Mechanical disturbance impacts on soil properties and lodgepole pine growth in British Columbia's central interior

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Blouin, V. M., Schmidt, M. G., Bulmer, C. E. and Krzic, M. 2005. **Mechanical disturbance impacts on soil properties and lodgepole pine growth in British Columbia's central interior.** Can. J. Soil Sci. **85**: 681–691. Forest landings are areas located adjacent to haul roads where harvested trees that were skidded from the cutblock are processed and loaded onto trucks. Soils on landings are often excessively compacted by heavy timber harvesting machinery and may take many years to recover from such disturbance. This study examined soil properties and tree growth on unrehabilitated landings (with and without natural regeneration) and adjacent naturally regenerated clearcuts in the central interior of British Columbia (BC), 23 yr after landing construction. Landings (both with and without natural regeneration) had less favorable conditions for tree growth than did clearcuts, including significantly greater surface soil bulk density and mechanical resistance (on some dates) and lower total porosity and concentrations of C and N. Landings without natural regeneration had the least favorable soil conditions, which may account for the lack of natural regeneration. Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) growing on portions of the landings did not differ in height from those growing in adjacent clearcuts. Site index, as estimated using the growth intercept method, did not differ between naturally regenerated landings (21.7 m) and clearcuts (22.0 m), suggesting that the soils may be equally capable of supporting productive forests.

Key words: Forest soil disturbance, soil mechanical resistance, soil productivity, soil water content, natural regeneration

Blouin, V. M., Schmidt, M. G., Bulmer, C. E. et Krzic, M. 2005. **Incidence des perturbations mécaniques sur les propriétés du sol et sur la croissance du pin tordu dans la région centrale intérieure de la Colombie-Britannique**. Can. J. Soil Sci. **85**: 681–691. Les jetées forestières sont contiguës aux chemins d'exploitation. Les troncs qui y sont amenés de la zone de coupe sont conditionnés à cet endroit puis chargés sur des camions. Le sol des jetées est souvent compacté à l'excès par la machinerie lourde qui sert à récolter le bois et maintes années s'écoulent parfois avant qu'il s'en remette. La présente étude portait sur les propriétés du sol et la croissance des arbres sur les jetées non restaurées (avec et sans régénération naturelle) et sur les zones de coupe à blanc adjacentes qui se sont régénérées d'elles-mêmes dans la région centrale intérieure de la Colombie-Britannique, 23 ans après l'édification des jetées. Les jetées (avec ou sans régénération naturelle) offrent des conditions moins favorables à la croissance des arbres que les zones de coupe à blanc, entre autres un sol de surface à masse volumique apparente significativement plus élevée, une résistance mécanique nettement plus grande (à certaines dates) ainsi qu'une plus faible porosité totale et concentration de C et de N. Le sol des jetées sans régénération naturelle présente les conditions les plus défavorables, ce qui explique peut-être l'absence de repousse naturelle. Les pins tordus (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) poussant à certains endroits des jetées avaient la même hauteur que ceux poussant dans les zones de coupe à blanc adjacentes. L'indice du site, estimé par la technique des points d'intersection de la courbe de croissance, est le même pour les jetées naturellement régénérées (21,7 m) que pour les zones de coupe à blanc (22,0 m), signe que les deux types de sol conviennent au développement d'une forêt productive.

Mots clés: Perturbation des sols forestiers, résistance mécanique du sol, productivité du sol, teneur en eau du sol, régénération naturelle

Landings, haul roads, and skid trails are constructed and used to access timber-harvesting sites. Soils on these areas are often extensively degraded due to excessive traffic loads that may be even higher than those normally experienced on public roads. Landings are areas located adjacent to the haul roads where harvested trees that were skidded from the forest are processed and loaded onto trucks (McNabb 1994). Degradation of soils on landings from compaction and topsoil removal may be so extensive that replanting in these areas is often not carried out (Bulmer 2000), in which case, the land is lost from the productive forest land base (Grigal 2000).

Landings, roads, and other access structures associated with forest harvesting are estimated to occupy approximately 3.1% of the timber harvesting land base in the Williams Lake Timber Supply Area of central interior British Columbia (BC Ministry of Forests 2001a). McNabb (1994) suggested that in the mid-1980s as much as a quarter of harvested blocks in west-central Alberta could be composed of roads and landings, but that modern harvesting techniques led to reduced amounts of disturbance related to access construction. In British Columbia, introduction of the Forest Practices Code in 1994 brought about regulations limiting

Abbreviations: **AWSC**, available water storage capacity; **CCT**, naturally regenerating clearcuts; **LNG**, landings with no natural regeneration; **NRL**, landings with natural regeneration the amount of permanent access areas (roads and landings) to 7% of the harvested area in most cases (BC Ministry of Forests 2001b). BC's Forest and Range Practices Act was implemented in 2004 as a replacement to the Forest Practices Code and maintains environmental standards for soil conservation, including default standards for soil disturbance related to permanent access. Rehabilitation of access areas that are no longer needed could make them available for tree growth and increase long-term timber production.

Forest soil rehabilitation practices in BC include restoration of drainage patterns, tillage, topsoil conservation and replacement, establishing cover crops, and application of soil amendments (e.g., woodchips, well-rotted sawdust, or organic residues from processing facilities). These practices are carried out to improve soil conditions and tree growth on sites that have experienced soil degradation. Soil rehabilitation techniques are expensive to implement and the most efficient use of rehabilitation would occur when techniques are prescribed based on actual soil conditions, rather than management history. For this reason, information on soil conditions and tree growth response is needed for access areas that were rehabilitated and also for those that were not. Identification of the most appropriate soil and vegetation indicators is essential for evaluating rehabilitation success.

Determining soil conditions responsible for reduced productivity on soils that have experienced mechanical disturbance is difficult since properties such as texture, soil mechanical resistance, and soil water content are interrelated (Greacen and Sands 1980). When soils are compacted, root growth is mechanically impeded, limiting access to water and nutrients, and reducing plant productivity. The plant response may be more dependent on the extent to which soil-water relationships are affected by compaction than on absolute changes of soil physical properties (Unger and Kaspar 1994; Gomez et al. 2002). Consequently, soil compaction effects on tree growth can be interpreted in terms of plant and soil air-soil water relationships. In this regard, integrating parameters such as least limiting water range (LLWR), relative bulk density, and compression index have been used (Carter 1990; Håkansson 1990; da Silva et al. 1994). Topp et al. (1997) and Håkansson and Lipiec (2000) indicated that the integration of parameters provides a strong link between soil responses to machinery traffic and plant response to the resulting conditions.

