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Ten-year results of seedling growth on calcareous soils in the interior of British Columbia, Canada

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ABSTRACT

Impaired soil quality due to compaction and organic matter removal following forest harvesting and mechanical site preparation is of concern, especially on calcareous soils which are believed to be particularly sensitive to disturbance. This study set out to determine the effects of organic matter removal and compaction on soil quality and seedling productivity on calcareous soils of a localized disturbance landscape (2.25 m^2). Here we report ten year post-establishment results of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) seedlings across four sites in southern British Columbia, Canada with eight treatment levels incorporating different quantities of organic matter removal and soil compaction. Pine seedlings suffered high rates of mortality when planted in deposits across all sites while Douglas-fir seedling mortality was high when planted in compacted undisturbed treatments at two sites and in deposits on the remaining sites. Douglas-fir volume was greatest on the deposit treatment regardless of site but grew significantly better on the non-calcareous site. Pine seedlings outgrew Douglas-fir seedlings and, after ten years, seedlings were largest on a mildly calcareous site. Seedling growth was generally found to be negatively affected by calcareous soils and compaction; however, the specificity of results, in terms of species and site interaction and changing response as the seedlings aged, reinforced the importance of treatment effects on soil quality and forest productivity across the entire length of a stand rotation.

1. Introduction

Changing forest practises due to increased mechanization through the mid-20th century in North America led to concerns of loss of subsequent forest productivity from the effects of compaction and organic matter removal on soil quality. A review by Greacen and Sands (1980) identified the mechanics, causes and consequences of compaction, and its detrimental effect on forest soils. A review of practices and research from the 1970s and 1980s on the effects of forest harvesting and mechanical site preparation in British Columbia (BC), Canada demonstrated overall forest degradation (Utzig and Walmsley, 1988). Reports of decreases in soil quality due to increased compaction (Smith and Wass, 1976) and decreases in nutrient contents from the loss of organic matter (Smith and Wass, 1985) were also noted. However, in the application of forest harvesting and mechanical site preparation, these treatments were known to be applied heterogeneously across the landscape (Smith and Wass, 1976). By the late 1980s forest managers recognized that organic matter loss and soil compaction were harmful to soil quality but few experiments were found to systematically address their effects at the site and landscape level in BC or elsewhere in North America.

Organic matter loss and compaction are negative effects on the respective properties of soil organic matter content and soil porosity; the two properties believed to be critical to soil quality (Powers, 2006; Schoenholtz et al., 2000) and in 1989 the Long-Term Soil Productivity (LTSP) trials were initiated to address this hypothesis across a forest stand rotation in a variety of ecosystems in North America (Powers, 2006). The term soil quality is an anthropocentric statement which summarizes the abiotic and biotic conditions of the soil as they relate to a desired outcome e.g., forest productivity or biodiversity. Soil porosity is critical to soil quality as it is a key determinant of soil gas and water exchange and when a force is applied to the soil the pore structure decreases and the bulk density increases i.e., compaction (Kozlowski, 1999). Soil quality for ideal

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growth conditions includes a variety of soil pore sizes as larger pores readily transmit water through the soil and medium sized pores provide the available water for plant growth. Loss of soil porosity by soil compaction is therefore generally referred to as unfavourable for soil quality and forest productivity.

The second property, soil organic matter, has an important role in nutrient cycling and is therefore believed to be critical in soil quality assessments (Schoenholtz et al., 2000). Effective nutrient cycling (e.g., nitrogen (N)) is the flux of nutrients within the forest floor and soil organic matter from decomposition by the soil microbial community and uptake by the growing plant roots to satisfy the plant's elemental requirements for growth. Tree growth may often be limited by the availability of organic matter nutrients e.g., N in the boreal (Maynard et al., 2014b) and interior BC forests (Brockley, 2006, 2007). Nutrient N-limitation in northern forest systems is often attributed to low rates of organic matter decomposition (e.g., Van Cleve et al., 1983) leading to greater quantities of soil organic matter and accumulation of forest floor. Decomposition rates are dependent on the quality of organic matter present, its quantity and stabilization within the soils and on climate (Schmidt et al., 2011). In contrast, other key nutrients for plant growth (e.g., potassium (K), calcium (Ca) and magnesium (Mg)) derive from the parent material and not the organic matter. Evaluating soil quality in terms of nutrient status may be done with a number of indicators including the assessment of: soil properties (e.g., total organic N), decomposition indices (e.g., litter-bag studies), and nutrient concentration in the soil available for plant use (e.g., ion exchange resin probes). Alternatively, soil quality may be assessed by the health of the trees as trees have been shown to be effectively monitored for nutrient deficiencies by elemental foliar analysis (van den Driessche, 1974).

Forest productivity, in addition to soil compaction and organic matter loss, is furthermore believed to be limited on calcareous parent material due to its low soil nutritional status (Kishchuk, 2000). In BC, forest soils in the southern Kootenay and Boundary regions were identified as potentially sensitive to disturbance due to their varying proportion of calcareous parent material (Hope, 2006; Maynard et al., 2014a). In the late 1990s work began to add research sites in southern BC to address the multiple concerns of parent material type, organic matter loss and compaction (Maynard et al., 2014a). The four sites of Mud Creek, Emily Creek, Kootenay East and Rover Creek characterized the region and, at each site, a mini-plot trial was established. Separate to the mini-plot trial but set up concurrently and adjacent at each site was a LTSP trial (Maynard et al., 2014a). The mini-plot trial was created to investigate the effects of organic matter removal and compaction on subsequent forest productivity on a localized landscape level by having plot sizes of 2.25 m^2. The objectives of this mini-plot trial were to: (1) determine the effect of site preparation (compaction and organic matter removal) on the productivity of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and pine (*Pinus contorta* var. *latifolia* Engelm.) seedlings; and (2) determine which soil quality indicators best explain seedling productivity. We hypothesize that: (1) organic matter removal and compaction will negatively affect seedling growth; (2) the sites with calcareous parent material close to the surface will negatively influence seedling growth.

2. Material and methods

2.1. Site descriptions

Four sites in the interior of British Columbia, Canada, were used to study the effects of compaction and organic matter removal on seedling establishment and growth of Douglas-fir, lodgepole pine and western white pine, hereafter called the mini-plot trial. The four sites were constructed as replicates across the landscape and established between 1999 and 2002. Detailed site information and establishment of Mud Creek (MC), Emily Creek (EC), Kootenay East (KE), and Rover Creek (RC) has been previously reported (Maynard et al., 2014a) therefore abbreviated site information follows. All four sites were established in conjunction with, and adjacent to, the LTSP sites in southeastern BC which were implemented by Ministry of Forests, Lands and Natural Resources Operations (formerly BC Forest Service) in collaboration with the larger LTSP program (Hope, 2006; Maynard et al., 2014a). Mud Creek, EC and KE sites are located within 13 km of Canal Flats (north of Cranbrook, BC) in the Interior Douglas-fir biogeoclimatic zone (Meidinger and Pojar, 1991) and all are on Orthic Eutric Brunisols (Soil Classification Working Group, 1998). Established in 1999, MC is located at an elevation of 1005 m, is of loam texture (21% clay) and has an average depth to carbonates of 22 cm. Emily Creek was established in 2000 at an elevation of 1180 m, on loam of 7% clay and with a depth to carbonates of 48 cm. Kootenay East was established in 2001 at an elevation of 1030 m, on silt loam (16% clay) and with a depth to carbonates of 24 cm. Rover Creek is located west of the other three sites, near Castlegar, BC, in the Interior Cedar-Hemlock biogeoclimatic zone, and was established in 2002 at an elevation of 625 m. The soil at RC is an Orthic Dystric Brunisol with a soil texture of loamy sand (5% clay) and has no evidence of carbonates within the top 100 cm.

2.2. Treatments

This study, the mini-plot trial, investigated the effect of differing levels of organic matter removal and varying levels of compaction on forest productivity after harvesting (Table 1). The first treatment type was undisturbed (no additional organic matter removal after harvesting) and uncompacted (UNNC). Second and third treatments were undisturbed but compacted with a light (UNLC) and heavy compaction (UNHC). Compaction was applied by an excavator with a vibrating plate where 5–10 s represented light compaction and 30 s for heavy compaction (Maynard et al., 2014a). Shallow gouge (SG) represented a mid-range disturbance with organic matter removal of the forest floor and mineral material to create a 1–20 cm depression and this disturbance was further treated with either light compaction (SGLC) or remained uncompacted (SGNC). Deep gouges (DG) were representative of more extreme mechanical site preparation conditions with holes ranging in depth from 16 to 51 cm and these either remained uncompacted (DGNC) or were treated with light compaction (DGLC). The deposit (DENC) was the final treatment and ranged in height from 9 to 69 cm. This treatment was created by the

Table 1
Treatment abbreviations and definitions for the mini-plot study.

Abbreviation	Disturbance	Compaction	Treatment
UNNC	Undisturbed	No compaction	Harvested and free of machine traffic
UNLC	Undisturbed	Light compaction	Harvested with 10 s vibration
UNHC	Undisturbed	Heavy compaction	Harvested with 30 s vibration
SGNC	Shallow gouge	No compaction	Harvested, gouge 1–20 cm
SGLC	Shallow gouge	Light compaction	Harvested, gouge 1–20 cm, 10 s vibration
DGNC	Deep gouge	No compaction	Harvested, gouge 16–51 cm
DGLC	Deep gouge	Light compaction	Harvested, gouge 16–51 cm, 10 s vibration
DENC	Deposit	No compaction	Harvested, deposit 9–69 cm

inversion of the forest floor and mineral material excavated from the gouge treatments. These eight treatments were applied to plots of 1.5 m by 1.5 m, with the exception of DENC which was, by definition, adjacent to either the SG or DG treatment and plot size was therefore determined by the mechanical abilities of the operator. Plots were separated by a minimum of 1.5 m. Treatments were randomly assigned to the plots located across the study site with at least 40 replicates of each treatment type per site.

Eastern sites of MC, EC and KE were planted with the same seedling stock of lodgepole pine and Douglas-fir while RC was planted to western white pine (*Pinus monticola* Dougl.) and Douglas-fir. Treatment plots were randomly assigned seedling species that were planted diagonally across the plot to a density of three seedlings per plot (except Emily Creek and Kootenay East which were planted with two seedlings of Douglas-fir per plot in UNHC and DENC). Therefore each species and treatment combination had 20 replicates on each site. Once planted, the seedlings at Emily Creek and Mud Creek were enclosed in net tubes for one and two years, respectively, to protect against animal grazing after which fencing was installed at the sites. Fencing was in place at the other sites at the time of tree planting. Plots were maintained with manual vegetation control for the first three years of growth. Seedlings were thinned to two trees per plot after five years and to one tree per plot after ten years of growth.

2.3. Soil properties

Bulk density samples were collected during the summer of site establishment (except RC which was sampled the second year). Soil bulk density was determined by the sand cone method (Maynard and Curran, 2008) at 0–10 cm across 4–6 randomly selected plots for each treatment. Each of the bulk density soil samples was subsampled and these subsamples were kept cool and returned to the laboratory within a week for sieving to 2 mm, air drying and for storage prior to analysis of general soil characteristics.

