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The effects of soil mixing on soil nutrient status, recovery of competing vegetation and conifer growth on cedar-hemlock cutovers in coastal British Columbia

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Application. Soil mixing decreased the overall soil nutrient status on the low-productivity sites, reduced regrowth of competing vegetation and slightly increased growth of western hemlock after 5 years. Soil mixing had a slight effect on all of these factors on adjacent sites of high-productivity. Considering the cost of soil mixing, this method appears economically suitable only if the aim is to improve early growth of western hemlock on the low-productivity sites.

Abstract. In 1988 an experiment was established to stimulate the effect of windthrow on low- and high-productivity forest types in coastal British Columbia. It was hypothesized that site productivity may be improved by mixing the upper 1 m of the organic matter and mineral soil. Results of this study indicated that soil mixing (1) slightly increased soil pH and temperature on both forest types after 2 and 5 years, (2) decreased all soil nutrient availability indices on the high productivity type after 2 years, but resulted in no difference from the control after 5 years, and (3) decreased microbial activity and cellulose loss rate and most soil nutrient availability indices on the low-productivity type after 2 and 5 years. Soil mixing greatly reduced *Gaultheria shallon* above-ground biomass on both low- and high productivity forest types, whereas biomass of *Epilobium angustifolium* and other plant species increased slightly on the high-productivity type after 2 and 5 years. *Tsuga heterophylla* was taller on high-productivity type and on mixed plots in both types after 2 and 5 years. *Thuja plicata* was taller on the high-productivity type after 5 years only. The increased conifer growth measured on the mixed low-productivity type was attributed to higher levels of available nutrients due to reduced *G. shallon* competition.

Introduction

The development of thick mor organic horizons at the surface of acidic conifer forest soils potentially removes large amounts of nutrients from active cycling (Ross and Malcolm 1988). Such accumulations of organic matter are caused by slow rates of decomposition that result from one or more of the following: (1) the physical and chemical nature of the litter, (2) the environmental conditions (i.e. soil temperature, moisture and aeration) of the forest floor, and (3) the kind, number, and activity of microorganisms present in the soil (Singh and Gupta 1977). Mechanical site preparation has been applied extensively in forestry to stimulate soil organic decomposition and nutrient mobilization by modifying at least one of these factors.

Many different methods of mechanical site preparation have been used, ranging from simple mixing of horizons (i.e. soil mixing) to complete elimination of the organic layer (often referred to as scalping). Whatever the method used, mechanical site preparation generally results in early increases in coniferous growth (Thomson and Neustein 1973; Pehl and Bailey 1983; Burger and Pritchett 1988), due to any combination of the following factors: (1) increase in the volume of soil available for rooting (Ross and Malcolm 1982), (2) improved aeration and drainage in the soil (Read et al. 1973; Ross and Malcolm 1982), (3) stimulation of nutrient mobilization (Burger and Pritchett 1988; Vitousek et al. 1992), (4) suppression of competing vegetation (Malcolm 1975; Pehl and Bailey 1983; Burger and Pritchett 1988), and (5) provision of a more suitable planting site for seedlings (Ross and Malcolm 1982).

The forests on better-drained sites on northern Vancouver Island, British Columbia, are a mosaic of high- and low-productivity forest types. The former type consist of relatively young (often less than 150 years) natural second growth stands of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* (Dougl. Forbes). These stands carry high timber volumes (1100 m^3), have high rates of tree growth (12/m^3/yr), and a friable mor humus layer. The latter type consists mainly of old-growth stands dominated by western redcedar (*Thuja plicata* Donn) and western hemlock that exhibit a lower productivity and a deeper compacted mor humus layer. It appears that the high-productivity forest type has repeatedly experienced catastrophic disturbance by wind, whereas the low-productivity type is characterized by the long-term absence of such disturbance. Germain (1985) and Prescott et al. (1993) have found better soil nutrient status on the high- than the low-productivity types prior to harvesting. These major differences between these two forest types have led to the hypothesis that soil mixing caused by windthrow may improve aeration, organic matter decomposition and nutrient cycling. Repeated windthrows are also believed to be responsible for the improved productivity on some sites in coastal Alaska (McClellan et al. 1990). If this hypothesis is correct, soil mixing techniques that simulate windthrow events on the low-productivity type may induce a series of reactions that could eventually lead to improved site productivity. Although such techniques are expensive, the potential long-term improvement in site productivity may justify the investment: the high-productivity forest type has a mean annual volume increment of 12 m^3/ha compared to 5 m^3/ha for the low-productivity type (Barker et al. 1986).

