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Ground-based wet weather yarding operations in coastal British Columbia: Effects on soil properties and seedling growth

J.P. Senyk and D. Craigdallie

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ABSTRACT

A wet weather ground-based yarding operation was studied to determine the impacts of skidders equipped with low ground pressure and conventional tires on soil physical and chemical properties and microclimate. To determine the effect of skidtrails on survival and subsequent growth of planted seedlings, plantations were established on segments of skidtrails in which equipment travel had been monitored and soil properties determined. Seedlings were planted on the track and between track disturbance types, as well as on adjacent undisturbed (non-skidtrail) soils of skidtrail segments on which five levels of equipment travel (<5, 10–15, 30–40, 60–70, and 100+ equipment turns) had been determined for both treatments (low ground pressure and conventional tires). An adjacent area with sharply contrasting soils was included in the study; however, skidder traffic was not monitored.

Total bulk density of the LFH layer (forest floor) and the upper 20 cm of mineral soil increased with increasing intensity of travel. However, no significant differences were found between different skidtrail segments in the low ground pressure (640) yarded treatment. In the conventional tire (740) treatment, significant differences existed between the lower and the highest level of equipment turns.

After the seventh growing season, no significant differences were found in mean height, diameter, or volume of western hemlock and Douglas-fir averaged for the track disturbance type between the 740 and 640 yarded treatments. For the between track disturbance type, no significant differences, in mean height, diameter, or volume of western hemlock were measured between treatments. However, diameter and volume of Douglas-fir were significantly lower on the between track disturbance type in the 640 treatment.

Height, diameter, and volume of western hemlock in both treatments were lowest on the 100+ turn trail segment and highest on the <5 turn segment. For Douglas-fir, similar trends occurred in the 640 treatment. However, in the 740 treatment, the 30–40 turn trail segment had the lowest height, diameter, and volume while the highest height, diameter, and volume were measured on the undisturbed soil. Seedlings planted in undisturbed soils suffered more severe moisture stress than seedlings planted in compacted track soils.

RÉSUMÉ

Des activités de débardage sur un sol par temps humide ont fait l'objet d'études pour déterminer l'impact de débardeuses équipées de pneus classiques et à basse pression au sol sur les propriétés physiques et chimiques du sol ainsi que sur le microclimat. Pour déterminer l'effet des pistes de débardage sur la survie et la croissance ultérieure de semis, on a aménagé des plantations sur des segments de pistes de débardage, où on a fait passer des débardeuses et suivi les propriétés du sol. Des semis ont été plantés sur les pistes, entre les pistes, ainsi que sur les sols voisins non perturbés (autres que des pistes) sur lesquels cinq niveaux de passages de débardeuses (<5, 10-15, 30-40, 60-70 et 100+ rotations) ont été choisis pour les deux traitements. Une zone voisine, aux sols très contrastants, a été incluse dans l'étude sans, cependant, le trafic de débardeuses.

La masse volumique apparente totale de la couche LFH (tapis forestier) et la couche supérieure de 20 cm de sol minéral ont augmenté avec le nombre croissant de passages. Cependant, il n'y avait aucune différence significative entre les différents segments de piste dans le cas du traitement à faible pression au sol (640). Pour le traitement avec les pneus classiques (740), on a constaté des différences significatives entre le minimum et le maximum de passages de débardeuses.

Après la septième saison de croissance, il n'y avait aucune différence significative entre la hauteur, le diamètre ou le volume moyens de la pruche occidentale et du Douglas taxifolié (valeurs moyennées) plantés sur les pistes mêmes, quel que soit le traitement (740 et 640). Dans le cas de la perturbation entre les pistes, aucune différence significative de hauteur, diamètre ou volume moyens n'a été constatée chez la pruche occidentale d'un traitement à l'autre. Cependant, le diamètre et le volume du Douglas taxifolié étaient sensiblement moindres entre les pistes dans le traitement à 640.

La hauteur, le diamètre et le volume de la pruche occidentale dans les deux traitements étaient minimaux pour le segment de piste à 100+ rotations, et maximaux dans le segment à < 5 rotations. Dans le cas du Douglas taxifolié, des tendances semblables ont été constatées dans le traitement à 640. Cependant, dans le traitement à 740, le segment de piste à 30-40 rotations présentait la hauteur, le diamètre et le volume les plus faibles, ces grandeurs étant maximales sur le sol non perturbé. Les semis plantés dans des sols non perturbés subissaient une contrainte moins sévère de l'humidité que les semis plantés dans les sols compactés des pistes.

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INTRODUCTION

Ground-based forestry operations are being applied more and more frequently in coastal British Columbia where timber and terrain conditions allow. A variety of methods and equipment, from horses to rubber-tired and steel-tracked skidders, are being used in partial and clearcut silvicultural systems mainly in second-growth stands, but also in suitable old-growth timber.

Until the early 1950's, ground skidding with large-tracked equipment (bulldozers) was common on all sites and under all weather conditions. As operations moved onto steeper terrain, mobile yarders came into use. During the 1980's, economic conditions, coupled with the emergence of second-growth forests, created renewed interest in ground-based operations. At first, operations were confined only to dry weather conditions. However, if ground-based yarding systems were to be an option for coastal British Columbia, a harvesting season of 9–10 months would be needed for industry to invest in appropriate equipment (Krag 1993). This option would require operating during wet weather and under wet soil conditions. If carefully planned and carried out the ground-based operations should be able to meet the soil disturbance criteria in the Soil Conservation Guidebook of the Forest Practices Code (B.C. Ministry of Forests and B.C. Environment 1995b) and still remain economically viable.

In November 1986, the Canadian Forestry Service (CFS) and the Forest Engineering Research Institute of Canada (FERIC), in collaboration with MacMillan Bloedel Ltd. undertook a study to compare harvesting productivity of rubber-tired skidders mounted with low ground pressure and conventional tires and a grapple yarder, identify site and soil impacts resulting from skidder travel, and monitor climate and seedling performance for a minimum of 5 years after harvest. The grapple-yarded area was not part of this study. The site chosen for the study was comprised of a nearly flat, glacio-fluvial deposit elevated above the valley floor. A small additional study area was located on the valley floor in an area of soils considered relatively sensitive to disturbance. Although no skidder travel was assessed on this area, soil and plantation studies similar to the previous were undertaken on skidtrails where the number of turns had been estimated.

Other cooperators on this project included Department of Fisheries and Oceans, B.C. Ministry of Forests, and B.C. Ministry of Environment, Lands and Parks, all of whom were vitally concerned with the potential on- and off-site environmental impacts.

The goal of the CFS component of this study was to assess the feasibility of yarding coastal forest stands with rubber-tired ground skidders in typical winter weather without creating excessive on- or off-site environmental damage. Specific objectives were to:

1. compare soil impacts resulting from grapple skidders equipped with conventional tires to those resulting from line skidders equipped with low ground pressure (LGP) tires
2. determine the effect of varying traffic intensity on soil bulk density and seedling performance
3. characterize and monitor above- and below-ground microclimate on disturbed and undisturbed soils.

STUDY AREA

Soils and Forest Cover

The study site, a 44.4-ha block, was located immediately to the north of Branch 60 road in the Franklin River Division, MacMillan Bloedel Tree Farm Licence 44 (lat 48°57' N, long 124°31' W) (Figure 1). The area falls within the Coastal Western Hemlock Submontane Very Wet Maritime Variant (CWHvm1) (Green and Klinka 1994).