Particle size analysis of the soil samples was determined by the Bouyoucos Hydrometer method (Kalra and Maynard, 1991). Soil pH was measured in 0.01 M $CaCl_2$ while carbonates were assessed with a 10% solution of HCl (Kalra and Maynard, 1991). Samples were also tested for cation exchange capacity (CEC) by extraction and analysis (inductively coupled plasma-optical emission spectrometer (ICP-OES)) and for total soil carbon and nitrogen (LECO CNS analyzer) (Kalra and Maynard, 1991).

Soil desorption curves were developed from soil cores collected in 2011 and 2012. Cores were taken with a 4.8 cm diameter metal cylinder from the mineral soil (0–2 cm). They were wrapped individually, kept cool and returned to the laboratory within a week. Curves were developed following the method of Reynolds and Clarke Topp (2008) with seven measurement points ranging from 0.005 to 1.5 MPa, including 0.033 MPa. Soil available water was determined as the difference between the volumetric water content at the wilting point (1.5 MPa) and the field capacity at 0.033 MPa.

2.4. Index of organic matter decomposition

An index of organic matter decomposition was investigated among the different treatment types by the mass loss of white birch tongue depressors for the first three years post-site establishment. Pre-dried at 50 °C for 48 h and weighed prior to field installation, the tongue depressors were placed horizontally at three depths (forest floor mineral soil surface interface, 5 cm and 10 cm deep in the mineral soil) for one year. After collection the tongue depressors were kept cool, returned to the laboratory within one week, washed, dried at 50 °C for 48 h and re-weighed.

2.5. Index of plant available nutrients

Soil plant available nutrient status was determined for the first three years of seedling growth using plant root simulator probes (PRS™ Probe, Western Ag Innovations Inc., Saskatoon, SK, CA). Paired anion and cation PRS probes were installed in four randomly assigned plots for each treatment within 15 cm of a seedling in mid-May and mid-June. Probes were removed from the soil after the one month interval; they were then washed, stored cool and sent to Western Ag Innovations Inc. for extraction and analysis of ammonium (NH_4^+-N), nitrate (NO_3^--N), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), phosphorus ($H_2PO_4^-$-P), iron (Fe^{3+}), manganese (Mn^{2+}), copper (Cu^{2+}), zinc (Zn^{2+}), boron ($B(OH)_4^{3+}$-B), sulfur (SO_4^{2-}-S), and (after 2002) aluminum (Al^{3+}). Probes were extracted with 0.5 N HCl for 1 h following which the solution was analyzed for ammonium and nitrate nitrogen by colourimetry using an automated flow injection analysis or by inductively coupled plasma spectrometer for the remaining ions (Hangs et al., 2004).

2.6. Index of seedling nutrient status

Elemental analysis of three-year old seedling above-ground biomass for current year foliage, old foliage, current year stem and old stem was determined on lodgepole pine samples from MC, EC and KE and western white pine from RC. Oven-dried (70 °C for 24 h), coarsely ground material was microwave digested with concentrated HNO_3, HCl and H_2O_2 and the resulting solution was tested for total potassium, calcium, magnesium, phosphorus, aluminum, iron, manganese, copper, zinc and sodium (K, Ca, Mg, P, Al, Fe, Mn, Cu, Zn and Na) with an ICP-OES (Kalra and Maynard, 1991). Biomass samples were tested for total carbon, nitrogen and sulfur using the same method as the soil samples. Three-year old Douglas-fir seedlings were not sampled for elemental concentrations or overall biomass quantities because of high levels of seedling mortality.

2.7. Seedling survival and growth

Seedling growth was monitored annually for the first five years after planting for height and root collar diameter; subsequent measurements were taken at 8 and 10 years. Measurements were collected with precision calipers, a meter stick and, when appropriate, with a height pole. Seedling mortality was also recorded at each assessment.

2.8. Environmental conditions

Mud Creek, Emily Creek and Kootenay East sites were each monitored in two locations per site for abiotic environmental conditions within one month of planting. The Rover Creek site was monitored from a single climate microstation which was installed in 2007 (five years after establishment). Environmental data was collected from five treatments (UNNC, SGLC, DGNC, DGLC and DENC) across the growing seasons. Air temperature was collected at 20 cm above the forest floor using a CSI 107 (Campbell Scientific Inc., Logan, UT, USA) and, in 2011, HMP45C air temperature and relative humidity sensors at 130 cm were installed. Soil temperature was monitored at 10 and 30 cm by a CSI 107b (Campbell Scientific Inc.). Soil moisture at 10 cm was recorded as soil water potential (CSI 227 Delmhorst cylindrical blocks; Campbell Scientific Inc.) at the Mud Creek site and as soil moisture (GroPoint sensors; E.S.I. Environmental Sensors Inc., Sidney, BC, CA) at the Emily Creek and Kootenay East sites. All data was collected every five minutes and averaged for an hourly value during the growing season and average daily means were recorded throughout the winter (CR10, Campbell Scientific Inc.). Data was retrieved and stations were maintained at least twice a year; at the start and end of the growing season. Within the LTSP project at Rover Creek, the Ministry of Forests, Lands and Natural Resources Operations established a weather station in OM_0C_2 treatment to record air temperature (1.3 m), soil temperature (CSI type T copper constantan thermocouples) and soil moisture (CSI 227 Delmhorst cylindrical blocks). The data from this station at Rover Creek was used to determine environmental conditions for the first five years after site establishment.

2.9. Data analysis

2.9.1. Analysis of productivity and of treatment significance

Seedling productivity measurements of 3-year biomass and ten-year volumes were summarized for site treatment sample means and assessed for within site differences among treatments at an $\alpha < 0.10$ using general linear models with least square means separation in SAS (SAS Institute). Ten-year pine seeding volume data were tested for treatment differences by random complete block design using treatment means of each site for treatment responses. Douglas-fir ten-year seedling volume productivity data were non-normal and were therefore assessed (using site treatment means) by the non-parametric test of Friedman's rank test. Both ten-year productivity assessments were performed in R (version 2.15.1, the R Foundation for Statistical Computing). Soil quality indicators of soil properties, index of organic matter decomposition, index of plant available nutrients and index of seedling nutrient status data were summarized for site treatment sample means and standard deviations using SAS version 9.2 and the results are presented in Supplementary Information (SI). These soil quality indicators were assessed for within site differences among treatments at an $\alpha < 0.10$ using general linear models with least square means separation in SAS and results are presented in SI.

2.9.2. Analysis of soil quality indicators for the explanation of seedling productivity

Linking soil quality indicators to seedling productivity was investigated through a variety of statistical procedures. Patterns in the data, for both the index of plant available nutrients and the index of seedling nutrient status, were explored using multivariate statistics to investigate connections between different soil quality indicators. Plant available nutrient data (PRS probes) for each treatment were summed by growing season (May and June) to better represent nutrient availability across treatments, sites and years. Data processing was initially the same for the plant available nutrient data matrix and a second multivariate data matrix of foliar elemental composition results. Both matrices were assessed for response and those elements which were not acquired at all sampling points or were below detection limits for >95% of the samples were removed from the matrix; this included Pb, Cd and Al for PRS data and B and Na for foliar elemental data. Values in the matrix which were below detection limits were assigned a value 10% of the minimum detection limit and were kept in the matrix. Data were visually examined for outliers with scatter plots and boxplots and outliers greater than two standard deviations from the median were replaced by the median value. While samples were all in the same units for each matrix, the sampling units varied in magnitude and therefore a Hellinger transformation was used to relativize the data prior to analysis (Legendre and Gallagher, 2001).

For the plant available nutrient data and the foliar elemental data, nonparametric multivariate statistical procedures were used to reduce the number of dimensions in the data for improved visualization while not imposing the assumption of linearity and lack of interaction between explanatory variables (De'ath, 2002). Nonmetric Multi-dimensional Scaling (NMS) ordination (PC-ORD software version 5 (MjM Software Design, Gleneden Beach, USA)) was used to explore both plant available and foliar elemental data by organizing the large data sets to minimize dimensions while preserving maximum distance relationships using only rank-order and not true distance relations (McCune and Grace, 2002). Thus similar samples are grouped and samples which are dissimilar are separated in space on a multidimensional plot with directionless axes (McCune and Grace, 2002); axes are used to indicate the fit of pattern. Ordinations were run with a Sorenson (Bray-Curtis) distance measurement with the transformed data forming the response (primary) matrix and variations expressed along the axes were investigated by correlations to the continuous variables of either PRS or foliar elemental concentrations in the explanatory (secondary) matrix. Categorical variables of site, treatment and tissue type were included and tested by non-parametric multiresponse permutation procedures (MRPP). Categorical testing by MRPP yields three terms: an overall significance (p), a term indicating the degree of separation among groups (T) with greater separation yielding smaller values and the separation within groups (A) with values closer to 1 being identical.

Multivariate regression tree (MRT) analysis, a nonparametric linear discriminant analysis of tree based modeling, was also used on the foliar matrix. MRT has been shown to be appropriate in summarizing large data sets while selecting for explanatory variables (Zuur et al., 2007) and is appropriate for analysis of data which is unbalanced, has missing values and is not linearly related to the explanatory variables (Legendre and Birks, 2012). The mvpart package in R was used to run MRT analysis on the data matrix with a manhattan distance measure. Explanatory variables for the foliar elemental data matrix included site treatment means of: plant available nutrient data, organic matter decomposition (surface, 5 cm and 10 cm) and soil data (Db, pH, TC, TN, C/N and CEC). MRT analysis provides an indicator of predictive ability (CV Error), where values close to zero are perfect, and describes the amount of variation explained by tree through the inverse of the Error term (De'ath, 2002).

Univariate regression trees (URT) were used to assess explanatory variables which contributed to three-year seedling survival, three-year mass and ten-year seedling volume results. Three-year seedling mass was determined from the sum of the above-ground biomass components collected from random samples after three growing seasons. Ten-year seedling volume was determined using the cone formula with seedling root collar diameter and height after 10 growing seasons. The tree response variables were untransformed and explanatory variables included site treatment means of: new and old needle seedling elemental concentrations, plant available nutrient data, organic matter decomposition (surface, 5 cm and 10 cm), soil data (Db, pH, TC, TN, C/N and CEC) and GDD. Univariate trees were run in R with the mvpart package and yielded the same Error and CV Error goodness of fit terms.

2.9.3. Analysis of environmental conditions

Environmental data were used to calculate growing degree days (GDD) and effective growing degree days (eGDD) where data were summed by growing year (e.g., June 2000–May 2001) across the five treatments and the three eastern sites (Mud Creek, Emily Creek and Kootenay East) for the first three years and for ten years of growth. Rover Creek GDD and eGDD were summed for the first three years using the Ministry of Forests, Lands and Natural Resources Operations environmental data; therefore it was only representative of the UNHC treatment. Growing degree day values at the eastern sites were determined from air temperature measurements >5 °C 20 cm above the ground following standard methodology (Womach, 2005). A more precise indicator of optimum environmental conditions for seedling growth was sought therefore we calculated an effective growing degree day (eGDD) by incorporating the limitations on air temperature measurements with limits to soil temperature (>0 °C at 10 cm) and restricting soil moisture data to within the available water range for each specific treatment (except DENC where UNNC values were used). Environment Canada weather data for Wasa station were accessed in October 2014 (http://climate.weather.gc.ca/) and the data were processed for average temperature, precipitation and GDD for the first three years of growth for each site and 10 year climate normals (1981–2010). Environmental data processing was determined using SAS version 9.2 (SAS Institute).