Several studies carried out in BC have sought to better understand the effect of compaction on soil properties and forest productivity on landings. Research by Plotnikoff et al. (2002) and Bulmer and Krzic (2003) examined soil properties of landings and adjacent clearcuts in the Interior Cedar Hemlock and Boreal White and Black Spruce biogeoclimatic zones, respectively. Both studies showed that rehabilitation techniques, which included winged subsoiling and seeding of grass-legume mixes, created conditions suitable for establishment of new forest on sites that otherwise would be considered non-productive. Reclamation was less successful on landings with >20% clay (Plotnikoff et al. 2002) emphasizing the challenges associated with restoring productivity to finer-textured sites. These two studies also highlighted the importance of developing rehabilitation prescriptions that consider local site conditions. Our study examined the effects of mechanical disturbance on soil properties in the context of an absence of rehabilitation practices on landings that were much older (23 yr) than landings in the studies mentioned above.

The objective of this study was to determine the effect of mechanical disturbance on tree growth and soil properties on unrehabilitated landings with and without natural regeneration and adjacent naturally regenerated clearcuts in the central interior of BC.

MATERIALS AND METHODS

Study Sites

Three sites were selected from reforested cutblocks in the Sub-Boreal Spruce biogeoclimatic zone (Meidinger and Pojar 1991). Study sites were located at Lynes Creek (52°19′23″N, 122°6′18″W). The mean annual air temperature is 3.4ºC, while annual precipitation is 460 mm (Steen and Coupé 1997). The soil is from the Alix soil association with sandy-skeletal glaciofluvial parent material and is classified as Orthic Dystric Brunisol (Lord and Walmsley 1988). The sites sampled in this study were within pockets of low stone-content soil.

This study was carried out on portions of landings with natural regeneration (NRL), on portions of landings with no natural regeneration (LNG), and on adjacent naturally regenerating clearcuts (CCT). Landing construction occurred in the winter of 1978 and landings in this study ranged in area from 0.13 to 0.29 ha. Stands on all sites were harvested by clearcutting in winter 1978–1979 and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) regenerated naturally on these areas. In 1994, portions of the stands in the clearcuts were spaced. The three study sites were selected using the following criteria:

1. landings were, for the most part, not rehabilitated, although small patches on two of the landings were tilled with a Bobcat tractor (these areas were not sampled);
2. sites were virtually free of coarse fragments, which allowed for soil mechanical resistance to be determined, and for the collection of undisturbed soil samples using a core sampler;
3. natural regeneration of lodgepole pine occurred on a portion of landing edges adjacent to clearcuts; and
4. sites were accessible by 4 × 4 vehicle.

Measurements

In late spring of 2002, one plot was located in each of three disturbance types (LNG, NRL, CCT) at two study sites and in each of two disturbance types (NRL, CCT) at the third study site. For each plot, five circular 0.005-ha subplots were systematically located 10 m apart along a transect running through the plot. Measurements of bulk density and soil chemical properties were made for five of the subplots per plot. All other measurements were made on three subplots per plot. For each subplot, forest floor depth was measured and percentage cover of coarse woody debris (diameter > 7.5 cm), and ground cover (grass, herb, and shrub) percentages were visually estimated during the summer of 2002. Other than landing construction, no other disturbance had taken place on the landings to influence the amount of vegetative or downed wood cover. Codominant and dominant trees (not damaged or suppressed) on the NRL and CCT subplots were counted to determine the tree density. Tree height, diameter at breast-height (dbh), and tree age were recorded for three to ten dominant and codominant trees per subplot. Site index equations were used to determine a 50-yr site index value for each subplot, based on the growth-intercept method (Nigh 1999).

Soil bulk density was determined in August 2002 on undisturbed soil cores (Blake and Hartge 1986) collected using a drop-hammer sampler with a 10-cm-diameter by 7-cm-deep core. At each of the subplots, two cores were taken at 2–9 cm depth, while one core was taken at 12–19 cm depth. Bulk density samples were air-dried and sieved to remove coarse fragments greater than 2 mm. A subsample of each sample was used to determine an oven-dry weight of the soil and this was used to calculate the bulk density for the air-dried samples. The air-dried samples were used for analysis of soil chemical properties. Fine fraction soil bulk density was calculated as the oven-dry mass of the fine soil fraction per volume of field-moist soil, where volume was also determined on a coarse-fragment free basis (Blake and Hartge 1986). Soil particle size distribution was determined on samples obtained at 2–9 and 12–19 cm depths using the hydrometer method (Kalra and Maynard 1991).

In June 2002, composite samples (ca. 30 kg each) of mineral soil were collected at each plot to determine maximum bulk density of the fine fraction using the standard Proctor test (American Society for Testing Materials 2000). This soil was air-dried, passed through a 4.75-mm sieve, and water was added to a 2.3-kg subsample of the dry, sieved sample until it neared the anticipated water content of maximum bulk density. The water content at which maximum bulk density was achieved (i.e., critical water content) is typically slightly less than the plastic limit. The critical water content was initially estimated by hand test. Once critical water content was determined, four more sub-samples were prepared, two with water content below and two with water content above this value. The five moistened samples were then left in sealed plastic bags to equilibrate overnight. The soil was compacted in a standard (9.43×10^{-4} m^3) mold using a 2.5-kg rammer falling freely from a height of 0.3 m. The soil was added to the mold in three layers and 25 blows of the rammer were applied to each layer. Total compactive effort applied to the sample was 600 kN m m^{-3} (or 595 kJ m^{-3}). Relative bulk density was calculated as a percentage by dividing field bulk density (determined by core method) by the maximum (Proctor) bulk density, where both field and Proctor bulk densities were corrected to a fine (<2 mm) fraction basis.

Smaller cores (5 cm diameter by 2 cm deep) of undisturbed soil were collected using a drop-hammer sampler for water retention analysis. At each of the subplots, two cores were taken at 4–6 cm and one at 14–16 cm depth and analyzed to determine soil water content at –5, –10, –33, –300, and –1500 J kg^{-1} with a pressure plate apparatus (Klute 1986). Following the analysis, the soil cores were sieved and fine soil fraction was used to calculate total porosity, aeration porosity (air-filled porosity at field capacity water content; Hillel 1982), water content at 10% air-filled porosity (calculated as the total porosity minus 0.10), and available water storage capacity (AWSC, calculated as the difference between water content at –10 J kg^{-1} and –1500 J kg^{-1}).