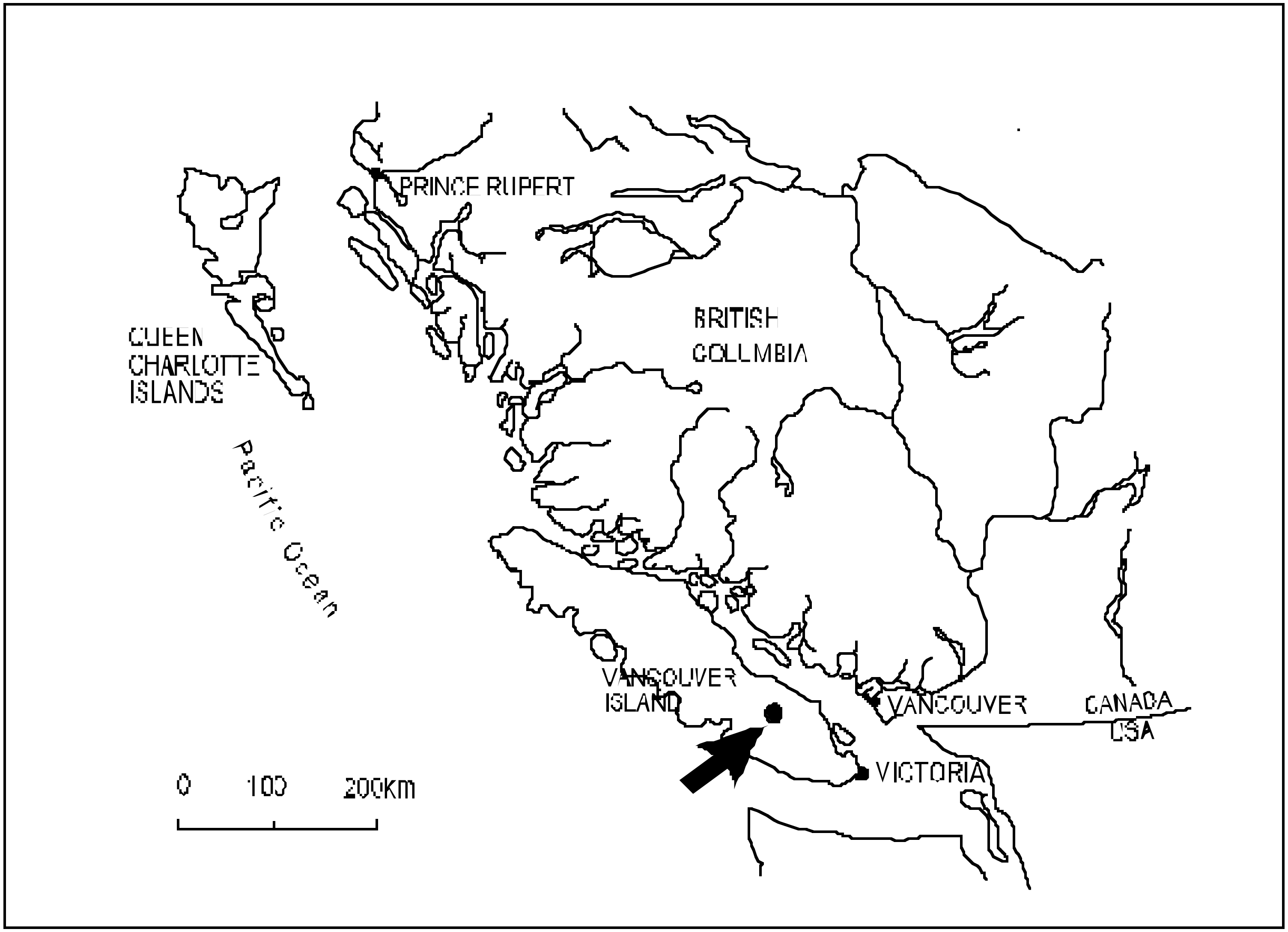

Figure 1. Location of study area (48° 57' lat N, 124° 51' long W)

The largest portion of the study area, about 39 ha, was located on a very gently sloping (<5%) glacio-fluvial terrace or fan deposit, with steeply sloping scarps. Soils were poorly graded very gravelly loamy sand with abundant cobbles, stones, and boulders. Duric Ferro-Humic and Duric Humo-Ferric Podzols of the Honeymoon Soil Association (Jungen 1985) predominated in this portion of the study area. Effective rooting depth was relatively shallow, averaging 50–70 cm (rarely to 100 cm), which coincided with the duric (cemented) horizon. Previous windthrow events resulted in mixed upper soil horizons (silvo-turbated) over much of the terrace area. The normal horizon sequence was displaced, organic matter buried, and voids created within the profile; occasionally, the duric layer itself was fractured. Soil-laden root mats (up to 5 m in diameter) of large windthrown Douglas-fir were scattered throughout.

The Honeymoon soils were rapidly to well drained to the impermeable duric horizon. During periods of heavy rainfall, the horizons above the cemented layer became completely saturated resulting in standing water at the surface and overland flow in a few locations. This period of saturation was relatively brief, given the rapidly drained nature of the soil and the gentle slope.

Charcoal was evident at the LFH-mineral soil interface; however it was easily distinguished only where no turbation had occurred. Earthworms were particularly abundant but confined to the F and H layers. Microtopography was moderately mounded, almost entirely the result of previous windthrow events. Large, downed tree boles (1.5–2 m in diameter), most still solid, occurred sporadically throughout the upper terrace. Rotten wood, frequently covered by an LF layer, was very common.

About 5.4 ha of the study area was located on recent fluvial deposits below the level of the glacio-fluvial terrace. Soils were generally well drained to moderately well drained Orthic Dystric Brunisols and Orthic Regosols, and belonged to the Snuggery Soil Association (Jungen 1985). The LFH layer (3–5 cm thick) was much shallower than on the Honeymoon soils, far less woody organic material was on the surface, and the horizon sequence was far less disrupted. Soil texture was silt loam to silty clay loam with frequent lenses of sand and occasional gravels. There were no apparent limitations to rooting on these soils.

The forest stand consisted of about 31 ha of old-growth, large diameter western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), and Douglas-fir (*Pseudotsuga menziesii*). The remaining 14 ha consisted of 80-year-old western hemlock and amabilis fir (*Abies amabilis*), with diameters ranging from 40 to 70 cm and heights to 30 m. Interspersed throughout the stand were a few very large Douglas-fir (150–200 cm diameter, 45–50 m height and 450- to 480-years-old) and a few old hemlock (80–100 cm diameter). A major windthrow event in 1906 toppled many of the large diameter Douglas-fir and hemlock, allowing the young stand to become established.

Harvesting Procedure

One contractor harvested the entire block. Tree falling started in late December 1986. The large trees were felled, limbed, and bucked manually. Large, sound windfalls common throughout the area were also bucked. The smaller trees were felled with an Antler Creek feller-buncher and skidded before the veteran Douglas-fir were felled.

Two John Deere 640 line skidders, equipped with Firestone 73 X 44-32 tires inflated to pressures of 16 psi or less, were initially used on the trial. These machines were later joined by a John Deere 740B grapple skidder with conventional 28" wide tires inflated to normal pressures and equipped with chains. Occasionally, a Caterpillar D7G or a D8H was brought on site to assist in yarding the larger diameter logs.

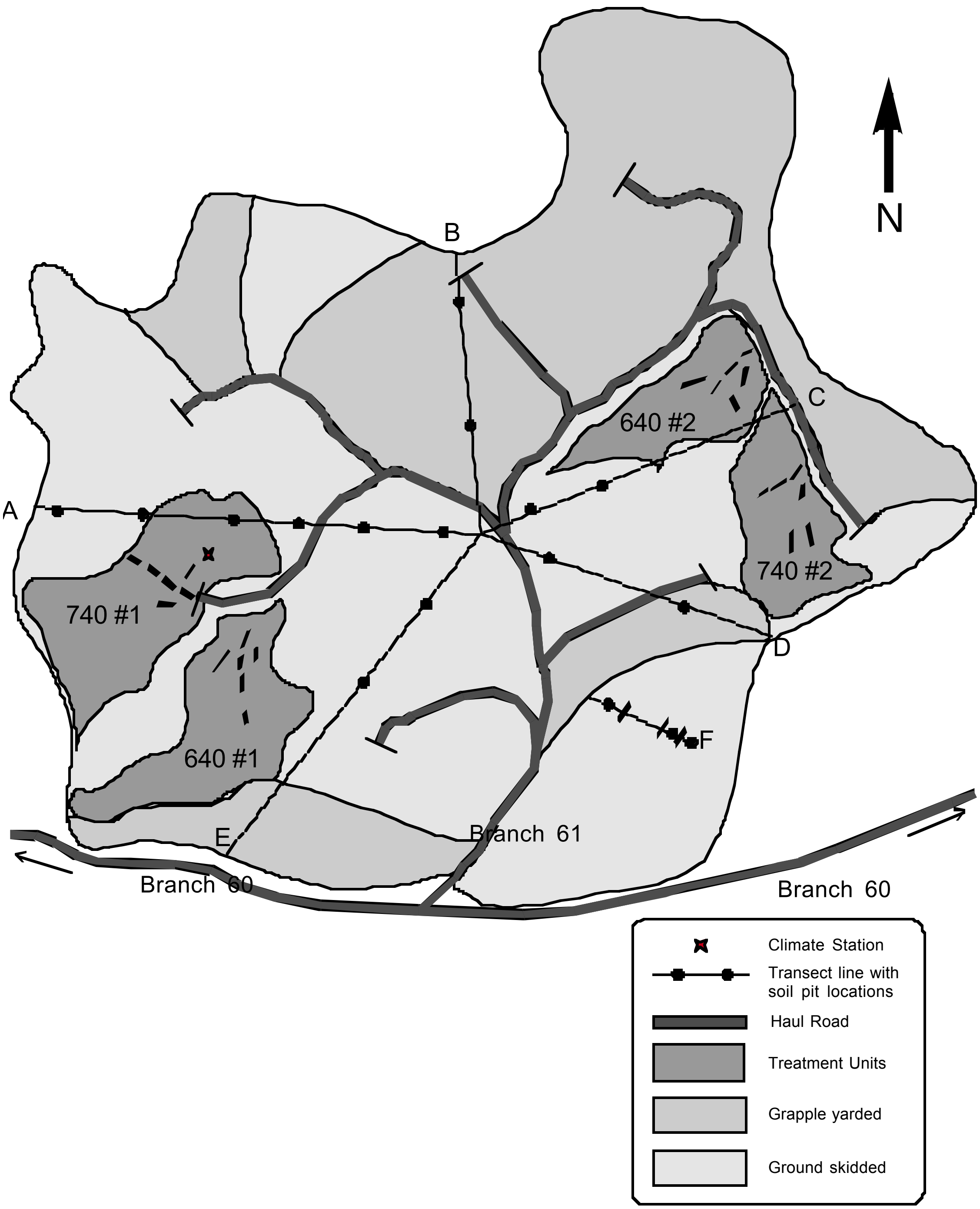

Figure 2. Study areas within cutblock showing roads, transect lines, soil pits, treatments (640 and 740), plantations within treatments, and climate station.

METHODS

Pre-Harvest

Transect Survey

Pre-harvest fieldwork began in mid-November 1986. Five randomly located transect lines radiating to the block perimeter from a central point were established using a hand compass and 100-m tape (Figure 2). These transects were marked at 25-m intervals with wooden stakes. A point-intercept tally of ground surface conditions at 5-m intervals along the transects was carried out (Smith and Wass 1976).