3. Results

3.1. Soil properties

Consistent treatment differences in soil properties across the four sites were not evident with many treatment differences in properties not being apparent at all (Table 2). However, applied treatments were effective in broadly changing soil properties. As expected the DENC treatment, a deposit of the material removed for the gouge treatments, had the lowest bulk density (0.85–1.00 g cm^{-3}) compared to the other treatments for a given site; except at Kootenay East where DENC (1.10 g cm^{-3}) remained similar or lower than the gouge treatments (1.09–1.43 g cm^{-3}). Available water holding capacity increased with light compaction in the undisturbed (non-gouged treatments) therefore, the changes in bulk density were also reflected in the water available for plant use although they did not necessarily correspond i.e., increasing bulk density did not always result in increased water content. The shallower depth to the calcareous parent material at MC and KE was particularly evident with the higher pH, total carbon and Ca CEC measurements in the DGNC, DGLC and DENC treatments (Table 2). At EC and RC, the higher total carbon concentration in DENC corresponded with an increase in total nitrogen and was therefore more likely due to the presence of organic matter.

3.2. Index of organic matter decomposition

Uniform pieces of white birch (tongue depressors) were used as an index of organic matter decomposition rate for the first three years after site establishment. Over 2800 pieces of wood were measured for rate of decomposition across the three years, four sites, eight levels of treatment and three soil depths (surface, 5 cm and 10 cm), for an average $n = 10$ per population of interest. Despite the large sample size, there was large variation in the data and few evident patterns (SI 1); therefore, for improved visualization of decomposition rate, treatments and years were combined (Fig. 1). One trend which was evident was generally <20% decomposition of the wood sticks when the sticks were applied to the soil surface although there were examples of >40% in year 3 at both KE and RC (SI 1). When the wood sticks were placed below the soil surface a greater loss in mass occurred with 11–75% at 5 cm and 11–69% at 10 cm (Fig. 1 and SI 1). Therefore location within the soil profile influenced the index of decomposition but significant treatment effects on wood stick decomposition were not evident. While it was evident there were yearly fluctuations in the index of decomposition (SI 1), taking the mean across the three years and all treatments gave indications of site effects as

Table 2

Soil properties for mini-plot trial at site establishment (0–10 cm). Mean values and standard deviation (sd, $n = 4–6$) are presented. Letters indicate statistical differences among treatments for a given site ($\alpha = 0.1$) and with ns indicating not significant. See Table 1 for treatment abbreviations.

Site	Treatment	Bulk density (g cm^{-3})		Available water (%)	pH		Total carbon (mg g^{-1})		Total nitrogen (mg g^{-1})		C:N	CEC (cmol kg^{-1})		Ca (cmol kg^{-1})		Mg (cmol kg^{-1})	
		Mean	Sd		Mean	Sd	Mean	Sd	Mean	Sd		Mean	Sd	Mean	Sd	Mean	Sd
Mud Creek	UNNC	1.13	0.20 ab	6.8	6.0	0.7 a	22.7	7.6 ns	1.24	0.22 ns	18.2	13.1	2.7 bc	10.0	2.8 ns	1.9	0.6 ns
	UNLC	1.15	0.16 ab	10.7	5.7	0.4 a	19.9	6.4	1.20	0.32	16.6	14.4	3.4 ab	9.6	1.6	2.1	0.5
	UNHC	1.17	0.14 ab	11.9	6.2	0.5 a	26.4	9.5	1.36	0.44	19.4	14.4	2.9 ab	10.0	2.9	1.9	0.7
	SGNC	1.22	0.15 ab	3.9	5.9	0.5 a	11.8	2.8	0.90	0.23	13.1	11.8	2.0 bc	7.8	2.5	1.7	0.5
	SGLC	1.30	0.11 bc	8.7	5.8	0.4 a	12.8	5.0	0.95	0.22	13.4	11.8	3.1 bc	8.9	2.2	2.2	0.6
	DGNC	1.51	0.22 d	10.5	7.2	0.5 b	28.0	22.6	0.65	0.13	43.2	7.3	4.0 c	11.9	5.7	1.1	0.9
	DGLC	1.44	0.06 cd	8.5	7.0	0.9 b	34.2	22.9	0.94	0.40	36.3	8.6	2.2 bc	13.8	4.9	1.6	1.0
	DENC	1.00	0.19 a	na	6.4	0.6 ab	78.2	24.0	3.42	4.26	22.9	20.6	13.0 a	16.3	11.8	2.6	2.5
Emily Creek	UNNC	1.08	0.15 ab	9.3	5.6	0.3 ns	18.7	6.7 abc	0.78	0.23 ab	24.0	11.7	4.6 bcd	8.2	2.7 bc	1.2	0.4ns
	UNLC	1.26	0.51 b	11.6	5.7	0.4	28.4	16.1 a	1.15	0.54 a	24.7	16.5	3.1 ab	10.5	4.3 ab	1.5	0.7
	UNHC	1.21	0.32 ab	13.6	5.5	0.5	20.3	9.2 abc	0.83	0.37 ab	24.4	15.8	4.4 ab	10.0	2.7 ab	1.7	0.5
	SGNC	1.34	0.19 bc	12.5	5.7	0.3	10.8	1.0 bc	0.51	0.08 bc	21.1	10.2	2.1 cd	7.6	1.9 bc	1.4	0.2
	SGLC	1.33	0.26 bc	11.7	5.6	0.2	21.8	6.9 ab	0.80	0.23 ab	27.3	15.1	4.6 abc	9.6	3.1 ab	1.3	0.5
	DGNC	1.74	0.30 d	4.5	5.8	0.5	6.6	3.1 c	0.26	0.09 c	25.6	7.9	1.9 d	5.5	1.1 c	1.5	0.5
	DGLC	1.69	0.10 cd	6.5	5.4	0.6	7.0	2.1 c	0.26	0.07 c	26.9	7.9	1.9 d	5.0	1.4 c	1.3	0.5
	DENC	0.85	0.21 a	na	5.7	0.4	31.2	17.5 a	1.06	0.49 a	29.4	17.4	7.3 a	12.2	4.6 a	1.9	0.6
Kootenay East	UNNC	1.01	0.09 a	6.1	5.9	0.4 d	20.2	6.2 c	0.96	0.23 ns	21.1	20.6	4.2 ns	12.6	2.4 c	4.1	0.9 ns
	UNLC	1.12	0.19a	11.5	6.0	0.3 cd	22.4	8.9 c	1.03	0.28	21.8	21.7	5.8	16.5	6.3 c	4.0	1.2
	UNHC	1.07	0.15a	10.7	6.1	0.4 cd	25.9	8.8 bc	1.23	0.35	21.0	27.2	3.8	17.5	4.6 c	4.9	1.3
	SGNC	1.09	0.07a	10.0	6.0	0.6 cd	18.2	14.8 c	0.85	0.36	21.5	19.0	7.8	14.7	7.7 c	4.0	2.2
	SGLC	1.24	0.15ab	6.3	6.6	0.6 bc	21.5	9.9 c	1.03	0.20	21.0	26.7	10.4	24.3	11.9 bc	5.5	2.2
	DGNC	1.43	0.27b	7.4	7.3	0.3 a	51.3	34.0 ab	1.20	0.47	42.7	21.9	9.6	36.7	7.3 a	4.4	2.7
	DGLC	1.43	0.20b	9.4	7.3	0.6 a	52.6	31.5 a	1.12	0.52	47.1	16.1	5.4	38.4	11.6 a	3.6	1.0
	DENC	1.10	0.24 a	na	6.8	0.7 ab	30.6	19.9 abc	1.08	0.29	28.4	27.5	7.8	30.6	13.0 ab	5.7	2.8
Rover Creek	UNNC	1.13	0.14 b	8.0	5.0	0.2 bc	19.7	10.5 ns	0.61	0.39 ns	32.5	5.3	2.3 ns	2.9	1.0 ns	0.2	0.1 ns
	UNLC	1.32	0.11 bc	9.8	4.9	0.4 c	19.0	2.1	0.49	0.09	38.5	6.1	1.8	3.6	2.5	0.3	0.2
	UNHC	1.43	0.12 cd	7.3	5.0	0.2 bc	14.5	2.6	0.35	0.14	41.5	4.2	1.2	2.3	1.1	0.2	0.1
	SGNC	1.18	0.09 b	9.6	5.4	0.2 ab	8.8	2.0	0.20	0.15	44.2	3.3	1.5	2.2	1.6	0.1	0.2
	SGLC	1.46	0.11 cd	9.1	5.6	0.3 a	9.1	1.2	0.21	0.12	43.0	4.3	1.5	2.9	1.7	0.2	0.1
	DGNC	1.30	0.08 bc	4.9	5.7	0.1 a	4.5	0.9	0.08	0.06	56.0	2.2	0.6	1.2	0.3	0.1	0.1
	DGLC	1.58	0.22 d	11.0	5.7	0.2 a	8.1	5.8	0.12	0.12	66.4	4.8	5.1	4.0	6.2	0.3	0.5
	DENC	0.90	0.36 a	na	5.0	0.8 bc	51.5	78.3	1.05	1.71	49.2	8.1	5.8	4.2	4.0	0.4	0.4

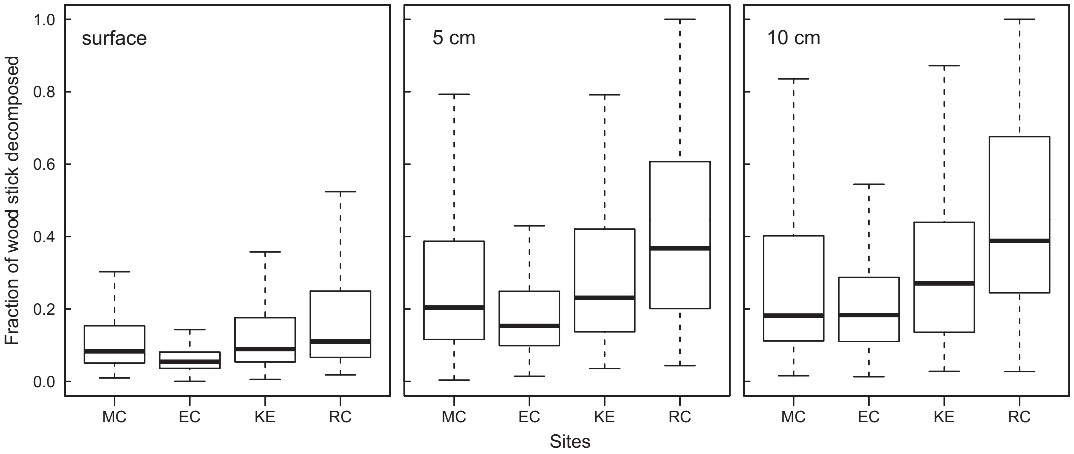

Fig. 1. Index of organic matter decomposition for four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)) presented as boxplots of the fraction of wood stick decomposed after one year of field incubation at either the forest floor mineral interface, 5 cm or 10 cm in the mineral soil. Values for each site represent data from all treatments and all three incubations (first three years after site establishment).

