

Fifteen-year tree growth on standard long-term soil productivity trials and various adjacent amelioration treatments at Interior Cedar-Hemlock sites in southeastern British Columbia and northern Idaho

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ABSTRACT

Understanding the relationship between soil disturbance and tree growth is key to sustainable forest management. We report fifteen-year tree growth results of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) and western white pine (*Pinus monticola* Dougl. ex D. Don) growth following clearcut harvesting and installation of three replicates of the international Long-Term Soil Productivity (LTSP) trial protocols. Additional amelioration plots were also established on each replicate site to study rehabilitation of the most severe disturbance, treatment of Armillaria root disease, and enhancement of soil organic matter. Stark differences were found among the various treatments and species. Vegetation control resulted in significantly better growth for both tree species across the core LTSP treatments and amelioration treatments. On the core LTSP treatments, organic matter removal had a significant negative effect on Douglas-fir growth. Amelioration treatments resulted in similar survival and similar or better volume growth than the core LTSP treatments, with the exception of poor volume growth after compaction rehabilitation with no organic matter returned into the soil. Compaction significantly influenced Douglas-fir survival and was often higher on moderate compaction plots. On some sites there was decreased survival and growth associated with heavy compaction that will likely influence longer-term outcomes with a more variable and changing climate. Overall, results to date on the core LTSP treatments, amelioration treatments, and adjacent miniplots reported elsewhere suggest that forest floor removal causes negative growth and, combined with severe compaction, caused both negative growth and poor survival. In the Interior Northwest it is still prudent to minimize soil disturbance and leave organic matter onsite unless there is site specific evidence to the contrary. Additional work is required to reap the full, long-term benefit of the installations. Recommendations are provided highlighting the critical work that should be completed in the near future before biological evidence is lost to decay, including suggestions for further data analysis and extension, the need to continue LTSP core, amelioration and miniplot measurements to demonstrate and calibrate sustainable forest resource management. Our data suggest considering changes to current soil disturbance policy and forest operations based on the current results regarding forest floor displacement.

1. Introduction

Soil disturbance from harvesting, site preparation or forest health treatments have been shown to cause soil degradation and have increased, decreased or neutral effects on long-term forest productivity depending on the net effect on growth limiting factors and hydrologic properties (Curran et al. 2005a; Heninger et al. 2002). In addition to

productivity effects, soil disturbance can affect site hydrology leading to decreased onsite water storage, increased runoff and erosion causing offsite effects and sedimentation of streams (Huang et al., 1996; Zimmerman et al. 2006; Curran and Maynard 2009). Invasive species abundance is also exacerbated when ecosystems or soils are disturbed (Hiero et al. 2006; Bauer 2012), particularly if disturbance co-occurs with other disturbances at one time or successively over several stand

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entries (Curran, unpublished guidance document; Sokol et al. 2017). Because these various effects can take more than two decades to measure and understand (Morris and Miller 1994; Tan et al. 2009), soil disturbance after harvesting and site preparation is used as a proxy for the longer-term effects on soil condition, forest productivity and hydrologic function (Curran et al. 2009; Page-Dumroese et al. 2009). Government agencies and forest land managers need to monitor these proxies through long-term research (validation monitoring) as well as implementation (compliance) and effectiveness monitoring, to ensure they are achieving the goals of sustainable resource development (Curran et al. 2005b; Curran and Maynard 2009). Ongoing validation research for the regulatory soil disturbance proxy needs to include studies related to soil disturbance from harvesting, silvicultural practices like root removal, and the ability to restore soil conditions through rehabilitation techniques.

The Long-Term Soil Productivity study (LTSP¹) is an international network designed to provide a controlled and extensively replicated experiment to isolate and study the usually confounded soil disturbance effects of compaction and organic matter removal (Powers et al. 1990; Powers 2006). The LTSP study sites focus on core questions related to forest resource management: how much compaction and how much organic matter removal will affect long-term soil and site productivity? The core experiment is three levels of compaction (none (C0), moderate (C1), and heavy (C2)) and three levels of organic matter removal (bole only (OM0), whole tree and slash removal (OM1), and whole tree harvesting plus forest floor removal (OM2)) and each site investigator had the option of including amelioration treatments. The underlying assumption was that forest management practices alter two main factors – soil porosity and site organic matter – and these factors can account for soil disturbance related changes in site biomass production.

Soil compaction alters numerous site processes (e.g., aeration, gas exchange, water infiltration, hydrologic function) and understanding and assessment of the long-term impacts and restoration timeline is critical (Busse et al., 2021). Soil recovery after harvest operations and site preparation can be difficult to predict because differences in logging practices, inherent soil properties, and climatic regimes (Han et al. 2009; Hwang 2020). In addition to soil compaction, organic matter removal is an ongoing question for forest managers, who need to know the amount of woody residues or forest floor needed to ensure nutrient cycling (Thiffault et al., 2011), create beneficial microclimate conditions, or reduce erosion (Clarke et al., 2015; Wan et al., 2018). Likely many of these changes will be site-specific (Littke et al., 2020).

Amelioration treatments may be used to restore or possibly enhance soil productivity. Rehabilitation of soil disturbance can be an effective way to restore productivity to temporary access structures (e.g., log landings, skid trails, haul roads) that are not needed until the next harvest entry (Bulmer 2002; Dykstra and Curran 2000). Because Armillaria root disease (*Armillaria ostoyae* (Romagn.) Herink), is endemic in the Cedar-Hemlock forests of the Interior Northwest, numerous studies have been undertaken over the decades to evaluate the effectiveness of stump removal treatments, and their effect on soil and resulting tree growth (Cleary et al., 2013; Norris et al., 2014); though further monitoring and evaluation of efficacy is needed. A novel treatment for Armillaria was initiated using *Hypholoma fasciculare* (Huds. ex Fr) Kummer; a naturally occurring decay fungus, in field trials

throughout southern BC, and Chapman et al., (2004) reported statistically lower mortality due to Armillaria as a result of stump inoculation on two trial sites in south central BC. In addition, it may be possible to enhance forest productivity on detrimentally or adjacent, non-detrimentally disturbed forest lands through additions of nutrients and/or organic matter. The addition of organic matter has been tried in landing rehabilitation trials in neighbouring, drier Interior Douglas-fir ecosystems, where it was shown to improve lodgepole pine survival, but individual tree growth was not different amongst the treatments (Bulmer et al., 2007).

This paper reports on 15-year tree growth and survival on LTSP treatments and adjacent ameliorative treatments on three ash cap soil sites in the Interior Northwest. These sites are in the Interior wet-belt forests, are highly productive, and may be responsive to amelioration treatments that reduce compaction and/or increase organic matter within the mineral soil. Because of the large range of treatments involved we focus on tree growth and survival. Our hypotheses were that (1) organic matter removal would have negative effects on tree survival and growth; (2) soil compaction would adversely affect tree survival and growth; (3) vegetation control would have positive effects on tree survival and growth; and, (4) ameliorative treatments (stump removal, reduced compaction and organic matter additions) would have positive effects on tree survival and growth.