This study investigated the effects of mixing the organic matter and mineral soil on soil nutrient status, soil microenvironment, recovery of co'peting vegetation, and growth of western redcedar and western hemlock seedlings in recently clear-cut low- and high-productivity forest sites. The main objectives of this research are (1) to compare the effects of soil mixing just after and past the initial phase of plantation establishment, and (2) to determine the possibility that tree growth on sites of low-productivity may be increased to levels found on sites of high-productivity by simulating windthrow events (i.e. mixing of organic and mineral matter).

Material and methods

Study area

The study was conducted on a gently undulating coastal plan about 100 m in elevation on northern Vancouver Island, British Columbia near the town of Port McNeill (Latitude 50 60′ N). This area is in the very-wet maritime subzone of the Coastal Western Hemlock biogeoclimatic zone (Pojar et al. 1991), which occupies the lower and middle altitudes of Vancouver Island and the coastal mainland of British Columbia. The research was conducted on sites that originated as either old-growth western hemlock and western redcedar or as second-growth western hemlock and amabilis fir. The main structural and ecological differences between these two forest types have been described previously by Keenan (1993) and Messier (1993). The old-growth forests of western redcedar and western hemlock (low-productivity type) are structurally diverse, with trees ranging up to 1000 years in age, 260 cm in diameter, and 45 m in height. The understory is dominated by salal (*Gaultheria shallon*, Pursh) with a smaller percentage of *Vaccinium* spp., ferns (*Blechnumm* spp.), and a thick ground cover of mosses (*Hylocomium splendens* and *Rhytidiadelphus loreus*). The second-growth, high-productivity type consists of western hemlock and amabilis fir at a stocking of about 650 stems per hectare, with relatively normal diameter class distributions. The mean diameter is about 50 cm, maximum diameter about 80 cm, and dominant height about 45 m. While the high-productivity type has a very uniform appearance suggestive of even-aged stands, there is a variation in ages, indicating that some stems originated as advanced growth prior to a major windstorm in 1906, while others have recruited more recently (Keenan 1993). The understory is dominated by advanced regeneration of hemlock and fir, and similar mosses and ferns as the low-productivity type. Transitions between the low- and high-productivity site types on the landscape are often abrupt and are not always related to obvious topographic features.

The study area receives approximately 1700 mm of rain annually, with 65% of the precipitation occurring between October and February. Although the summer months experience less rainfall than the winter months, rainfall during the growing season is sufficient to prevent any soil moisture deficit. The number of hours of sunshine varies from an average high of 6.4 h/day in July to an average low of 1.5 h/day in December; these low values reflect the frequent occurrence of fog in the summer and frontal clouds in the winter. Mean daily temperature ranges from a low of 3.0 °C in January/February to a high of 13.7 °C in July/August. All weather data were obtained from the Port Hardy Airport weather station located within 15 km of the study area at an elevation of 50 m. These data represent an average for the last 36 years.

Experimental design and treatments

The experiment was established in a 97-ha clear-cut that included two large patches of the low-productivity forest type and four smaller patches (between 3 and 8 ha) of the high-productivity type. The area was logged in 1986 and slashburned in the spring of 1987. Some part of it was mechanically mixed in January of 1988 using a backhoe (215 cat excavator) with a 3 tined rake with 70–100 cm long teeth. Twenty randomly located areas (approximated 70×70 m) in the low-productivity type, and 20 in the high-productivity type within the 97-ha clear-cut were mixed, which covered approximately one-fifth of the 97-ha clear-cut area. Another half of the clear-cut area was used for the control treatment, and the rest was not used. The objectives of the soil mixing were (1) to remove salal rhizomes, (2) to simulate windthrow by mixing the organic matter and mineral soil within the upper 100, and (3) to remove or redistribute slash so as to facilitate planting. The mixing treatment was part of a larger experiment aimed at investigating the growth of western redcedar and western hemlock seedlings planted at three densities (500, 1500 and 2500 seedlings/ha), with and without fertilization, and with and without soil mixing for the 2500 seedlings/ha density only, on the two forest types. A total of 128 plots were assigned randomly to the different treatments. Western hemlock and western redcedar seedlings were planted in February 1988. Of the 64 plots with and without soil mixing planted with 2500 seedlings/ha on the two forest types, 16 plots planted with western redcedar and 16 plots planted with western hemlock were selected randomly for this study. The planting layout within each plot consisted of an inner plot of 16×16 m, and an outer buffer plot of 36×36 m in size. The experiment for the seedling growth was a 2×2×2 factorial and for the soil and competing vegetation factors a 2×2 factorial using a completely stratified randomized design. The three main factors investigated were as follows: (1) low- and high-productivity types, (2) untreated and mixed plots, and (3) planted western hemlock and western redcedar seedlings. Within each of these plots, 5 to 13 observations were made depending on the factor measured. The experimental unit was the plot in all cases. Since the experiment was either a 2×2×2 or a 2×2 factorial, orthogonal contrasts were used to compare treatment means and interactions. When the interactions were highly significant (i.e. $P < 0.01$) and contributed more than 5% of the total sum of squares of all factors and interactions, it was discussed in the text. The interpretations were then made on the interactions and not on the individual treatments. The standard errors of the mean shown in the figures were then used to interpret the significance of the differences.