RC generally had the greatest levels of decomposition while EC had the smallest.

3.3. Index of plant-available nutrients

Clear differences were evident in the nutrients available to tree seedlings between the eastern sites of MC, EC and KE and the more westerly RC, based on PRS probe data (Fig. 2 and SI 2). Multivariate analysis by Non-metric Multidimensional Scaling (NMS) was used to visualize the data and to reduce the number of dimensions in the data. A two dimensional solution was obtained with a stress of 10.2 after 72 iterations. NMS ordination illustrated the divide between the three easterly sites and RC while demonstrating the variation within the data. Both evaluating sites and grouping the sites as east (MC, EC, KE) and west (RC) by multi-response permutation procedures (MRPP) showed that both categorical classifications were significant (sites: $p < 0.001$, $T = -184$, $A = 0.35$ and east/west: $p < 0.001$, $T = -256$, $A = 0.28$) and all sites were significantly different from each other ($p < 0.001$). Separation in the data was driven by concentrations of Ca and Mg, as demonstrated by the correlation ($r = 0.6$) of these elements as explanatory variables. Wood decomposition measurements and soil properties were also included as explanatory variables but did not correlate at $r = 0.6$. High concentrations of plant-available Ca and Mg in the eastern soils were explained by high soil CEC values (7.3–27.5 cmol kg^{-1}; Table 2) and high soil Ca and Mg concentrations at the KE and MC sites. Differences among sites were demonstrated by key plant available nutrients of Ca, Mg and NH_4^+-N and the micronutrient Cu (Fig. 3). The plots clearly illustrate the low concentrations of Ca and Mg and the elevated NH_4^+-N concentration for RC compared to the eastern sites. Plant available nutrients in May and June of the first three growing seasons were therefore similar across the eastern sites with EC tending to form a continuum in nutrient availability between the other eastern sites (MC and KE) and RC (Fig. 2 and 3).

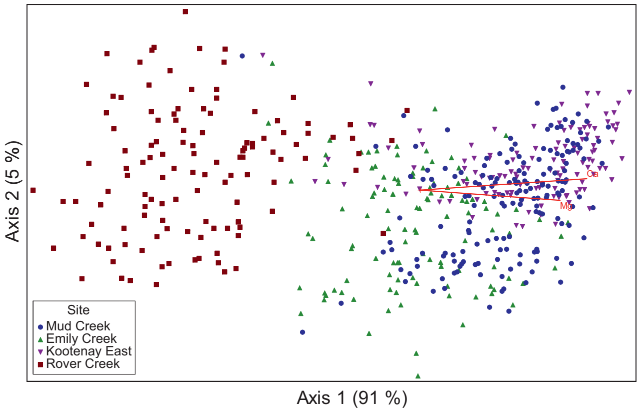

Fig. 2. NMS ordination of the plant available nutrients for May and June of the first three years after site establishment across four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)). Sample points represent the composition of plant available nutrients for May and June of each specific growing year, treatment and site. Points are colored by site as sites were determined to be different among each other ($p < 0.001$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Index of seedling nutrient status

Two elements, N and Ca, best explained the variation in three-year old pine seedling above-ground biomass elemental composition data (Fig. 4). No Douglas-fir seedlings were sampled for biomass or elemental composition due to their poor health and survival after three years. Elemental nutrient composition of the pine seedlings was determined on four components (current needles (SI 3), old needles (SI 4), current stem and old stem) and the resulting data set was examined for patterns by NMS ordination. A two dimensional solution was obtained with a stress of 12.8 after 84 iterations. Variation in the dataset was best described first by Axis 1 (60%), where the concentration of Ca was determined to correlate ($r = 0.65$), and then by Axis 2 (31%), where N concentrations were found to correlate ($r = 0.65$) in the same general direction. Categorically, the seedling component was determined to be significant by MRPP analysis ($p < 0.001$, $T = -557$, $A = 0.35$) with seedling tissue types significantly different from each other ($p < 0.001$).

Ordination demonstrated the differences in composition among tissue types; therefore, data were subset and investigated for patterns in elemental composition of current needles using a multivariate regression tree (MRT). The transformed composition data were examined for patterns to determine if the measured index of seedling health was linked to the soil quality indicators of plant available nutrients, rate of organic matter decomposition and soil properties. Therefore the explanatory variables of soil nutrients, decomposition and soil properties were included in the assessment and the solution, after 1000 multiple cross-validations, had a cross-validation error of 0.691 (accounted for 38% of the

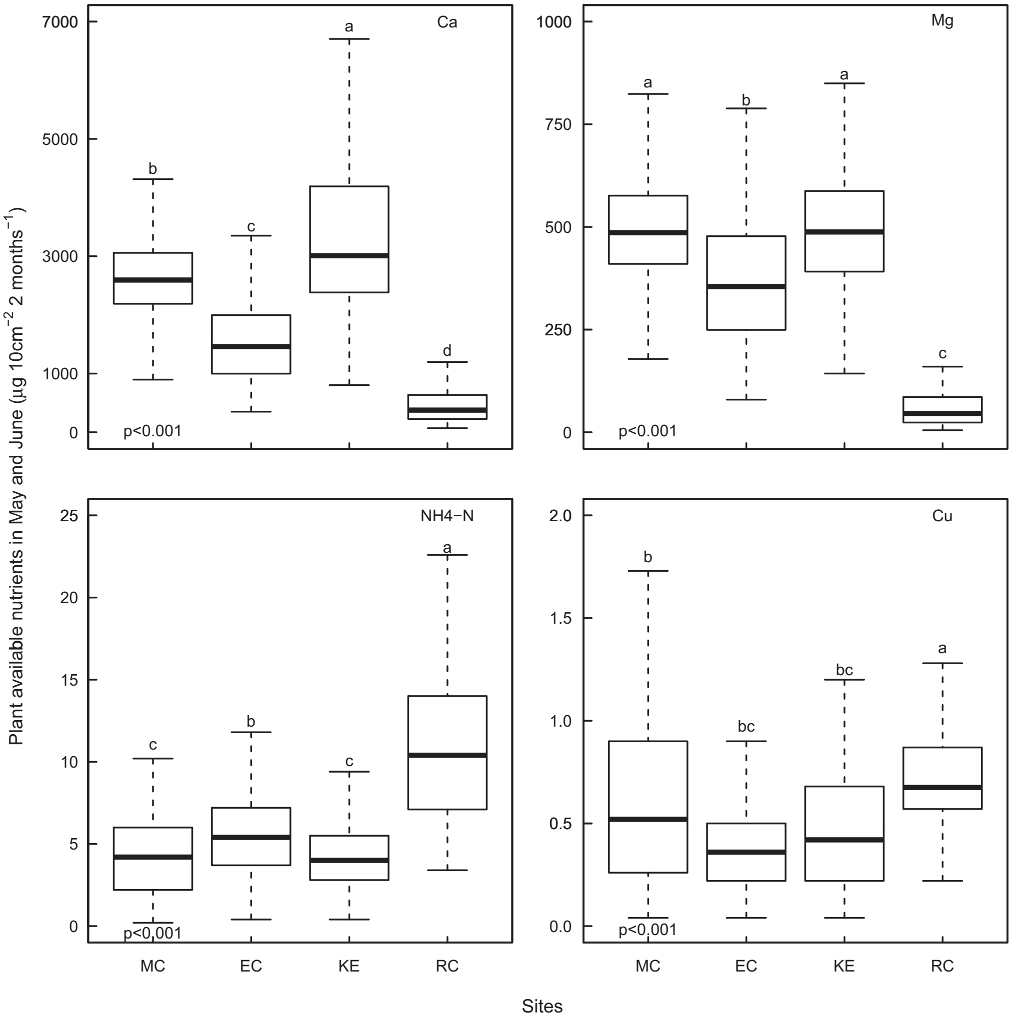

Fig. 3. Select plant available nutrients (calcium (Ca), magnesium (Mg), ammonium-nitrogen (NH_4-N) and copper (Cu)) presented as boxplots for four mini-LTSP plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)). Nutrient values were for the sum of availability for nutrient for May and June of a given year, treatment and site where the boxplots here present all values for each site, treatment and all three incubation years (first three years after site establishment).

variation). Available Ca was found to determine 22% of the separation in composition of current pine needles (Fig. 5). While Fig. 2 illustrates the variation within site for select nutrients, plant-available nutrients were summed for May and June and then the mean of the first three years of growth was used as the explanatory variable in this analysis. At EC and RC, all treatments were below a soil Ca nutrient availability of 2462 µg 10 cm^{-2} 2 $months^{-1}$; as were the UNNC, UNLC and DENC treatments at MC. Multiple variables (available NH_4^+-N, Ca, Mg and S) explained a further 10% of the separation in the composition of the tree. Ammonium-N illustrated the split with RC needle element composition being separated from EC and MC UNNC, UNLC and DENC composition which followed the much greater plant available NH_4^+-N concentrations at RC. The final separation explained the last 6% of the variation in the data and was based on plant availability of Mn; where concentrations were lower (KE UNLC, SGNC, DGNC and DGLC) the foliar elemental composition was more similar.

3.5. Seedling survival

Survival after 10 years ranged from a low of 22% of pine on DENC at RC to 100% of Douglas-fir on DGNC at EC but both species suffered high and low mortality across all sites; except RC pine which was lower than the rest with 22–65% survival (Fig. 6). Seedling survival of both pine and Douglas-fir was dependant on site treatment as opposed to the site itself. Survival of the seedling, across 10 years of growth, was little affected by the gouge treatments while mortality was high for pine in the DENC treatments and for DENC, UNLC and UNHC for Douglas-fir (Fig. 6). In an effort to determine the possible causes for the high mortality on DENC and undisturbed treatments an index of local environmental conditions (effective Growing Degree Day (eGDD), SI 5) was developed as an explanatory variable. While GDD (SI 5) incorporated limitations on air temperature readings, eGDD included restrictions to air temperature, soil temperature, and soil moisture measurements from within each of the five instrumented treatment plots (UNNC, SGLC, DGNC, DGLC and DENC).