2. Materials and methods

2.1. Site descriptions

Three LTSP replicates were established on volcanic ash influenced soils in the Interior Cedar Hemlock (ICH) biogeoclimatic zone of the interior wetbelt: two were located in southern British Columbia (BC) near Nelson, Canada and one in northern Idaho near Priest River, USA. The BC replicates were installed in 2003 and 2004 and the Priest River replicate installed in 1992 (Table 1). The ICH is the most productive forest zone in the interior wetbelt and is found on the lower slopes of the Columbia Mountains and adjoining parts of the northern United States on the western side of the Rocky Mountains (Meidinger and Pojar 1991). The climate in this zone is strongly influenced by air masses from the west that produce cool wet winters and warm dry summers. Mean annual temperatures range from 2 to 8.7°C; temperatures remain below 0°C for 2–5 months and above 10°C for 3–5 months per year. Annual precipitation is between 500 and 1200 mm, with 25–50 % falling as snow (Table 1). For additional site-specific information on the British Columbia sites see Berch et al., (2019) and for additional information on the Idaho site see Page-Dumroese et al., (1998).

2.2. Experimental design and treatments

The various treatments are summarized in Table 2, and described in detail below:

2.2.1. Core LTSP study

The core LTSP study design is a 3 × 3 factorial experiment with two factors: (1) OM removal (OM0: bole only; OM1: whole tree and slash removal; OM2: whole tree + forest floor removal) and (2) compaction (C0: none; C1: moderate; C2: heavy) The experiment is applied at each of three replicate installations, resulting in a total of 27 experimental units (three study sites with 9 treatment units each). Each treatment plot was at least 40 m × 70 m in size and was split in half and planted with Douglas-fir *Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco or western white pine (*Pinus monticola* Dougl. ex D. Don). Each plot is split so that there is vegetation control (VC) on one plot half (by periodic herbicide applications in Idaho, manual brushing during the first 10 years in BC) and no vegetation control (NVC) on the other half. After a thorough pre-harvest evaluation, harvesting occurred in winter on snowpack in British Columbia and in late summer, early fall at Priest River. Trees were hand

¹ Abbreviations used in this paper include: LTSP (long-term soil productivity study); C0, C1, and C2 for no, moderate and heavy compaction; OM0, OM1, and OM2 for bole-only harvest, whole tree and slash removal; and whole tree with forest floor removal; IDF for interior Douglas-fir Biogeoclimatic zone (the system of biome classification used in BC); ICH for interior cedar hemlock zone; VC and NVC for vegetation control and no vegetation control; “Rehab” and “Rehab+FF” for rehabilitation of a heavily compacted, forest floor removed soil without and with forest floor added back; and FF+ for extra forest floor tilled into an otherwise undisturbed site.

Table 1

Site Characteristics for the three study sites (from Berch et al. 2019; Page-Dumroese et al. 1998).

	Priest River	Rover-Sedlack	McPhee Creek
Year planted	1992	2003	2004
Biogeoclimatic zone/subzone ^b	ICHdw	ICHdw	ICHdw
Site series	01ab/CwFd – Falsebox*	01ab/CwFd - Falsebox	01ab/CwFd - Falsebox
Latitude;	48 21 N, 116 50	49 27 N, 117 30 W	49 19 N, 117 36 W
Longitude	W		
Elevation (m)	725	835	820
MAT, MAP	6.6°, 838 mm	6.7°, 843 mm	6.8°, 813 mm
Slope and aspect	0–5% south	0–5% west	0–15% west
Landform	Eolian veneer/blanket over lacustrine with some glaciofluvial Ochreptic Fraxigeraalf	Eolian veneer/blanket over morainal blanket with some glaciofluvial Orthic Dystric Brunisol ^a	Eolian veneer over morainal blanket and some fractured bedrock Orthic Dystric Brunisol ^a
Soil classification of modal soil pedons			
Predominant humus form	Hemimor (some mormoder)	Hemimor (some lignomor)	Hemimor (some mormoder)
Soil texture (surface layer)	Silt loam	fine sandy loam	fine sandy loam to silt loam
Coarse fragment content (%)	0–10%	0–30	0–50
Dominant pre-harvest tree spp. / approximate stand age	<i>Pinus occidentalis</i> , <i>Tsuga heterophylla</i> , <i>Pseudotsuga menziesii</i> , <i>Larix occidentalis</i> 90 years	<i>Pseudotsuga menziesii</i> , <i>Larix occidentalis</i> , <i>Pinus contorta</i> , <i>Pinus ponderosa</i> , <i>Pinus occidentalis</i> , Variable ages	<i>Pseudotsuga menziesii</i> , <i>Larix occidentalis</i> , <i>Pinus contorta</i> , <i>Pinus ponderosa</i> , <i>Pinus occidentalis</i> , Variable ages
Site index (m@50 yr)	Fd – 21	Fd – 22	Fd – 24
Net merchantable volume (m ³ /ha)	450	500	600

* The local habitat type is classified as *Tsuga heterophylla* *Clintonia uniflora* (Cooper et al. 1991)

^a Soil Classification Working Group 1998;

^b Meidinger and Pojar 1991.

Table 2

Treatment details.

Table 2. Abbreviations and descriptions of the treatments used in this study		
Abbreviation	Treatment	Description
Core LTSP study plots		
OM0	bole only	only logs removed
OM1	whole tree	logs, slash, and woody debris removed
OM2	whole tree and forest floor	logs, slash, woody debris, and forest floor removed
C0	no compaction	no machine traffic
C1	moderate compaction	moderate level of compaction
C2	heavy compaction	heavy level of compaction
Amelioration study plots		
Stumped	stump removal	removal of stumps from the soil
Hypholoma	biocontrol fungus	addition of biological control fungus
Rehab	simple rehabilitation (decompaction) with excavator bucket	most severe LTSP plot (OM2C2) subject to rehabilitation to restore soil function
Rehab + FF	simple rehabilitation with the extra step of incorporating the forest floor and slash back onto the plot	OM2C2 then rehabilitation with forest floor and slash put back on site
FF+	addition of extra forest floor into soil	OM0C0 then tillage with added forest floor

felled and tractor or skidder yarding and there was no machine traffic on the C0 plots and minimal machine traffic on the other treatments (no traffic on all plots at Priest River until treatment installation). Compaction was achieved in the growing season following harvesting with a rubber-tired skidder weighted with an 1800 kg block in BC and a suitably weighted harvesting equipment in Idaho. Field tests determined the amount of traffic required to achieve the desired compaction level (Berch et al., 2019; Powers et al., 1990). In BC, 10 passes in each direction by the skidder were used for moderate compaction and 20 passes for the heavy compaction treatment; at Priest River the soil was at field capacity and moderate compaction was achieved with two passes in each direction with a grapple skidder and heavy compaction with four passes in each direction with a D-6 Caterpillar tractor (Page-Dumroese 1993). Hand or excavator compaction plates were used to compact areas around stumps.

