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Soil properties and tree growth on rehabilitated forest landings in the interior cedar hemlock biogeoclimatic zone: British Columbia

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Abstract

We studied operational landing rehabilitation programs in three forest districts of interior British Columbia (BC). Winged subsoiling and grass/legume seeding, followed by planting of lodgepole pine (*Pinus contorta* var. *Latifolia*) generally resulted in successful re-establishment of forest cover on landings. In the Boundary district, fifth year tree heights on landings were not significantly different from those in adjacent plantations, and fifth year growth increments were also similar despite evidence of delayed seedling establishment caused by cattle grazing damage. Trees on landings in the Kalum district were shorter than those in plantations, but fifth year increments were similar. Landings in the Kalum with >20% clay had lower stocking densities, tree heights, and probe depths compared to landings with <20% clay content. In the Kispiox district, average fifth year tree heights and fifth year increments were lower on landings than those on plantations. In the Kispiox district, landings with >20% clay content had shorter trees growing on them when compared to tree heights on landings with <20% clay. Landings in the Kispiox had the least probe depth of the three districts, and the greatest difference in height and increments between landings and plantations, supporting field reports of poor decompaction effectiveness there. In all districts, there was no forest floor present on landings 7 years after subsoiling, and cover of non-coniferous vegetation was lower than for plantations. Higher soil temperatures and lower soil moisture contents were recorded on landings relative to plantations in all districts during the growing season of 1998. Landing soils also had lower total C, N and mineralizable-N (min-N) than plantation soils in the Boundary and Kispiox, but such differences were not statistically significant in the Kalum. Reduced levels of total C, N and min-N on landings did not appear to have affected current foliar nutrient status of trees growing on these sites, as most nutrients appeared in concentrations considered adequate or only slightly deficient, except for foliar S on all sites. Average concentrations of N, P, K and S in foliage were either similar to or significantly higher for trees on landings relative to plantations, but these differences were attributed to dilution in plantation foliage rather than deficiency. Our results support the conclusion that operationally feasible techniques for soil rehabilitation can create conditions suitable for establishment of a new forest on sites that otherwise would be considered non-productive. Stocking levels and tree growth rates observed in our study are consistent with the conclusion that a commercial forest may be produced on some of the rehabilitated areas.

Keywords: Soil conservation; Forest soil productivity; Reclamation; Forest restoration

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1. Introduction

Soil rehabilitation is an important component of forest management strategies aimed at reducing the effect of soil degradation on forest productivity (Froehlich and McNabb, 1984; Forest Practices Code of British Columbia, 1995a). The success of such strategies depends on the establishment and favourable growth of commercial tree species on rehabilitated soils.

Forest soil degradation can result from the passage of heavy logging equipment over unprotected soils, and from construction of trails, access roads and log landing areas (Froehlich, 1988). Log landings are constructed by removing surface soils and levelling the site, and the landing area experiences intensive use by heavy equipment and loaded log trucks during loading operations. Degraded soils on landings are often characterized by compaction and displacement of surface soils rich in organic matter and nutrients (Greacen and Sands, 1980; Krag et al., 1986). Soil rehabilitation usually involves techniques that alleviate soil compaction, and may include steps to restore organic matter and nutrients (Bulmer, 1998).

A variety of equipment options is available for rehabilitation of forest soil. The winged subsoiler was shown to be effective for decompaction in Oregon (Andrus and Froehlich, 1983), and was previously used successfully in BC (Carr, 1989). However, the winged subsoiler was not effective on medium- and fine-textured soils in Alberta because of adverse soil moisture conditions during treatment (McNabb, 1994).

The objective of our study was to compare soil properties and tree growth on rehabilitated sites with those on adjacent forest plantations. We used the retrospective study approach (Powers, 1989a; Smith, 1998) to evaluate the productivity of a group of landings that were rehabilitated by operational forestry staff in the early 1990s. Long-term treatment effects in forests are often hard to evaluate because of the long maturation time of forest trees, so retrospective studies of existing sites have a role in providing interim information before results from designed experiments are available.

2. Methods

2.1. Study sites and sampling design

Study sites were randomly selected from a complete list of 368 rehabilitated forest landings in the Boundary, Kalum and Kispiox forest districts of interior BC (Table 1). Landing soils were decompacted with a winged subsoiler in 1991 and a mixture of grass and legume seed was applied. In the Kalum district, additional treatments involved spreading any ash piles over the landing area, and adding 200 kg ha^{-1} of 19–23–15 fertilizer. Landings in all districts were planted with lodgepole pine seedlings in 1992. Plantations in all districts were clear-cut harvested between 1987 and 1990, and replanted with lodgepole pine seedlings. A total of 88 landing sites and adjacent plantations were sampled between May and August 1998. All sites were within the interior cedar hemlock (ICH) biogeoclimatic zone.

Three circular, 0.005 ha subplots were randomly located on each sampled landing, ensuring that all portions of a landing had an equal probability of being selected. Three subplots were randomly located in the adjacent plantation along a transect that best resembled the slope, aspect, and landscape position of the landing. Plantation plots were only established in areas where more than three lodgepole pine seedlings were growing, and where there was no evidence of detrimental soil disturbance caused by logging equipment. We assumed that the tree heights determined for adjacent plantation sites reflected the growth potential, or “expected” growth for lodgepole pine at each site.

In the Boundary district, harvested areas are often used for cattle grazing, which can affect both the landing areas and the adjacent plantations. Because grazing is widely practiced in the Boundary district, we considered cattle to be part of the ecosystem there, and simply recorded the grazing intensity on each plot as indicated by signs of cattle. No grazing occurred in the Kispiox and Kalum districts.