Seedling survival after three years was explored with several univariate analysis procedures including either the full data set or data from a subset of treatments (i.e., those with eGDD results: UNNC, SGLC, DGNC, DGLC and DENC) and including either categorical or continuous explanatory variables. Neither GDD nor eGDD (indices of growth conditions) accounted for any variation in the subset of survival data i.e., high mortality on DENC treatments was not explained by either index of growth conditions. These explanatory variables were therefore removed and subsequent analysis was based on data from all treatments. For the

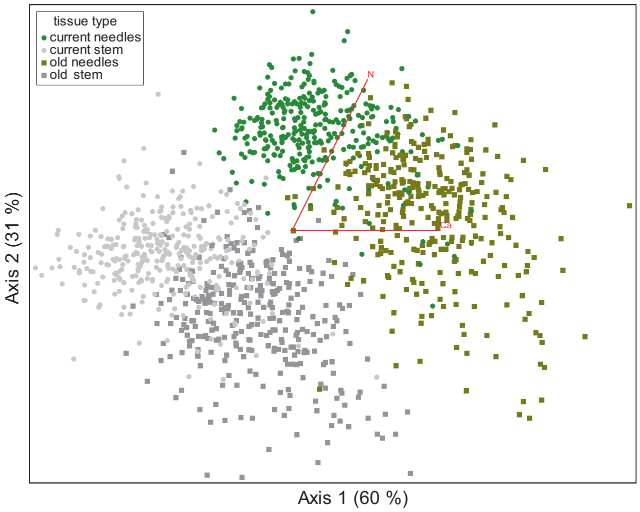

Fig. 4. NMS ordination of the elemental composition of four tissue types from pine seedlings three years after site establishment across four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)). Sample points are the elemental composition of pine specific to each tissue type, treatment and site. Points are colored by tissue type as types were determined to be different among each other ($p < 0.001$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

univariate analysis of survival data from all treatments, continuous explanatory variables included soil properties, index of decomposition and plant available nutrients and the categorical variables included treatment type and site. However, Fig. 7 illustrates the effect of treatment type on both pine and Douglas-fir survival and both data sets were best explained by this categorical analysis. Separation of the gouge treatments from DENC and undisturbed accounted for 22% and 15% of the data variation. A second division based on site further described the data variation with MC and RC having lower rates of survival than EC and KE.

3.6. Seedling growth

To determine the effect of compaction and organic matter removal on pine and Douglas-fir seedling productivity we examined the 10 year seedling volumes across the eight treatments as a random complete block design and determined that the treatments had no significant effect (Fig. 8 and Table 3). Instead it was the block, or site, parameter which was significantly different in the model for pine. Douglas-fir seedling volumes had a non-normal, bi-modal, distribution and were analyzed with a non-parametric testing function. When pine (Fig. 9) and Douglas-fir (Fig. 10) seedling volumes were plotted and tested for treatment differences by site, treatment differences became more apparent. Therefore,

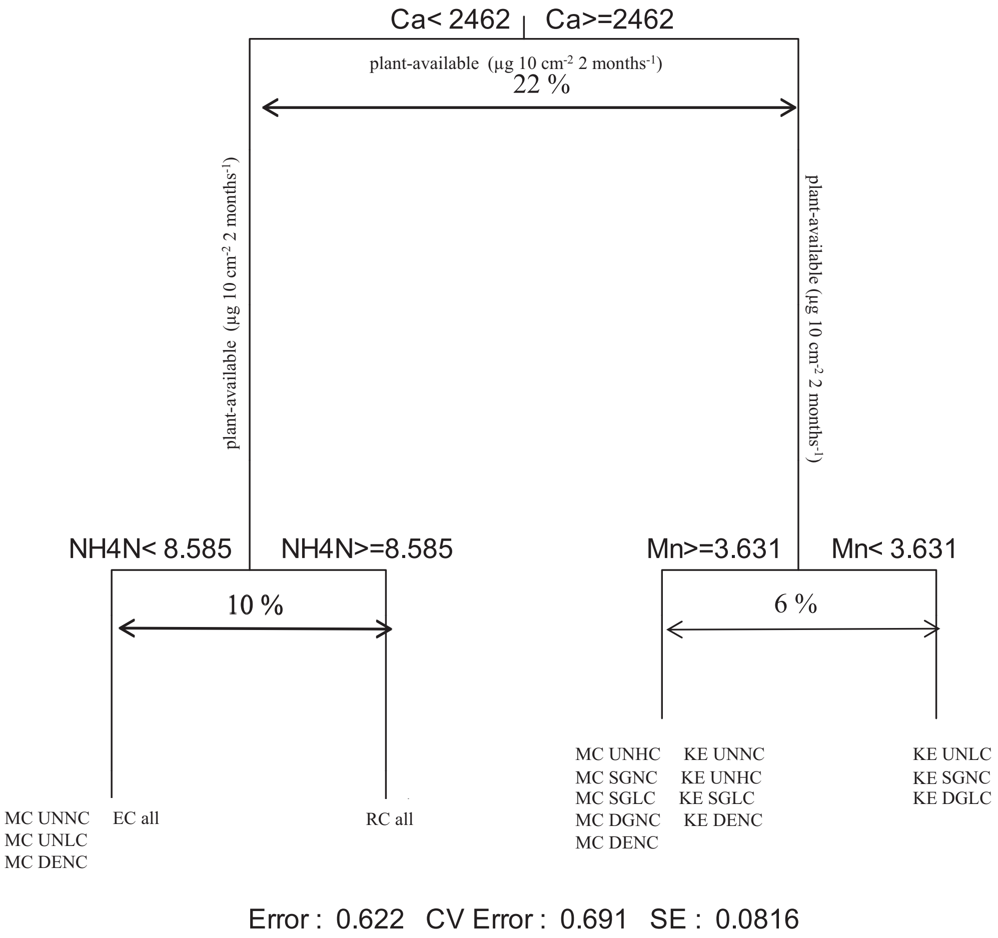

Fig. 5. Multivariate regression tree analysis of current pine needle elemental composition from seedlings three years after site establishment across four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)).

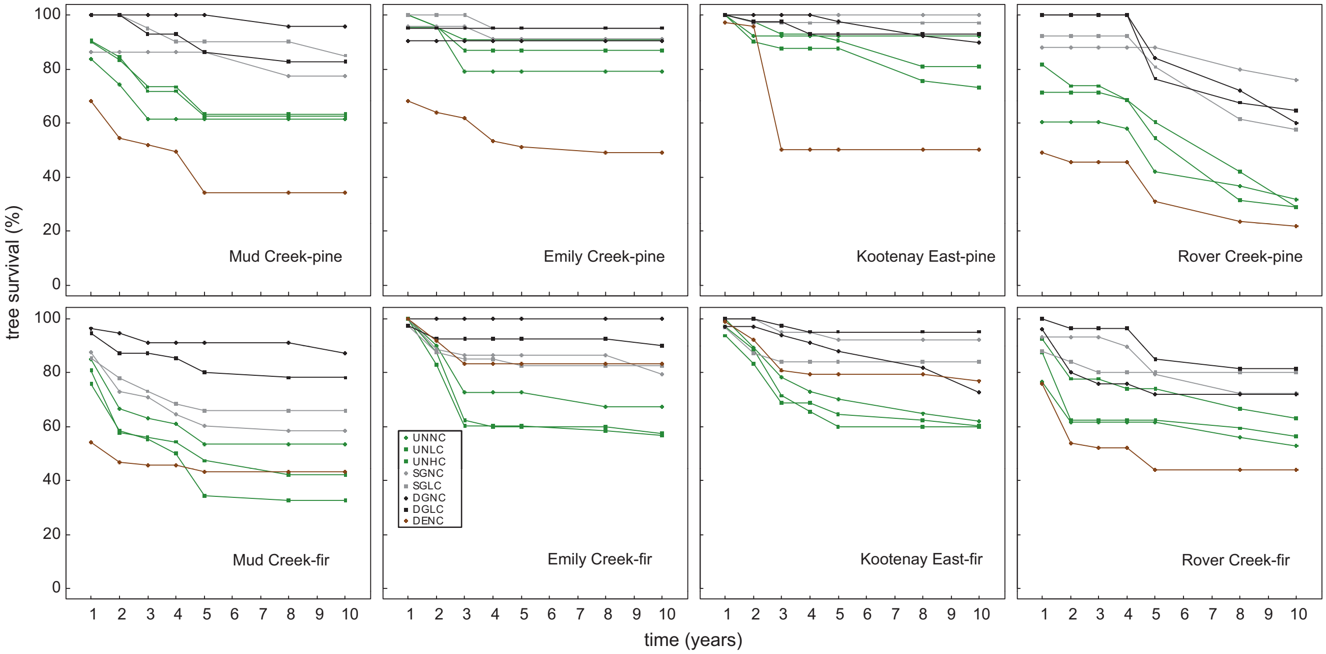

Fig. 6. Pine and Douglas-fir seedling survival percentages across eight treatment types for ten years at four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)). See Table 1 for treatment abbreviations.

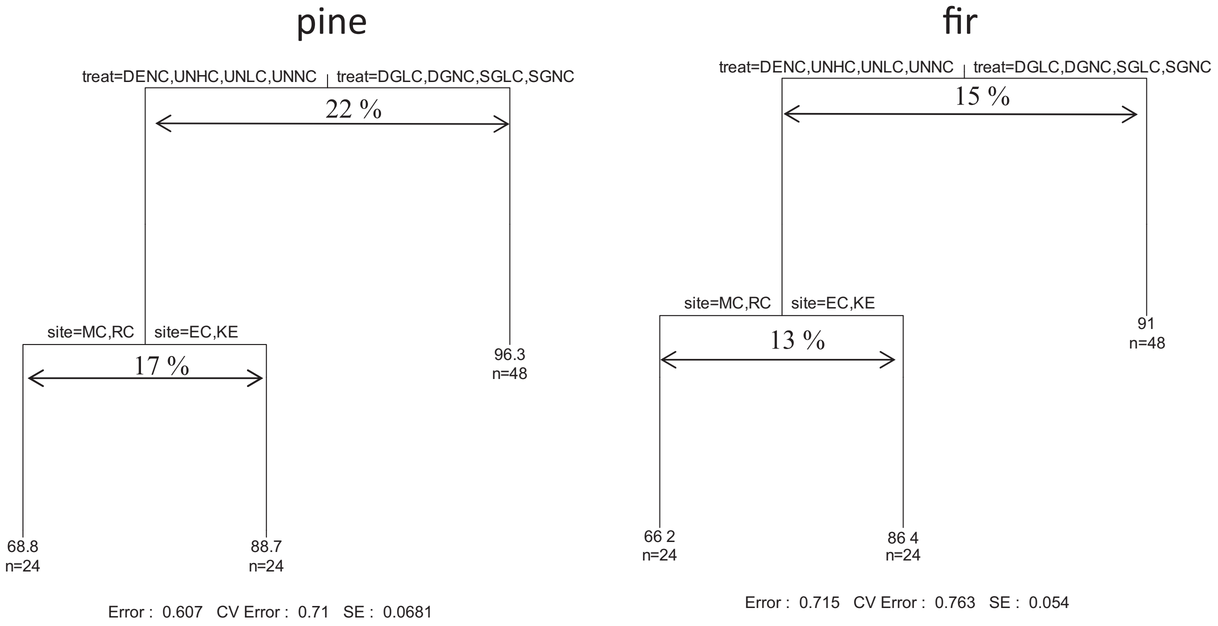

Fig. 7. Univariate regression tree analysis of pine and Douglas-fir survival after three years of growth across eight treatments at four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)).

instead of examining treatment effects across the landscape, these results indicate that the treatments must be evaluated on a site basis.