Organic matter removal occurred by machine and by hand. If machines were necessary for OM removal then it was confined to brush mats that were empirically determined to be sufficiently deep to prevent compaction of the underlying soil. For OM0 and OM1 treatments, plot compaction was achieved by running the compaction machinery on top of the forest floor in BC and in Idaho by removing the forest floor, which was replaced after the treatment. For OM0, slash was removed prior to compaction of plots and replaced with machinery or by hand following compaction. Vegetation control (VC) on half of each treatment plot was done by periodic herbicide application (hexazinone tablets; post treatment, year 3 and year 5) at Priest River and by manual brushing during the first 10 growing seasons on the BC sites.

2.2.2. Amelioration treatments

The ICH LTSPs are unique in that they also include adjacent amelioration plots as part of the same research installation. Amelioration treatments included stump removal on all three replicates. Stumps were extracted by mechanical pulling after harvest (Priest River) or by pushing over the tree to dislodge the root system at harvest (BC sites) and were initiated as a method to control *Armillaria* root disease. The goal of stump removal was to extract the entire stump and attached major roots from the soil to reduce the food source and inoculum potential of *Armillaria* remaining on smaller, more isolated root fragments. Stump removal occurred at Priest River immediately following harvest and the stumps were left onsite (with up to 50 % retention of stumps in the soil at Priest River; Page-Dumroese et al., 1998).

Four additional amelioration treatments (inoculating stumps with *Hypholoma*, rehabilitation (tillage) to reduce bulk density (Rehab), rehabilitation with added forest floor material (Rehab + FF), and an undisturbed plot with extra forest floor added into the soil (FF +) were replicated at Rover-Sedlack and McPhee Creek in BC. Treatment with *Hypholoma fasciculare* (*Hypholoma*) was used to reduce *Armillaria*-induced tree losses (Chapman and Xiao 2000; Rayner 1977). Fungal samples for the inoculum were collected from within a 100-km radius of the study sites and followed the methods outlined in Chapman and Xiao 2000). The inoculum was transferred to a mixture of wheat bran (20%) and conifer sawdust (80%) which had been moistened. Once the bags of inoculum were fully colonized, they were buried against each stump at the interface between the surface OM and mineral soil. Two other amelioration treatments were two forms of rehabilitation: Rehab and Rehab + FF which were prepared in the spring following installation of the core treatments and before planting. During installation an additional replicate of the most severe LTSP treatment (OM2C2) was added. This plot was divided in half and the rehabilitation treatments were randomly assigned. Rehabilitation consisted of simple tillage with with an excavator bucket to break up heavy compaction (Rehab), and in the Rehab + FF half, the plot also had the forest floor added back into the soil with some slash replaced on top. As a final amelioration treatment, we added extra forest floor (FF +), which had been removed from an adjacent plot, into the soil of an extra undisturbed (OM0C0) plot by spreading and excavator tillage into the soil.

2.3. Seedling establishment and tree measurement

Locally grown Douglas-fir and western white pine seedlings were planted the spring following treatment installation. Each plot had at least 100 measurement trees located in rows in the centre of the plot halves. Buffer rows of trees were planted around the measurement trees. Elk fences were established on the BC plots to prevent ungulate browse. Tree height and survival were measured in the first year and at least every five years thereafter. We use the 15 year measurements where diameter was measured with DBH tape and height was measured with height poles or triangulation with a sonic angle device (e.g., a Vertex hypsometer).

2.4. Tree volume calculation and data interpolations

Individual tree species volume equations followed those identified by Nigh (2016) for the ICH region. The various volume equations and their height criteria are noted here with diameter at root collar (*rcd*) or breast height (*d*, both in cm), height (*h*) in m, and volume (*V*) in m³:

1. if height < 1.3 m then

$$V = 0.33 \times \pi \times \left(\frac{rcd}{2000} \right)^2 \times h$$

2. if height > 1.3 m and < 2.6 m for Douglas fir or 6.8 m for western white pine then

$$V = 0.4 \times \pi \times \left(\frac{d}{2000} \right)^2 \times h$$

3. if western white pine height > 6.8 m then

$$V = e^{-9.934} \times d^{1.771} \times h^{1.12}$$

4. if Douglas-fir height > 2.6 m then

$$V = e^{-10.119} \times d^{1.172} \times h^{1.203}$$

At Priest River, due to budget constraints, few plots were measured during the 15-year cycle, so 15-year volume (*V*₁₅) was interpolated from the 5-, 10-, and 20-year volume (*V*₅, *V*₁₀, *V*₂₀) data using the following equation that was based on the linear nature of the observed growth trend:

$$5. V_{15} = (V_{20} + (3 \times V_{10}) - V_5) / 3$$

Total volume (*^TV*), expressed at m³ ha⁻¹, was calculated using the following equation, which is based on the original 100 measurement trees being planted in a 2 × 2 m grid (occupying 1 m on each side; resulting in the measured total volume representing an area of 22 × 22 m (484 m²), and 10,000 m²/ha divided by 484 m² resulting in 22.66116 as the multiplication factor to convert the total volume to a per ha basis):

$$6. {}^T V = V \times 20.66116$$

2.5. Data analysis

Individual tree volumes, plot averages, and confidence limits were calculated using Excel spreadsheets. Confidence limits were presented for survival, average tree volume, and volume per hectare (*n* = 3). Confidence limits were also presented for average tree volume across the different sites (*n* = live trees), but not for survival or volume per hectare as *n* = 1 for both. Survival, average volume, and volume per hectare data (Supplementary Information 1) were analyzed by species using ANOVA with a randomized block design for two study groupings: the Core LTSP

plots, and the Amelioration plots. Amelioration plot analyses included plots with the two most different LTSP treatments (OM0C0 and OM2C2) for comparison. The bole only, no compaction (OM0C0) and whole tree forest floor, heavy compaction (OM2C2) were considered good comparisons for the amelioration plots of Stumped, Hypholoma, and FF + plots, and the Rehab and Rehab + FF plots, respectively. Data were tested for assumptions of normality and variance prior to statistical testing. Average volume data were transformed with a logarithmic function for normality. Alpha was set at 0.05, and when the ANOVA *p*-values were below this threshold, treatment differences were tested by a Tukey HSD post hoc test. Figures were generated, along with statistical testing, with R version 3.5.0 (R Development Core Team) using RStudio.