Soil mechanical resistance (Bradford 1986) was measured on five dates (2002 Jun. 05 and 25, Aug. 12, and Oct. 03, and 2003 Sep. 23) using a Rimik CP20 digitally recording cone penetrometer (Agridry Rimik PTY Ltd., Toowoomba, Queensland, Australia). The recording cone penetrometer had a cone base of 13 mm and cone angle of 30° and was equipped with a data logger. Readings were stored at 1.5-cm increments down to a depth of 20 cm or until large roots, buried logs or rocks were encountered. Penetration data were recorded for the soil profile on each subplot at each date. Three measurements were taken per subplot. On the same five dates, soil mechanical resistance was recorded at a 10-cm depth using a smaller, hand-held penetrometer that consisted of a force gauge (HFG-44, Transducer Techniques, Temecula, CA) with a 12-cm shaft ending in a 30° cone (4 mm base). A shovel was used to expose a fresh face of the mineral soil in a small soil pit. The hand-held penetrometer was inserted into the horizontal face at a depth of 10 cm. Five measurements were taken per subplot.

Volumetric soil water content was measured on the five dates that the soil mechanical resistance measurements were made and on 2002 Sep. 18, using a ThetaProbe soil water sensor model ML2 (Delta T Devices, Cambridge, UK). Volumetric water content was measured at 10-cm depth on the face of the soil pit where soil mechanical resistance was determined with the hand-held penetrometer. Three measurements were taken per subplot.

Air-dried, sieved samples that had been collected for bulk density at 2–9 and 12–19 cm depths were analyzed for total C and N, mineralizable N, available P, exchangeable cations, CEC, and soil pH. Total C and N were determined with high temperature combustion on a Fisons NA-1500 NCS Analyzer (McGill and Figueiredo 1993; Tiessen and Moir 1993). Mineralizable N was determined from ammonium-N in a potassium chloride extract of soil that had been incubated in water for two weeks at 30°C (Keeney 1982). Available P was determined with a Bray P-1 procedure (Kalra and Maynard 1991). Exchangeable ions and CEC were determined by a 0.1 M barium chloride extraction (Hendershot et al. 1993). Soil pH was determined using a 0.01 M calcium chloride solution (Kalra and Maynard 1991).

Statistical Analyses

Soil data were analyzed as a randomized incomplete block design with three replicates for NRL and CCT, two replicates for LNG, and three to five subplots per plot. Tree growth data were analyzed as a randomized complete block design with three replicates and three subplots per plot. The Tukey HSD multiple comparison test was used to determine if differences existed among disturbance types. The JMP Fit model procedure was used (SAS Institute, Inc. 2001) and an α value of 0.10 was considered significant.

RESULTS AND DISCUSSION

Site Conditions

The LNG sites had no forest floor development (Table 1) since the removal of the topsoil during landing construction 23 yr ago. The CCT sites had the thickest forest floors and the NRL had less than half the forest floor depth of the CCT. The non-existent and poor forest floor development on the LNG and NRL sites, respectively, indicates that it may take several decades for the forest floor to develop on these sites. The presence of forest floor on the NRL sites suggests that forest floor development is occurring as the trees and other vegetation grow on these sites. These results are consistent with a study on medium- to coarse-textured soils in the Sub-Boreal Spruce zone of central BC where forest floor cover on bladed treatments was significantly thinner compared with other site preparation treatments 15 yr after stand establishment (Bulmer et al. 1998). Similarly, there was no forest floor development in studies by Plotnikoff et al. (2002) and Bulmer and Krzic (2003) on landings 5 and 7 yr, respectively, after rehabilitation by tillage and forage seeding.

Forest floor removal prevents the formation of stable aggregates and may lead to increased soil erosion (Rab 1996). Decreased nutrient availability and water-holding capacity and increased soil temperature may also occur after topsoil removal (Kranabetter and Chapman 1999; McNabb 1994). In addition, removal of organic matter can affect mycorrhizal colonization of tree roots by removing mycorrhizae inoculates (Perry et al. 1987).

The percentage of coarse woody debris did not differ among the three disturbance types, though there was a trend of greater percent coarse woody debris in CCT than LNG sites (Table 1). Plotnikoff et al. (2002) and Bulmer and Krzic (2003) also found significantly lower amounts of coarse woody debris on rehabilitated landings compared with surrounding clearcuts. Coarse woody debris is thought to be beneficial for long-term growth as it is effective at water retention, which is important for tree roots and ectomycorrhizal fungi during dry periods (Harmon et al. 1986).

Percentage cover of grasses and shrubs was lowest for LNG, intermediate for NRL, and highest for CCT (Table 1). Low grass and shrub cover values on LNG are likely related to poor soil conditions caused by landing construction (discussed below). In spite of the substantial disturbance of soil and vegetation that occurred during landing construction on NRL, grass and shrub cover was able to establish. Though there is a trend for grass and shrub cover values to be lower on NRL than CCT, they are not significantly lower.

Tree Density and Growth

Twenty-three years after landing construction, no trees had regenerated on the LNG sites. On NRL sites, however, lodgepole pine had grown and the density of dominant and codominant trees did not differ significantly from that on CCT sites (Table 2). There was a trend ($P = 0.16$) for NRL to have greater tree density than CCT and this may be related to spacing of portions of CCT that took place in 1994. Both CCT and NRL disturbance types were above the expected minimum stocking standard for coniferous trees of 700 stems ha^{-1} (BC Ministry of Forests 2002).

Height, diameter at breast height, and breast height age for dominant and codominant trees were not significantly different between NRL and CCT disturbance types (Table 2). These results indicate that trees were able to grow as well on portions of the landings (NRL) as in the surrounding clearcuts. There was a weak trend ($P = 0.28$) for breast height age to be greater for CCT than NRL, indicating that it may take trees 2 yr longer to reach breast height on NRL than on CCT. Site index, as estimated using the growth intercept method, did not differ between naturally regenerated landings (21.7 m) and clearcuts (22.0 m), suggesting that the soils may be equally capable of supporting productive forests.

Our results differ from those of previous studies also carried out in British Columbia, which found that trees on rehabilitated landings were significantly shorter than those on plantations (Plotnikoff et al. 2002; Bulmer and Krzic 2003). One reason for the difference in findings may relate to tree age. The trees in our study were 23 yr old, whereas the trees in the previous two studies were 5 and 7 yr old, respectively. It is possible that differences in tree height between landings and the surrounding reforested areas may decrease as trees get older.