2.2. Measurements

For each subplot, we recorded percent slope, aspect, presence of standing water, evidence of post-subsoiling soil disturbance, evidence of cattle grazing,

Table 1
Characteristics of the study sites in Boundary, Kalum and Kispiox, forest districts

Forest district, major town: latitude/longitude	Ecological classification[a]	No. of sites	Elevation range (m.a.s.l.)	Mean annual temperature[b]	Mean annual precipitation[b] (mm)	Parent material[c]	Soil classification[d]
Boundary, Grand Forks:	ICHdw	2	1200–1275	7.6	471	Colluvium	Humo-ferric
49.0°N latitude/118.5°W longitude	ICHmw	15	1275–1540			Moraine	Podzols
	ICHmk	14	720–1500				Eutric Brunisols
Kalum, Terrace:	ICHmc	25	400–620	6.1	1136	Alluvium	Humo-ferric
54.5°N latitude/128.5°W longitude						Colluvium	Podzols
						Morainal	Dystric Brunisols
Kispiox, Hazelton:	ICHmc	32	340–500	4.3	625	Morainal	Humo-ferric
55.3°N latitude/127.7°W longitude						Colluvium	Podzols

[a] Braumandl and Curran (1992), Banner et al. (1993). d, dry; m, moist; w, warm; k, cool, c, cold.

[b] Boundary: Grand Forks (Environment Canada, 1993); Kalum: Terrace (Environment Canada, 1993); Kispiox: Temlahan (Environment Canada, 1982) and Date Creek (Coates et al., 1997).

[c] Holland (1976), Banner et al. (1993) and Coates et al. (1997).

[d] Luttmerding (1992), Luttmerding (1994) and Banner et al. (1993).

characteristics of non-coniferous vegetation, presence of coarse woody debris (CWD) and forest floor depth. All undamaged and unsuppressed lodgepole pine trees taller than 0.15 m were counted to determine the stocking density, and height increments for each year of growth were recorded.

Soil temperature was recorded at each subplot at the 0.10 m depth. Soil temperature measurements on paired landing and plantation plots usually occurred within 1 h, and never exceeded 1.5 h. Soil water content of surface soil was determined at each subplot, either using a theta probe (Delta T devices) or by gravimetric analysis.

A hand-pushed 0.013 m diameter steel probe was used to determine depth to a restricting or compacted layer. An estimated force of 68 kg was applied to the probe, representing a cone index value of approximately 5000 kPa. Probe measurements were taken at a minimum of 15 locations within each subplot. Maximum, minimum, and average probe depth was recorded, along with a description of obstructions such as bedrock, buried CWD, or large coarse fragments that may have halted the probe. Probe depths as determined with this method were considered to represent depth of loose soil available for rooting.

Composite soil samples were collected throughout the top 0.25 m of mineral soil at three locations within each subplot (Petersen and Calvin, 1986). Samples were air dried and passed through a 0.002 m sieve to separate coarse and fine soil fractions. Total C and N were determined by dry combustion using a Fisons NA-1500 elemental analyser (Tiessen and Moir, 1993; McGill and Figueirdo, 1993). Min-N was determined from ammonium-N in a KCl extract of soil following a 2 week anaerobic incubation at 30 °C (Bremner, 1996). Particle size distribution was determined for all samples using a variation of the hydrometer method (Gee and Bauder, 1986). Soil pH in 0.01 M calcium chloride ($CaCl_2$) solution was also determined (Hendershot et al., 1993).

On a randomly selected subset of 10 landings and adjacent plantation sites within each district, bulk density samples were collected to 0.15 m depth using an excavation method (modified from Blake and Hartge, 1986). Bulk density samples were dried and sieved through 0.002 m to remove coarse mineral and organic fragments, and fine fraction bulk density was calculated (Culley, 1993; Federer et al., 1993).

Foliage samples were collected (Ballard and Carter, 1985) during the dormant season from the same sites where bulk density was determined. Foliage samples were oven-dried at 70 °C for 16 h, and ground. Total C and N were determined using a Fisons NA-1500 elemental analyser. Total Ca, K, Mg, P, S, B, Cu, Fe, Mn and Zn were determined by ICP-AES following a microwave assisted, strong acid digestion (Kalra and Maynard, 1991).

2.3. Statistical analysis

Paired *t*-tests were used to test for significant differences ($\alpha = 0.05$) between landing and plantation sites within each district. Landing and plantation values used in paired comparisons (*t*-tests) were comprised of averages generated from the three subplots on each site. Where no significant differences were found, power $(1 - \beta)$ was calculated using software developed by Borenstein and Cohen (1988).

Pearson correlations were applied to selected variables describing growth, soil factors and foliage nutrient concentrations, and although some correlations were chosen a priori, Bonferroni adjusted probabilities were used throughout since they are appropriate when scanning a data matrix for significant correlations (Wilkinson et al., 1997). Simple correlations were calculated using all subplots (landing and plantation) within each district, both separately and in combination. Variables that did not meet underlying statistical assumptions (Norcliffe, 1987), especially concerning normality, were either square root or log transformed.

To evaluate the effect of clay content on establishment, growth and other soil variables, *t*-tests were used to compare subplots with >20% clay and those with <20% clay. The 20% value was chosen because it separates the sandy loam texture class from sandy clay loam (Gee and Bauder, 1986), and also approximates the level of 15% clay, above which soils can exhibit plastic behaviour (Brady, 1996).

3. Results and discussion

3.1. Site conditions and non-coniferous vegetation

Landing construction resulted in complete removal of forest floor (L + FH), and CWD coverage of the

Table 2
Site conditions and non-coniferous vegetation composition (values in parentheses represent S.D.)

	Landing	Plantation	*p* (*t*-test)[a]
Boundary			
CWD (%)	10 (5.3)	24 (6.6)	0.00
L (cm)	0.0 (0.06)	0.2 (0.25)	0.00
FH (cm)	0.0 (0.04)	2.4(0.98)	0.00
Grass (%)	27 (20.5)	39 (24.8)	0.04
Herb (%)	18 (12.9)	35 (17.5)	0.00
Shrub (%)	11 (8.8)	27 (13.5)	0.00
Kalum			
CWD (%)	8 (4.9)	23 (9.8)	0.00
L (cm)	0.0 (0.0)	0.3 (0.42)	0.00
FH (cm)	0.0 (0.0)	2.1 (1.04)	0.00
Grass (%)	29 (24.8)	2 (3.5)	0.00
Herb (%)	22 (12.2)	40 (21.6)	0.00
Shrub (%)	7 (7.9)	29 (18.4)	0.00
Kispiox			
CWD (%)	13 (9.6)	26 11.6	0.00
L (cm)	0.0 (0.0)	0.3 (0.26)	0.00
FH (cm)	0.0 (0.0)	4.1 (2.58)	0.00
Grass (%)	37 (27.4)	5 8.9	0.00
Herb (%)	23 (12.9)	48 (17.3)	0.00
Shrub (%)	9 (11.5)	24 (11.2)	0.00

[a] Significant differences at $p < 0.05$.

ground surface was substantially lower for landings than plantations (Table 2). Seven years after subsoiling, no forest floor development was observed. The CWD we observed on landings was either buried in the soil surface during landing construction and unearthed by the subsoiler, or it was debris that had remained on the surface after logging and loading operations.