Soil Studies

Soil bulk density sampling began in early December 1986 at randomly selected 25-m points along each transect line on the Honeymoon Soil Association. A total of 14 soil pits were excavated (Figure 2), and bulk density sampling using a sand funnel–excavation technique (Blake and Hartge 1986) was completed by the end of December, just as tree falling was underway. Each pit was sampled to a minimum 50-cm depth if possible, in 10-cm increments, or to a duric layer, whichever came first. The profile for each pit was described briefly (Agriculture Canada Expert Committee on Soil Survey 1987). No pre-harvest sampling was undertaken on the lower terrace (Snuggery soils). The samples collected for bulk density calculations were also used for chemical analyses, (carbon, nitrogen, C/N ratio, and pH) (McKeague [editor] 1978). Bulk density figures for the humus and mineral soil were calculated for the total soil and fine soil fraction (< 2 mm diameter). Coarse fragment content of each bulk density sample was determined by sieving and weighing. The Bouyoucos hydrometer method was used to determine soil texture (McKeague [editor] 1978).

Climate

A Campbell Scientific 21X data logger equipped with a tipping bucket rain gauge was established immediately south of the cutblock (off-site) on January 16, 1987, shortly before yarding operations began. Precipitation alone was monitored at this site during active yarding (January–May 1987).

Harvest and Post-Harvest

After falling but before yarding, two separate 4-ha areas (trial blocks) were identified on the upper terrace Honeymoon soils (Figure 2). These two areas were divided approximately in half. Each half or treatment unit was yarded using one of the following two skidder types: (1) JD 640 line skidder equipped with a winch, chokers, and LGP tires (referred to as 640 in following text); and (2) JD 740 grapple skidder equipped with conventional tires and chains (referred to as 740 in following text). The area outside the trial blocks was ground skidded using both skidder types; the steeper topography and the terrain that sloped towards Worthless Creek were grapple-yarded (Figure 2).

Yarding was carried out from January to May 1987 in random trail or dispersed fashion. FERIC mapped skidding patterns and identified skidtrail cross-sections based on the number of loaded skidder trips (Krag 1993). These skidtrail cross-sections were later grouped into five broad categories of traffic intensity (i.e. <5, 10–15, 30–40, 60–70, and 100+ equipment turns). Each cross-section was marked and referenced. Skidtrails were not similarly assessed on the Snuggery soils where yarding was completed using mostly the LGP skidder.

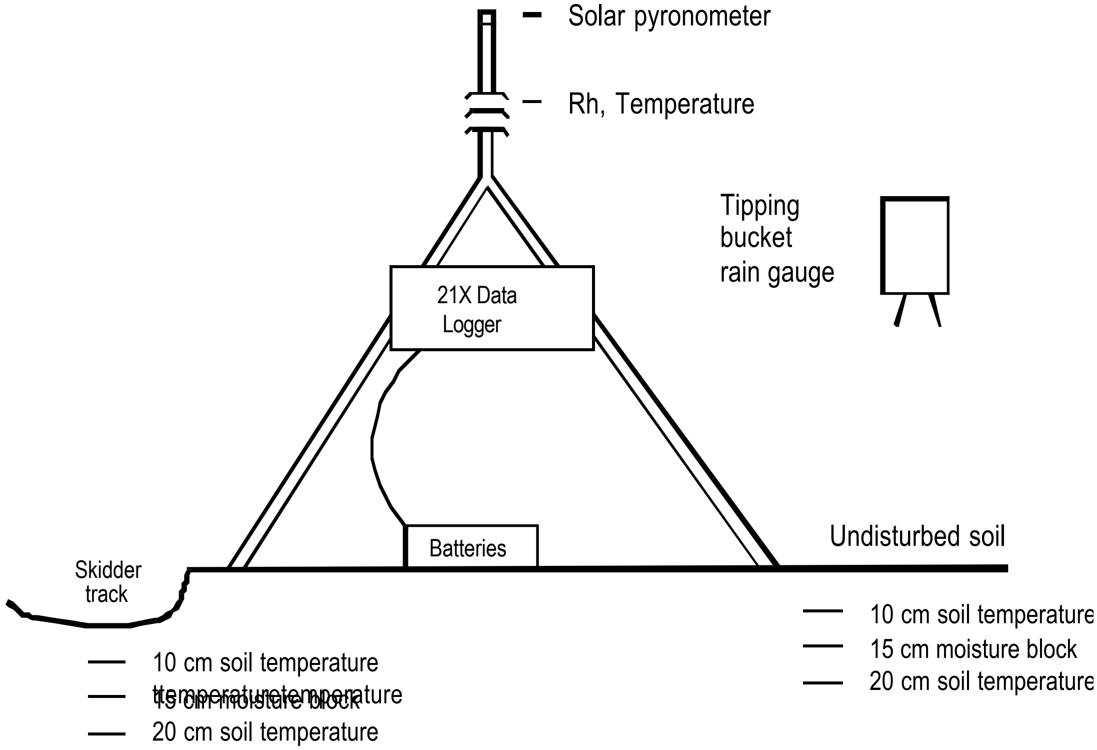

Figure 3. Climate station showing location of sensors

Climate

When yarding was completed, the climate station was moved to the upper terrace and located adjacent to plantations in the 740 #1 area (Figure 2) so that sensors could be positioned to monitor both disturbed (30–40 equipment turns) and undisturbed soils (Figure 3). Besides the tipping bucket rain gauge, sensors were added to monitor below-ground temperatures at 10 and 20 cm and moisture at 10 cm in both undisturbed and track positions. A solar pyronometer, and air temperature and relative humidity sensors were also installed.

Transect Survey

After harvesting, the pre-harvest transect lines were relocated and a point intercept tally which replicated as closely as possible the pre-harvest survey was carried out. A new transect line (F) was added on the recent fluvial deposits of the lower terrace. This latter transect served to locate soil bulk density sampling sites for undisturbed soils, skidtrail tracks, and plantation sites (Figure 2).

Soil Studies

Post-harvest soil bulk density was sampled from July to November 1987. Twenty soil pits were excavated and sampled on the upper terrace (10 in the 740 treatment and 10 in the 640 treatment). Within each treatment replicate, five pits were sampled one pit at each cross-section identified by turn counts (i.e. <5, 10–15, 30–40, 60–70 and 100+). Soils were sampled in 10-cm increments to a minimum 50-cm depth, or to the duric layer, whichever came first. At each cross-section, both track and between track positions of the skidtrail were sampled. At the same time, three pits were sampled on the lower terrace: one in undisturbed (non-skidtrail) soils and the other two on skidtrails at points where equipment passed or turn counts were estimated.

Plantations

In March 1988, seedlings were planted by a contractor at pre-determined spots in segments of skidtrail identified by number of equipment turns and in the adjacent undisturbed soil. As sections of skidtrails having a uniform number of equipment passes were very short, each plantation trial was limited to 15 seedlings: five on each track and five in the between track position. An equal number of seedlings was planted in the undisturbed soil adjacent to the skid trail trials. Seedlings were planted at approximately 1-m spacing. Since 1+0 plug western hemlock and 2+0 bareroot Douglas-fir stock had been prescribed for the operational planting, the same stock and species were used in the trials. The species were assigned random positions in a proportion of about 85% western hemlock (12–13 seedlings) to 15% Douglas-fir (2–3 seedlings), as in the operational prescription. In total, 405 seedlings were planted in 1988: 360 in the skidder trials on the upper terrace and 45 on the lower terrace. In 1991, 30 additional western hemlock seedlings (1+0) were planted on the lower terrace, expanding the total number of seedlings for all trials to 435.

Monitoring and Maintenance

The site has been visited every spring and fall since establishment. During the first 3 years after establishment (1989, 1990, and 1991), dead seedlings were replaced each spring with 1+0 plug western hemlock stock supplied by MacMillan Bloedel Ltd. Seedlings were remeasured annually to year 5 then again at year 7. At each measurement total height and basal diameter were measured and health and vigor were assessed. The 1995 measurement marked the seventh growing season for seedlings planted in 1988; only these seedlings are used in the analyses in this study. The climate station has been serviced every spring and fall since establishment. Manual vegetation control was undertaken in 1991 on all plantation trials.

Data Analyses

Statistical comparisons for ranges of means were conducted using analysis of variance (ANOVA) followed by the Student-Newman-Keuls' multiple range test (p=0.05) (Zar 1974; SAS Institute Inc. 1985).

RESULTS

Soil Disturbance Transect Surveys

316 ground-surface points were assessed in the pre-disturbance point-intercept survey taken along the radiating transects (Figure 2). Of these, 307 points (97%) were classed as undisturbed. Of the total 316 points, 133 (42%) had greater than 50% (by volume) rotten wood and bark within the LFH layer, 174 points (55%) were typical LFH, and only nine points (3%) were exposed mineral soil and surface rock that resulted from windthrow.

Post-harvest levels of soil disturbance were assessed in a similar fashion to the pre-harvest procedure. The transects were re-established as close as possible to the pre-disturbance transect positions. Of the 316 points sampled, 67% had visible signs of disturbance that resulted from log drag or equipment travel; however, only 11% of the points had ruts between 5 and 25 cm deep into the mineral soil and 7% had ruts deeper than 25 cm. The number of points that had rotten wood or bark in the LFH layer increased slightly from 42 to 49%, over the undisturbed due mainly to a spreading effect and a slight decrease in average depth of the humus layer from 21.5 to 19.6 cm. The number of points that had surface slash cover (all sizes) increased sharply from almost 0 to 23%.

Soil Characteristics

Texture of the Honeymoon soils was very gravelly loamy sand with a sand content from 55 to 76% and clay ranging from 4 to 15%. Coarse fragment content (>2 mm) averaged over 70% in the entire profile. Boulders and cobbles were common. The humus form was a Humimor (Klinka et al. 1981). The pH ($CaCl_2$) of the mineral soil tended to increase with depth while percentage organic carbon and nitrogen and C/N ratio tended to decrease (Table 1).

