, and the low site sensitivity to compaction. These low impacts on soil and reduced vegetative competition on disturbed soil resulted in tree growth rates which were significantly greater after 10 years on deposits (12% in height and 18% in diameter) and gouges (6% in height and 8% in diameter) than on undisturbed soil.

Résumé

Des études sur le degré de perturbation du sol causée par les opérations de dessouchage contre les maladies racinaires et sur les répercussions des perturbations ont été entreprises sur un parterre de coupe de la partie sud de l'île de Vancouver, immédiatement avant l'application du traitement et l'établissement d'une plantation de Douglas (*Pseudotsuga menziesii*). L'état de la surface du sol de la zone dessouchée a été évalué, et la perturbation du sol a été mesurée dans 699 emplacements de plantation. Le développement de la végétation a été évalué dans 10 % des emplacements. De toutes les zones de plantation, 180 ne présentaient pas de perturbations, 277 des amoncellements, et 242 des ornières.

La densité du sol (limon sableux-graveleux) augmentait en fonction de la profondeur, passant de 1,05 mg/m^3 à la surface à plus de 1,60 mg/m^3 à des profondeurs de plus de 40 cm. La perturbation n'augmentait pas de façon significative la densité du sol. Contrairement aux observations faites lors d'études antérieures de cette nature, l'arrachage des souches a permis une plus grande pénétrabilité du sol; le développement de la végétation différait peu entre les sols perturbés et les sols non perturbés. Les impacts assez faibles sur le sol s'expliquent par l'habilité de l'excavateur à empiler les souches sans déplacer le sol superficiel et à la faible susceptibilité du sol au compactage. En raison de ces impacts négligeables et de la compétition végétative réduite dans le sol perturbé, le taux de croissance des arbres, après 10 ans, était nettement supérieur dans les amoncellements (12 % de plus en hauteur et 18 % de plus en diamètre) et dans les ornières (6 % de plus en hauteur et 8 % de plus en diamètre) que dans les sols non perturbés.

Acknowledgements

We thank Dr. John Muir, Pathologist, British Columbia Ministry of Forests (BCMOF), for bringing the stump uprooting operation to our attention. Analyses of soil for organic carbon and total nitrogen were conducted by staff of the Pacific Forestry Centre (PFC) under the direction of Ann Van Niekerk. Thanks also go to Darwin Burgess and Art Shortreid (PFC) and Chuck Bulmer (BCMOF) for thorough reviews, to Steve Glover and Jennifer Adsett (PFC) for editorial assistance and TM Communications for production and graphics.

1.0 Introduction

Stump uprooting activities are conducted to reduce the spread of root diseases from previously infected stumps to roots of planted or naturally regenerated seedlings and young trees (Wallis 1976; Morrison 1981; Thies 1984). The practice has generated concerns about potential soil damage (Smith 1981; Thies and Russell 1983), which have been substantiated in some but not all cases (Smith and Wass 1991, 1994a; Thies and Nelson 1988; Thies et al. 1994). Like soil damage associated with skidroad construction and use (Smith and Wass 1980), it is clear that, in addition to the particular type and level of soil disturbance, the level of deleterious impact depends on the sensitivity of the site. This has been recognized in the British Columbia Forest Practices Code guidelines (British Columbia Ministry of Forests [BCMOF] and Ministry of Environment, Lands and Parks [BCMOELP] 1995), but a wider range of sites needs to be studied to ensure that relationships are understood sufficiently well for application to forest management. The present study extends the geographic range of stump removal impact studies to south-coastal British Columbia, and it provides an opportunity to examine the influence of site preparation excavator operations on soils and seedlings.

The study commenced in 1985, on a cutover on southern Vancouver Island, British Columbia where stump uprooting operations had recently been completed. The major objectives were to describe the effects of stump uprooting on soils, the composition and development of vegetation, and the growth of planted seedlings. The hypothesis was that disturbance caused by stump uprooting would have effects on soil properties and on vegetation that would in turn influence subsequent vegetation development and tree growth.

2.0 Study Area

The study area is southwest of Shawnigan Lake, Vancouver Island, British Columbia, in the Eastern Very Dry Maritime variant of the Coastal Western Hemlock biogeoclimatic zone (CWHxm1) (Green and Klinka 1994). The major site series identified was No. 03 (Douglas-fir–Western hemlock–Salal) (Green and Klinka 1994). Average elevation is 175 m, and the general aspect is southeast with a 10% average slope.