Soil properties and microenvironment

Six forest floor cores were taken in 1989 and 1992 (i.e. 2 and 5 years after soil mixing) from depths of 0–20 cm on each of the western redcedar plots for a total of 16 plots: 8 plots on low-productivity type and 8 plots on high-productivity type. The fresh samples were stored at 3 °C for less than one week prior to being passed through a 2-mm sieve before analysis. A subsample was oven-dried at 70 °C for 24 h to determine the moisture content. All the results are reported on an over-dry basis.

Forest floor pH was determined in distilled water with a glass electrode using a soil-water ratio of 1:4 (gram:mL). Extractable N was determined by extracting and shaking 5 g (fresh mass) of forest floor material with 100 mL 2 M KCl solution for one hour. Available P was determined by extracting and shaking 5 g (fresh mass) of forest floor material with 100 mL 0.01 M HCl solution for five minutes. Mineralizable N was determined by extracting 5 g (fresh mass) of forest floor material with 100 mL 2 M KCl solution following anaerobic incubation in 25 ml of distilled water at 30 °C for 7 days. The digest solutions were then analyzed for N and P using a Technicon AutoAnalyser II (Technicon Instrument Corp., Tarrytown, NY). Soil organic was determined by loss on ignition (24 h at 500 °C).

Microbial activity was assessed in the laboratory by measuring the amount of CO_2 released over a 48 hr period. Most live roots and undecomposed woody debris were removed from soil samples, and 80 grams (fresh mass) of the residual forest floor per sample were added to 500 mL containers (canning jars, Le Parfait). In 1989, a crucible containing twenty mL of 0.1 M NaOH was placed in each 500 mL container. The containers were tightly sealed and incubated in the dark for 48 hrs at room temperatures (18 to 21 °C). The amount of CO_2 trapped in the 0.1 M NaOH was determined by precipitating the carbonate with 0.3 mL of 50% $BaCl_2$ and then titrating the excess alkali with 0.1 M HCl. In 1992, the amount of CO_2 released in the containers was determined using a infra-red gas analyser. Results were presented per unit mass of organic matter.

In early May of 1989 and 1992, eight ion-exchange resin bags of each cation (21 g of 68% moisture Amberlite IRC-50 C.P. RCOO-H-) and anion (29 g of 65% moisture Amberlite IRC-45 C.P. RNH_3^+OH-) exchange resin enclosed in stocking bags, and seven cellulose discs (4.25 cm diameter Whatman #1) enclosed in one-mm nylon mesh bags, were buried for four months at depths of 15 cm in the forest floor on each plot. The resin bags had cation and anion exchange capacities of approximately 33 $mmol^c$ each, and were used to compare the relative levels of soil ammonium, nitrate and phosphate availability and relative decomposition rate between sites and treatments. Laboratory and field studies have shown a good correlation between the ion-exchange resin bag method and many conventional methods of assessing nutrient availability (Binkley and Matson 1983; Binkley et al. 1986; Lajtha 1988). Moreover, it is believed that *in situ* ion-exchange resin bags may behave similarly to plant roots in terms of ion uptake (Gibson 1986), and be sensitive to micro-environmental conditions that influence nitrogen availability (Binkley and Matson 1983). Decomposition of cellulose (filter paper) has been found to be well correlated with *k* values from conifer litter among 16 Alaskan taiga forest stands (Fox and VanCleve 1983).