Our results also differ from those of Wert and Thomas (1981) who found significantly shorter Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] trees on skid roads as compared with undisturbed areas, 32 yr after harvest. They found that trees growing in skid roads took 4.1 yr longer to reach breast height than those growing in undisturbed areas. Differing results for different studies illustrates that tree growth response is specific to site and soil conditions.

The lack of statistical differences in tree parameters could be related to low power of the statistical tests due to relatively small sample size and high data variability. These differences could be investigated further by making measurements on a larger number of landings; however, it would be challenging to find suitable landings of an age near those in our study.

Particle Size Distribution and Bulk Density

The texture of the soils ranged from loam to sandy loam. No significant differences were found in the percentages of sand, silt, or clay among the three disturbance types at either the surface or subsurface (Table 3). This suggests that the soils developed from similar parent materials, and that removal of upper soil layers during landing construction did not translate into a difference in particle size distribution between landings and clearcuts.

The bulk densities at 2–9 cm depth of the LNG and NRL were significantly greater than that of the CCT (Table 3). The LNG had significantly greater bulk density at 12–19 cm

Table 1. Site conditions and percent cover of non-coniferous vegetation on LNG, NRL, and CCT disturbance types at Lynes Creek, BC

Property	LNG	NRL	CCT	*P* (*F*-test)
LFH (cm)	0.0*c* (0.00)ᶻ	1.7*b* (0.33)	4.0*a* (0.00)	0.0002
Coarse woody debris (%)	2.5*a* (2.5)	5.7*a* (3.8)	13.3*a* (0.9)	0.10
Grass (%)	10.0*b* (3.0)	22.0*ab* (5.9)	39.7*a* (5.4)	0.04
Herb (%)	23.0*a* (0.0)	17.7*a* (2.9)	17.0*a* (5.8)	0.64
Shrub (%)	7.5*b* (0.5)	18.7*ab* (2.3)	35.0*a* (6.8)	0.03

ᶻValues in parentheses are standard errors.
a,b Values in the same row followed by a different letter are significantly different according to Tukey's test ($P < 0.10$).

Table 2. Tree measurements on the NRL and CCT disturbance types at Lynes Creek, BC

Property	NRL	CCT	*P* (*t*-test)
Density (dominants and codominants) (stems/ha)	1855*a* (520)ᶻ	911*a* (160)	0.16
Height (m)	7.9*a* (0.8)	8.9*a* (0.9)	0.44
Dbh (cm)	10.3*a* (1.56)	10.9*a* (1.59)	0.79
Breast height age (years)	12.7*a* (1.45)	14.7*a* (0.67)	0.28
50-yr site index (m)	21.7*a* (0.3)	22.0*a* (0.6)	0.64

ᶻValues in parentheses are standard errors.
a Values in the same row followed by a different letter are significantly different ($P < 0.10$).

depth compared with the CCT. The higher bulk densities on landings than in the surrounding clearcuts are not surprising since these areas were not rehabilitated. Even rehabilitated landings in other studies in BC (Plotnikoff et al. 2002; Bulmer and Krzic 2003) had greater bulk density relative to plantations. Rab (1996) also observed greater bulk density on landing and primary skid trail soils than undisturbed areas of forest in southern Australia. The bulk densities at lower depth on NRL and CCT were not significantly different. This indicates that disturbance may have been less in the NRL portion of the landing than the LNG portion.

Bulk density is slow to change (i.e., recover from mechanical disturbance) and is a widely used property for measuring forest soil compaction (Froehlich et al. 1986; Cullen et al. 1991; McNabb et al. 2001). This static property, however, may not completely describe how soil responds to compaction or its effect on plant growth. Attempts to create standardized values of compaction include the relative bulk density (Carter 1990) and the degree of compactness (Håkansson 1990). Standardized compaction values, as compared with field bulk density, may better describe the state of a soil after compaction, especially regarding the effect of compaction on properties such as aeration, water availability, and mechanical resistance, which are important for plant growth. In our study, maximum (Proctor) bulk density was used as the reference value to determine the relative bulk density.

Maximum (Proctor) bulk density was significantly higher for LNG as compared with CCT (Table 3). Greater organic C content (Table 4) on CCT than either LNG or NRL likely played a significant role in decreasing maximum bulk density values on CCT sites. In our study, the relative bulk density obtained for the LNG disturbance type was approximately 80% at 2–9 cm depth, and 89% at 12–19 cm depth (Table 3). Carter (1990) found that relative bulk density values near 85% were associated with reduced cereal crop yield for sandy loam soils on Prince Edward Island. In addition, da Silva et al. (1994) showed that when relative bulk density exceeded approximately 80%, factors associated with water availability, aeration, and soil mechanical resistance were within the range where reduced plant growth is expected. Values of relative bulk density were 80% or below for NRL and CCT (Table 3).

Soil Water Retention and Porosity

Water content at field capacity and permanent wilting point and AWSC were not significantly different among disturbance types at either depths (Table 5). There was a weak trend for higher water content at permanent wilting point for LNG, indicating that compaction may have somewhat increased the proportion of very small pores. Other studies also found that an increase in the bulk density due to compaction did not affect or only slightly affected the soil's field capacity, permanent wilting point, or AWSC (da Silva et al. 1994; Startsev and McNabb 2001).

Total porosity was significantly different among the disturbance types (Table 5). The LNG had the highest total porosity and CCT had the lowest. There was a trend ($P = 0.17$) for aeration porosity to differ among the disturbance types. Aeration porosity was lower (not significantly) on LNG than NRL and CCT (Table 5), suggesting that there may have been a decrease in large pores on LNG. A number of studies have found that mechanical disturbance decreases aeration porosity. A study on medium-textured soils in Alberta (McNabb et al. 2001) and a study in southeastern Australia on different types of loam soils (Rab 1996) found that aeration porosity decreased with an increase in machine traffic on skid trails. Research by Startsev and McNabb (2001) on Alberta skid trails found that compaction on medium-textured forest soils did not significantly affect the soil's pore size distribution if compaction occurred when the soils were drier than field capacity. Since aeration porosity either was not affected or was fairly minimally affected by mechanical disturbance in our study, landing soils may have been drier than field capacity when they were compacted.