3. Results

3.1. Tree survival

3.1.1. Core LTSP treatments survival

For Douglas-fir, compaction had a significant affect on survival (*p* = 0.002; Table 3) and on all three sites the moderate compaction (C1) treatment often displayed higher survival, while the lowest survival was often on the no compaction (C0) treatment, which was significantly different from moderate (C1) (*p* = 0.003) and heavy (C2) (*p* = 0.01 Table 3; Fig. 1). Vegetation control (VC), through manual brushing or herbicide, did not clearly improve Douglas-fir survival across all treatments, but it was greater on whole tree (OM1) and whole tree forest

Table 3

Long-Term Soil Productivity core treatment ANOVA results for 15-year Douglas-fir and western white pine trees for Priest River, Idaho, and Rover-Sedlack and McPhee Creek, BC sites.

Analysis of Variance Table					
Treatment	Df	Douglas-fir		Pine	
		F value	Pr(>F)	F value	Pr(>F)
Survival					
OM	2	2.28	0.1	4.56	0.03
C	2	9.02	0.002	1.04	0.4
VC	1	0.1	0.8	8.91	0.008
OM*C	4	2.01	0.1	0.28	0.9
OM*VC	2	2.99	0.1	0.73	0.5
C*VC	2	0.3	0.7	0.55	0.6
OM*C*VC	4	1.19	0.3	0.37	0.8
Average Volume					
OM	2	9.76	0.002	0.95	0.4
C	2	0.99	0.4	0.38	0.7
VC	1	32.74	<0.0001	36.9	<0.0001
OM*C	4	0.42	0.8	0.49	0.7
OM*VC	2	2.89	0.08	3.11	0.06
C*VC	2	0.03	1	0.72	0.5
OM*C*VC	4	1.37	0.3	1.81	0.2
Volume per hectare					
OM	2	2.23	0.1	0.002	1
C	2	1.94	0.2	0.85	0.4
VC	1	17.24	0.0006	22.52	0.0002
OM*C	4	0.69	0.6	0.29	0.9
OM*VC	2	1.68	0.2	0.87	0.4
C*VC	2	1.08	0.35	0.24	0.8
OM*C*VC	4	0.42	0.8	0.43	0.8
Tukey Post-Hoc comparison					
Pine	Survival	OM0	vs	OM1	<i>p</i> = 0.4
		OM0	vs	OM2	<i>p</i> = 0.02
		OM1	vs	OM2	<i>p</i> = 0.2
Douglas-fir	Survival	C0	vs	C1	<i>p</i> = 0.003
		C0	vs	C2	<i>p</i> = 0.01
		C1	vs	C2	<i>p</i> = 0.7
	Avg Vol	OM0	vs	OM1	<i>p</i> = 1
		OM0	vs	OM2	<i>p</i> = 0.004
		OM1	vs	OM2	<i>p</i> = 0.004

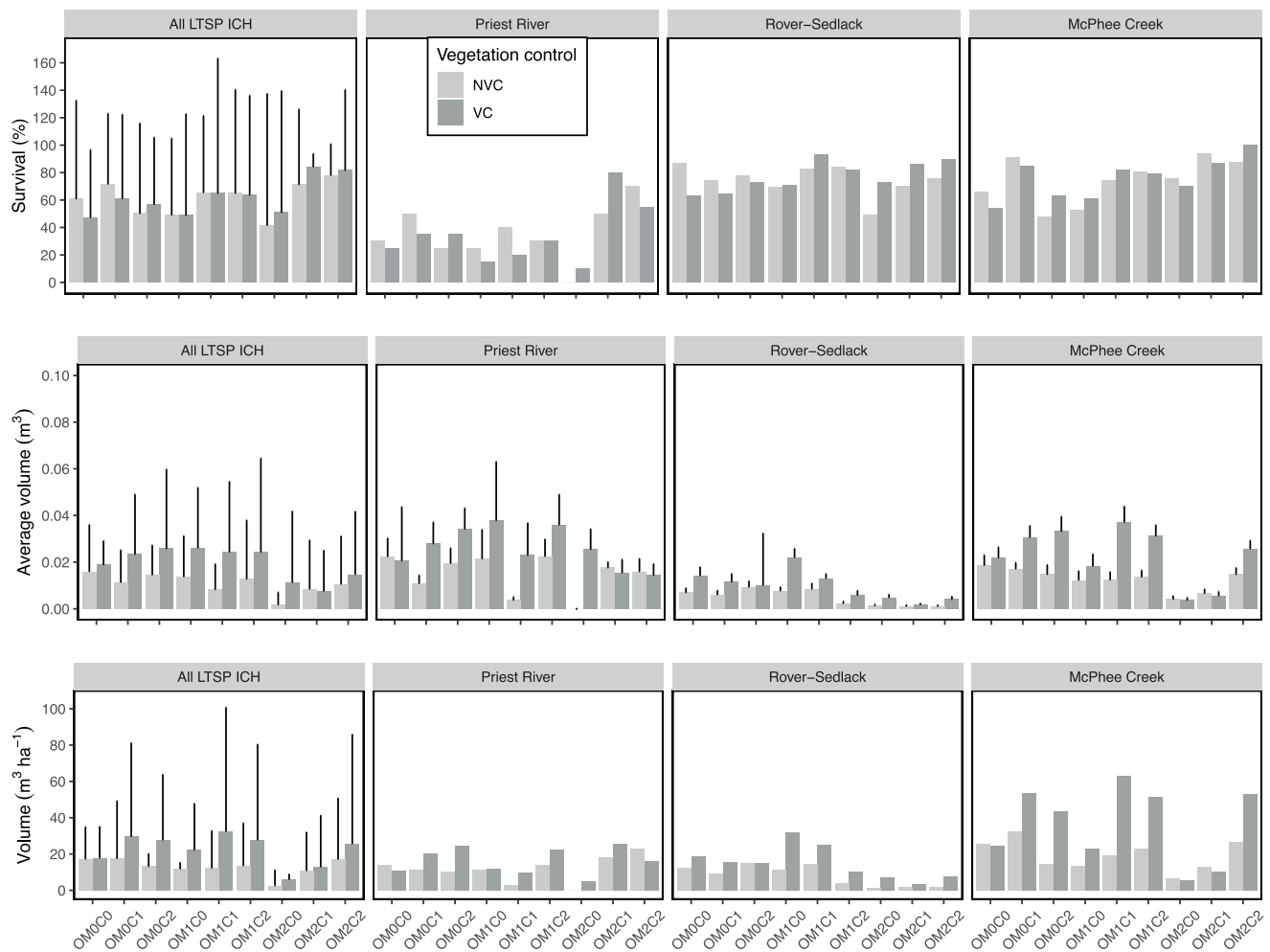


Fig. 1. Fifteen-year Douglas-fir growth from core Long-Term Soil Productivity (LTSP) Interior Cedar Hemlock (ICH) plots. All LTSP ICH figures ($n = 3$) include data from the individual sites of Priest River, Rover-Sedlack, and McPhee Creek.

floor removed (OM2) treatments (Fig. 1). Survival on the core plots was generally lower on heavy compaction treatments (C2) with bole only harvest (OM0), except on the sandier Rover-Sedlack site and on the no compaction, whole tree forest floor C0OM2 treatment; particularly on the Priest River site which had lower survival than the other two sites.