Snuggery soil textures ranged from silt loam to loam with frequent lenses of sand and gravel. Percentage of sand averaged about 30% (4–46%), clay 12% (3–28%), and silt 58%. Coarse fragment content (>2 mm) was generally less than 10% to a depth of 70 cm, except where a sand-gravel lens was encountered. As with the Honeymoon soils, pH tended to increase with soil depth while percentage organic carbon, percentage nitrogen and C/N ratio tended to decrease (Table 1).

Soil Bulk Density

The average pre-harvest or undisturbed total and fine soil bulk density, percentage pore space, and moisture and coarse fragment content for the Honeymoon soils (samples from Transects A to E) are shown in Table 2. As expected, total and fine soil bulk density increased with depth in the soil profile while percent pore space and moisture content (gravimetric measurement) decreased. Coarse fragment content was relatively uniform throughout the profile; however, the size of coarse fragments (>25 mm) increased slightly with depth.

Post-harvest total soil bulk density at 0–10 cm was highest on the tracks in both treatments in the 30–40, 60–70 and 100+ turn skidtrail segments; however, in no case were these values significantly higher at the 0.05 level than the undisturbed soil (Table 3). Undisturbed percent pore space in the upper 20 cm of mineral soil in both treatments was greater than in the 30–40 and 100+ turn skidtrail segments, respectively (Table 4). Percent moisture content in the upper 20 cm of mineral soil decreased with depth on the undisturbed soil and 30–40 turn skidtrail segment and increased on the 100+ turn segment in the 640 treatment. In the 740 treatment percent moisture content decreased with depth in the undisturbed soil and the 100+ turn skidtrail segment while it increased on the 30–40 turn segment . Only the undisturbed soil showed a decreasing trend in percent moisture with depth (Table 5).

On the lower terrace (Snuggery Soil Association), pre-harvest conditions were not sampled. Total and fine soil bulk density on undisturbed soil and on the track, and the percentage difference between the two are shown in Table 6. Inherent total and fine soil bulk density, which are nearly identical (except for the 10- to 20-cm depth where a sand lens was encountered), increased with depth. Percent pore space and field moisture content decreased with depth while coarse fragment content was very low and remained relatively constant through the profile (Table 7).

Seedling Growth

At the time of planting, no significant differences were found in the size (height, root collar diameter) of either western hemlock or Douglas-fir seedlings among skidtrail segments with different traffic intensities (turn counts), disturbance types, or treatments. Seedling survival after the seventh growing season is shown in Table 8.

The best survival of western hemlock in treatments 640 and 740 on the upper terrace was on the undisturbed soil (survival of seedlings planted on the track ranged from 45 to 85% of those on undisturbed soil). On the lower terrace (Transect F), survival was best on the between track disturbance type. Douglas-fir survival was highest on the between track disturbance type in the 640 treatment, highest on the undisturbed soil in the 740 treatment and on the between track position on Transect F.

Seedling Performance by Treatment

No significant difference in mean height, diameter, or volume of Douglas-fir was found between treatments or disturbance types within or between treatments. Although not significant, Douglas-fir had greater mean height, diameter, and volume on all disturbance types in the 740 treatment than in the 640 treatment (Figures 4–6). Mean height, diameter, and volume of western hemlock showed no significant difference between disturbance types within and between treatments. Although the differences were not significant, height, diameter, and volume of western hemlock growing on undisturbed soil were greater in the 740 treatment than in the 640 treatment (Figures 7–9).

Seedling Performance by Disturbance Types

Within the 640 treatment, height and diameter of western hemlock seedlings were significantly greater on the <5 turn skidtrail segment than on the undisturbed, 30–40 turn, and 100+ turn skidtrail segments. Volume was significantly greater on the <5 turn than on all except the 60–70 turn skidtrail segment. Height and diameter were significantly lower on the 100+ turn skidtrail segment than on all other turn counts. Volume was significantly lower on the 100+ turn skidtrail segment than on the <5 turn and 60–70 turn trail segments (Figures 10–12).

On the 740 treatment the height of western hemlock seedlings was significantly lower on the 100+ turn skidtrail segment than on all other segments except the 60–70 turn segment; seedling diameter and volume on the 100+ turn segment were significantly lower than on the <5 and 10–15 turn segments (Figures 13–15).

There was no significant difference in Douglas-fir seedling height, diameter, or volume between skidtrail segments with different turn counts in the 640 and 740 treatments (Figures 16–21).

On Transect F (Snuggery soils on the lower terrace), 7-year height of western hemlock on the track and between track disturbance types was less than on undisturbed soil. Diameter was greatest on the track while volume was greatest on undisturbed soil. For Douglas-fir, height was nearly the same on undisturbed soil and between track disturbance types and was least on the track. Diameter and volume were highest on the between track and undisturbed and lowest on the track (Table 9). However, none of the differences was significant.

Climate

The mean, maximum, and minimum monthly air temperatures at 1.3 m are shown in Table 10. Maximum air temperatures approaching 40°C occurred in July, August, and September. Minimum temperatures below -10°C occurred during November, December, January, and February. Snow cover was generally light and rarely lasted long. The last spring frost at 1.3 m can occur in May and the earliest fall frost in September. Mean annual temperature and growing degree days >5°C at 1.3 m are shown in Table 11. Mean annual temperatures were extremely uniform, averaging about 10°C (Table 11).

Ground level (seedling environment) temperature data were not collected. Air temperature near the ground surface generally varies more diurnally and annually than air temperatures at 1.3 m (Spittlehouse and Stathers 1990).

Total yearly solar radiation shows little variation from 1988 to 1994, averaging about 3800 MJ/m^2 per year, (Table 11). Total mean monthly solar radiation (Table 10) increases gradually each month, peaks in July at over 600 MJ/m^2 then drops off rapidly in October to less than 100 MJ/m^2 during November, December, and January. Total annual rainfall over a 4-year period ranged from 295 to 360 cm (Table 11). Total rainfall (monthly averages) is highest in November (about 65 cm) and slightly less in December and January. It averages about 4 cm in July and 12 cm or less during June, August, and September (Table 10).

Low and infrequent precipitation coupled with peak solar radiation levels during the summer growing period (May to September) would tend to maximize transpiration and evaporation rates, creating periods of seedling moisture stress (Spittlehouse and Stathers 1990).

Mean monthly soil moisture block readings, averaged from 1988 to 1994 for both the skidtrail and undisturbed soil, are shown in Table 10. Seedlings growing on both the skidtrail track and in the undisturbed soil are never subjected to severe moisture stress; however, during June, July, August, and the early part of September, water potentials can approach 3 bars. Moisture retention in a compacted, coarse-

textured soil can be higher than in the same undisturbed (non-compacted) soil (Froehlich and McNabb 1984). As indicated, the soil moisture block results support these findings.
Mean monthly soil temperatures at -10 cm and -20 cm for undisturbed soil and track positions are shown in Table 10. Skidtrail track temperatures are consistently higher than temperatures at corresponding depths in undisturbed soil. Averaged annually, the track is about 4°C warmer than undisturbed soil at a 10-cm depth; the difference in temperature is only slightly less at a 20-cm depth (Table 11).

DISCUSSION AND CONCLUSIONS

Soils

Honeymoon soils had a moderate susceptibility to forest floor displacement and exposure of unfavourable substrate (cemented or duric layer); low susceptibility to compaction, surface erosion, and mass wasting; and hence an overall low potential for detrimental disturbance from ground-based yarding (Lewis et al. 1991; B.C. Ministry of Forests 1994; B.C. Ministry of Forests and B.C. Environment 1995a). Inherent total bulk density of the mineral soil varied considerably; it was relatively high at the surface and increased with depth in the profile. Fine soil bulk density was low and remained relatively constant with depth. Given the poorly sorted nature of the surficial deposit, its high coarse fragment content and pervious nature, it is unlikely that moisture content contributed to the severity of soil compaction to any extent. Similar results could likely be expected had the soil been dry (Froehlich and McNabb 1984; Rollerson 1989).

Inherent soil bulk density in the Honeymoon soils varied greatly from one location to another (0.8–1.4 Mg/m^3 and 0.9–1.6 Mg/m^3 at the 0–10 cm and 10–20 cm levels, respectively). This result, coupled with the frequent turbated soils and subsurface voids, and variation in slash cover, humus depths, and root mat, resulted in highly variable background conditions that did not always react predictably to increasing traffic. Only at the high end of turn numbers were bulk densities increasing with increasing traffic. Rollerson (1989) found that background variation in the soils often masked trends of increasing bulk density with increasing traffic up to a point.

Soil disturbance directly related to feller-buncher traffic was not assessed except where it may have been overridden by skidder traffic. Visual observations confirmed that severe soil disturbance (displacement) resulted during feller-buncher operation, mainly at turning points. The extremely coarse-textured (coarse fragments around 70%), highly turbated Honeymoon soils on the upper terrace made soil bulk density sampling procedures very difficult. Factors such as voids, cobbles, and root channels added to the variability of the final results.

Substantial increases in total soil bulk density at the 0–10 cm depth, reaching a level considered critical to normal root development of about 1.4 Mg/m^3 and greater (Heilman 1981) in both treatments, occurred at about the 30–40 and greater turn level. Total percentage pore space did not drop much below the 50% level considered optimal for plant growth (Glinski and Lipiec 1990), and did not approach the threshold levels (27–30%) considered limiting to root development (Heilman 1981). At the 10–20 cm and 20–30 cm depth, only the 740 treatment showed a consistent increase in bulk density at 60–70 and 100+ turns. No significant differences were found in the degree of compaction by turn count between treatments. The wide tire (LGP) equipped skidders did not appear to offer an advantage over the skidders equipped with conventional tires and chains in the prevention of soil compaction on the Honeymoon soil.