The forest floor and CWD serve important functions in forest ecosystems (Fisher and Binkley, 2000). Removal of the forest floor has been shown to negatively affect nutrient status and tree growth (Nyland et al., 1979; Weber et al., 1985), yet Bulmer et al. (1998) found no reduction in tree growth after 10–15 years on bladed sites in the sub-boreal spruce (SBS) biogeoclimatic zone of central BC, despite reduced soil organic matter and nutrients. Munson et al. (1993) also showed no negative effect of organic matter removal associated with site preparation, and Orlander et al. (1996) did not observe long-term negative effects of site preparation, despite some nutrient losses. Factors such as reduced vegetation competition and accelerated warming of cold soils, i.e. a site preparation effect, may explain why growth was not negatively affected in these studies.

Average grass cover was significantly higher for landings in the Kalum and Kispiox districts relative to plantations, but significantly lower on Boundary landings compared to the plantations (Table 2). In Kalum and Kispiox, the successful establishment of seeded grasses on landings, in the absence of grazing cattle, likely resulted in higher coverage of grasses on landings than plantations. Range management activities in the Boundary district may have included seeding grasses and legumes on the plantations.

The differences we have observed in grass and herb cover illustrate the effect on forest ecosystems of established practices like grass seeding. In modern soil rehabilitation programs, the goals often involve creating ecosystems that closely resemble some pre-disturbance condition. The use of agronomic grass seed may be reduced in favour of native species, except where short-term erosion control is a necessity (Forest Practices Code of British Columbia, 1997).

Ground cover of shrubs was substantially lower on landings than plantations in all districts (Table 2), and likely reflected the removal of vegetation and surface soil at the time of landing construction (Carr, 1987). Many shrub species compete with coniferous vegetation on forested sites in BC, and increased competition for water and nutrients may result in reduced growth of coniferous species (Brand, 1990; Glover and Zutter, 1993; Nambiar and Sands, 1993).

Several studies suggest that short-term benefits of reduced competition may be realized at the expense of long-term site productivity because of nutrient depletion or other factors, especially when amounts of competing vegetation are reduced by intensive treatments such as removal of organic-rich surface horizons (Tuttle et al., 1985; Burger and Pritchett, 1988). Simard (1990) has suggested that up to 35% cover of Sitka alder (*Alnus viridis* ssp. *Sinuata*) may benefit lodgepole pine. Levels of shrub cover reported here were all below 35%.

3.2. Stocking and tree growth

The majority of sampled landings had stocking densities greater than 1000 stems ha^{-1} (Fig. 1). Average stocking densities for plantations were 2153 stems ha^{-1} for Boundary, 1617 stems ha^{-1} for

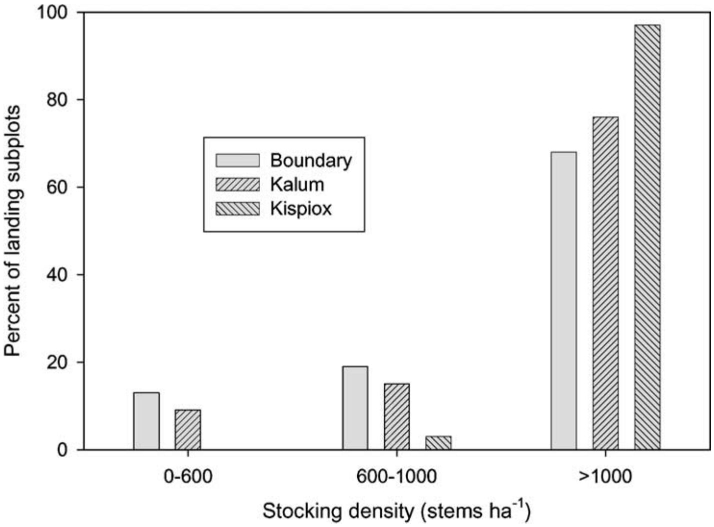

Fig. 1. Average stocking densities on landings, for the Boundary, Kalum, and Kispiox districts. In all districts, most of the landing sites had stocking densities greater than 1000 stems ha^{-1}.

Kalum, and 1289 stems ha^{-1} for Kispiox. The Forest Practices Code of British Columbia (1995b,c) defines target densities of well-spaced lodgepole pine, for the ICH subzones studied here, as a range between 1000 stems ha^{-1} and 1200 stems ha^{-1}, with minimum stocking levels of 500–700 stems ha^{-1}. These results indicate that most of the subsoiled landings supported acceptable forest cover.

In the Boundary, 8 of 31 landings had no established trees with at least 5 years growth compared with 1 of 25 landings in the Kalum, and 1 of 32 landings in the Kispiox. Evidence of grazing cattle was observed on 6 of 31 landings (19%) in the Boundary. Planting records showed that 5 of the 6 grazed landings required fill-planting to replace dead trees, compared with 5 of the remaining 25 landings. Seedlings are most at risk to trampling and browsing damage by cattle in the first 2 years after planting (Newman and Powell, 1997). Our results support the conclusion that cattle grazing damage contributed to low survival on some sites in the Boundary.