The original stand was second-growth Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco), western red cedar *(Thuja plicata* Donn), and red alder *(Alnus rubra* Bong.). The soils are gravelly loam to sandy loams derived from glacial till.

3.0 Methods

3.1 Stumping Trial

The harvested stand was infested with the root rot *Phellinus weirii* (Murr.) Gilbn. Stumps on approximately 10 ha were uprooted with a Caterpillar 210 excavator with bucket and thumb. Uprooted stumps and attached roots were piled in windrows.

3.2 Transect Survey

Using a point-transect method (Smith and Wass 1976), the area of stump uprooting was surveyed in March 1986 to determine the extent, degree, and type of soil disturbance. Points were spaced 3 m apart along a system of transects located and oriented as recommended by Bloomberg et al. (1980). Soil disturbance was categorized as deposits, or gouges, by cause and by three depth classes: <5 cm, 5–25 cm, and >25 cm, or undisturbed. A total of 201 points were surveyed and described.

3.3 Soil Studies

3.3.1 Bulk density

Using a sand cone apparatus, soil bulk density was measured in 1987 and 1988, by soil displacement and by utilizing a factor to convert the weight of dry sand to volume to determine the volume of excavated holes (Blake 1965). Plantation trees were used as focal points for the bulk density samples. Tree numbers were randomly selected to obtain 12 samples in undisturbed soil, 24 in deposits, and 36 in gouges at each of two depths (0–10 cm and 10–20 cm). Each bulk density sample was located 30 cms beyond the edge of the tree crown. Bulk densities were calculated for the total soil and for the fraction made up of particles less than 2 mm in diameter (the fine fraction).

3.3.2 Penetrability

Penetrability was measured with a Farnell penetrometer equipped with a 1.3 cm^2 cone. Four 20-cm depth probes were made at each of the bulk density sites in the deposit and gouge disturbance categories. After removing any humus, four probes were made at each of the bulk density sites in the undisturbed mineral soil. To reduce variation due to differing soil moisture content, penetrability measurements were conducted on the same day.

3.3.3 Particle size

Coarse fragment content of each bulk density sample was determined by sieving and weighing. Texture of the fine fraction of selected samples was determined by the Bouyoucos hydrometer method (McKeague 1978).

3.3.4 Chemistry

The fine fraction of bulk density samples was analyzed for the following characteristics:

1. pH – potentiometrically in 0.01 M $CaCl_2$ (McMullan 1971).
2. Organic carbon – LECO induction furnace (McKeague 1978).
3. Total nitrogen – automated semi-micro Kjeldahl (McKeague 1978).

3.3.5 Soil profiles

Two soil pits were described, sampled and classified (Walmsley et al. 1980; Agriculture Canada Expert Committee on Soil Survey 1987) in an adjacent non-stumped harvested area. Samples taken from the centre of each soil horizon were sieved, the coarse fragments were weighed, textures of the fine fraction were determined and tests were made for total nitrogen, pH and organic carbon. Bulk densities were measured at 10-cm intervals to a depth of 80 cm.

3.4 Plantation

3.4.1 Establishment

Operational planting was completed by the BCMOF in March 1986. The 1+2 Douglas-fir bareroot stock were planted with a planting shovel at a 3×3 m spacing. A block of trees from the stump uprooting area were selected for tree growth measurements. At each tree spot, the extent, degree and type of soil disturbance were recorded. Soil disturbance was classified as in the transect survey. A total of 699 trees were measured: 277 planted in deposits, 242 planted in gouges and 180 planted in undisturbed soil.

3.4.2 Monitoring and maintenance

Tree height and ground-level stem diameter of all seedlings were measured immediately after planting, after each subsequent five growing seasons, and after the eighth and tenth growing seasons. Tree condition and damage were assessed (BCMOF 1982) at the same time as measurements were made; dead seedlings were recorded and removed.

After noting some evidence of deer browsing, Deer-Away Big Game Repellent (BGR–P) was applied in April and May of 1989 and 1990. A strip of red plastic flagging was attached to the terminal leader just below the terminal bud sufficiently loose so as not to girdle the terminal. Needles and flagging were moistened with water from a spray bottle and Deer-Away Repellent (1 g of powder per tree) applied. This procedure was similar to that developed by Campbell and Evans (1987). A survey was carried out to assess the deer damage to terminal leaders of treated versus non-treated trees (in an area adjacent to the study plot).