The Snuggery soils had an overall moderate potential for detrimental disturbance given their medium to high susceptibility to compaction, puddling, and forest floor displacement; moderate susceptibility to surface erosion; and low susceptibility to mass wasting (Lewis et al. 1991; B.C. Ministry of Forests 1994;

B.C. Ministry of Forests and B.C. Environment 1995a). Due to the relatively fine, uniform texture of the parent material, inherent total and fine soil bulk densities were similar. Total soil bulk density of the track estimated at less than 30 passes was about 17% higher than that in undisturbed soil in the upper 30 cm.

In wide-tire skidder trials on northern Vancouver Island, Rollerson (1989) found that bulk density in the tracks on soils with a similar texture to the Snuggery soils was about 15% higher than in undisturbed soil for the upper 30 cm. According to Froehlich (1979), this kind of increase in soil bulk density can reduce seedling height growth by 10–20%. However, predicting long-term growth losses or gains based on soil bulk density is often unreliable.

On Transect F (Snuggery soils), the increase in total soil bulk density in the track over the undisturbed soil was 10% at the 0–10 cm depth, increased to 24% at 10–20 cm depth and 16% at the 20–30 cm depth. Compaction to a depth of about 30 cm was clearly evident in these relatively fine-textured soils. Total percentage pore space decreased by 4%, 11%, and 8% at the above depths, respectively. Despite the relatively deep ruts (20–25 cm), soil bulk density did not approach the levels considered potentially detrimental to tree root development (about 1.4 Mg/m^3), nor did total soil porosity percentage approach levels considered detrimental to root growth.

Given the random or dispersed nature of the ground-based yarding operation, repeated travel over the same ground occurred only near spur haul roads where wood was decked or delivered directly to the processor. Towards the outer boundaries of the cutblock, travel was minimal. Slash cover, relatively thick LFH layer, and the existing shallow root mat on the Honeymoon soils provided initial support (floatation) for equipment. After a number of passes over the same piece of ground (approximately 15–17, varying with skidder type), the humus was compacted, the slash and root mat were broken down, and the mineral soil became impacted. Dispersed skidder travel on the Honeymoon soils minimized potentially detrimental disturbance.

On the Snuggery soils, trees were more deeply rooted and the LFH layer thinner than on the Honeymoon soils so that, except for the slash cover, the mineral soil was more susceptible to compaction and showed signs of rutting and compaction after one or two skidder passes. Using dispersed skidtrails on these soils created potentially detrimental disturbance over a broader area than if designated skidtrails had been used.

With increasing equipment travel on the Honeymoon soils, the LFH layer, which often contained an abundance of rotten wood, was pulverized and mixed with the top few centimetres of organic-rich mineral soil in wheel ruts. This mixing was pronounced after 30 passes and was particularly evident during periods of high rainfall, which were frequent during the early yarding operations. This saturated mixture of organic material and mineral soil would be displaced by the skidder tires only to flow back into depressions once the equipment had passed. Upon drying, this "slurry" or "puddled" material covered parts of skidtrails, particularly sections of wheel ruts in depressions, to depths of 20 cm. Characteristically, the bulk density of this "puddled" material (organic-mineral soil mixture) was low and the percent porosity and moisture content high. The bulk density of these "puddled" soils was frequently much less than the bulk density of the upper 20 cm of undisturbed mineral soil. The bulk density of the puddled material in the tracks was considerably higher than the undisturbed LFH bulk densities. These differences show up clearly in Table 3, particularly in the 640 treatment at the 20–10 cm and 10–0 cm soil depths.

On the lower terrace (Snuggery soils), rutting was severe on the well-travelled trails; however, extensive puddling was not common. This part of the block was logged during April and May, when soils were relatively dry.

In many cases, total soil bulk density in the track at the 0–10 cm depth was less than that at the 10–20 cm depth, opposite to what one might expect. This result probably reflects the incorporated humus material at the surface as previously mentioned.

Seedling Growth

The poor physical condition of soils (compacted, occasionally puddled) on the tracks of the 640 and 740 treatments and Transect F was probably responsible for the poor survival rates of western hemlock seedlings compared to those planted on undisturbed soil and the between track positions. Similar trends for Douglas-fir occurred except on Transect F where survival on undisturbed soil was the lowest. On Transect F, the highest survival of both western hemlock and Douglas-fir occurred on the between track disturbance type. Soils were only slightly impacted in this portion of the skidtrail and competition from vegetation during the first few years after planting was minimal, allowing seedlings to become established without serious impediments.

Average height, diameter and volume of western hemlock in the 640 treatment (track, between track, and undisturbed soil) were greatest on the <5 turn skidtrail segment and least on the 100+ turn segment. Results in the 740 treatment were similar except that the growth on the 10–15 turn segment was nearly identical to the <5 turn segment. For Douglas-fir, trends were similar on the 640 treatment. However, in the 740 treatment, height, diameter, and volume were greatest on the undisturbed and least on the 30–40 turn trail segment.

This result could indicate that actual mineral soil compaction was minimal at these lower impact levels (due to the slash layer and shallow root mat). Given the porous nature of the soil, availability of moisture was more of limiting factor to tree growth than was aeration. Some soil consolidation from compaction (collapsing voids and a percentage of the macro-pores) may have improved moisture holding capacity while maintaining adequate aeration porosity for tree root development.

The inherent low water storage capacity of the Honeymoon soils placed seedlings under only minimal moisture stress during extended dry periods from June through September in most years. Moisture retention, however, increased in compacted and puddled soils. Seedlings planted in tracks were not subject to the same moisture stress as those planted in the undisturbed soil. However, poor aeration resulting from reduced pore space, coupled with increased moisture retention, can be detrimental to root growth, especially if flooding occurs and soils remain saturated for extended periods (Van Miegroet et al. 1994).

One of the 740 treatments was located beside a drainage channel that flooded during heavy rains. This factor, as well as the decreased permeability and reduced infiltration capacity that resulted from skidder traffic, often caused seedlings in this treatment to become partially submerged for short periods during the winter months. In 1990, the haul road that separated the 640 and 740 treaments was extended to allow for timber harvesting adjacent to the study block along the western boundary. During this extension, the existing haul roads were upgraded and the access to skidtrails entering haul roads was removed by piling soil and debris at the trail entrances. Consequently, natural drainage channels were dammed. On the 740 treatment mentioned above, prolonged flooding of a number of trials resulted in heavy seedling mortality.

The relative differences in height and diameter for both western hemlock and Douglas-fir after one growing season (Senyk 1990; Senyk and Smith 1991) were maintained through the seventh growing season except on the undisturbed soil. Percentage gains in height have declined on the undisturbed soil relative to the average height for all disturbance types on the skidtrail segments. In the 640 treatment, after 1 year, height of western hemlock on the heavily (100+ turns), moderately (30–40) and least (<5) impacted skidtrail segments was 53%, 38%, and 20% less respectively, than the height of seedlings growing on undisturbed soil. After 7 growing seasons, these differences had declined to 33% of the undisturbed on the 100+ turn segment and 6% on the 30–40 turn segment. On the <5 turn segment, seedlings were actually 28% taller than those on the undisturbed soil. In the 740 treatment, height of western hemlock after the first growing season was 52% less than the height on the undisturbed soil for the 100+ turn segment, 49% less on the 30–40 turn segment, and 37% less on the <5 turn segment. After 7 years, the difference remained the same on the 100+ turn segment but had decreased to 17% on the 30–40 turn segment. On the <5 turn segment seedlings were about 3% taller than on the undisturbed soil.

On the Snuggery soils, the average height and volume of western hemlock after 7 years was greatest on the undisturbed soil while Douglas-fir growth was greatest on the skidtrail. On the Honeymoon soils, the relative difference in growth rates between undisturbed soil and the skidtrail had decreased. After the first growing season, height of western hemlock on the skidtrail was 32% of that on undisturbed soil. By the end of the seventh growing season, height on the trail had increased to 56% of that on undisturbed soil.

Decreasing differences in seedling growth with time on disturbed soils relative to undisturbed soils have been reported previously (Smith and Wass 1976; Senyk and Smith 1991). These differences may be attributed to increasing vegetation competition on the undisturbed soils, natural soil amelioration in disturbed soils, and root migration to more favourable physical and nutritional conditions in the undisturbed soils adjacent to the skidtrail.

The reliability of growth rate projections based on tree measurements taken on different disturbance types will vary considerably and largely depend on tree age at the time of measurement. Projections based on measurements taken early in the plantation could overestimate actual growth reductions expected at harvest (Smith and Wass 1976; Thompson et al. 1990; Senyk and Smith 1991).

Management Considerations

Poorly sorted glacio-fluvial deposits with characteristics similar to those of the Honeymoon Soil Association have a low sensitivity to soil degrading processes. Impacts on long-term forest productivity resulting from ground-based forest operations on these soils are likely to be minimal and the potential for erosion and off-site sediment transport negligible, regardless of soil moisture conditions or weather during operations. Using a dispersed or random skidtrail pattern, particularly suited to grapple skidders, will have less impact on these soils than concentrating travel on a few skidtrails.

Soils with characteristics similar to the Snuggery Soil Association have a moderate to high sensitivity to soil degradation resulting from ground-based forest operations. Operating on these soils during wet weather will severely impact soil properties and create the potential for erosion and sediment transport both on- and off-site. Pre-locating skidtrails, using line skidders equipped with LGP tires, and operating when soil conditions are dry will reduce considerably the negative impacts on soil properties and long-term forest productivity.