Five years after establishment, trees on landings were shorter than plantation trees in both Kalum ($p = 0.00$) and Kispiox ($p = 0.00$). Tree heights were not significantly different between landings and plantations in the Boundary (power = 0.014). Five years after establishment, the growth rate of trees on landings and plantations appeared equal in the Boundary district (Fig. 2) and in the Kalum district (Fig. 3). For the Kispiox district (Fig. 4), fifth year growth rate was lower on landings than on adjacent plantations. Average fifth year height of established trees on landings was greater on 11 of 25 sites in the Boundary, compared to plantations, while only one landing site in the Kalum, and no landing sites in the Kispiox had greater fifth year height than the adjacent plantation.

The height of trees on Kispiox landings after 5 years was not only below those in adjacent plantations, but also substantially below those for Kalum landings (Table 3), despite similar climatic regimes in the two study areas. Growth differences between landing sites in the Kispiox and Kalum could partly be attributed to: (1) use of fertilizer in the Kalum at time of planting, (2) different effectiveness of subsoiling within the two districts, and/or (3) other factors. Operational staff in Kispiox noted numerous configuration problems with the subsoiler being used (Marsland, 1994), resulting in less effective decompaction and depth of treatment than in the Kalum. McNabb and Hobbs (1989) found that shallow tillage with a rock ripper (to 0.30 m depth) of compacted skid trails in Oregon failed to increase the growth of ponderosa pine (*Pinus ponderosa* Laws.) seedlings planted in the rip-furrow relative to those planted between furrows, through 5 years growth.

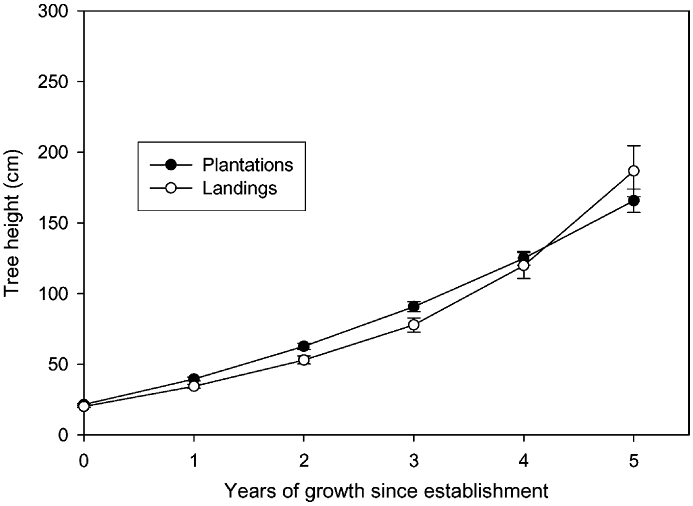

Fig. 2. Growth of lodgepole pine on landings and plantations in the Boundary forest district. Trees on landings and plantations had similar height after 5 years. Error bars represent point-wise 95% confidence intervals.

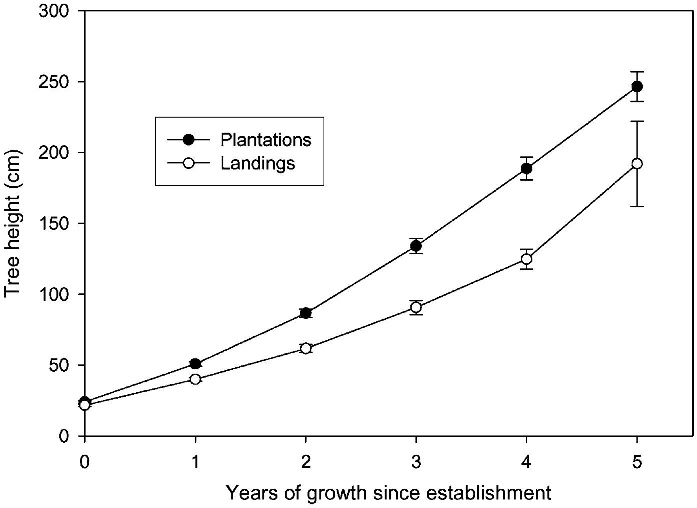

Fig. 3. Growth of lodgepole pine on landings and plantations in the Kalum forest district. Trees on landings were shorter than those on plantations. Error bars represent point-wise 95% confidence intervals.

Table 3
Comparison of average height of established trees (m) after 5 years growth[a]

	Boundary			Kalum			Kispiox		
	Height	S.D.	*n*	Height	S.D.	*n*	Height	S.D.	*n*
Landing	1.29	(0.29)	23	1.25 a	(0.26)	24	1.07 a	(0.34)	31
Plantation	1.24 bc	(0.18)	31	1.89 abd	(0.29)	25	2.11 acd	(0.31)	32

[a] Values with the same letter represent significant differences at $p < 0.05$.

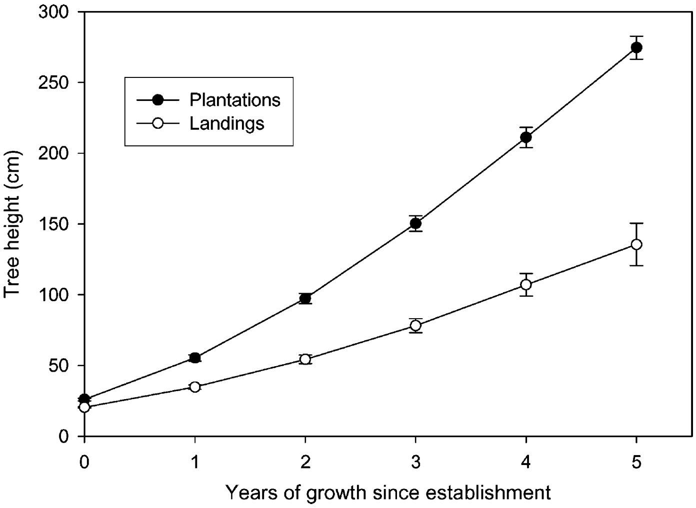

Fig. 4. Growth of lodgepole pine on landings and plantations in the Kispiox forest district. Trees on landings were generally shorter than those on plantations. Error bars represent point-wise 95% confidence intervals.