After four months, the resin was removed from the bags, air-dried, shaken with 200 mL 1 M KCl for 1 hour, and the extract analyzed for NH_4^+, NO_3^-, and phosphate-P as described above. The cellulose discs were cleaned in distilled water, dried at 70 °C for 24 hrs, and their loss of mass determined.

Soil temperature was measured with dial and digital soil thermometers at depths of 10 and 25 cm on all plots between 11:00 am and 2:00 pm at different periods during the growing season of 1989 and 1992. Soil water tension was measured at the same time in 1989 with a quick draw soil tensionmeter at depths of 10 and 25 cm.

Competing vegetation

The above-ground biomass of the competing vegetation was assessed on the same sites where the soil measurements were taken. Five 1-m^2 quadrats were clipped in each plot at the end of July of 1988, 1989 and 1992 (after 1, 2, and 5 years, respectively). The end of July corresponded with the peak biomass production of the most important species. The biomass collected from each quadrat was separated by species and then further divided into leaf and stem+fruit components. The biomass was dried at 70 °C for 24 h and weighed to determine the oven-dry weight for each species and plant component.

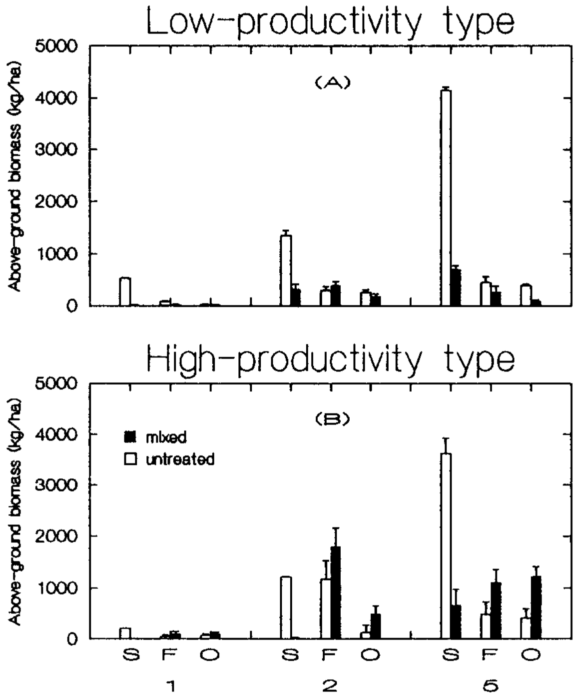

Fig. 1. Effects of soil mixing on the early recovery of salal (S), fireweed (F) and all other competing species (O) on low- (A) and high-productivity (B) sites after 1, 2, and 5 years. The vertical bars represent one standard error of the mean.

Coniferous seedlings

Western redcedar and western hemlock height and diameter at root collar were measured in October of the first (1988), second (1989) and fifth (1992) growing seasons. Every fifth of the 64 seedlings planted in each inner plot were systematically selected for measurement for a total of 13.

Results

Competing vegetation

Soil mixing significantly ($P < 0.01$) reduced salal above-ground biomass on both the low- and high-productivity site types after 1, 2 and 5 years (Fig. 1). There was a significant interaction between treatments and site types for fireweed ($P = 0.003$) and other species ($P = 0.005$). These interactions indicated that both fireweed and other species above-ground biomass were decreased by soil mixing on the low-productivity type, but were increased on the high-productivity type (Fig. 1). After five years, salal above-ground biomass on the mixed sites was less than 25% of that measured on the untreated sites. The regrowth of salal above-ground biomass was rapid on both treatments and in both forest types. On the low-productivity type, it went from 8 and 532 kg ha^{-1} in the first year to 705 and 4144 kg ha^{-1} in the fifth year on mixed and untreated sites, respectively. On high-productivity sites, salal went from 1.5 and 207 kg ha^{-1} in the first year to 667 and 3619 kg ha^{-1} in the fifth year on mixed and untreated sites, respectively.