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Table 1. Selected chemical properties for Honeymo…

Soil depth (cm)		-30–-20	-20–-10	-10–0	0–10	10–20	20–30	30–40	40–50	50–60
Carbon (%)	HM*	46.2	49.3	30.4	7.5	5.5	4.6	4.6	4.1	3.1
	SG**	-	-	-	2.3	1.5	1.2	1.1	0.8	0.6
Nitrogen (%)	HM	0.770	0.520	0.765	0.209	0.167	0.104	0.140	0.104	0.095
	SG	-	-	-	0.10	0.07	0.06	0.06	0.04	0.03
C/N ratio	HM	60.5	56.4	40.3	34.3	45.3	33.3	34.3	31.9	33.0
	SG	-	-	-	23.0	21.4	20.1	18.3	20.2	20.0
pH ($CaCl_2$)	HM	2.72	2.93	3.34	4.04	4.46	4.79	4.84	4.85	5.15
	SG	-	-	-	4.54	4.48	4.74	4.85	5.26	5.12

Table 2. Soil properties by depth on Transects A to E, Honeymoon Soil Association

Soil depth (cm)	Total bulk density (Mg/m^3)	Fine bulk density (Mg/m^3)	Pore space (%)	Moisture content (%)	Coarse fragment >2 mm (%)
30–20	0.14	0.12	95	255	-
20–10	0.33	0.10	88	73	-
10–0	0.49	0.16	82	103	-
0–10	1.11	0.44	60	28	71
10–20	1.21	0.50	56	24	72
20–30	1.31	0.50	52	21	76
30–40	1.33	0.50	51	22	76
40–50	1.44	0.51	47	18	79
50–60	1.67	0.69	39	13	78

Table 3. Total soil bulk density by treatment, soil depth, and number of turns on the Honeymoon Soil Association

			Total soil bulk density Number of turns				
Treatment	Soil depth (cm)	Undisturbed	<5	10–15	30–40	60–70	100+
640	20–10	0.33	-	0.43	-	-	0.95
	10–0	0.49	0.37	0.67	0.95	0.69	0.66
	0–10	1.11 a*	1.26 a	1.08 a	1.40 a	1.44 a	1.51 a
	10–20	1.21 a	1.26 a	1.22 a	1.27 a	1.74 a	1.28 a
	20–30	1.31	1.48	1.42	1.43	1.27	1.20
	30–40	1.33	1.54	1.62	1.26	1.53	1.44
	40–50	1.44	1.67	–	1.23	–	–
	50–60	1.67	1.61	–	–	–	–
740	20–10	0.33	–	0.29	–	–	–
	10–0	0.49	–	0.70	–	–	0.63
	0–10	1.11 ab	0.87 b	0.91 b	1.32 ab	1.38 ab	1.52 a
	10–20	1.21 ab	1.03 b	1.32 ab	1.28 ab	1.48 ab	1.68 a
	20–30	1.31	1.07	1.37	1.25	1.66	1.68
	30–40	1.33	1.10	–	–	1.52	1.59
	40–50	1.44	1.17	–	–	1.62	–
	50–60	1.67	1.27	–	–	1.40	–

* Values associated with the same letter are not significantly different at the 0.05 level.

Table 4. Percent pore space by depth, treatment and a moderate and high number of turns compared to undisturbed soil on the Honeymoon Soil Association

Treatment	Soil depth (cm)	Number of turns		
		Undisturbed	30–40 turns	100+ turns
640	20–10			
	10–0	80.8	65.3	75.8
	0–10	59.5 a*	48.7 a	44.7 a
	10–20	55.6 a	53.4 a	53.1 a
	20–30	51.9	47.6	56.2
	30–40	51.3	54.0	47.4
740	20–10			
	10–0			
	0–10	59.5 a	51.8 a	44.5 a
	10–20	55.6 a	53.3 a	38.4 b
	20–30	51.9	54.5	38.5
	30–40			

* Values associated with the same letter are not significantly different at the 0.05 level.

Table 5. Percent moisture content by treatment, depth and a moderate and high number of turns compared to undisturbed soil on the Honeymoon Soil Association

Treatment	Soil depth (cm)	Number of turns		
		Undisturbed	30–40 turns	100+ turns
640	20–10			
	10–0	89.8	40.7	91.4
	0–10	28.1 a*	26.7 a	17.6 a
	10–20	24.4 a	27.3 a	36.0 a
	20–30	21.3	22.0	36.5
	30–40	21.6	26.2	21.9
740	20–10			
	10–0			
	0–10	28.1 a	24.9 a	23.8 a
	10–20	24.4 b	37.5 a	18.4 b
	20–30	21.3	36.0	16.9
	30–40			

* Values associated with the same letter are not significantly different at the 0.05 level.

Table 6. Average post-harvest total and fine soil bulk density and percentage differences (by soil depth) for undisturbed and track disturbance types on the Snuggery Soil Association

Soil depth (cm)	Total bulk density			Fine bulk density		
	Undisturbed (Mg/m^3)	Track (Mg/m^3)	Difference (%)	Undisturbed (Mg/m^3)	Track (Mg/m^3)	Differenc e (%)
0–10	0.66	0.73	10	0.61	0.66	9
10–20	0.80	1.00	24	0.54	0.97	81
20–30	0.85	0.99	16	0.85	0.95	12
30–40	0.93	0.97	04	0.90	0.90	0
40–50	1.14	1.02	–	1.13	1.01	–
50–60	1.46	1.05	–	1.46	1.01	–
60–70	1.41	1.26	–	1.40	1.21	–

Table 7. Average post-harvest pore space, field moisture content, and coarse fragment content (>2 mm) for undisturbed and track disturbance types on the Snuggery Soil Association

Soil Depth (cm)	Pore space (%)		Field moisture (%)		Coarse fragment (%)	
	Undisturbed	Track	Undisturbed	Track	Undisturbed	Track
0–10	76	73	81	60	10	12
10–20	71	64	73	55	41	4
20–30	69	64	61	59	1	5
30–40	66	64	50	60	5	10
40–50	58	63	31	52	1	3
50–60	46	62	14	50	1	6
60–70	48	54	14	34	1	6

Table 8. Seedling survival by species, disturbance type, and treatment (7-year data)

Species/ treatment	Disturbance type		
	Undisturbed	Track	Between track
Western hemlock			
640 treatment (%)	85	72	65
740 treatment (%)	89	47	66
Transect F (%)	64	29	100
Douglas-fir			
640 treatment (%)	75	68	86
740 treatment (%)	100	73	82
Transect F (%)	50	85	100

Table 9. Seedling height, diameter, and volume (cc) growth on Transect F (Snuggery Soil Association) (7-year data)

	Undisturbed	Track	Between Track
Western hemlock			
Height (cm)	314.7 a*	180.5 a	175.0 a
Diameter (cm)	35.1 a	39.0 a	36.2 a
Volume (cc)	1376 a	847 a	779 a
Douglas–fir			
Height (cm)	373.5 a	337.0 a	383.9 a
Diameter (cm)	59.8 a	50.6 a	66.4 a
Volume (cc)	3880 a	3139 a	5010 a

* Values associated with the same letter are not significantly different at the 0.05 level.

Table 10. Monthly averages for selected climatic parameters (1987–1994)

Month	Air temp. (°C) Mean	Max.	Min.	Solar radiation (W/m^2)	Rainfall (cm)	Soil temp. (°C) -10 cm control	-10 cm under trail	Soil temp. (°C) -20 cm control	-20 cm under trail	Soil m...
Jan.	4.0	17.0	-12.0	70	54	7.2	4.0	6.8	4.0	.4
Feb.	4.5	23.0	-10.0	150	37	7.2	4.2	6.8	4.0	.4
Mar.	6.0	27.0	-7.0	270	34	9.0	6.5	8.5	6.0	.4
Apr.	9.0	29.0	-3.0	380	28	13.0	9.0	12.0	8.5	.35
May	12.0	33.0	-1.0	520	14	17.0	11.5	15.0	11.0	.35
June	14.0	36.0	2.0	560	12	18.5	13.5	17.0	13.0	.35
July	17.0	38.0	4.0	620	4	21.0	15.5	20.0	14.5	.4
Aug.	17.5	38.5	5.0	550	12	22.0	16.0	21.5	15.5	1.0
Sept.	14.2	28.0	-1.0	430	7	19.6	14.6	19.0	14.0	.5
Oct.	10.5	30.0	-6.0	220	24	15.3	12.0	14.0	11.5	.35
Nov.	7.5	18.0	-10.0	80	67	11.5	8.5	11.0	7.5	.35
Dec.	4.0	15.0	-13.0	50	45	8.0	5.6	7.5	5.5	.35

Table 11. Mean annual totals of selected climatic parameters (1988–1994)

	1988	1989	1990	1991	1992	1993
Mean annual temp. (°C at 1.3 m)	9.90	9.90	9.95	10.10	10.80	9.95
Growing degree days >5°C	1900	2020	2100	2050	2300	2060
Solar radiation (Mj/m^2)	3800	3900	3700	3800	3950	3600
Rainfall (cm)	330	——	——	360	340	295
Soil temp. (°C)						
– 10 cm track	14.2	14.1	13.9	13.9	15.2	13.9
– 10 cm undisturbed	10.2	9.8	9.8	10.0	11.0	9.8
Soil temp. (°C)						
– 20 cm track	12.8	12.8	13.8	13.9	14.8	13.7
– 20 cm undisturbed	10.1	9.7	9.8	9.7	10.5	9.2

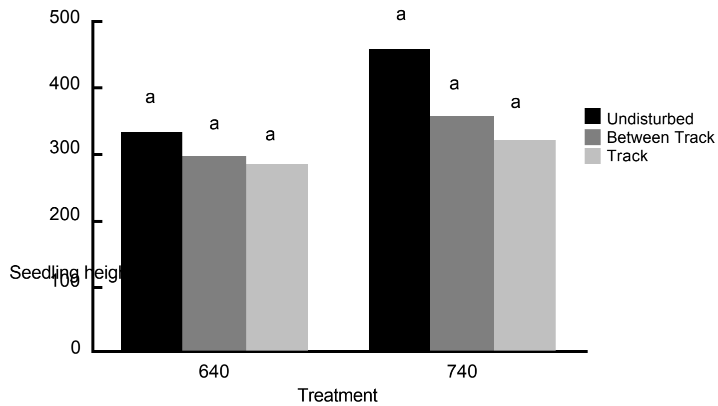

Figure 4. Douglas-fir height (7-year data) by disturbance type averaged for treatments. As represented by bars, means within treatments associated with the same letter are not significantly different at the 0.05 level.