Total above-ground seedling biomass was greater for EC and RC for the three-year old pine seedlings (Fig. 9). Seedlings from MC and KE averaged 38.2 g in biomass and it was the plant available Ca in the soil that was found to best explain the separation from EC and RC samples by univariate regression tree (21% of variance explained; Fig. 11). In addition to plant-available nutrients, index of decomposition measures and soil properties, both the current and old needle elemental compositions were included as explanatory variables. Neither current elemental composition nor ratios of elemental compositions (i.e., N:P, N:S, N:K, N:Mg) explained the variation in seedling biomass; rather it was plant-available Ca (15% variance explained) and concentration of Cu (8% variance explained) in the old needles. Mean plant-available Ca concentrations of May and June (PRS probe data) were all greater than 2073 μg 10 cm^{-2} 2 months^{-1} for MC and KE. Copper concentrations of old needles from RC were never above 24 mg kg^{-1} while EC Cu concentrations ranged from 123 mg kg^{-1} to below 20 mg kg^{-1}. Detection of Cu concentrations in pine needles must be viewed cautiously as concentrations were often

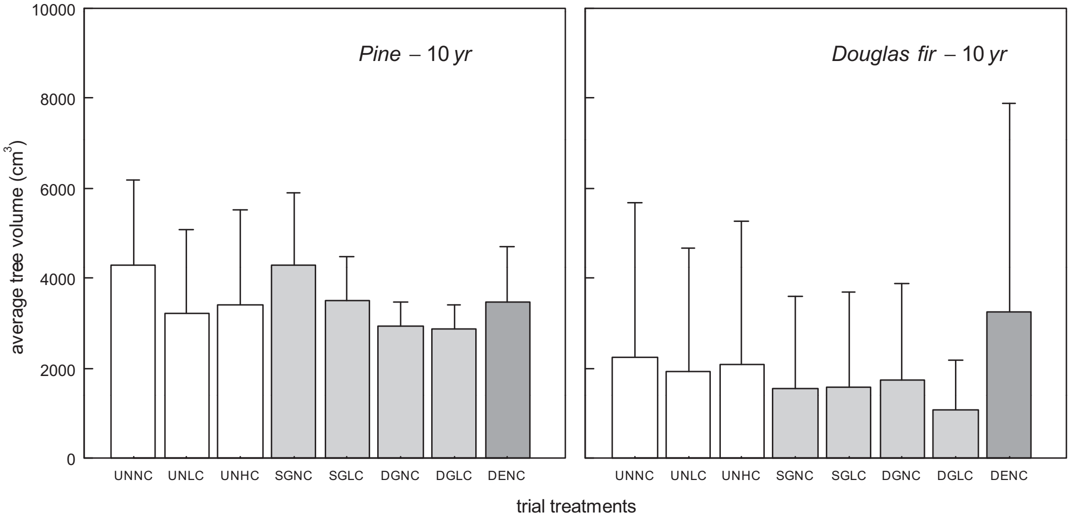

Fig. 8. Pine and Douglas-fir seedling ten year volume growth in a mini-plot trial across a variety of treatments of organic matter removal and compaction in southern BC. See Table 1 for treatment abbreviations.

Table 3
Statistical results on ten-year pine and Douglas-fir volume growth for an eight treatment mini-plot trial in southern BC which varied organic matter and compaction levels.

Model	$Y = \mu$ + treatment + block + error				
Pine					
Analysis of variance table	Df	Sum Sq	Mean Sq	*F* value	Pr(>*F*)
Treatment	7	8199,496	1,171,257	1.33	0.2853
Block (site)	3	32,743,490	10,914,497	12.392	<0.0001
Residuals	21	18,495,605	880,743		
Douglas-fir					
Friedman rank sum test					
Friedman chi-squared	Df	*p*-Value			
12.833	7	0.076			

below detection limits for entire sites (e.g., MC and KE) and within site (e.g., EC) and it was therefore unclear what the true spread of Cu concentrations was. Plotting old needle concentrations of Cu to three year total above-ground biomass for EC pine seedlings hints at a possible positive correlation, although there were obviously numerous seedlings which were large in mass yet had concentrations of Cu below detection limits (SI Fig. 1).

Overarching treatment effects on three-year pine biomass were not evident (Fig. 9). While MC and KE had greater growth on the SGLC treatment, this was one of the smallest treatment responses for EC and RC where growth was greatest on UNNC and DENC treatments. A negative effect of some treatments was evident for ten-year seedling volume assessments (Fig. 9). Compaction clearly had a negative effect on pine growth at RC with the largest volumes on UNNC, SGNC and DENC treatments. At the eastern

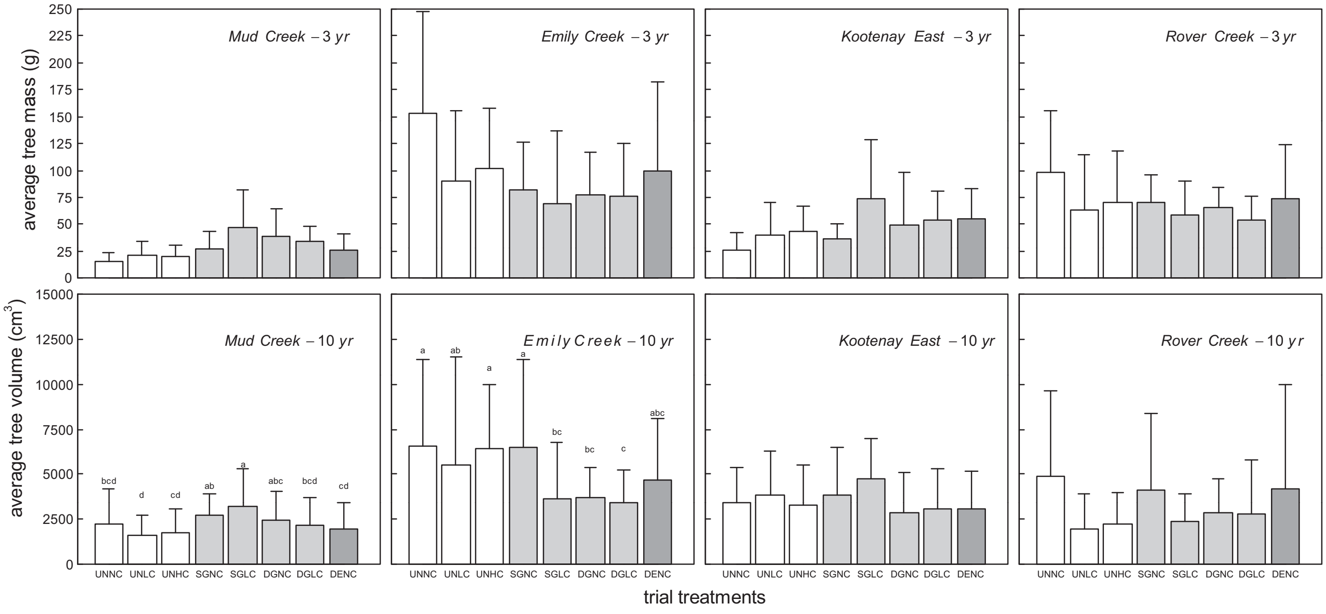

Fig. 9. Pine seedling growth across four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)) three and ten years after site establishment. Three year results are presented as mass of all aboveground biomass and ten year results are presented as the volume of the seedlings. See Table 1 for treatment abbreviations.

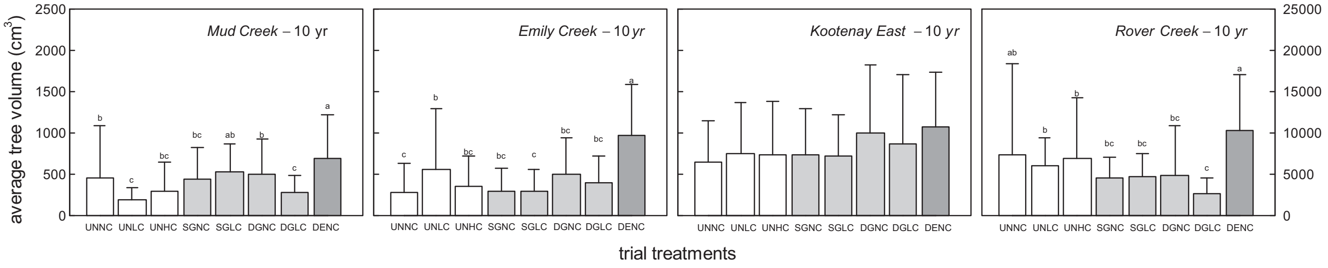

Fig. 10. Douglas-fir seedling growth across four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)) ten years after site establishment. Ten year results are presented as the volume of the seedlings. See Table 1 for treatment abbreviations.

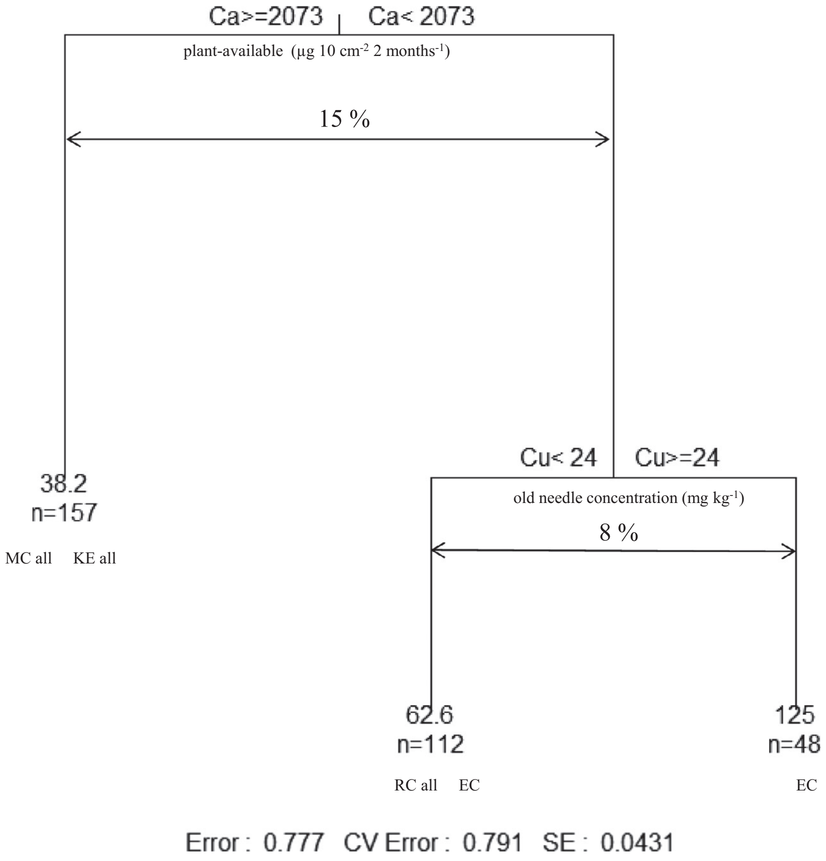

Fig. 11. Univariate regression tree analysis of pine three year biomass growth across eight treatments at four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)).

sites, the effect of compaction was less clear, with possible smaller effects at MC in the undisturbed and deep gouge treatments and in the EC shallow gouge treatment. Overall, EC maintained its growth advantage with larger volumes in the undisturbed and SGNC treatments compared among sites while MC seedlings remained some of the smallest. Ten-year pine volumes were not well explained using a univariate regression tree which included three-year foliar data, three-year plant-available nutrients, indices of decomposition and soil data. While the explanation of variation in the data was low (<10%), Fig. 12 indicates that seedling foliar nutrient ratios may account for 5% of variation in 10 year pine tree volumes; three-year old seedlings with a high N:S ratio in current needles had smaller 10 year volumes. These smaller pine trees included all those from MC and those from several treatments at KE (UNNC, UNHC, SGNC, DGNC and DGLC). This division separated out all RC and EC seedlings as no treatments were above a ratio of 14.4 and RC and EC DGNC and DGLC were further separated as mean plant-available Cu concentrations were greater than 0.54 µg 10 cm^2 2 months^{-1}. The largest tree volumes were then those of low N:S, low plant available Cu and low current foliar Mg (EC UNNC, UNLC, UNHC and SGNC); however, these variables only explained 6% of the data and caution must be exercised in interpreting the results.