Water content at 10% air-filled porosity was 1.5 times higher for CCT as compared with LNG at both depths (Table 5). This latter finding agrees with other studies that found that increasing compaction generally resulted in a decrease in water content at 10% air-filled porosity (da Silva et al. 1994; Smith et al. 2001).

Soil Water Content

Volumetric water contents measured on two dates in June 2002 did not differ among the three disturbance types (Table 6). However, later in the year (August and October

Table 3. Soil bulk density, maximum (Proctor) bulk density, and percentages of soil mineral particles on LNG, NRL, and CCT disturbance types at Lynes Creek, BC

Property	Depth (cm)	LNG	NRL	CCT	*P* (*F*-test)
Bulk density (kg m^{-3})	2–9	1486*a* (36)[z]	1340*a* (41)	1030*b* (3)	0.04
	12–19	1643*a* (9)	1436*ab* (75)	1247*b* (45)	0.07
Maximum (Proctor) bulk density (kg m^{-3})	0–20	1846*a* (48)	1795*ab* (24)	1713*b* (5)	0.04
Relative bulk density (%)	2–9	80.4	74.7	60.1	–
	12–19	89.0	80.0	72.8	–
Sand (%)	2–9	48*a* (15.5)	51*a* (9.0)	50*a* (5.5)	0.97
	12–19	45*a* (19.5)	48*a* (9.8)	51*a* (3.2)	0.92
Silt (%)	2–9	33*a* (11.0)	33*a* (5.8)	37*a* (4.6)	0.85
	12–19	33*a* (15.0)	34*a* (5.5)	37*a* (3.3)	0.94
Clay (%)	2–9	20*a* (4.5)	17*a* (3.3)	13*a* (0.9)	0.34
	12–19	23*a* (4.5)	17*a* (4.5)	13*a* (0.3)	0.26

[z] Values in parentheses are standard errors.

a,b Values in the same row followed by a different letter are significantly different according to Tukey's test ($P < 0.10$).

Table 4. Soil chemical properties on LNG, NRL, and CCT disturbance types at Lynes Creek, BC

Property	Depth (cm)	LNG		NRL		CCT		*P* (F-test)
Total C (g kg^{-1})	2–9	9.2*b*	(2.6)[z]	9.4*b*	(0.3)	17.0*a*	(0.1)	0.009
	12–19	3.3*b*	(0.2)	5.2*ab*	(0.5)	6.7*a*	(1.1)	0.09
Total N (g kg^{-1})	2–9	0.55*b*	(0.050)	0.47*b*	(0.03)	0.77*a*	(0.07)	0.02
	12–19	0.30*a*	(0.00)	0.33*a*	(0.03)	0.37*a*	(0.03)	0.43
Mineralizable N (mg kg^{-1})	2–9	18.1*a*	(1.3)	14.8*b*	(0.4)	25.1*a*	(0.26)	0.02
	12–19	5.7*b*	(0.3)	7.2*ab*	(0.4)	10.5*a*	(1.4)	0.04
Available P (mg kg^{-1})	2–9	25.6*b*	(5.8)	39.0*ab*	(6.3)	53.7*a*	(1.2)	0.03
	12–19	25.6*b*	(8.7)	35.4*ab*	(2.3)	53.0*a*	(3.8)	0.02
CEC (cmol kg^{-1})	2–9	10.3*a*	(1.5)	8.1*a*	(1.2)	6.5*a*	(0.5)	0.15
	12–19	11.7*a*	(2.3)	8.50*a*	(2.2)	4.9*a*	(0.1)	0.11
Ca (cmol kg^{-1})	2–9	6.4*a*	(0.9)	5.4*a*	(0.6)	4.4*a*	(0.5)	0.19
	12–19	6.9*a*	(1.4)	5.4*a*	(1.2)	3.3*a*	(0.0)	0.13
Mg (cmol kg^{-1})	2–9	3.5*a*	(0.60)	2.2*ab*	(0.5)	1.3*b*	(0.1)	0.05
	12–19	4.4*a*	(0.80)	2.6*ab*	(0.9)	1.0*b*	(0.1)	0.06
K (cmol kg^{-1})	2–9	0.33*a*	(0.034)	0.24*a*	(0.03)	0.25*a*	(0.04)	0.32
	12–19	0.30*a*	(0.012)	0.22*a*	(0.05)	0.18*a*	(0.02)	0.22
Fe (cmol kg^{-1})	2–9	0.001*b*	(0.001)	0.004*b*	(0.001)	0.009*a*	(0.000)	0.003
	12–19	0.009*a*	(0.007)	0.005*a*	(0.002)	0.010*a*	(0.002)	0.44
Mn (cmol kg^{-1})	2–9	0.050*c*	(0.009)	0.136*b*	(0.004)	0.240*a*	(0.029)	0.004
	12–19	0.042*a*	(0.010)	0.083*a*	(0.013)	0.077*a*	(0.024)	0.38
Al (cmol kg^{-1})	2–9	0.027*b*	(0.016)	0.114*b*	(0.037)	0.293*a*	(0.028)	0.005
	12–19	0.038*a*	(0.009)	0.109*a*	(0.035)	0.197*a*	(0.058)	0.15
Soil pH in $CaCl_2$	2–9	5.3*a*	(0.21)	4.8*b*	(0.1)	4.4*c*	(0.04)	0.01
	12–19	5.4*a*	(0.16)	4.9*b*	(0.1)	4.6*b*	(0.1)	0.01

[z] Values in parentheses are standard errors.

a–c Values in the same row followed by a different letter are significantly different according to Tukey's test ($P < 0.10$).