Total number of vascular species varied considerably from one quadrat to another, but both high- and low-productivity site types had similar number of them (Table 1). From this table, we observed that soil mixing increased both total number and frequencies of most species on both forest types. A few vascular plant species were found exclusively on mixed or untreated low- or high-productivity sites, but the frequencies of those species was generally low. One exception was *Cornus canadensis*, which was fairly abundant on both mixed and untreated low-productivity sites, but was not present at all on high-productivity sites.

Soil properties and microenvironment

Soil mixing significantly ($P < 0.05$) decreased percentage of organic matter and increased soil pH in the upper 20 cm on both low- and high-productivity site types after 2 and 5 hears (Fig. 2). There was a slight decrease in soil pH for the low-productivity type after 2 years, but the interaction between treatments and site types was not significant ($P = 0.09$). Soil mixing increased soil temperature slightly (up to 1.5 °C) but non-significantly ($P > 0.12$) on both forest types after 2 and 5 years. No significant ($P > 0.25$) differences were found for soil pH, soil percent organic matter and soil temperature between the low- and high-productivity types. There was a significant interaction ($P < 0.01$) between treatments and site types for both microbial activity and cellulose loss rate. These interactions indicated that soil mixing decreased microbial activity and cellulose loss rate only on the low-productivity site type; both factors were either unchanged or increased on the high-productivity site type in both years. No significant ($P > 0.1$) differences in soil water potential were found between both forest types and treatments after 2 years, so that it was not measured after 5 years.

The effects of soil mixing on soil nutrient availability on the low- and high-productivity site types are compared after 2 and 5 years following treatment in Fig. 3. After 2 years, all of the nutrient availability indices were significantly ($P < 0.01$) decreased by soil mixing, except for resin N in which the interaction between treatments and site types was significant ($P = 0.002$). This interaction indicated that resin N was increased by soil mixing on the low-productivity site type, but decreased on the high-productivity type. All of these indices

Table 1. Frequencies of each vascular plant species (number of occurrences per 20 1 m^2 quadrats) on soil mixed and untreated low- and high-productivity sites in 1992.

Plant species	Low productivity		High productivity	
	Mixed	Untreated	Mixed	Untreated
Menziesia ferrugine	2	2	–	–
Pinus contorta	1	–	–	–
Cornus canadensis	8	5	–	–
Lysichitum americanum	–	1	–	–
Pteridium aquilinum	–	–	–	1
Sambucus racemosa	–	–	3	1
Anaphalis margaritavea	–	–	1	–
Polystichym munitum	–	–	2	1
Asarum caudatum	–	–	1	–
Picea sitchensis	–	–	1	–
Gymnocarpium dryopteris	–	–	2	4
Equisetum spp.	–	1	2	–
Grasses	1	–	4	–
Ribes spp.	2	–	10	2
Ambrosia spp.	2	1	16	4
Blechnum spicant	10	8	17	8
Rubus spectabilis	4	8	20	6
Vacciunium parvifolium	2	1	2	3
Vaccinium alaskaense	4	1	4	3
Athyrium filix-femina	1	1	5	1
Taraxacum spp.	5	3	12	4
Thuja plicata	5	2	2	2
Tsuga heterophylla	10	1	6	4
Gaultheria shallon	19	20	9	19
Epilobium angustifolium	16	19	20	16
Total number of species	16	15	20	16

were significantly ($P < 0.01$) higher on the high- than the low-productivity types, except for resin P which was not significantly different (P 0.24). After 5 years, the interactions between treatments and site types were significant ($P < 0.01$) for all of the factors measured. Figure 3 shows that, except for resin N, all of the nutrient availability indices were lower on the soil mixed than the untreated plots on the low-productivity site type, but were not different on