In contrast to pine seedlings, Douglas-fir had ten times greater the volume at RC than the eastern sites (Fig. 10). Following site, there was a clear positive treatment effect on growth on DENC disturbance treatments; however, after 10 years there were no further obvious treatment effects on Douglas-fir growth. Douglas-fir volumes were investigated for trends using univariate regression tree analysis (Fig. 13). The results clearly defined the difference in RC growth from eastern sites with the first split accounting for 35% of the variation and divided on plant available NH_4^+-N, Ca, or Mg, which are all variables which were sharply different between eastern and western sites. Eastern sites were minimally separated (2%)

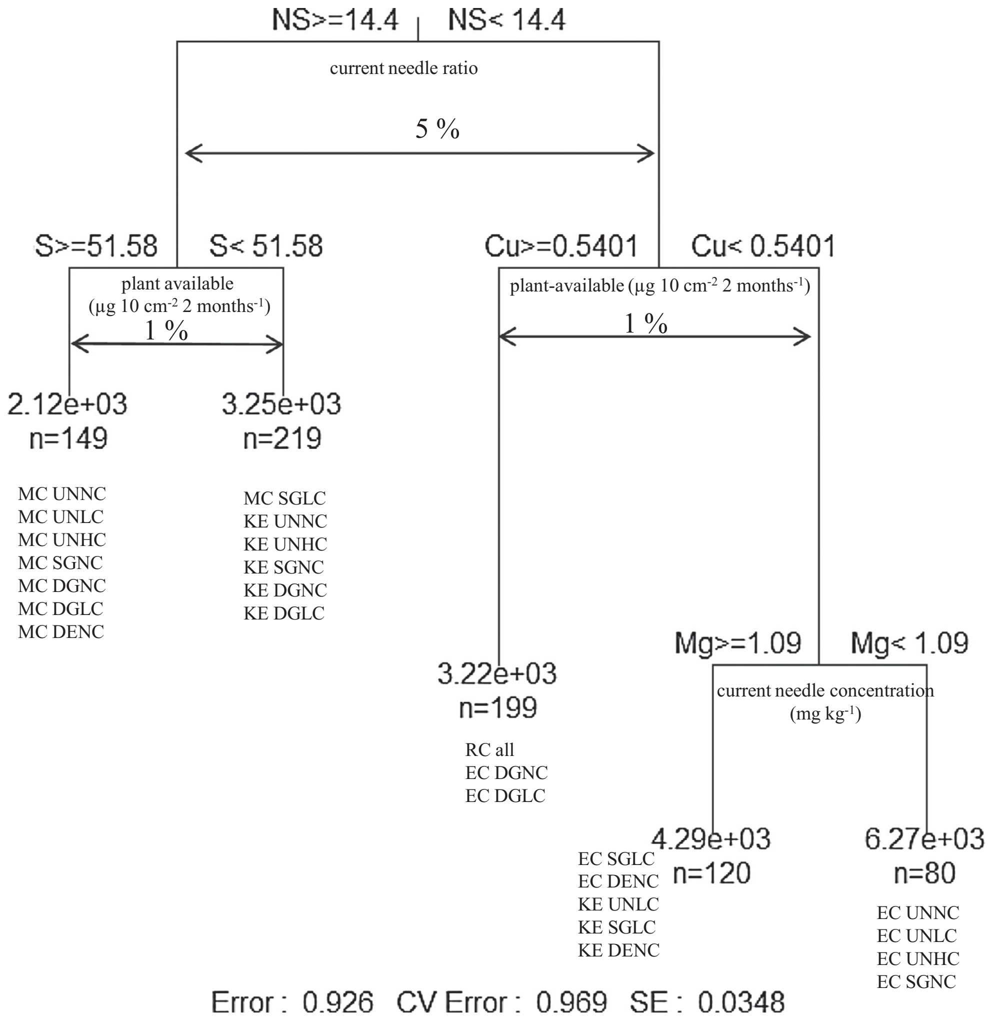

Fig. 12. Univariate regression tree analysis of pine ten year biomass growth across eight treatments at four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)).

with the smallest Douglas-fir trees growing on sites which were low in plant-available NH_4^+-N and had low soil CEC (<16 cmol kg^{-1}). Explanatory variables for ten-year Douglas-fir volume data included soil properties, indices of decomposition and plant-available nutrients but did not include any elemental foliar data as this information was not collected.

4. Discussion

Trial treatments did not significantly affect seedling productivity after 10 years (Fig. 8). Rather, it was the sites which affected seedling productivity (Table 3) and, when seedling volume was viewed on a site basis, treatment effects did become significant at some sites (Figs. 9 and 10). Seedling productivity due to treatment effects did, however, change with time as evidenced by comparing the three and ten year pine seedling growth results (Fig. 9); results which illustrate the need for long term research on compaction and organic matter removal treatment effects.

The overall LTSP project was established to systematically address the effects of organic matter removal and soil compaction throughout a stand rotation across a variety of ecosystems (Powers, 2006). Our study had similar aims to the overall LTSP project with treatment extremes resembling those in the LTSP project from a minimally disturbed harvested treatment (UNNC = OM_1C_0) to a more severe treatment where, in our study, mineral material was removed (DGLC) in addition to the compaction after removal of forest floor in the LTSP treatment (OM_3C_2). One striking difference in this study, however, was the inclusion of a deposit treatment (DENC). Furthermore, instead of a 2800 m^2 plot size, this study examined the effects of organic matter and compaction on a more localized scale (2.25 m^2). An initial objective at establishment of this mini-plot study was to compare results with the adjacent LTSP trial and to make inferences on the effects of treatment plot size, however, LTSP ten-year data across these four LTSP sites have not yet been processed.

An analysis of five-year LTSP results by Fleming et al. (2006) reported that growth responses were not affected by organic matter removal while compaction without a forest floor did not change growth patterns yet compaction with an intact forest floor increased tree stand biomass. These same trends held for ten-year LTSP results (Ponder et al., 2012) which reported that compaction in conjunction with retention of forest floor increased tree biomass in all regions; however, the combination of compaction with the removal of forest floor did not increase tree growth to the same extent. Despite the difference in plot size, the treatment responses after three years in the mini-plot trials were similar to five-year LTSP results as the UNNC treatment had the smallest pine mass for MC and EC. However, ten-year pine volume results for three of the sites had compacted treatments as the smallest, either with an intact forest floor (MC and RC UNLC) or with a gouge (EC DGLC).

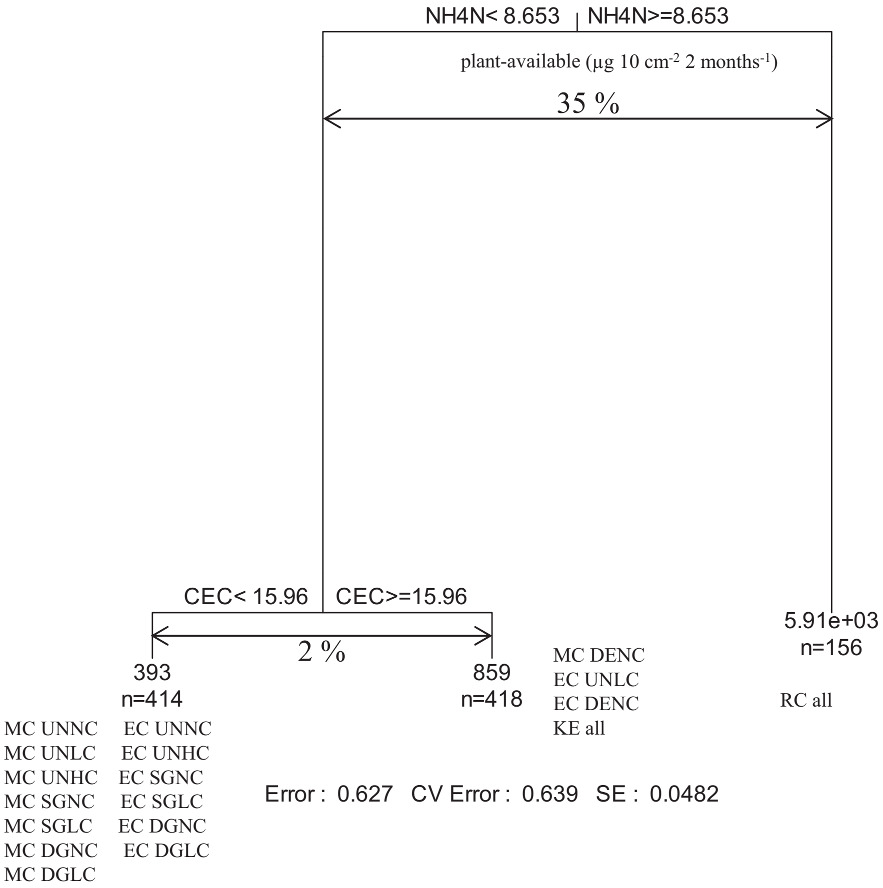

Fig. 13. Univariate regression tree analysis of Douglas-fir ten year biomass growth across eight treatments at four mini-plot sites (Mud Creek (MC), Emily Creek (EC), Kootenay East (KE) and Rover Creek (RC)).

Impeded seedling growth on deep gouge treatments would have been, to some extent, expected because the denser and less developed solum was exposed in this treatment and, based on Krzic et al. (2004) determination of maximum bulk density of the fine fraction (particles < 2 mm) for LTSP sites in BC, this exposure of parent material meant the fine bulk density for deep gouge treatments for the mini-plots (1.02–1.34 Mg m^{-3}) almost met or reached their determined maximum bulk density (1.34–1.55 Mg m^{-3}).

In addition to volume growth, seedling survival must be considered when evaluating treatment effects. With a large plot size (e.g., LTSP 2800 m^2), seedling volumes may be presented on a per hectare basis and thus include seedling survival but on our mini-plots, with an initial 3 seedlings planted in 2.25 m^2, seedling volume on area basis would be skewed. Instead, we present survival as the percentage of the total number of trees which survived for each treatment across each site (Fig. 6). From this figure, and the URT three-year pine survival analysis which looked for patterns in the data to determine which variables best explained survival data (Fig. 7), it was evident that the DENC and UNNC treatments had high pine mortality across all sites and this must be considered in conjunction with the greater ten-year seedling volumes found in these treatments. In our mini-plots at these sites, the highest mortality at three-years was in undisturbed and, most frequently, DENC (Fig. 4). In contrast, the three eastern LTSP sites (MC, EC and KE) were reported to have the greatest mortality in OM_1C_2 and OM_1C_1 treatments for pine and OM_0C_1 and OM_0C_0 treatments for Douglas-fir after three years (Tan et al., 2009). Comparing these three-year seedling survival results among the 2800 m^2 and 2.25 m^2 plots, there appeared to be increased seedling survival on the smaller gouged treatments compared to OM_2 and this could have been due to the smaller plot size and the ability of seedling roots to spread beyond the disturbance footprint. Similar patterns of survival to that found in the mini-plots were noted in long-term stumping trials in BC where both the harvest uncompacted and deposit treatments suffered high mortality after five years in both Douglas-fir and pine (Norris et al., 2014). In the five-year LTSP review by Fleming et al. (2006), seedling survival was noted to be lowest for the OM_0C_0 treatment and to increase with compaction of the forest floor or the removal of the forest floor. Increased survival following compaction or organic matter removal and compaction could be because of mitigation of competition as illustrated by Simard et al. (2003) for pine growth in BC following chemical and mechanical site preparation.