Table 5. Soil physical properties on LNG, NRL, and CCT disturbance types at Lynes Creek, BC

Property	Depth (cm)	LNG	NRL	CCT	*P* (*F*-test)
Total porosity (cm^3 cm^{-3})	4–6	0.42*c* (0.03)[v]	0.48*b* (0.02)	0.55*a* (0.007)	0.007
	14–16	0.45*b* (0.05)	0.50*b* (0.01)	0.58*a* (0.01)	0.02
Aeration porosity[z] (cm^3 cm^{-3})	4–6	0.14*a* (0.09)	0.24*a* (0.04)	0.30*a* (0.02)	0.17
	14–16	0.19*a* (0.11)	0.25*a* (0.03)	0.31*a* (0.02)	0.36
Available water storage capacity (cm^3 cm^{-3})	4–6	0.13*a* (0.04)	0.13*a* (0.03)	0.17*a* (0.01)	0.42
	14–16	0.13*a* (0.04)	0.15*a* (0.03)	0.18*a* (0.01)	0.35
Water content at 10% AFP[y] (cm^3 cm^{-3})	4–6	0.32*c* (0.03)	0.38*b* (0.02)	0.45*a* (0.007)	0.007
	14–16	0.34*b* (0.05)	0.40*b* (0.01)	0.48*a* (0.01)	0.02
Water content at field capacity[x] (cm^3 cm^{-3})	4–6	0.28*a* (0.07)	0.24*a* (0.03)	0.25*a* (0.02)	0.80
	14–16	0.25*a* (0.06)	0.25*a* (0.02)	0.27*a* (0.02)	0.84
Water content at wilting point[w] (cm^3 cm^{-3})	4–6	0.15*a* (0.03)	0.11*a* (0.03)	0.08*a* (0.009)	0.22
	14–16	0.12*a* (0.03)	0.10*a* (0.02)	0.09*a* (0.007)	0.55

[z] Aeration porosity = air-filled porosity at field capacity.

[y] AFP = air-filled porosity.

[x] Field capacity is determined at –10 J kg^{-1}.

[w] Wilting point is determined at -1500 J kg^{-1}.

[v] Values in parentheses are standard errors.

a–c Values in the same row followed by a different letter are significantly different according to Tukey's test ($P < 0.10$).

Table 6. Soil water content measured with a ThetaProbe at 10 cm depth on LNG, NRL, and CCT disturbance types at Lynes Creek, BC

Date	LNG	NRL	CCT	*P* (*F*-test)
	Soil water content (cm^3 cm^{-3})			
2002 Jun. 05	0.21*a* (0.02)[z]	0.22*a* (0.04)	0.26*a* (0.03)	0.54
2002 Jun. 25	0.13*a* (0.04)	0.12*a* (0.03)	0.13*a* (0.02)	0.97
2002 Aug. 12	0.20*a* (0.04)	0.07*b* (0.03)	0.03*b* (0.03)	0.01
2002 Sep. 18	0.18*a* (0.05)	0.10*a* (0.05)	0.05*a* (0.01)	0.17
2002 Oct. 03	0.30*a* (0.03)	0.16*ab* (0.05)	0.13*b* (0.01)	0.06
2003 Sep. 23	0.22*a* (0.02)	0.15*ab* (0.03)	0.12*b* (0.01)	0.09

[z] Values in parentheses are standard errors.

a, b Values in the same row followed by a different letter are significantly different according to Tukey's test ($P < 0.10$).

2002 and September 2003) volumetric water contents were significantly higher for the LNG disturbance type as compared with the CCT (Table 6). The NRL did not differ in water content from the other two disturbance types in September and October 2002 as well as in September 2003. In August 2002, the NRL had lower water content than LNG. The greatest difference in volumetric water contents between LNG and CCT was in August 2002 with volumetric water contents of 0.20 and 0.03 cm^3 cm^{-3}, respectively.

It is likely that higher water content on LNG than CCT was a result of lower transpiration on LNG treatment, which had minimal vegetative cover. In contrast, the trees and more abundant vegetative cover of the clearcut sites would have had higher water requirements and resulted in lower soil water contents. These findings differ from studies by Plotnikoff et al. (2002) and Teste et al. (2004) who found lower water contents on landings than clearcuts. This illustrates that generalizations concerning differences in soil water content between landings and clearcuts are problematic, since so many factors vary from one study to another. The trees in the previous two studies were much younger (7 and 2 yr old, respectively), the landings had been rehabilitated and trees were planted on them. Thus, differences in transpiration between landings and clearcuts were likely minimal in the previous two studies whereas these differences were likely significant in our study.

Soil Mechanical Resistance

Soil mechanical resistance on CCT was often lower than for LNG soils at the same depth (Figs. 1 and 2). Lower values of soil mechanical resistance for CCT soils relative to LNG coincide with lower bulk density (Table 3). Surface soils at the Lynes Creek sites showed a temporal trend of low soil mechanical resistance in the late spring, with increasing resistance toward the end of the summer, and then decreasing soil resistance into the fall (Figs. 1 and 2). The highest soil mechanical resistance was obtained on 2002 Jun. 25 and Aug. 12 (Fig. 1). High soil mechanical resistance may lead to long-term decreases in tree growth, and in particular, decreases in root growth (Clark et al. 2003).

Soil mechanical resistance was strongly affected by the soil water content at the time of measurement (Fig. 3). As a soil dries out, its mechanical resistance increases (Greacen and Sands 1980; Bar-Yosef and Lambert 1981). For the first two measurement dates in June 2002, the soil water content did not differ (Table 6) and the soil mechanical resistance did differ (Fig. 1) among the three disturbance types. The LNG had the highest soil mechanical resistance followed by NRL and then CCT. At the later dates (2002 Aug. and Oct. and 2003 Sep.) soil mechanical resistance values were either not significantly different among disturbance types or they were not as divergent as on the two earlier measurement dates. The similar soil mechanical resistance values for the latter three dates are likely due to the lower water contents on NRL and CCT as compared with LNG (Table 6), which increased soil mechanical resistance values on NRL and CCT relative to LNG.

Soil Chemical Properties

Many of the soil chemical properties differed among the disturbance types (Table 4) and these differences were likely due to the removal of forest floor and topsoil during landing construction. The results suggest that landing construction may reduce N and P availability, but at the same time may improve soil properties related to pH. Total C and total N concentrations were significantly lower on the LNG and NRL disturbance types as compared with CCT at the 2–9 cm depth (Table 4). This pattern of lower C and N concentrations in the more severe types of disturbance was also seen in other studies (Burger and Pritchett 1984; Plotnikoff et al. 2002; Simard et al. 2003). Mineralizable-N was significantly lower for NRL than CCT at 2–9 cm and was lower for LNG than CCT at 12–19 cm (Table 4). Available P was lower for LNG than CCT at both 2–9 cm and 12–19 cm depths.

Soil pH at 2–9 cm depth was significantly different among the three disturbance types with LNG having the highest pH, followed by NRL and then CCT. Soil pH at 12–19 cm depth and exchangeable Mg concentrations at both depths were significantly higher for LNG compared with CCT. Exchangeable Fe and Al concentrations at 2–9 cm were significantly lower for LNG and NRL compared with CCT (Table 4). Possible reasons for the differences in pH and pH-related properties may be: (1) decreased organic acid production on landings as compared with clearcuts associated with the removal of forest floor and woody debris from landings; and (2) the exposure of mineral soil of higher pH associated with possible scalping of surface mineral soil during landing construction. Our findings are in agreement with a study by Bulmer and Krzic (2003) on medium-textured soils in northeastern BC that found higher soil pH on landings compared to clearcuts.