After the third growing season, competing vegetation on the experimental area was cut to near ground level, and in later years vegetation greater than half the height of the nearest tree was also cut.

3.4.3 Vegetation

Characteristics of vegetation (cover, vigor, distribution) by species and layers were measured using procedures outlined by Walmsley et al. (1980). Vegetation on the stump uprooting area was assessed using mil-acre (4.05 m^2) plots established at every tenth tree in the plantation. In each of 1986, 1987 and 1988 (i.e. before any vegetation control), 71 mil-acre, tree-centered plots were surveyed. All plants identified for each disturbance category were used to produce dissimilarity percentages (PD) (Pielou 1984). Additionally, the composition of common plants found in over 40% of the plots within a disturbance category over the 3 years of observation were tabulated by soil disturbance categories.

3.5 Data Analysis

A one-way analysis of variance (ANOVA) was performed using a general linear model procedure for unbalanced designs. The Least-Square Means ($p=0.05$) was used to separate significant differences in disturbance category means. Percentage data were transformed to the arscine before ANOVA. Appendix 1 presents the mean square (MS), F value, and probabilities for parameters that were analyzed by disturbance category. All statistical analyses were performed with SAS computer programs (SAS Institute Inc. 1985).

4.0 Results

4.1 Undisturbed Soil Profile Characteristics

The soil, a gravelly sandy loam derived from glacial till, was classified as an Orthic Humo–Ferric Podzol (Agriculture Canada Expert Committee on Soil Survey 1987), with a thin humus classified as a felty mor (Klinka et al. 1981). Visually estimated volumes of coarse fragments ranged from 10% at the surface to 50% at depth. Sand, silt and clay percentages ranged from 53–78%, 15–35% and 8–12%, respectively. There was a natural increase in total soil bulk density with depth, from an average of 1.05 Mg/m^3 in the 0–10 cm mineral soil layer to 1.65 Mg/m^3 in the 70–80 cm layer, and with a denser layer of 1.70 Mg/m^3 at 40–50 cm depth (Table 1). Nitrogen and organic carbon decreased with depth from the surface to 80 cm (Table 1). Over the same range the C/N ratio decreased and pH increased slightly (Table 1).

Utilizing keys developed for rating the sensitivity of forest sites to soil disturbance (BCMOF and BCMOELP 1995), the site sensitivity was rated low for soil displacement and mass wasting, and moderate for soil compaction and erosion.

Table 1. Physical and chemical data for undisturbed mineral soil, averaged from two soil profiles

Depth (cm)	Total bulk density (Mg/m^3)	Fine bulk density (Mg/m^3)	pH	Organic carbon (%)	Total nitrogen (%)	Carbon: nitrogen ratio
0–10	1.05	0.67	4.8	4.43	0.168	26.4
10–20	1.36	0.83	5.0	1.89	0.100	20.1
20–30	1.36	0.88	5.1	1.53	0.085	18.8
30–40	1.50	0.89	5.0	1.47	0.067	21.6
40–50	1.70	0.89	5.0	1.14	0.068	17.8
50–60	1.59	0.90	5.1	1.04	0.058	19.7
60–70	1.62	0.98	5.1	0.73	0.045	18.7
70–80	1.65	1.07	5.1	0.55	0.040	15.6

4.2 Ground Surface Conditions

Eighty-five percent of the surface of the stump-uprooted area was categorized as disturbed soil, with disturbance on 74% of the surface caused by the stump-uprooting operation (stump removal plus intervening excavator tracks) (Table 2). Disturbance on 11% of the surface was caused by the harvesting operation. Of the 74%, 58% was caused by the stump uprooting process, and 16% by slash pile of windrowed root wads (Table 2). Most of the stump uprooting disturbance was in the very deep category (>25 cm). Twenty-eight percent of the stump uprooting process disturbance was caused by actual stump removal and 30% from action of the excavator tracks (Table 2). Fifty-seven percent of the stump removal disturbance was categorized as deposits, 32% as gouges, and 11% as a combination of the two; 50% of the excavator track disturbance was classified as deposits and 47% gouges (tracks). The remainder (3%) was classified as a combination of the two.

Average depth of humus at undisturbed spots was 5 cm, 79% of which was classified as humified with no rotten wood, 4% as rotten wood, and 17% as mixtures of rotten wood and humified material. Recent slash covered 45% of the area. There was no cover of natural rotting logs for the stump-uprooting area.