Western white pine survival was generally greatest on the vegetation control (VC) plots (ANOVA $p = 0.008$; Table 3; Fig. 2) and poorer on the bole only (OM0) treatments (Fig. 2). Organic matter level was a significant factor ($p = 0.03$) with survival usually highest on the whole tree forest floor removed OM2 treatment plots and significantly different from bole only (OM0; $p = 0.02$; Table 3; Fig. 2). Lowest seedling survival was on the most severe OM removal and compaction treatment (OM2C2) treatment at Priest River, on the bole only harvest (OM0) treatments at Rover-Sedlack, and often on the bole only (OM0), and no to moderate compaction (C0 or C1) treatments at McPhee Creek (Fig. 2). Brush competition for both species was heaviest at the McPhee Creek site, lowest at Priest River, and was usually lower on the more compacted treatments (data not shown). McPhee Creek is dominated by hardwood species competition; whereas, the other two sites have more mixed shrub species competition.

3.1.2. Amelioration treatments survival

For both species, the amelioration treatments were not a significant factor affecting survival (Table 4). Stump removal survival was similar to the core LTSP treatments on all sites, with lowest survival usually on the NVC plots (Figs. 3 and 4). The Rehab, Rehab + FF and FF+ (the

tillage and OM addition) amelioration treatments on Rover-Sedlack and McPhee Creek sites had similar or better survival than in the core LTSP plots, except for western white pine on some of the FF + and Rehab treatments on the brushier McPhee Creek site.

3.2. Tree growth

3.2.1. Average volume

3.2.1.1. Core LTSP treatments average volume. For both species in the core LTSP treatments, vegetation control (VC) was a significant factor dictating tree volume ($p < 0.0001$ in each case; Table 3), although Douglas-fir average volume varied considerably across the various core LTSP treatments (Fig. 1). As expected, VC typically resulted in the largest trees. On the core LTSP treatments, all OM treatments were a significant factor influencing Douglas-fir volume production ($p = 0.002$); with the largest trees occurring on the vegetation control (VC) plus whole tree (OM1) or VC plus bole only (OM0) treatments. Removal of all OM including forest floor (OM2) resulted in significantly smaller Douglas-fir average volume than both OM1 and OM0 ($p = 0.0004$ in both cases; Fig. 1 and Table 3).

Western white pine average volume (Fig. 2) varied considerably across the treatments. On the core LTSP treatments, OM treatments were not a significant factor ($p = 0.4$; Table 3). However, VC treatment was significant in the ANOVA ($p < 0.0001$; Table 3) and typically resulted in the largest western white pine trees, as follows: OM1C0 at Priest River;

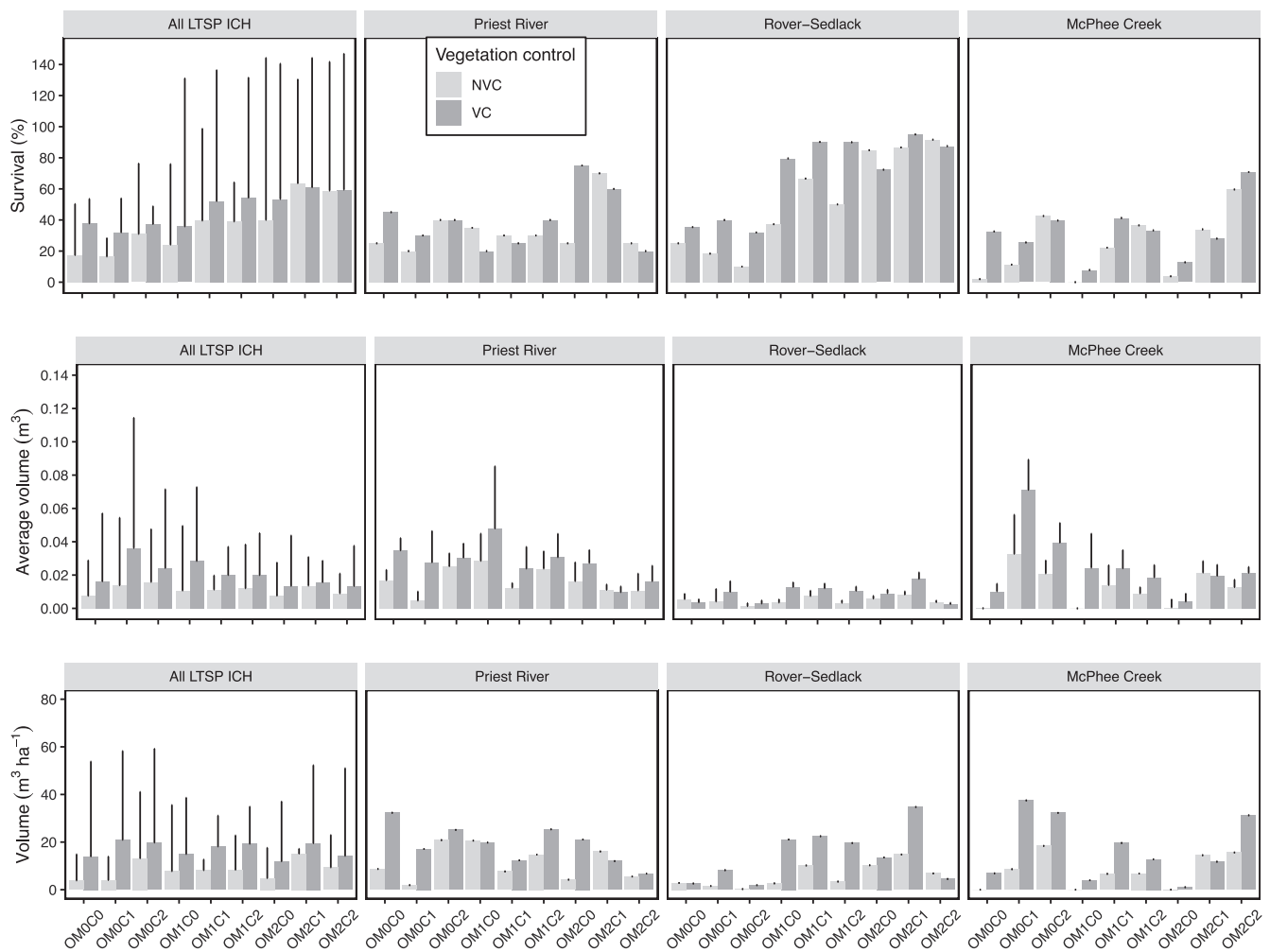


Figure 2. Western white pine LTSP core treatments

Fig. 2. Fifteen-year western white pine growth from core Long-Term Soil Productivity (LTSP) Interior Cedar Hemlock (ICH) plots. All LTSP ICH figures ($n = 3$).**Table 4**

Long-Term Soil Productivity amelioration treatment ANOVA results for 15-year Douglas-fir and western white pine trees for Priest River, Idaho, and Rover-Sedlack and McPhee Creek, BC sites. Treatments (T) include those from amelioration Table 2 and, for comparison, OM0C0 and OM2C2 with and without vegetation control (VC).