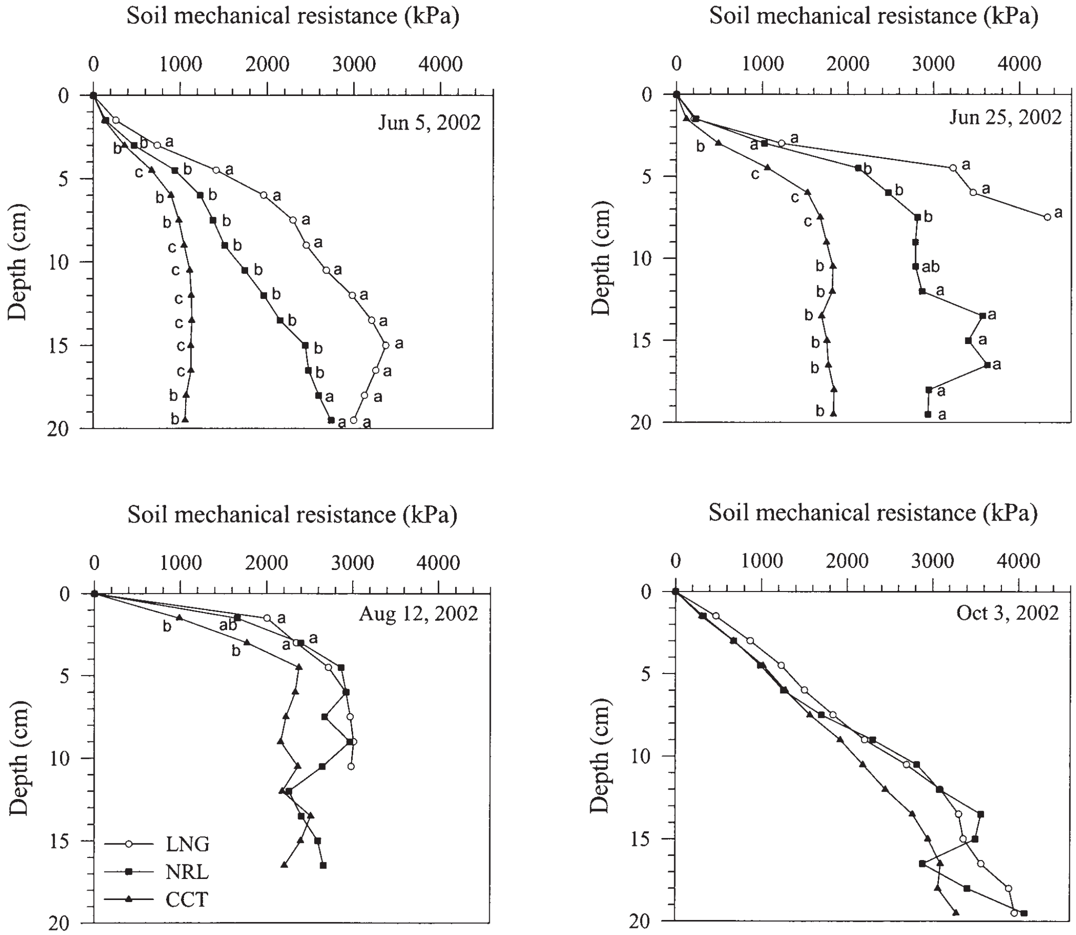

Fig. 1. Soil mechanical resistance (kPa) on LNG, NRL, and CCT disturbance types obtained in 2002 at Lynes Creek, BC. Means followed by the same letter within the same depth are not significantly different ($P > 0.10$). Letters are shown only at depths where disturbance types had a significant effect on soil mechanical resistance.

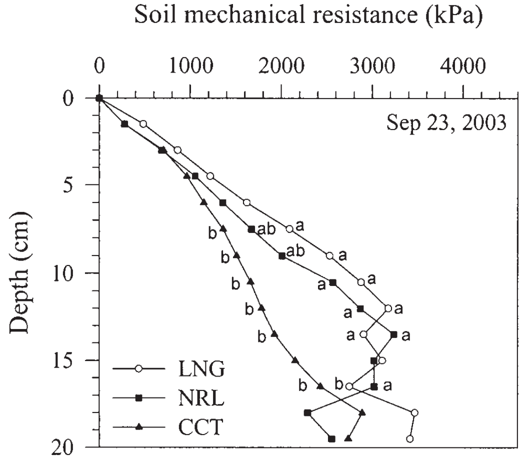

Fig. 2. Soil mechanical resistance (kPa) on LNG, NRL, and CCT disturbance types obtained in 2003 at Lynes Creek, BC. Means followed by the same letter within the same depth are not significantly different ($P > 0.10$). Letters are shown only at depths where disturbance types had a significant effect on soil mechanical resistance.

Interaction between Soil Properties and Tree Establishment and Growth

The soil conditions on LNG appear to be less optimal for plant growth than those on CCT and this likely accounts for the minimal vegetation and lack of naturally regenerated trees on LNG sites. Twenty-three years after landings had been constructed, the effects of mechanical disturbance were still detectable. The LNG had increased soil bulk density, maximum (Proctor) bulk density, and soil mechanical resistance, and decreased vegetative cover, forest floor depth, total porosity, and surface soil C and N compared with CCT. The lack of forest floor and low C and N in the surface mineral soil for LNG compared with CCT may result in nutrient limitations on these sites.