Table 2. Categories and depths of soil disturbance in the stump uprooted area

Disturbance category	Depth of soil disturbance*				
	None (%)	S (%)	D (%)	VD (%)	Total (%)
Undisturbed**	15	0	0	0	15
Stump removal					
Deposit**	0	3	5	8	16
Gouge**	0	0	4	5	9
Combined	0	0	1	2	3
Excavator tracks					
Deposit**	0	0	6	9	15
Gouge**	0	0	9	5	14
Combined	0	0	<1	<1	1
Slash pile***	0	0	0	16	16
Skidroad	0	0	2	<1	2
Fireguard	0	0	1	1	2
Mainroad	0	<1	<1	<1	1
Landing	0	0	1	5	6
Yarding	0	<1	0	0	<1
Total	**15**	**4**	**30**	**52**	**100**

* S=Shallow (<5 cm) gouge or deposit; D=Deep (5–25 cm) gouge or deposit; VD=Very deep (>25 cm) gouge or deposit.

** Soil disturbance categories on which trees were planted and utilized in this study.

*** Mainly excavated root wads.

4.3 Soil Bulk Density

In comparisons of the three disturbance categories, total soil bulk density and fine soil density at 0–10 cm and 10–20 cm were not significantly different (Table 3).

Table 3. Mean soil bulk densities (Mg/m^3) of total and fine soil fractions for two disturbance categories plus the undisturbed soil at two depths

Disturbance category	Samples	Depth: Total soil 0–10 cm	Depth: Total soil 10–20 cm	Depth: Fine soil 0–10 cm	Depth: Fine soil 10–20 cm
Undisturbed	12	1.25 a*	1.48 a	0.76 a	0.91 a
Deposit	24	1.45 a	1.37 a	0.90 a	0.84 a
Gouge	36	1.42 a	1.50 a	0.89 a	0.93 a

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

4.4 Soil Penetrability

Undisturbed soil showed significantly greater resistance to penetration than soils in deposits or gouges, for all depths tested to 20 cm (Figure 1). Deposits were significantly more easily penetrated than gouges for all depths (Figure 1).

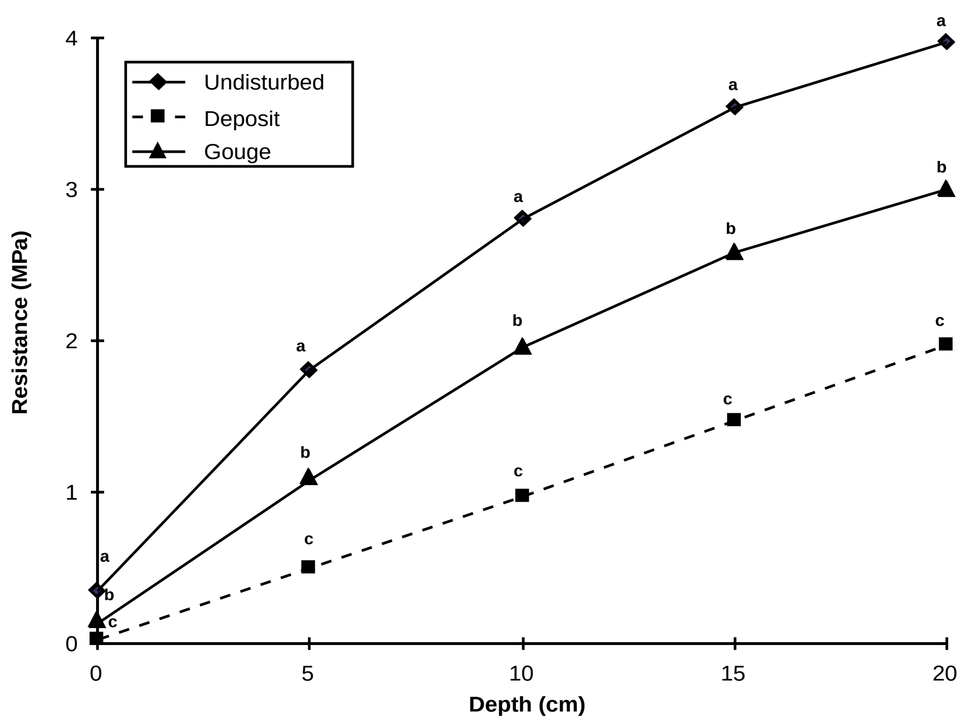

Figure 1. Resistance (MPa) to penetration of stump uprooting gouges, deposits and undisturbed mineral soil to a depth of 20 cm. Means at the same depth with the same letter are not significantly different.