Analysis of Variance Table					
Treatment	Df	Douglas-fir		Pine	
		F value	Pr(>F)	F value	Pr(>F)
Survival					
T	6	3.08	0.07	0.97	0.5
VC	1	0.04	0.8	3.45	0.09
T*VC	6	1.97	0.2	0.97	0.5
Average Volume					
T	6	1.34	0.3	1.59	0.3
VC	1	14.91	0.003	9.13	0.01
T*VC	6	1.42	0.3	1.73	0.2
Volume per hectare					
T	6	1.14	0.4	1.64	0.2
VC	1	11.14	0.008	11.77	0.006
T*VC	6	1.5	0.3	2.32	0.11

OM0C1 at McPhee Creek; and OM2C1 at Rover-Sedlack.

3.2.1.2. Amelioration treatments average volume. In the amelioration treatments, vegetation control (VC) was also a significant factor for Douglas-fir and western white pine volume growth (Figs. 3 and 4; $p = 0.003$ and $p = 0.01$; Table 4). Stump removal resulted in Douglas-fir volume that was in the middle of the LTSP range of core treatments at Priest River and near the top of the core LTSP treatment range at the other two sites (Fig. 3). For the other amelioration treatments, the largest Douglas-fir volumes were measured on the Rehab + FF and FF + treatments at Rover-Sedlack and in the Hypholoma treatment at McPhee Creek. Rehabilitation with no FF replacement (Rehab) had low average volumes. At the brushy McPhee Creek, Douglas-fir volume in the Rehab + FF with no vegetation control (NVC) treatment did not fair well.

Western white pine seedlings with vegetation control (VC) had significantly greater volume in the amelioration plots ($p = 0.01$; Table 4). Average tree volume in the stump removal treatment was near the top of the LTSP core treatment volume range at all three sites. However, with no vegetation control (NVC) western white pine volume was low at Rover-Sedlack and McPhee Creek. For all the amelioration treatments, the largest trees were measured on the Rehab + FF and FF + treatments at Rover-Sedlack, and the Hypholoma and the Rehab + FF at McPhee Creek. Rehabilitation with no FF replacement (Rehab) had lower average tree volumes but were still growing well in comparison to the main LTSP treatments; with the exception of the VC plot halves. McPhee Creek Rehab + FF with no vegetation control (NVC) had only

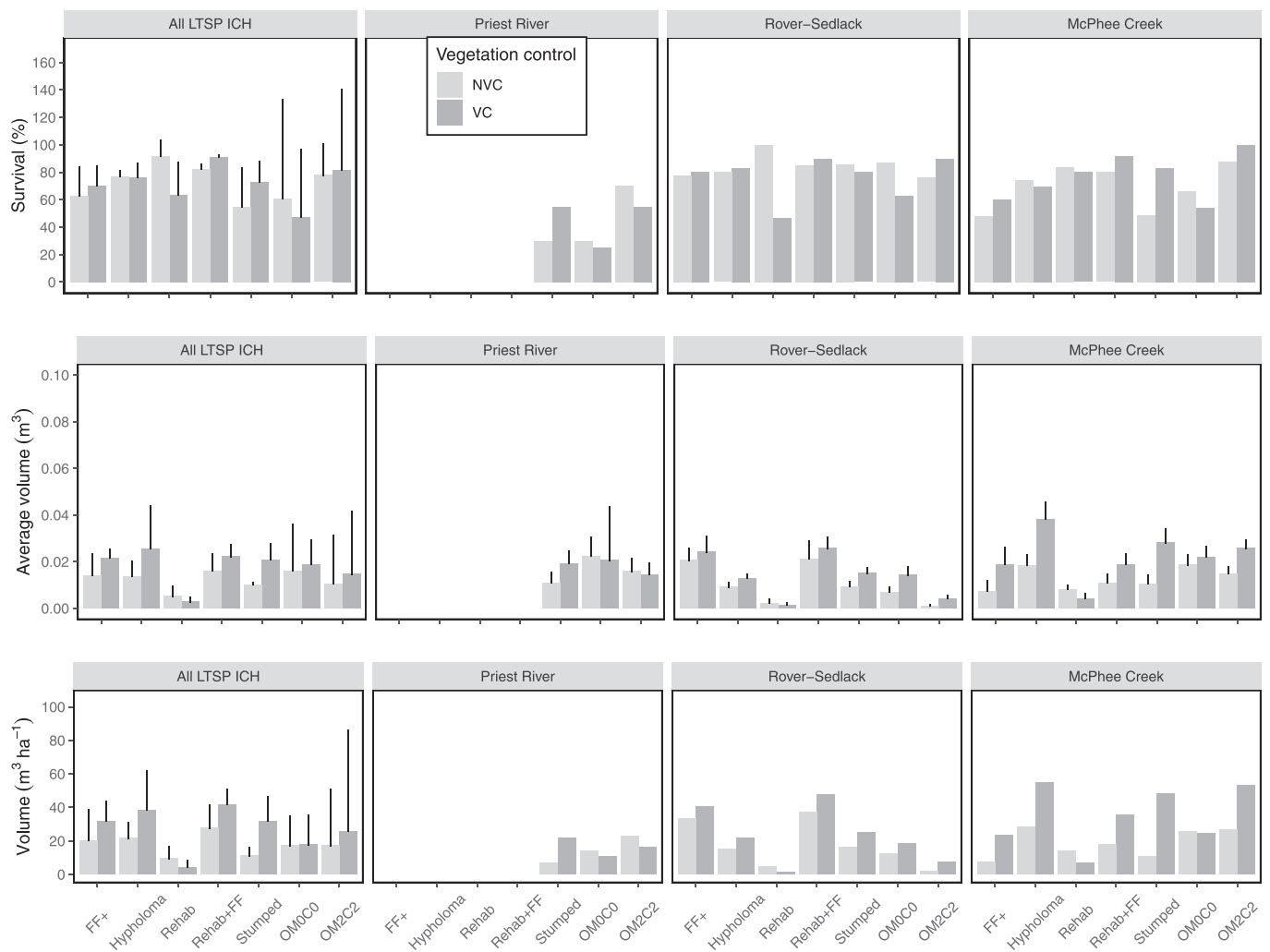


Fig. 3. Fifteen-year Douglas-fir growth from amelioration Long-Term Soil Productivity (LTSP) Interior Cedar Hemlock (ICH) plots. The All LTSP ICH figures summarize data from the individual sites of Priest River, Rover-Sedlack, and McPhee Creek for Stumped treatment ($n = 3$). For remaining treatments, All LTSP ICH summarized Rover-Sedlack and McPhee data. Core treatments of OM0C0 and OM2C2 are included for comparison.

two surviving trees of very different heights which resulted in the large confidence interval (Fig. 4).