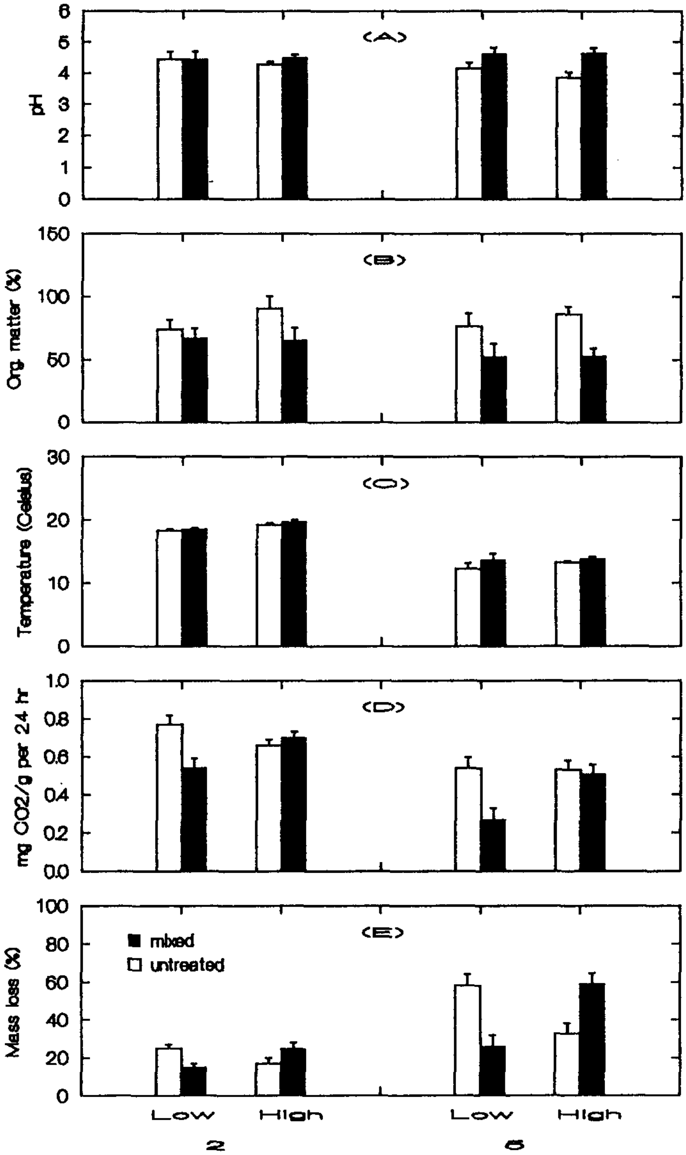

Fig. 2. Comparisons of soil pH (A), percentage organic matter (B), soil temperature at 10 cm (C), microbial activity (D), and cellulose loss rate (E) between mixed and untreated low- and high-productivity sites after 2 and 5 years. The vertical bars represent one standard error of the mean.

the high-productivity type. The results after 5 years for resin N were similar to those found after 2 years. After 5 years, there was a tendency for all of the soil nutrient availability indices to be not different between site types for the