4.5 Coarse Fragment Content

There were no significant differences in soil coarse fragment content between the disturbance categories for either the 0–10 cm layer (range 52 to 55%) or the 10–20 cm layer (range 55–57%).

4.6 Soil Chemistry

The undisturbed soil had a significantly higher concentration of organic carbon and total nitrogen, and a significantly lower pH, than either the deposit or gouge categories for the 0–10 cm layer (Table 4). There were no significant differences for any of the soil chemical parameters for the 10–20 cm layer.

Table 4. Soil chemistry of bulk density soil samples (basis = 12 samples for undisturbed soil, 23 for deposits, and 34 for gouges for each depth)

Disturbance category	Depth class (cm)	Organic carbon (%)	Total nitrogen (%)	Carbon/ nitrogen ratio	pH
Undisturbed	0–10	4.7 a*	0.189 a	26.1 a	4.6 b
Deposit	0–10	2.3 b	0.089 b	26.0 a	4.9 a
Gouge	0–10	3.1 b	0.110 b	28.7 a	4.8 a
Undisturbed	10–20	2.1 a	0.100 a	23.7 a	4.8 a
Deposit	10–20	2.0 a	0.081 a	24.9 a	4.9 a
Gouge	10–20	1.9 a	0.078 a	29.0 a	4.7 a

* Means within columns and depth class followed by the same letter are not significantly different at the 0.05 level.

4.7 Tree Seedling Survival

After ten growing seasons, survival of Douglas-fir was not significantly different over the disturbance categories (range 90–93%, p=0.601). Drought was the main cause of mortality for the deposit category (Table 5). Mortality caused by the root rot *Armillaria ostoyae* (Romagn.) ranged from 2 to 3% over the disturbance categories (Table 5).

Table 5. Percentage and cause of seedling mortality after 10 growing seasons

	Disturbance category		
Cause of mortality	Undisturbed (%)	Deposit (%)	Gouge (%)
Drought	3	5	3
Unknown	1	2	1
Stem damage	0	<1	<1
Armillaria ostoyae	3	2	3
Total	**7**	**10**	**8**

4.8 Tree Seedling Growth

After five growing seasons, height of Douglas-fir seedlings was significantly greater for those planted in deposits than for those planted in gouges or undisturbed soil, while no significant difference occurred between gouges and undisturbed soil (Table 6). Stem diameter was also significantly greater for trees growing in deposits than for those planted in gouges and undisturbed soil (Table 6).

After ten growing seasons, tree height and stem diameter of Douglas-fir were significantly different between all the disturbance categories; height and diameter were greatest for deposits and least for the undisturbed soil (Table 6).

Douglas-fir growing in deposits had greater average height than those in undisturbed soil after two growing seasons and were 12% taller after ten growing seasons (Figure 2). Seedlings in gouges were 6% taller by the tenth year than seedlings growing in the undisturbed soil. After the first growing season, stem diameter of seedlings growing in deposits was greater than that of seedlings growing on undisturbed soil; it was 15% more after the fifth year growing season and then, based on breast height, increasing to an 18% advantage after the tenth growing season (Figure 3). The stem diameter of seedlings growing in gouges was 5% greater than that of seedlings growing in undisturbed soil after five growing seasons and, based on breast height, 8% greater after ten growing seasons.

Table 6. Mean tree height and stem diameter of Douglas-fir seedlings for disturbance categories and undisturbed soil after five and ten growing seasons

Disturbance category	Trees (no.)	Tree height (cm)	Stem diameter (mm)
After 5 growing seasons			
Undisturbed	172	225 b*	44 b**
Deposit	257	254 a	50 a
Gouge	229	235 b	46 b
After 10 growing seasons			
Undisturbed	166	645 c	77 c***
Deposit	250	723 a	91 a
Gouge	224	687 b	83 b

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

** Diameter at tree base.

*** Diameter at tree breast height (1.3 m).

4.9 Browsing

Five weeks after the first application of deer repellent, 0.2% of the seedlings from the stumped area showed terminal shoot browsing by deer. In an untreated stumped area adjacent to the study plantation, 21% of the seedlings had terminal shoot damage.