3.3. Soil properties and foliar nutrient concentrations

The most common surface soil textures for all sites were sandy loam, loam and loamy sand (Table 4). In the Boundary district, 100% of landings and 81% of plantations had textures of sandy loam or coarser. In the Kalum district, 44% of landings and 12% of plantations had soil texture of sandy clay loam or finer. Clay content was similar for landings and plantations in the Boundary district, while Kalum and Kispiox landings had higher clay content than plantations (Table 5). Texture affects response to soil disturbance (Powers, 1989b), and the subsequent effects on root growth through processes such as water retention, aeration, and soil strength development (Jones, 1983; Kramer and Boyer, 1995).

Differences in texture and coarse fragment content between landings and plantations in Kalum and Kispiox (Table 5) may reflect differences between surface soils and subsoils that were uncovered by removal of the upper layers during landing construction. Many of the landings had debris and surface soil piled at the perimeter.

Table 4
Number of sites by average texture class, by district

	Sand	Loamy sand	Sandy loam	Loam	Silt loam	Sandy clay loam–clay loam	Silty clay loam–silty clay	Clay	Total
Boundary									
Landing	1	5	25	0	0	0	0	0	31
Plantation	0	3	22	1	5	0	0	0	31
Kalum									
Landing	0	3	10	1	0	5	2	4	25
Plantation	0	3	13	6	0	3	0	0	25
Kispiox									
Landing	0	4	17	9	1	1	0	0	32
Plantation	0	2	21	9	0	0	0	0	32
Total	1	20	108	26	6	9	2	4	176

Table 5
Soil conditions on the study sites, including coarse fragment content (visual estimates), clay, moisture, bulk density, probe depth and selected soil chemical properties (values in parentheses represent S.D., probe values from all sites, bulk density from a subset of 10 sites in each district)

	n	Landings	Plantations	p (t-test)[a]	Power $(1-\beta)$
Boundary					
Coarse fragments (%)	31	50 (13.8)	30 (14.5)	*0.00*	
Clay content (%)	31	4.1 (2.04)	3.5 (2.01)		0.21
Temperature (°C)	31	15 (4.3)	12 (3.8)	*0.00*	
H_2O (w/w)[b]	24	0.186 (0.091)	0.322 (0.145)	*0.00*	
H_2O (v/v)[c]	7	0.188 (0.077)	0.245 (0.058)	*0.11*	0.30
Bulk density (kg m^{-3})	10	1015 (175.9)	813 (137.1)	*0.00*	
Probe depth (m)	31	0.18 (0.058)	0.26 (0.07)	*0.00*	
pH	31	4.63 (0.14)	4.56 (0.14)	*0.30*	
Total C (%)	31	20.86 (12.22)	29.3 (8.99)	*0.00*	
Total N (%)	31	0.84 (0.46)	1.20 (0.37)	*0.00*	
Min-N (mg kg^{-1})	31	21.3 (10.87)	32.3 (12.79)	*0.00*	
Kalum					
Coarse fragments (%)	25	36 (22.6)	29 (21.9)	*0.04*	
Clay content (%)	25	22.3 (17.35)	15.8 (8.26)	*0.21*	
Temperature (°C)	25	16 (3.0)	12 (1.4)	*0.00*	
H_2O (w/w)	25	0.096 (0.042)	0.128 (0.051)	*0.00*	
Bulk density (kg m^{-3})	10	991 (289.8)	987 (211.3)	0.96	0.03
Probe depth (cm)	25	0.20 (0.079)	0.19 (0.058)	0.52	0.07
pH	25	4.43 (0.13)	4.25 (0.30)	*0.00*	
Total C (%)	25	22.0 (10.54)	23.3 (7.60)		0.07
Total N (%)	25	1.47 (0.49)	1.44 (0.48)		0.04
Min-N (mg kg^{-1})	25	27.6 (19.73)	32.7 (24.93)		
Kispiox					
Coarse fragments (%)	32	61 (14.7)	48 (17.6)	*0.00*	
Clay content (%)	32	14.1 (6.83)	10.8 (3.21)	*0.01*	
Temperature (°C)	32	15 (3.1)	10 (1.5)	*0.00*	
H_2O (v/v)	32	0.201 (0.079)	0.244 (0.077)	*0.01*	
Bulk density (kg m^{-3})	10	1095 (217.7)	1068 (192.2)	0.61	0.05
Probe depth (m)	32	0.13 (0.05)	0.28 (0.076)	*0.00*	
pH	32	4.63 (0.25)	4.17 (0.24)	*0.00*	
Total C (%)	32	24.6 (13.00)	29.5 (10.57)	*0.00*	
Total N (%)	32	0.97 (0.47)	1.31 (0.47)	*0.00*	
Min-N (mg kg^{-1})	32	17.4 (10.49)	32.3 (15.29)	*0.00*	

[a] Italic values represent significant differences at $p < 0.05$.
[b] $H_2O\,(w/w) = g\ H_2O/g$ soil.
[c] $H_2O\,(v/v) = cm^3\ H_2O/cm^3$ soil.

In all districts, summer daytime soil temperatures were higher, and water content was lower on landings than plantations (Table 5), likely reflecting, in part, the removal of forest floor from landings. Forest floor acts as a mulch, preventing evaporative water losses and regulating soil temperature (Brady, 1996; Grunwald et al., 1995). Although, our results do not directly address soil temperature differences during the spring, analysis of seasonal patterns of soil temperature change suggests that the landings will also warm more quickly in the early season than the plantations. Warmer soils on landings as compared to plantations are expected to promote early root growth (Sutton, 1991), and are likely an important component of the rehabilitation success observed on many of our sites.

Increased evaporative loss of soil water from exposed mineral soils on landings may be responsible for reduced levels of soil moisture, and could result in plant moisture stress on dry sites (Brady, 1996; Nambiar and Sands, 1993). Summer moisture deficits in the ICH are not so severe as in other biogeoclimatic zones, however, so drought stress may be less of a concern than in other areas.