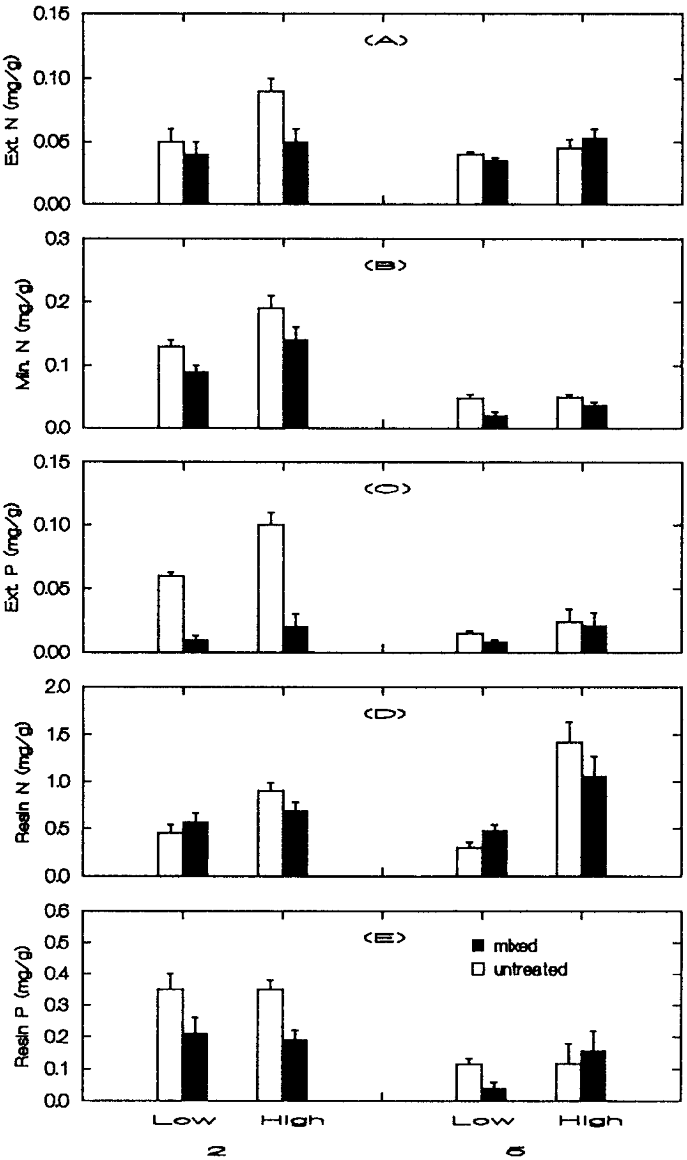

Fig. 3. Comparisons of extractable N (A), mineralizable N (B), available P (C), Resin N (D), and Resin P (E) between mixed and untreated low- and high-productivity sites after 2 and 5 years. The vertical bars represent one standard error of the mean.

control treatment, except resin N, and to be higher on the high-productivity type for the soil mixed treatment (Fig. 3).

Table 2. ANOVA summary table showing variance ratios (*F*), *P*-values and error mean-square for total height of western hemlock and western redcedar after 1, 2 and 5 years between mixed and untreated low- and high-productivity.

Source	Df	First year (sq. height)		Second year (height)		Five year (log height)	
		F-ratio	*P*	*F*-ratio	*P*	*F*-ratio	*P*
Site types (S)	1	116.7	0.000	122.5	0.000	36.1	0.000
Treatment (T)	1	3.4	0.078	9.8	0.005	19.9	0.000
SPecies (SP)	1	0.1	0.709	67.7	0.000	16.2	0.000
S×T	1	0.1	0.813	0.1	0.839	0.2	0.642
S×SP	1	3.8	0.064	27.4	0.000	22.4	0.000
T×SP	1	7.2	0.013	9.4	0.006	3.6	0.071
S×T×SP	1	0.4	0.054	0.146	0.706	5.5	0.014
Error MS	24	50.1		15.3		0.042	

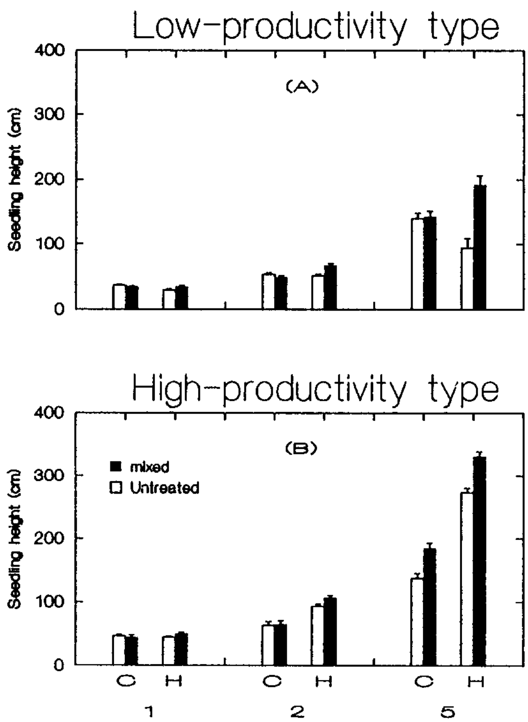

Fig. 4. Comparisons of total height of western hemlock (H) and western redcedar (C) between mixed and untreated low- and high-productivity sites 1, 2 and 5 years after treatment. The vertical bars represent one standard error of the mean.

Conifer seedling growth

Table 2 shows the anova table for height growth of western hemlock and western redcedar seedlings planted on the two site types and two soil treatments. Of all the possible interactions, only the interactions between site types (S) and species (SP) were significant (i.e. $P < 0.01$) and contributed more than 5% of the total sum of squares after 2 and 5 years. Overall, soil mixing significantly ($P < 0.01$) increased total height of both conifer species on both site types after 2 and 5 years (Table 2; Fig. 4). However, the increase was more important for western hemlock than for western redcedar. The significant interactions between site types and species after 2 and 5 years indicated that there were no height differences between site types for western redcedar, whereas total height was higher on the high-productivity type for western hemlock. Western hemlock seedlings were twice as tall on the mixed as on the untreated low-productivity plots after 5 years (Fig. 4A). Identical results were found for total root collar diameter.