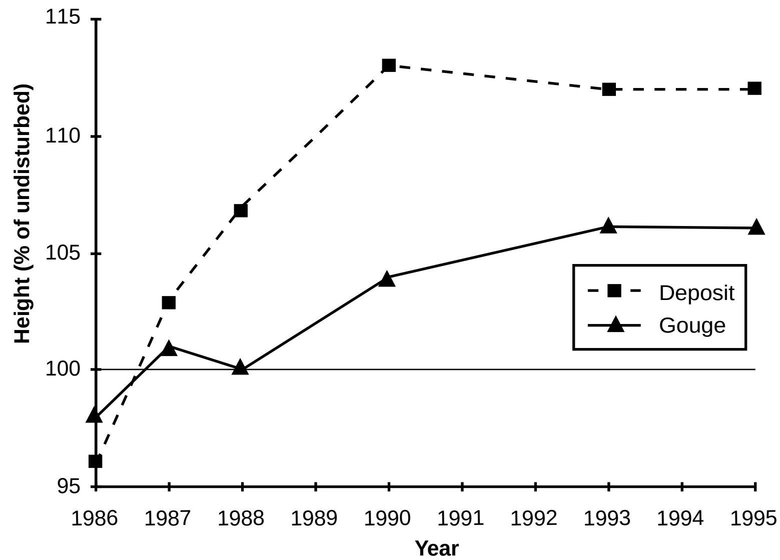

Figure 2. Mean height of seedlings growing on disturbed soil, as a percentage of that for seedlings growing on undisturbed soil.

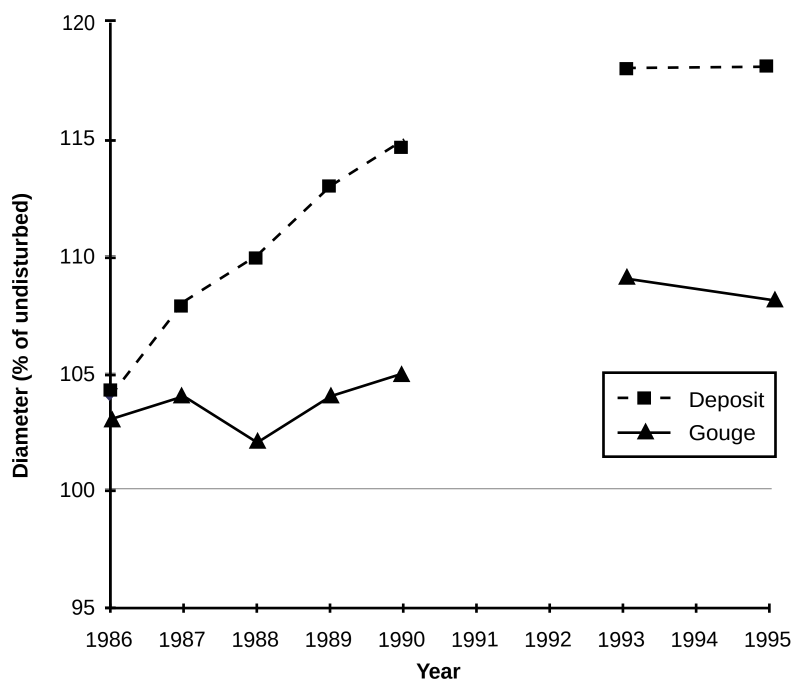

Figure 3. Mean diameter of seedlings growing on disturbed soil, as a percentage of that for seedlings growing on undisturbed soil. Basal diameter was measured from 1986 to 1990, and diameter at breast height (1.3 m) was measured for years 1993 and 1995.

4.10 Vegetation Cover and Composition

By 1986, one year after the stumping operation, total vegetative cover on undisturbed soil was almost twice that on deposits and on gouges (Figure 4). In the following two years, the percent cover on undisturbed soil and deposits increased at the same rate, while the rate of increase on gouges was less.

In comparing disturbance categories, vegetation composition and cover were most dissimilar between undisturbed soil and deposits, and least dissimilar between deposits and gouges (Table 7).

Rubus ursinus Cham. & Schlecht. occurred frequently (40% or more of plots) only in the undisturbed soil (Table 8). *Rubus leucodermis* Dougl. and *Cirsium vulgare* (Savi) Tenore were frequent on gouges and deposits but did not occur frequently on undisturbed soil. *Epilobium minutum* Lindl. was frequent only in the gouges. Eight frequently occurring plant species were present in all disturbance categories and undisturbed soil (Table 8).