Surface soil bulk densities were higher for landings than plantations only in the Boundary (Table 5). For all sites, surface soil bulk density 7 years after treatment was not within the range expected to be growth limiting (Daddow and Warrington, 1983; Tuttle et al., 1988; Bulmer, 1998). Because we were not able to obtain pre-treatment soil bulk density samples for all sites, our results cannot directly determine whether: (1) subsoiling restored soil densities to values near those of undisturbed soils, or (2) the landing soils were not compacted before treatment. However, bulk density sampling done in the Kalum district prior to, and following subsoiling (unpublished data), found a decrease in bulk density after treatment of landings, with an average 15% reduction at 0.10 m depth and 12% reduction at 0.30 m depth, suggesting that the treatment was at least partly responsible for improving soil conditions.

Probe depth was less on landings than plantations in Boundary and Kispiox. The average difference in probe depth between landings and plantations was 0.08 m in the Boundary district and 0.15 m in the Kispiox district (Table 5). Because the maximum cone index exerted by the steel probe was approximately 5000 kPa, which is at the high end of the range of values considered limiting for root growth (Carter, 1988; Bulmer, 1998), probe depths reported here should be considered a maximum depth of loose soil available for rooting.

Landing soils had slightly higher pH values than plantation soils in Kispiox and Kalum, while differences in pH between the two site types were not statistically significant for Boundary soils (Table 5). Values of pH for both landing and plantation soils are well within the range considered acceptable for lodgepole pine growth (Cochran, 1984).

Lower values of total C, N and min-N on landings in Boundary and Kispiox districts (Table 5) likely reflect removal of forest floor and surface mineral soil horizons during construction of the landings. In the Kalum district, similar values of total C, N and min-N on landings and plantations suggest that either less surface soil was displaced during construction, or organic matter and nutrient losses associated with landing construction were partly replenished by spreading available ash and debris piles during landing rehabilitation.

Trees growing on landings had slightly higher concentrations of macronutrients in their foliage than trees in plantations, except for P in the Kispiox and K in the Kalum. Ratios of macronutrient concentrations in foliage (data not shown) were similar for trees growing on landings and plantations in all districts, indicating that lower concentrations in foliage of plantation trees likely indicate nutrient dilution. According to interpretations offered by Carter (1992), Ballard and Carter (1985), and Brockley (2001), foliar nutrient concentrations for trees growing on landings and plantations in all districts were not deficient, with the exception of S on all sites (Table 6). Deficiency of S often results in impaired N uptake by plants (Ballard and Carter, 1985; Brockley, 1996), but this does not appear to be the case for our sites, as foliar N status generally appeared favourable.

3.4. Relationships among tree growth, soil properties and foliar nutrients

Table 7 summarizes some of the statistically significant results of correlation analysis on selected soil and productivity variables. Although, Fisher and Binkley (2000) suggest that the organic fraction of mineral soil may be the most influential property affecting soil processes, correlations of soil C, N and min-N with foliar N and tree height were weak or non-significant. Bulmer et al. (1998) also found weak or non-significant relations between soil and foliar nutrients for burned and bladed sites in the SBS of central BC.

Average coarse fragment content and probe depth on landings in the Kispiox and Boundary districts were negatively correlated (Table 7), but not in Kalum. Probe depth and tree growth were not well correlated in Kalum and Boundary districts (Table 7), but landings in the Kispiox had less probe depth than plantations, which corresponded with shorter trees (Fig. 5). These results suggest that rocky and compact subsoils in the Kispiox and Boundary may limit rooting depth, but that 0.18 m of loose soil on landings in the Boundary allowed ca. 6-year-old trees to grow at the expected rate, while 0.13 m of loose soil on

Table 6
Average foliar nutrient concentrations (g kg^{-1}) by district ($n = 10$) (values in parentheses represent S.D.)

	Landing	Plantation	Adequate[a]	p (t-test)[b]	Power $(1 - \beta)$
Boundary					
N	15.2 (1.3)	13.3 (1.0)	13.5	*0.00*	
P	1.50 (0.09)	1.36 (0.14)	1.5	*0.01*	
K	5.96 (0.35)	5.46 (0.42)	5.5	*0.01*	
S	0.92 (0.08)	0.79 (0.07)	1.6	*0.00*	
Kalum					
N	14.1 (0.9)	12.0 (1.2)	13.5	*0.00*	
P	1.40 (0.10)	1.25 (0.08)	1.5	*0.01*	
K	4.73 (0.60)	4.72 (0.46)	5.5	0.96	0.03
S	0.84 (0.09)	0.72 (0.05)	1.6	*0.00*	
Kispiox					
N	14.4 (0.5)	13.4 (1.2)	13.5	*0.05*	
P	1.45 (0.08)	1.48 (0.18)	1.5	0.63	0.07
K	4.86 (0.32)	5.44 (0.29)	5.5	*0.00*	
S	0.85 (0.04)	0.79 (0.07)	1.6	*0.03*	

[a] Source: Carter (1992) and Ballard and Carter (1985).

[b] Italic values represent significant differences at $p < 0.05$.

landings in the Kispiox was too shallow to allow tress to achieve their expected growth.

Probe depth was strongly and inversely correlated with clay content for landings in the Kalum district (Table 7). Landing subplots with >20% clay in the Kalum also had lower stocking ($p = 0.00$), height ($p = 0.02$) and probe depth ($p = 0.00$) than subplots with <20% clay (Fig. 6). Grass cover was higher for subplots with >20% clay ($p = 0.01$). Fifth year heights of landing trees on subplots with >20% clay were also lower in Kispiox ($p = 0.00$) but differences in other soil properties between plots with >20% clay and those with <20% clay were generally not statistically significant in the Kispiox. These results suggest that, in the Kalum, depth of decompaction and effectiveness of subsoiling may have been reduced on

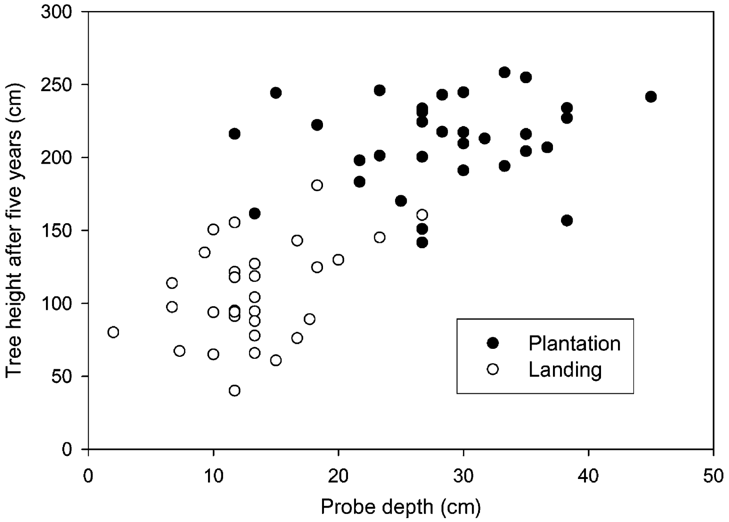

Fig. 5. Probe depth vs. 5 years growth for landings and plantations in the Kispiox district ($r = 0.63$). Landings had shorter trees and less probe depth than plantations.