Competition was not considered to be a factor in this study because of its manual control for the first three years. Instead, pine and Douglas-fir seedling survival was best explained by categorical assignment of the treatment and then site type (Fig. 7), with lower rates of survival on UNNC, UNLC, UNHC and DENC in particular. Therefore, in contrast to seedling productivity, treatment had a greater affect on seedling survival than site. We believe seedling survival results were due to environmental conditions, specifically the availability of water throughout the growing season. An index of environmental properties was calculated (eGDD: SI 2) but was not found to explain Douglas-fir or pine survival. The proportion of available water in a soil at field capacity was determined for all treatments except the DENC (Table 2); however, if the observed general trend of increasing available water with light compaction and increased bulk density holds, then we would expect soil in the DENC treatment to have lower levels of available water. In addition, the DENC (followed by UNNC) treatment was observed to exceed 0 °C in soil temperature earlier in the spring and to maintain this higher temperature throughout the growing season (data not shown). It was therefore expected that soil moisture measurements in the DENC treatment reached wilting point values earlier in the growing season and were at this critical threshold for longer than soil in the SGLC, DGNC or DGLC treatments (data not shown). Combined, these results indicate that growth conditions included severe moisture limitations and likely caused water stress later in the summer and may have contributed to the higher mortality in the DENC treatments. Furthermore, beyond the treatment differences, it must be noted that environmental conditions, in particular for the first three years of seedling establishment, were different among the sites (SI 5). Regional climate normals and yearly fluctuations (Table 4) were determined from the nearest Environment Canada meteorological station in the same geographic region as the eastern sites (Wasa, within 45 km). In the first year of growth for MC, GDD at Wasa was greater than the climate normal yet it was also drier with almost half the normal precipitation. Neither EC nor KE suffered drought to the same extent in their first year of growth and we therefore hypothesize that it was this difference in precipitation conditions which caused the difference in survival between the otherwise similar sites of MC and KE.

This trial was undertaken with two seedling species planted on each site (Douglas-fir and lodgepole pine, with western white pine at RC) and species response differed to both treatments and, particularly, to sites (Figs. 9 and 10). Differing species growth responses have been noted on LTSP sites after five (Fleming et al., 2006) and ten years of growth (Ponder et al., 2012) where, for example, Douglas-fir and ponderosa pine had opposing responses to heavy compaction in an Idaho LTSP site (Ponder et al., 2012) and responses differed between lodgepole pine and hybrid white spruce (*Picea glauca* × *engelmannii* [Moench] Voss) on subboreal BC LTSP sites (Kranabetter et al., 2006). In our study, Douglas-fir growth on RC was ten times greater than on the eastern sites and, at the treatment level, Douglas-fir growth was best on the DENC treatment after ten years while pines grew well on a range of treatments: SGLC at MC and KE, UNNC at RC and UNNC and SGNC at EC. Despite the pine species differences between the eastern and western sites, western white pine growth at RC was similar in scale and response to lodgepole pine at EC.

Seedling species response to specific treatments and sites would be expected to vary as Douglas-fir and pine are known to differ in growth form and Douglas-fir seedlings are more sensitive to variable moisture levels (Hermann and Lavender, 1990) while lodgepole pine seedlings have a wider environmental tolerance (Lotan and Critchfield, 1990). Rooting habits are also different between the two species, with Douglas-fir quickly growing a deep taproot while pine has a shallower root system (Hermann and Lavender, 1990; Lotan and Critchfield, 1990). In addition, Douglas-fir has a higher nutrient N demand, particularly for inorganic NO_3–N, and this preference for NO_3–N has been shown to increase with increasing soil temperature (Boczulak et al., 2014; Hawkins et al., 2008). Foliar elemental analysis and three-year biomass were not sampled for Douglas-fir seedlings as there was greater than 30% mortality on many treatments and mean seedling heights were less than 40 cm at the eastern sites. Ten year heights were similar to other harvested but undisturbed sites in the interior of BC (i.e., Gates, Phoenix and Marl ranged in height from 94 to 211 cm; (Norris et al., 2014)) with Douglas-fir at RC growing exceptionally well (UNNC mean height of 357 cm (SI 6)). Douglas-fir growth has been reported to be limited by N on medium to good productivity sites in the interior of BC (Brockley, 2006) and, while we cannot comment on the foliar elemental composition of our Douglas-fir seedlings, Douglas-fir growth was significantly greater at RC where there was a greater concentration of plant available ammonium (Figs. 3 and 13). Another explanation for the greater growth at RC could be the lower concentration of plant available Ca as a significantly smaller biomass of Douglas-fir seedlings was reported when seedlings were grown with high Ca concentrations in a greenhouse experiment (Hawkins and Robbins, 2014).

Pine seedling health was largely driven by site differences and not treatment differences when evaluated with three-year elemental above-ground biomass analysis (Figs. 4 and 5). Specifically, it was Ca concentrations within the biomass which characterized much of the separation in the foliar data and, as expected, this was best explained by soil available Ca concentration which derived from the site soil properties. Calcareous soils were observed to have high exchangeable Ca concentrations in the soil (Table 2), high plant available Ca concentrations (Fig. 3), and led to high Ca concentrations within the three-year biomass (SI 3 and 4) and were lower in overall growth at 3 and 10 years (Fig. 11). These results indicate that calcareous soils negatively affect pine growth.

One explanation for poor pine growth on calcareous soils was the possibility of an elemental foliar imbalance as, for example, almost all treatments at MC and KE were above a N:S ratio of 14.4. This level has been identified as a threshold for optimum pine health (Brockley, 2001). An alternative explanation could be a micronutrient imbalance of, for example, Cu. Copper has been identified as a micronutrient required for plant growth; however, quantifying Cu concentration has been difficult because of its low concentration in biomass and the current detection limits of analytical instruments. Copper deficiency in coniferous trees on calcareous soils, particularly in plantations, has been noted (Turvey and Grant, 1990) and is perhaps caused in part by the precipitation of Cu with carbonates on soil surfaces in calcareous soils (Ponizovsky et al., 2007). Foliar biomass Cu from the less calcareous EC site was consistently above detection limits and, furthermore, three-year pine biomass was greater at EC when the Cu concentration of old needles was greater (Fig. 11). The scatter plot of Cu concentration in old needles in relation to total biomass suggests a positive linear relationship (SI Fig. 1); however, there was also high variation in biomass when Cu was below detection limits ($20\ g\ kg^{-1}$). Whether this was an example of nutrient limitation or some other confounding feature was not clear but it does present an interesting question for further study – is there a micronutrient limitation of pine growth in the interior of BC?

Table 4

Environment Canada Wasa climate station normal temperature (Temp.), precipitation (Precip.) and growing degree days (GDD) for 1981–2010 and Wasa station differences from normal for the first three years of growth at three sites (Mud Creek, Emily Creek and Kootenay East).

Growth year	1			2			3		
Site	Temp. (°C)	Precip. (mm)	GDD	Temp. (°C)	Precip. (mm)	GDD	Temp. (°C)	Precip. (mm)	GDD
Wasa normal	6	358.4	1665.2	6	358.4	1665.2	6	358.4	1665.2
Mud Creek	−0.2	−163.5	34.1	0.3	−10.8	72.7	1.6	−117.0	−33.7
Emily Creek	0.3	−10.8	72.7	1.6	−117.0	−33.7	1.2	−108.0	382.8
Kootenay East	1.6	−117.0	−33.7	1.2	−108.0	382.8	1.0	3.4	165.0

Seedling productivity after ten years of growth was site dependent and this was due to the differences in site soil quality, as measured by soil properties, organic matter decomposition and plant available nutrients (Table 2 and Figs. 1–3). RC was distinctly different with lower pH and CEC, higher rates of decomposition and greater plant available NH_4^+-N. Of the three eastern sites, EC had a greater depth to carbonates which was reflected in lower pH and a differing pattern of plant available nutrients; a plant available nutrient pattern driven by the lower rates of plant available Ca and Mg. Three-year pine biomass was clearly dependant on these site differences in plant available nutrients with larger seedlings in soils with lower Ca concentrations (EC and RC). A literature review by Kishchuk (2000) suggested that calcareous soils negatively affect seedling growth; however, few studies which tested this hypothesis were found to exist, especially in western Canada. Studies from other regions found that the first two years of Douglas-fir seedling growth in a field trial were negatively affected by calcareous soil (Stanislaw Motschalow, 1988) and nutrient limitations were reported in a *Pinus nigra* Arn. plantation growing on calcareous soil in Italy (Cenni et al., 1998). More recently, calcareous soils were determined to be the key factor limiting growth of Norway spruce (*Picea abies* [L.] Karst.) in a survey of 60 study sites in the Bavarian Alps (Mellert and Ewald, 2014). At sites in Sweden, Vestin et al. (2013) indicated that tree basal area of Norway spruce was greater on non-calcareous soils after 90 years of growth, while noting growth in the last five years was greater on the calcareous sites. In western Canada, twenty-year growth of interior spruce (*P. glauca* × *engelmannii*) in southeastern BC was determined to be limited on calcareous soils (Maynard and Curran, 2009). Our results indicated that after ten years of growth pine seedlings were negatively affected by calcareous parent material. With approximately ten times the Douglas-fir volume on RC, results suggest that Douglas-fir growth was significantly impaired on the eastern sites (MC, EC and KE); although, it was unclear if this was because of the calcareous soils or some other factor (e.g., soil texture or environmental conditions).

Further monitoring of these sites is required in order to begin to understand the long-term implications of compaction and organic matter removal on forest succession and productivity following harvesting on calcareous soils. Specific treatment effects relate more to survival than to growth with high mortality on DENC and UNNC treatments. Treatment effects may become more evident in the second and third decade of growth as was found when a compaction treatment following harvesting was determined to negatively affect subsequent pine volume in a long-term BC stumping trial (Norris et al., 2014). Similar results were indicated here where compaction treatments at EC and RC were found to negatively influence pine growth with trends more evident after ten years than three. Short-term results indicate that pine growth is negatively affected by calcareous soils and Douglas-fir is a poorer stocking choice on the three eastern sites (MC, EC, KE). Douglas-fir is, however, typically managed using partial cutting regimes in which seedlings are more protected from the adverse growing season frosts and not typically planted in exposed areas as in this study. Pine growth has historically been considered unaffected by compaction; but, with indications of decreased volume on compacted treatments after ten years, this may need to be re-evaluated and further assessments of nutrient status and growth of both species on these sites will provide key information to determine best management practices on calcareous soils of interior British Columbia.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.02.036.

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