The average bulk density for LNG (1486 kg m^{-3}) was higher than the expected growth-limiting values near 1400 kg m^{-3} for fine-textured soils (Daddow and Warrington 1983), while CCT sites were below the threshold (1030 kg m^{-3}). The growth-limiting threshold value of 2500 kPa (Greacen et al. 1969; Greacen and Sands 1980; Busscher et al. 1986; Conlin and van den Driessche 2000) for soil

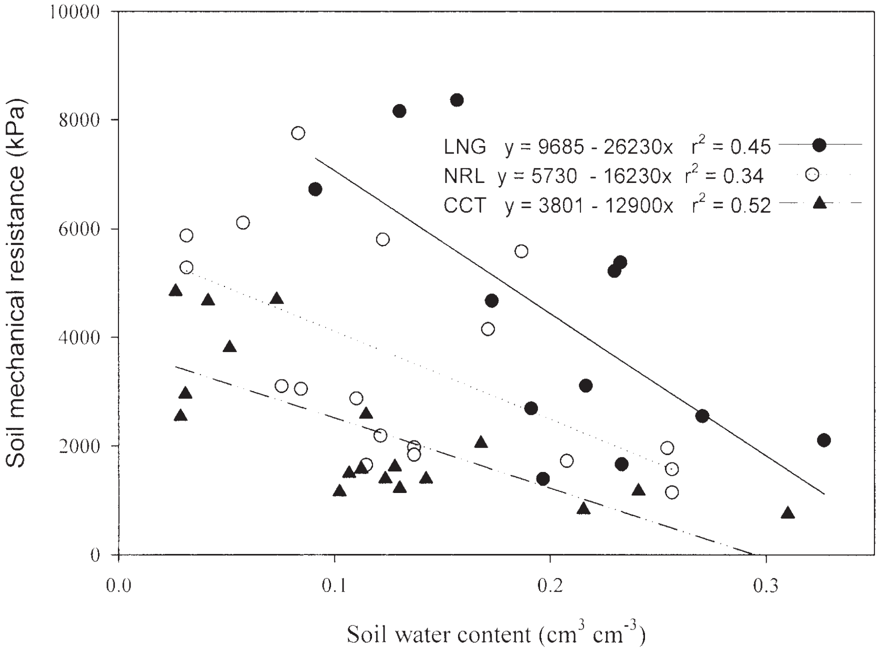

Fig. 3. Relationships between soil mechanical resistance (kPa), obtained at 10 cm depth with the hand-held cone penetrometer and water content (cm3 cm3) obtained with the ThetaProbe on LNG (solid line), NRL (dashed line), and CCT (dotted line) disturbance types in 2002 and 2003 at Lynes Creek, BC.

mechanical resistance was usually exceeded by 10 cm depth for the LNG disturbance types for all dates of measurement in 2002 and 2003 (Figs. 1 and 2). The CCT soil exceeded this threshold only in October 2002 and September 2003 at 12 cm and 17 cm depth, respectively. In general, surface soils on LNG experienced extended periods of time when soil water content was within the plant available range, but soil mechanical resistance was limiting to root growth (Fig. 3). In contrast, trees growing on CCT soils were likely to be limited by soil mechanical resistance only at low soil water contents.

Low soil water contents could have been limiting for plant growth at times on both NRL and CCT. Soil water content was above the permanent wilting point on all measurement dates (Tables 5 and 6) for LNG, but fell below the permanent wilting point in August 2002 for NRL and in August and September 2002 for CCT.

At air-filled porosities of 0.10 cm^3 cm^{-3} or less it is generally thought that plant growth will be significantly limited (Hillel 1982). In our study, measured soil water contents did not exceed the calculated water contents at 0.10 cm^3 cm^{-3} air-filled porosity for any of the disturbance types on any of the measurement dates. Soil on the LNG had aeration porosity (0.14 cm^3 cm^{-3}) that was close to the commonly cited critical level of 0.10 cm^3 cm^{-3}, whereas the other two disturbance types had aeration porosities well above the critical level (0.24 and 0.30 cm^3 cm^{-3}, respectively). Our results suggest that poor aeration is not likely a concern on our study sites.

Natural regeneration was able to establish and grow on portions of landings (NRL) and not on the rest of the landings (LNG). It is possible that LNG experienced greater mechanical disturbance than NRL at time of landing construction 23 yr ago. Some of our results support this idea: NRL had significantly lower total porosity and mechanical resistance (May and June 2002) than LNG and values for most measured soil properties were intermediate for NRL compared with LNG and CCT. Whether soil conditions were better on NRL than LNG at the time of landing construction or for some other unidentified reason, trees have established and grown on NRL. Furthermore, the trees on NRL appear to be growing as well as those in the surrounding clearcuts as indicated by the lack of significant differences in tree height between NRL and CCT.

A dominant factor influencing our study results is the texture of the soil. The soils in our study are medium-textured (loams and sandy loams) and thus have a distribution of pore sizes that is more optimal for plant growth than fine- or coarse-textured soils would have. Medium-textured soils typically have adequate amounts of large pores to allow aeration, as well as smaller pores to retain water. Furthermore medium-textured soils are expected to be more resistant to compaction than fine-textured soils. Our finding that trees can regenerate and grow well on portions of landings likely pertain only to soils of similar particle size distribution as those in our study.

CONCLUSIONS

Twenty-three years after landings had been constructed, portions of the unrehabilitated landings had no trees growing on them and other portions of the unrehabilitated landings and the surrounding clearcut had naturally regenerated to lodgepole pine. The landing areas without regeneration had higher bulk density and soil mechanical resistance, and lower total porosity and surface soil C and N compared with clearcuts. The lack of tree growth on portions of the landings is likely due to high soil mechanical resistance caused by mechanical disturbance at time of landing construction and use.

There were no significant differences in height, age or site index of codominant and dominant trees on naturally regenerated portions of the landings and the surrounding clearcuts. The portions of the landings with trees have lower total porosity and higher mechanical resistance on some measurement dates than portions of landings without trees. These differences may be due to variable impact on the soil during landing construction. Our work illustrates that on disturbed areas such as these landings and under conditions similar to those in our study, unrehabilitated soils may support productive forests. It is possible that some disturbed areas, under certain conditions, could be reforested without carrying out expensive rehabilitation treatments.

Our results are particularly useful for managers operating in a results-based regulatory environment, where new opportunities and approaches can be explored with less emphasis on prescribed treatments. Forest practices in British Columbia can benefit from considering a wide variety of options for restoring productivity to degraded sites, including minimal options such as simply planting. But such an approach requires that initial results and trends be confirmed through long-term monitoring on a range of site types. Further research is needed to clarify under what conditions rehabilitation is necessary.

ACKNOWLEDGEMENTS

This work was supported by Forest Renewal BC and Forest Innovation Investment. The technical assistance of Amanda Bridge in the field and the staff at the BC Ministry of Forests analytical laboratory in Victoria, BC are greatly appreciated. Bill Chapman of the BC, Ministry of Forests (Williams Lake) located the study sites, which were part of a larger study of landing rehabilitation in the BC interior. We also acknowledge helpful statistical suggestions from Ian Bercovitz during preparation of this manuscript.

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