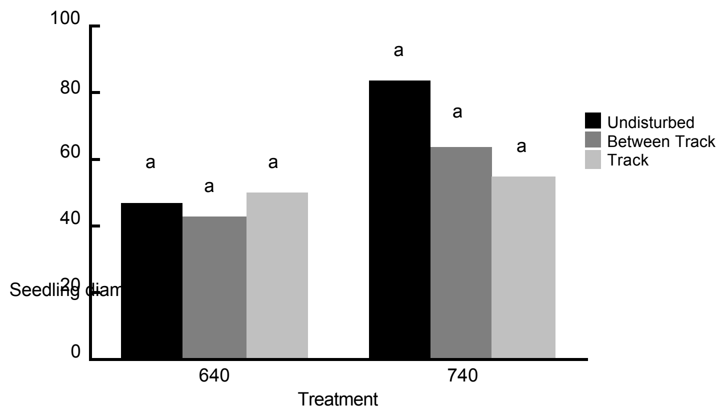

Figure 5. Douglas-fir diameter (7-year data) by disturbance type averaged for treatments. As represented by bars, means within treatments associated with the same letter are not significantly different at the 0.05 level.

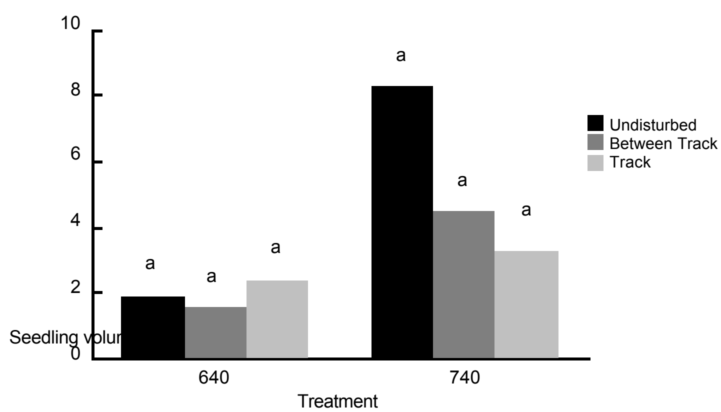

Figure 6. Douglas-fir volume (7-year data) by disturbance type averaged for treatments. As represented by bars, means within treatments associated with the same letter are not significantly different at the 0.05 level.

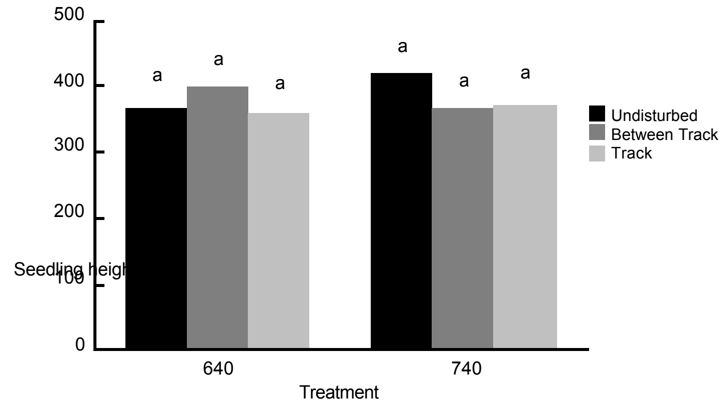

Figure 7. Western hemlock height (7-year data) by disturbance type averaged for treatments. As represented by bars, means within treatments associated the same letter are not significantly different at the 0.05 level.

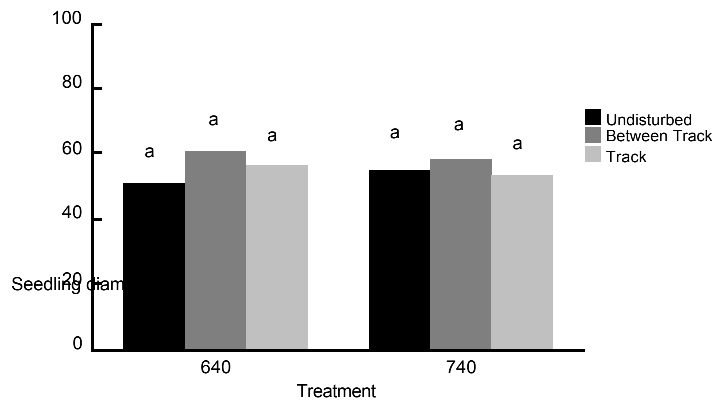

Figure 8. Western hemlock diameter (7-year data) by disturbance type averaged for treatments. As represented by bars, means within treatments associated with the same letter are not significantly different at the 0.05 level.

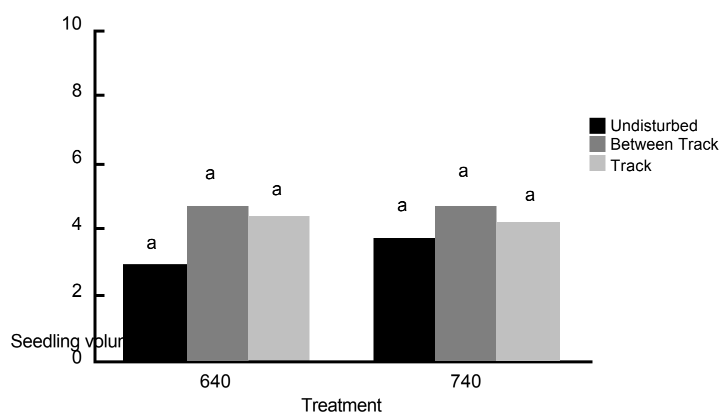

Figure 9. Western hemlock volume (7-year data) by disturbance type averaged for treatments. As represented by bars, means within treatments associated with the same letter are not significantly different at the 0.05 level.

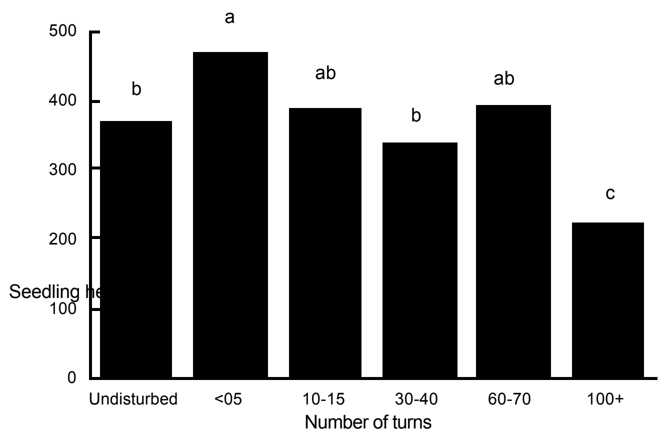

Figure 10. Western hemlock seedling height (7-year data) by turn groups for the 640 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

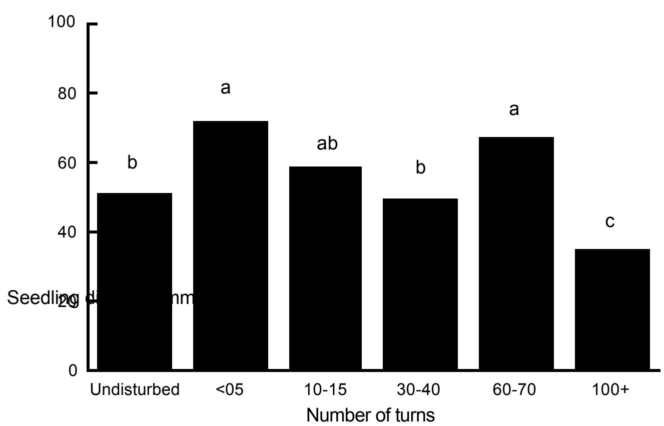

Figure 11. Western hemlock seedling diameter (7-year data) by turn groups for the 640 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

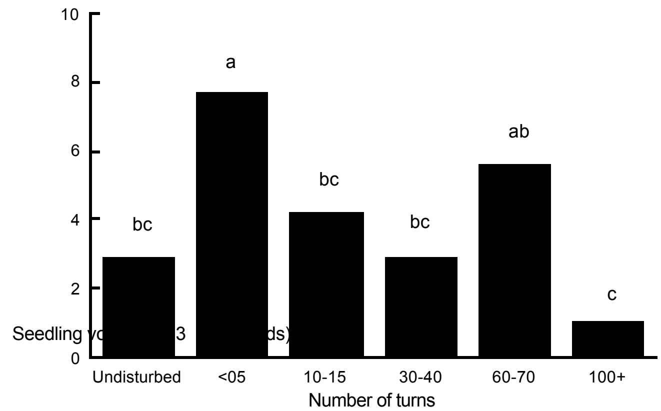

Figure 12. Western hemlock seedling volume (7-year data) by turn groups for the 640 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