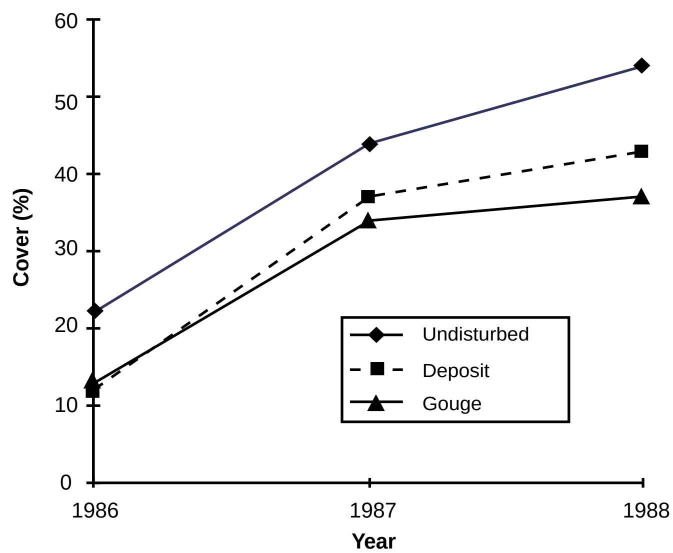

Figure 4. Trends in total vegetative cover by disturbance category and undisturbed soil.

Table. 7. Average dissimilarity indices for plant species for the three years (1986–1988) by soil disturbance category

Disturbance category	Undisturbed (%)	Deposit (%)	Gouge (%)
Undisturbed	0	38	31
Deposit		0	24
Gouge			0

Table. 8. Average frequency (F) and cover (C) of plant species for three years (1986–88) present in more than 40% of sampled plots for the undisturbed soil and disturbance categories

	Undisturbed		Deposit		Gouge	
	F (%)	C (%)	F (%)	C (%)	F (%)	C (%)
Rubus ursinus	45	5	–	–	–	–
Lactuca biennis	79	1	62	1	76	1
Epilobium angustifolium	81	1	67	2	76	2
Mahonia nervosa	76	2	51	1	52	2
Senecio sylvaticus	83	4	92	4	82	4
Pteridium aquilinum	83	8	76	6	83	7
Gaultheria shallon	71	5	58	3	62	3
Epilobium watsonii	69	1	61	1	80	1
Hypochaeris radicata	55	3	54	1	55	2
Cirsium vulgare	–	–	48	1	50	1
Rubus leucodermis	–	–	74	4	64	2
Epilobium minutum	–	–	–	–	44	1

5.0 Discussion and Conclusions

Previous studies of this kind have produced varying results that have been tentatively explained by the nature of the soil and by the severity of disturbance. In particular, reductions in tree growth have been found on tractor tracks gouged and compacted during stump removal operations in seepage influenced soil (Smith and Wass 1991), and in soils that are calcareous at depth (Smith and Wass 1994a). The excavated portions of skidroads also display significantly lower tree productivity than undisturbed soil in a variety of soil conditions (Smith and Wass 1979, 1980, 1994b). Other soils, particularly those well drained, non-calcareous and moderately coarse textured, have responded to disturbance with rates of tree growth equal to or greater than those on undisturbed soil (Morrison et al. 1988, Smith and Wass 1979, 1980, 1991, Thies and Nelson 1988). Seemingly contrary to this, Thies et al. (1994) found that stump removal operations on a silty clay loam did not significantly affect growth of planted Douglas-fir after nine years. Although soil density was significantly increased by the stump removal operation in this study, the increase amounted to only 7%, and the density level of 1.1 Mg/m^3 is not considered detrimental to root penetration.

In the study reported here, survival rates were high for all disturbance categories and the undisturbed soil. After ten years, 3% of the trees had been killed by *Armillaria ostoyae.* In another stump uprooting operation where Douglas-fir trees were pushed over with a bulldozer and then yarded to the landing with roots attached, Morrison et al. (1988) found that ten years after treatment, 2% of the Douglas-fir regeneration had been killed by *Armillaria ostoyae*.