Table 7
Summary of Pearson correlation results for soil properties and stand characteristics

	All plots		Landings		Plantations	
	r[a]	n[b]	r	n	r	n
All districts						
Grass vs. min-N[c]	0.16	527	0.42	263	NS[d]	264
Probe depth vs. CF[e]	−0.37	525	−0.33	261	−0.24	264
Probe depth vs. clay[f]	−0.29	528	−0.34	264	−0.20	264
Probe depth vs. height[g]	0.32	476	0.30	213	NS	263
Clay[f] vs. height	NS	476	−0.27	213	0.49	263
Boundary						
Grass vs. min-N[c]	0.32	186	0.59	93	NS	93
Probe depth vs. CF	−0.55	186	−0.30	93	−0.51	93
Probe depth vs. clay[c]	NS[d]	186	−0.25	93	NS	93
Probe depth vs. height	0.21	152	NS	60	0.27	92
Clay[c] vs. height	−0.18	152	−0.31	60	NS	92
Kalum						
Grass vs. min-N[f]	NS	150	0.39	75	NS	75
Probe depth vs. CF	−0.16	150	NS	75	−0.43	75
Probe depth vs. Clay[f]	−0.47	150	−0.67	75	NS	75
Probe depth vs. height	NS	136	NS	61	NS	75
Clay[f] vs. height	NS	136	−0.28	61	NS	75
Kispiox						
Grass vs. min-N[c]	NS	191	0.39	95	NS	96
Probe depth vs. CF	−0.53	189	−0.47	93	−0.42	96
Probe depth vs. clay[c]	−0.31	191	NS	95	NS	96
Probe depth vs. height	0.63	187	0.33	91	NS	96
Clay[c] vs. height	−0.37	188	−0.51	92	NS	96

[a] Pearson's correlation coefficient.
[b] Number of observations (plots) used in correlation.
[c] Denotes square root transformed data.
[d] Non-significant result (adjusted p-value > 0.05).
[e] Average coarse fragment content.
[f] Denotes log transformed data.
[g] Average 5 years growth of established trees.

fine-textured soils leading to reduced establishment success and early growth of planted trees.

Other studies have also shown that subsoiling and deep tillage treatments were more successful on coarse textured soils (Andrus and Froehlich, 1983; Froehlich and McNabb, 1984). The amount of soil loosening achieved by subsoiling depends on soil texture and water content because these factors influence soil strength, and the efficiency with which energy is transferred from the subsoiler up through the soil profile (Bulmer, 1998). Soil strength is particularly dependent on moisture in fine-textured soils (Greacen and Sands, 1980), so effective decompaction of fine textured soils strongly depends on water content at the time of treatment (Fewer, 1992; McNabb, 1994).

Foliar N concentrations and tree height on Kalum plantations (Table 8) showed a negative correlation, suggesting dilution of N (Timmer and Stone, 1978; Ballard and Carter, 1985). Average foliar P concentrations for both Kalum and Kispiox plantations were also negatively correlated with tree height (Table 8) also suggesting dilution. Average foliar P and K concentrations showed positive correlations with tree heights and/or 1998 height increments for Boundary plantations, Kispiox landings, and Kalum landings (K only), suggesting that growth improvements could be realized with increased availability of P and K on

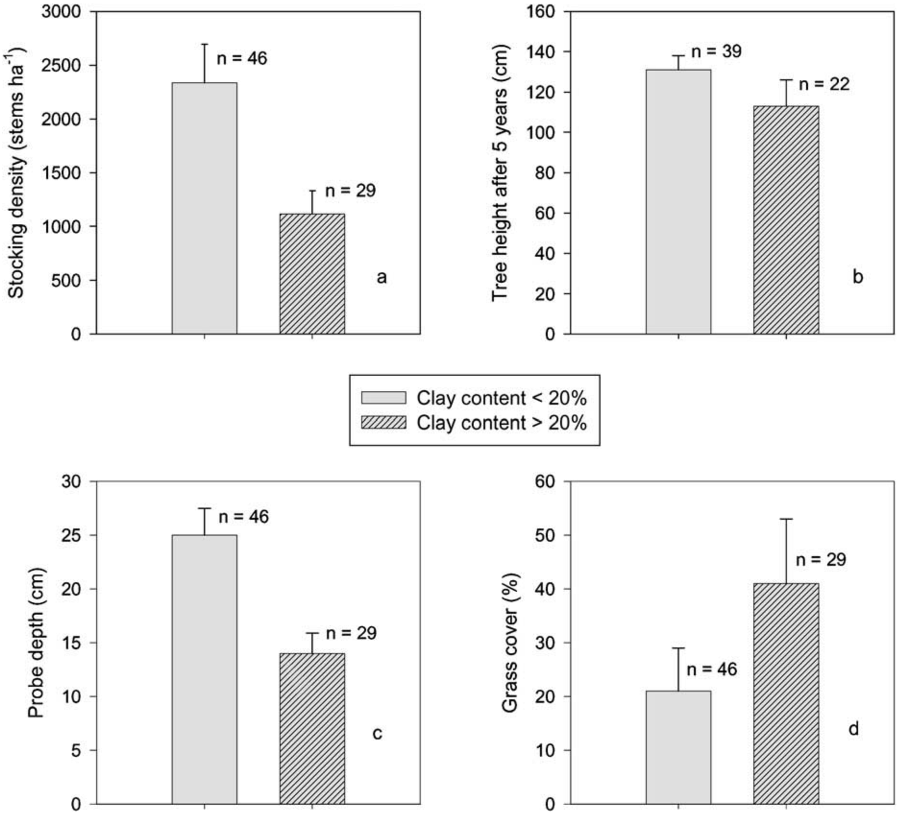

Fig. 6. Effect of clay content of landing soils on: (a) stocking, (b) 5 year height growth, (c) probe depth and (d) grass cover for landings in the Kalum district. Error bars show 95% confidence intervals. Stocking levels, tree height, and probe depth were all less for subplots with more than 20% clay. Grass cover was higher for subplots with more than 20% clay.

these sites. In general, relations between foliar and soil variables could not be described by simple linear correlations.