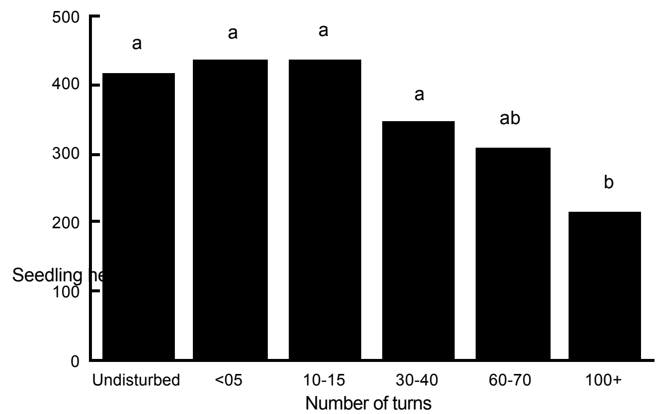

Figure 13. Western hemlock seedling height (7-year data) by turn groups for the 740 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

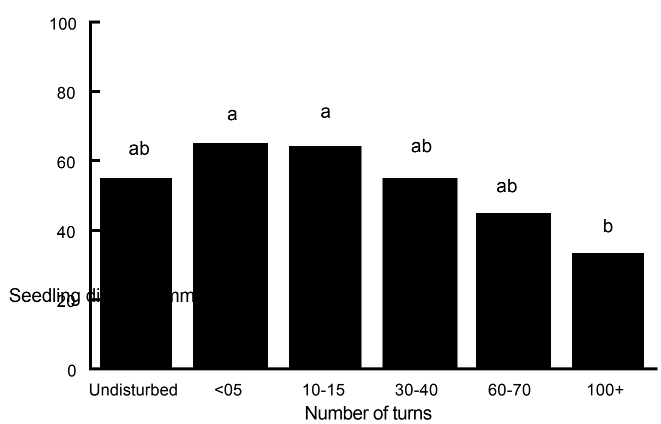

Figure 14. Western hemlock seedling diameter (7-year data) by turn groups for the 740 treatment. As represented by bars, means with the same letter are not significantly different at the 0.05 level.

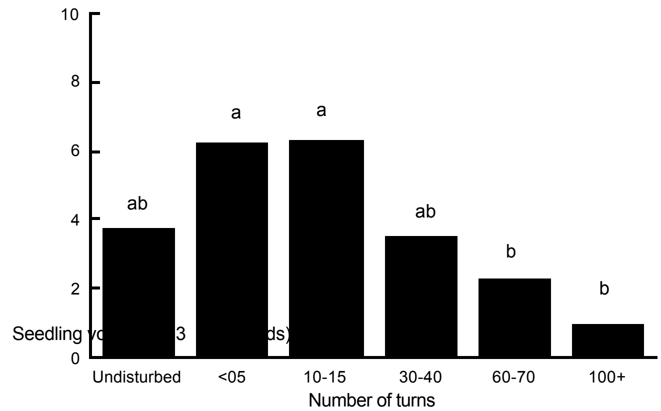

Figure 15. Western hemlock seedling volume (7-year data by turn groups for the 740 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

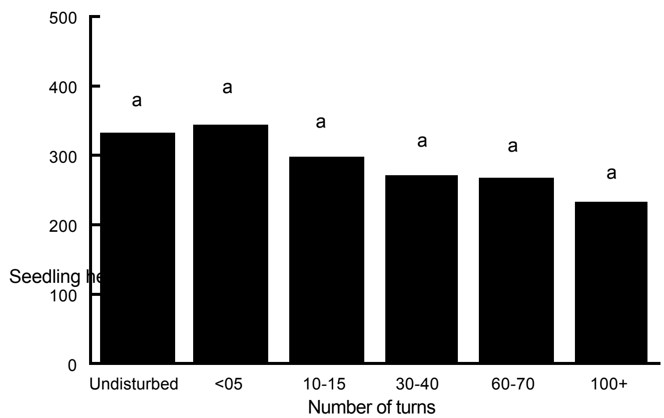

Figure 16. Douglas-fir seedling height (7-year data) by turn groups for the 640 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

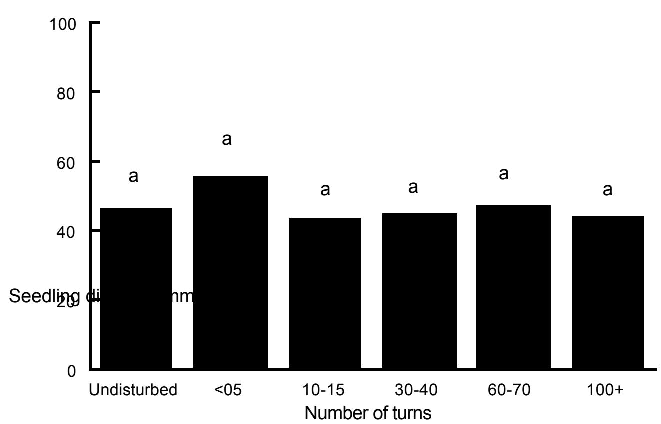

Figure 17. Douglas-fir seedling diameter (7-year data) by turn groups for the 640 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

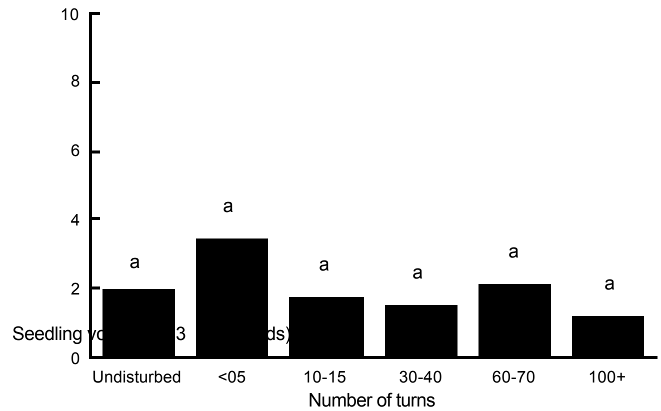

Figure 18. Douglas-fir seedling volume (7-year data) by turn groups for the 640 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

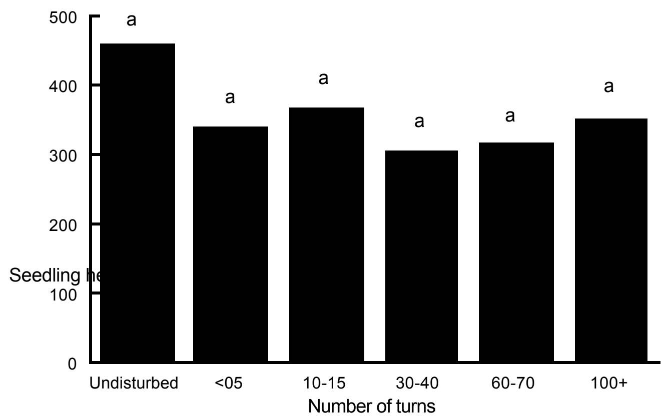

Figure 19. Douglas-fir seedling height (7-year data) by turn groups for the 740 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

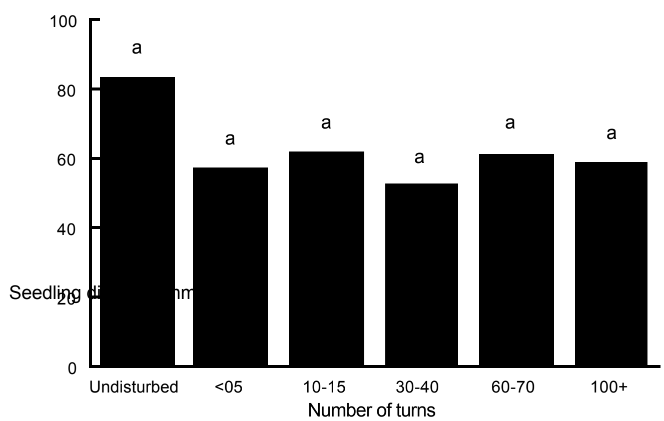

Figure 20. Douglas-fir seedling diameter (7-year data) by turn groups for the 740 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.

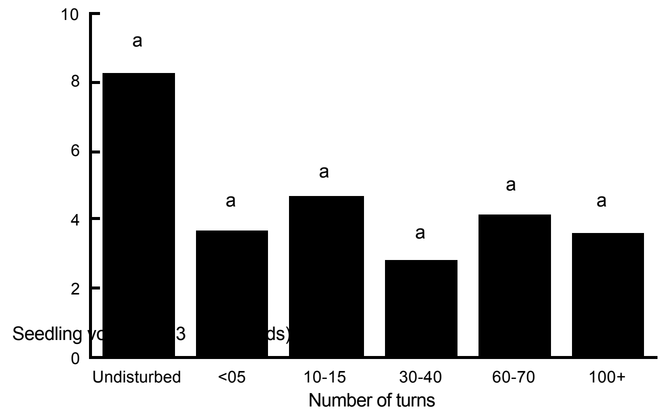

Figure 21. Douglas-fir seedling volume (7-year data) by turn groups for the 740 treatment. As represented by bars, means associated with the same letter are not significantly different at the 0.05 level.