3.2.2. Total volume

Total volume, expressed as $\text{m}^3 \text{ha}^{-1}$, is a good measure of tree productivity as related to the various treatments. It combines the effects of survival and average tree growth. For both species, and for both the core LTSP and amelioration treatments, the highest total volumes typically occurred in the vegetation control (VC) treatments (plot halves).

3.2.2.1. Core LTSP treatments total volume. For both species, VC was a significant factor for total volume ($p = 0.0006$ for Douglas-fir and $p = 0.0002$ for western white pine; Table 3). Douglas-fir total volume varied by site and treatment (Fig. 1), with significantly greater total volume due to vegetation control (VC). At Priest River, the largest total volume in the core LTSP treatments occurred with VC with both moderate and heavy compaction (C1 and C2) treatments. At McPhee Creek and Rover-Sedlack there were clear OM removal effects on core LTSP treatment total volumes. Lower total volumes were measured in the whole tree forest floor removed (OM2) treatments, with the one exception of OM2C2 with VC at McPhee Creek, perhaps due to a moister microsite on part of that plot. On both sites, the highest total volumes were on the bole only (OM0) treatments, with either moderate (C1) at McPhee Creek or no compaction (C0) at Rover-Sedlack.

Western white pine total volume also varied by site and treatment (Fig. 2), and similar to Douglas-fir vegetation control (VC) resulted in significantly greater total volume ($p = 0.0002$; Table 3) in most cases. At Priest River in the core LTSP treatments, the greatest total volume occurred in VC half of the bole only, no compaction (OM0C0) treatments followed by heavy compaction (C2) with bole only and whole tree and slash removal (OM0 and OM1) treatments. The smallest total volume was measured on whole tree forest floor removal (OM2) treatments, particularly those with heavy compaction (C2). Total volume for the McPhee Creek core LTSP treatments was of similar amounts to Priest River, except highest total volumes were measured in the compaction (C1 and C2) treatments and the lowest total volume on the no compaction (C0) treatments. The sandier soils at Rover-Sedlack had lower average volumes but higher survival, resulting in similar total volumes to the other two sites, with lowest total volumes on bole only OM0 treatments and the most severe whole tree forest floor removed, heavy compaction (OM2C2) treatment.

3.2.2.2. Amelioration treatments total volume. Vegetation control (VC) was again a significant factor determining total volume for both tree species (Douglas-fir $p = 0.008$ and western white pine $p = 0.006$; Table 4). Douglas-fir trees in the stump removal treatment at all three sites had better total volume production when the competing vegetation was removed as compared to the no vegetation control (NVC) plots. This

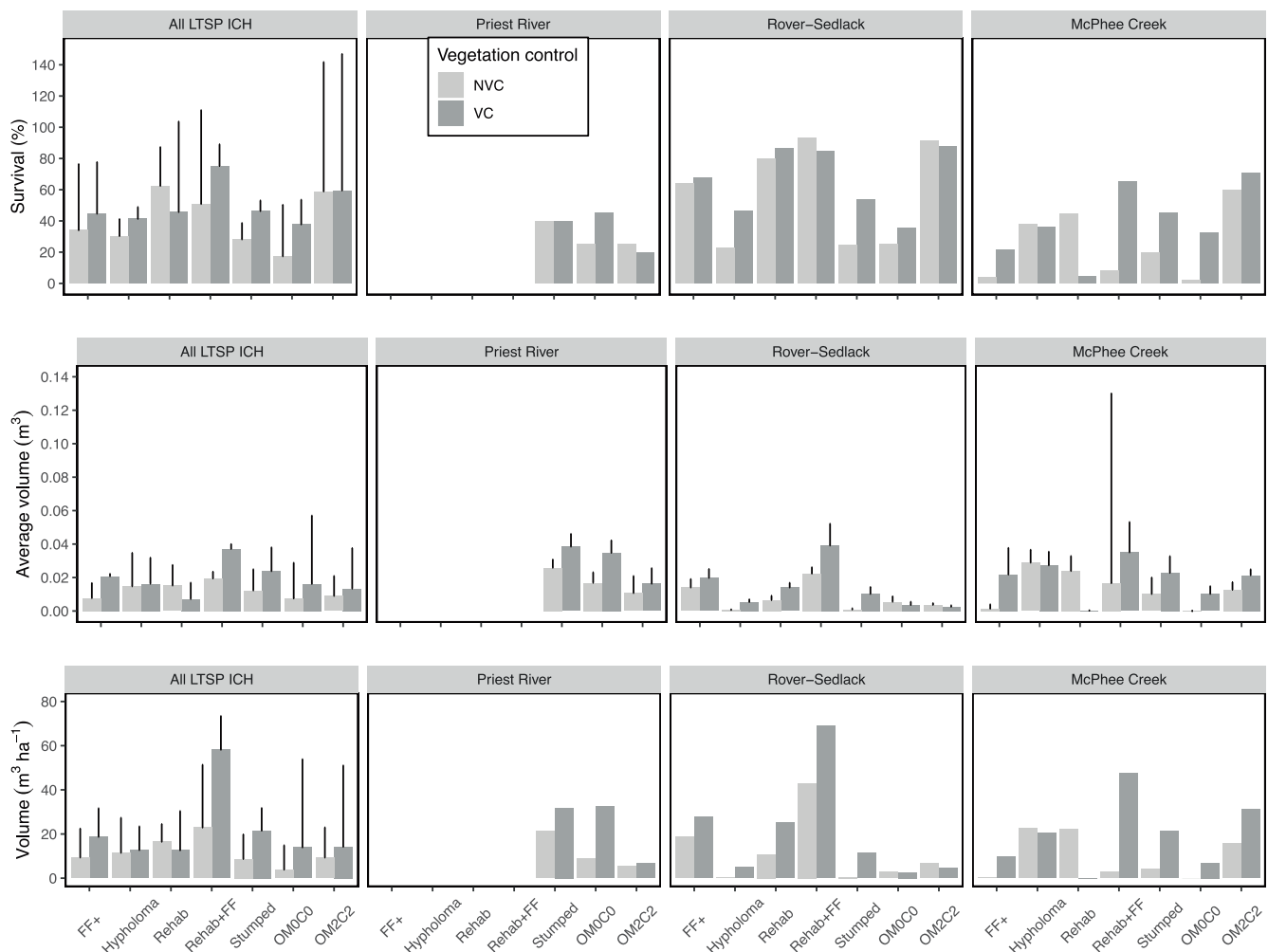


Figure 4. Western white pine amelioration treatments with OM0C0 and OM2C2 core treatments