4. Summary and management implications

Winged subsoiling and grass/legume seeding, followed by subsequent planting of lodgepole pine has generally resulted in re-establishment of forest cover on landings in each of the districts. Stand density data for these sites show that the majority of landings sampled in each district met or exceeded applicable stocking requirements in their region. Cattle damage apparently delayed seedling establishment on a number of sites in the Boundary district, and may have resulted in reduced growth on others. We recommend that, where possible, grazing be limited or delayed during the first few years after planting (Forest Practices Code of British Columbia, 1997).

Height growth of trees on reclaimed landings equalled that for the adjacent plantation in the Boundary was somewhat lower in the Kalum, and was markedly lower in the Kispiox. Reduced height growth for trees on landings in the Kispiox was at least partly attributed to ineffective operation of the subsoiler, which did not break up compacted and rocky soils below about 0.13 m. Landings in the Boundary with 0.20 m of loose soil appeared to meet expectations at this time, but our results do not address the question of whether this is an adequate depth for trees over an entire rotation.

In Kalum and Kispiox, reclamation was less successful on landings with >20% clay, illustrating the special challenges associated with restoring productivity to clay-rich sites. These results highlight

Table 8
Summary of Pearson correlation results for foliar nutrient concentrations, by district

	All plots		Landings		Plantations	
	r[a]	n[b]	r	n	r	n
All districts						
Total Ht[c] vs. foliar N	−0.54	180	NS[d]	90	−0.39	90
Total Ht vs. foliar P	NS	180	0.43	90	NS	90
Total Ht vs. foliar K	NS	180	NS	90	NS	90
98 Inc[e] vs. foliar N	−0.30	180	NS	90	NS	90
98 Inc vs. foliar P	NS	180	NS	90	NS	90
98 Inc vs. foliar K	NS	180	NS	90	NS	90
Boundary						
Total Ht vs. foliar N	NS	60	NS	30	NS	30
Total Ht vs. foliar P	NS	60	NS	30	0.57	30
Total Ht vs. foliar K	NS	60	NS	30	0.66	30
98 Inc vs. foliar N	NS	60	NS	30	NS	30
98 Inc vs. foliar P	NS	60	NS	30	NS	30
98 Inc vs. foliar K	NS	60	NS	30	0.59	30
Kalum						
Total Ht vs. foliar N	−0.70	60	NS	30	−0.74	30
Total Ht vs. foliar P	−0.56	60	NS	30	−0.64	30
Total Ht vs. foliar K	NS	60	0.59	30	NS	30
98 Inc vs. foliar N	NS	60	NS	30	NS	30
98 Inc vs. foliar P	NS	60	NS	30	NS	30
98 Inc vs. foliar K	0.42	60	0.67	30	NS	30
Kispiox						
Total Ht vs. foliar N	−0.49	60	NS	30	NS	30
Total Ht vs. foliar P	NS	60	0.66	30	−0.72	30
Total Ht vs. foliar K	0.53	60	NS	30	NS	30
98 Inc vs. foliar N	NS	60	NS	30	NS	30
98 Inc vs. foliar P	NS	60	0.65	30	NS	30
98 Inc vs. foliar K	0.64	60	0.57	30	NS	30

[a] Pearson's correlation coefficient.
[b] Number of observations (plots) used in correlation.
[c] Mean sampled tree height for foliar analysis.
[d] Non-significant (adjusted p-value > 0.05).
[e] Final (1998) increment of trees sampled for foliar analysis.

the importance of prescribing reclamation equipment that is appropriate to the soil conditions, and ensuring that it is working as intended during the operational phase of the work.

Seven years after subsoiling, restored soils on landings in all districts had no forest floor, and cover of non-coniferous vegetation was substantially below that of adjacent plantations, which may have contributed to favourable establishment and early growth of trees on some sites through beneficial effects on soil temperature and moisture. Landing soils had lower concentrations of total C, N and min-N than plantations in the Boundary and Kispiox. Such differences were not observed in the Kalum, which supports recommendations that replacing topsoil and associated ash piles is effective for replenishing organic matter and nutrients that were lost from degraded soils.

Despite differences in soil nutrient levels, foliar nutrient concentrations on all sites were generally adequate or only slightly deficient, with the exception of S. Differences in foliar nutrient concentrations for trees on landings relative to plantations were likely a result of dilution in plantation foliage rather than an indication of relative deficiency. None of the landing sites appeared to be candidates for N fertilization to enhance growth rates. However, correlations suggest some growth response could be realized with increased availability of P and K on Boundary plantations, and Kalum and Kispiox landings.

Although, our short-term results are encouraging, and support the conclusion that low cost soil rehabilitation methods are a useful strategy for enhancing the productivity of BC's forests, there are still potential concerns for the longer term. The young trees we studied did not appear to be suffering from nutrient deficiency or water stress as a result of reduced levels of soil organic matter and nutrients on the rehabilitated landings, compared to plantations. However, as the trees age, their demands for moisture and nutrients will increase, and landing sites with shallow soils, or those depleted in forest floor and surface soil organic matter may not provide adequate moisture and nutrients to support a fully productive forest.

Long-term concerns support recommendations encouraging conservation and replacement of topsoil and other organic materials during rehabilitation; these techniques may be necessary even in the short-term, for establishing species other than lodgepole pine on rehabilitated soils.

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