Even with piling of stumps into windrows, the Caterpillar 210 excavator resulted in soil disturbance levels that were less than similar operations using bulldozers (Smith and Wass 1991), greater than stumping operations employing a backhoe and leaving uprooted stumps in situ (Smith and Wass 1989) and about the same as *in situ* operations employing bulldozers (Smith and Wass 1989, 1994a). Compared to a bulldozer, the excavator was better able to pile stumps without pushing topsoil.

Soil density levels did not reach critical levels for root penetration reported elsewhere (Minore et al. 1969; Heilman 1981) until a depth of 40–50 cm.

Reflecting the low impact of the stump removal operation on the soil, ease of soil penetrability was actually increased, even on excavator gouges. In contrast, other studies on finer or wetter soils demonstrated that tracks were significantly less penetrable at depths to 20 cm (Smith and Wass 1991, 1994a).

Another indication of the resilience of this particular soil to impacts by mechanical disturbance is the fairly close similarity of vegetation cover established in the gouged tracks to those established on undisturbed soil. The index of dissimilarity of 31% calculated in this study compares with other studies as follows: 50% for tracks versus undisturbed, on moderately fine textured soil (Smith and Wass 1994a); 75–90% for tracks versus undisturbed seepage influenced soil, and 63–65% for tracks versus undisturbed well-drained soil (extracted from Smith and Wass 1991); and 83–86% for inner skidroad versus moderately fine textured undisturbed soil (Smith and Wass 1994b).

The soil in the present study is rated as having low sensitivity to displacement and moderate sensitivity to compaction. These ratings are consistent with the lack of any deleterious effect on tree growth caused by the soil disturbance. In fact, due at least in part to reduced vegetation competition on the disturbed soil, tree growth was significantly enhanced on the deposit and gouge disturbance categories. Still, the result is somewhat perplexing given the significantly higher organic matter and nitrogen concentrations in the upper 10 cm of the undisturbed compared with disturbed soil. Perhaps with increasing tree-to-tree and vegetative competition the growth advantage may decrease on the disturbed soil. Trends for both tree height and stem diameter indicate a movement in this direction.

6.0 Recommendations

Equipped with a bucket and thumb, excavators are effective in removing stumps. However, in this study, windrowed stumps covered 16% of the treated area. Planting trees on these windrows would be impossible and successful natural regeneration on these piles would likely be delayed for many years. It is recommended that instead of piling, uprooted stumps should be turned upside down but otherwise left in place. In most operations, leaving stumps in place would reduce machine travel over the ground.

As with other soil-disturbance plantations, it is planned to remeasure the trees after 15 and 20 growing seasons. Because soil studies were conducted only at the time of plantation establishment, there would be merit in re-examining soil properties for changes associated with time. Particularly soil density, penetrability, and organic matter and nitrogen concentration should be remeasured.

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Appendix 1. Analysis of variance for parameters measured by disturbance category (df=2)

Parameter	MS	F	PR>F
Tree growth			
After 5 growing seasons			
Tree height	47823	11.83	0.0001
Stem diameter	2401	17.29	0.0001
After 10 growing seasons			
Tree height	306199	17.24	0.0001
Stem diameter	106	21.34	0.0001
Total soil bulk density			
0–10 cm depth	179×10^{-3}	2.75	0.0709
10–20 cm depth	123×10^{-3}	2.76	0.0702
Fine soil bulk density			
0–10 cm depth	86×10^{-3}	2.50	0.0896
10–20 cm depth	58×10^{-3}	1.98	0.1465
Soil coarse fraction			
0–10 cm depth	44×10^{-4}	0.49	0.6128
10–20 cm depth	21×10^{-4}	0.20	0.8153
Soil chemistry			
0–10 cm depth			
pH	273×10^{-3}	4.72	0.0121
Organic carbon	18×10^{-3}	8.02	0.0008
Total nitrogen	7×10^{-3}	13.99	0.0001
C/N ratio	312×10^{-3}	0.36	0.6999
Soil chemistry			
10–20 cm depth			
pH	278×10^{-3}	0.69	0.5071
Organic carbon	2×10^{-4}	0.21	0.8081
Total nitrogen	6×10^{-5}	1.20	0.3080
C/N ratio	1	0.80	0.4558
Cone penetrometer			
0 cm	5171	18.93	0.0001
5 cm	92168	24.86	0.0001
10 cm	190391	26.36	0.0001
15 cm	232485	26.23	0.0001
20 cm	205446	21.37	0.0001

MS = mean square

F = MS(treatment)/MS(error)

PR>F = probability value of F-ratio