Discussion

It is generally considered that ploughing or soil mixing disaggregates and exposes new organic matter surface areas for decomposition, increasing nutrient mobilization (Ross and Malcolm 1988). Mixing of L, F and H Horizons in a black spruce (*Picea mariana*) forest resulted in enhanced respiratory activity in the mixture compared to that of the three separate horizons (Salonius 1978). Krause and Ramlal (1987) found that a treatment that mixed mineral soil and organic matter reduced resin NH_4^+ twofold and resin P fourfold in the balsam fir (*Abies balsamea*) and black spruce forest in New Brunswick. In our study, mixing of forest floor and mineral soil decreased most of the measures of N and P availability on both forest types after 2 years. After 5 years, most indices of nutrient availability, except resin N which increased slightly, were negatively affected by soil mixing on the low-productivity site type, but did not differ from the untreated plots on the high-productivity type. The reduced mobilization of N and P induced by soil mixing could be partly explained by the lower amount of organic matter found in the upper 20 cm of the soil of the mixed plots compared to the untreated plots. The greater decrease in available and resin P caused by soil mixing could be further explained by the reaction of $H^2PO_4^-$ with Fe^{3+} and Al^{3+} or with the hydrate oxides of these metals which are believed to be particularly abundant in acidic mineral soils (Krause and Ramlal 1987). Moreover, mixing brings to the surface a large proportion of the H horizon, and this could have a negative impact on the quality of the substrate available to the decomposer. Prescott et al. (1993) and DeMontigny et al. (1993) reported the H horizon on similar sites to be poorer in nutrients and generally more recalcitrant than the L and F horizons. This could also explain the lower microbial activity and cellulose loss rate found on the mixed low-productivity sites after 2 and 5 years. The slight increase in pH in the mixed plots was presumably caused by the increase amount of mineral soil. Soil temperature and moisture were only slightly modified by soil mixing, and presumably changes to these factors were not important.

Soil mixing is commonly applied to cutovers to improve planting and early tree growth. In this study, it was intended to stimulate mobilization of nutrients and to decrease the cover of non-crop vegetation. As found in other studies, soil mixing increased the early growth of both conifer species on both forest types. However, it had negative or no effects on soil nutrient status on low- and high-productivity site types after 2 and 5 years. In this study, both site types had very deep forest floor with a very thick H layer (often greater than 30 cm), and the competing vegetation was not mixed with the soil as is usually done (Binkley 1986). Moreover, soil mixing had very little effects on soil temperature in both forest types, so that this very important soil condition for the decomposers was not improved. These factors could explain why no increase in soil nutrient availability were found in this study following soil mixing. Better early growth of conifer seedlings on the mixed plots appears to be mediated by reduced competition for nutrients from non-crop vegetation, and not by increased nutrient mineralization. Messier and Kimmins (1991) and Messier (1993) reported a very strong below-ground competition for nutrients by salal on some adjacent low-productivity sites. The higher values of resin N found on the mixed compared to the untreated low-productivity plots after 2 and 5 years (Fig. 3) tend to agree with this explanation.

There are conflicting opinions on the long-term merits of soil mixing on tree growth. Several studies have reported that the early advantageous effect of intensive soil preparation may not persist throughout the rotation (Lennartz and McMinn 1973; Haines et al. 1975; Ross and Malcolm 1982; Pehl and Bailey 1983; Vitousek et al. 1992). Although longer time periods are certainly required to fully assess the potential of soil mixing as a means of stimulating mobilization of nutrients on the low-productivity forest site type, our study shows that it had an early detrimental effect on the soil nutrient status. Krause and Ramlal (1987) found similar results from a balsam fir and black spruce forest in New Brunswick, Canada. Soil mixing has had a lasting effect on the regrowth of competing vegetation, especially salal, and this may explain the improved conifer growth on mixed plots, especially of western hemlock. Pehl and Bailey (1983) and Ross and Walstad (1986) found that the effects of soil mixing in reducing competing vegetation was still evident several years after treatment.

Western redcedar showed only a small growth response to site types or treatment differences that increased or decreased soil nutrient availability. Similar results were found by Messier and Kimmins (1991) and Messier (1993) on adjacent low- and high-productivity sites, and Messier (1993) suggested several possible explanations for such differences. Although Weetman et al. (1989) showed that older western redcedar planted on low-productivity sites did respond to fertilization, caution should be exercised in applying a silvicultural treatment aimed at promoting the growth of western redcedar on low-productivity sites in this area.

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