Fig. 4. Fifteen-year western white pine growth from amelioration Long-Term Soil Productivity (LTSP) Interior Cedar Hemlock (ICH) plots. The All LTSP ICH figures summarize data from the individual sites of Priest River, Rover-Sedlack, and McPhee Creek for Stumped treatment ($n = 3$). For remaining treatments, All LTSP ICH summarized Rover-Sedlack and McPhee data. Core treatments of OM0C0 and OM2C2 are included for comparison.

is particularly noticeable at McPhee Creek (Fig. 3). At the two BC sites, this same trend was also true for Douglas-fir total volume on the Hypholoma treatments. At Rover-Sedlack, Douglas-fir trees planted in the Rehab + FF and FF + treatments are clearly producing total volume that is greater than the core LTSP treatments. On the brushier McPhee Creek site Douglas-fir in the Rehab + FF with vegetation control (VC) had a similar total volume trend, but this was lower than the Hypholoma or stumped VC treatments. The Rehab treatment (no forest floor replacement) did not have as much total volume as the other treatments at both Rover-Sedlack and McPhee Creek.

Western white pine total volume at all sites and in most treatments showed a clear positive effect with vegetation control (VC) in the ameliorative treatments ($p = 0.006$; Table 4). Western white pine growing in the stumped treatments had greater total volume on the McPhee Creek and Priest River sites, but this was not the case at the sandier Rover-Sedlack site (Fig. 4). At McPhee Creek, western white pine growing near Hypholoma treated stumps had no response to VC. Further, few trees survived to produce volume on the vegetation control (VC) half of the Rehab (with no forest floor replacement). However, the same VC with Rehab treatment at Rover-Sedlack had better total volume production as compared with the stumped and Hypholoma treatments. Similar results were found in those same treatments at McPhee Creek. The vegetation control (VC) half of FF + had few trees survive and this affected total volume production. Western white pine total volume was

greater on Rehab + FF on both sites (vegetation control, VC only at McPhee Creek), and the FF + treatment at Rover-Sedlack (VC only) than the various LTSP treatments.

4. Discussion

Our first hypothesis was that OM removal would negatively affect tree survival and growth. After fifteen years the OM removal effect was significant in this study for Douglas-fir in the species level ANOVA on the core LTSP experiment, where average volume was lower on most whole tree forest floor removal (OM2) plots.

Compaction, the subject of our second hypothesis and the other main core treatment, was a significant factor in Douglas-fir survival, possibly due to machine traffic effects on initial competing vegetation, and due to compaction increasing water holding capacity on the low-density volcanic ash derived soils. However, in this 15 year study, compaction has not significantly altered Douglas-fir and western white pine growth (and western white pine survival), but this was treatment- and site-specific and may change over time. Compaction has been shown to increase water holding capacity on more porous soils (Gomez et al. 2002; Powers 1999) and bulk density data for these sites (Page-Dumroese et al., 1998; Berch et al., 2019) do not indicate that the generally accepted biological thresholds were crossed very often (eg, Daddow and Warrington 1983), and more recent studies suggest a broader tolerance

of microbial communities and that moisture content and resulting aeration may also play a role (eg, Shestak and Busse 2005; Weisskopf et al., 2010).

Earlier results from these Interior wetbelt (ICH) LTSP sites have noted compaction effects, including the observed reduction in root tips in both compaction (C1 and C2) treatments (Amaranthus et al., 1996). Amaranthus et al., (1996) suggested this represented a lost ability of establishing seedlings to capture site resources and adapt to changing conditions, at least in the first year. Page-Dumroese et al., (1998) reported reduced short roots in Douglas-fir and western white pine on soil compaction and stump removal treatments on the Priest River LTSP, with smaller root collar diameters and less total N content in both species at three years, also suggesting that productivity may have been decreased.

Tan et al., (2009) studied three-year growth effects on three neighbouring Interior Douglas-fir (IDF) LTSP sites (100 km northeast) and noted the effects of soil compaction and organic matter removal on tree growth were both site- and species-specific. Moderate soil compaction increased 3-year diameter and height increment of both species within the bole only (OM0) harvest treatment on all three sites, particularly at a slightly coarser textured site (Emily Creek). In addition, compaction tended to reduce tree mortality. Different from results presented in this ICH paper, growth of both species was reduced by whole tree and forest floor removal (OM2) in the non compacted (C0) soil at two sites (Mud Creek and Emily Creek), and in OM1C1 soil at two sites (Mud Creek and Kootenay East), possibly due to treatment-induced water limitation (Tan et al., 2009).

Seedling physiology and foliar $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ studies at the Mud Creek LTSP, demonstrated that decreases in soil moisture availability and altered soil N dynamics caused by soil compaction and organic matter removal affected seedling net photosynthesis, and may have played an important role in influencing tree growth (Choi et al., 2005; Kamaluddin et al., 2005). Lodgepole pine (*Pinus contorta* Douglas ex. Loudon) and Douglas-fir responded to water stress and altered soil N dynamics differently (Choi et al., 2005), with lodgepole pine continuing to respire and suffer different consequences from taxing its available resources, while Douglas-fir shut down photosynthesis and respiration under drought conditions. Lodgepole pine did not shut down respiration and photosynthesis during drought events at Mud Creek (Kamaluddin et al., 2005). Choi et al., (2005) also reported that forest floor removal (OM2) reduced lodgepole pine height growth two years after plot establishment. Based on foliar $\delta^{13}\text{C}$ and shoot water potential data, they showed that reduced soil moisture availability after forest floor removal (OM2) limited seedling growth by causing water stress. Similarly, Tan et al., (2009), looking at a typical year, showed growing season soil water potential at Mud Creek decreasing with forest floor removal and heavy compaction, stating that forest floor removal with heavy soil compaction reduced soil water potential during the growing season. This was also demonstrated in Mud Creek microclimate data that demonstrated forest floor removal (OM2) plots typically entering permanent wilting point three weeks earlier than other OM treatments, and six weeks earlier in droughty years (Curran, unpublished data). It is likely that similar factors are at play on the ICH sites reported here because both sets of sites display the formation of biological soil crusts on the forest floor removal plots, which can inhibit water infiltration. It is also possible that western white pine has similar physiology to lodgepole pine under drought conditions.

Our third hypothesis held true and, in this study in southeastern BC and northern Idaho, after 15 years we found that tree growth in vegetation control (VC) plots had significantly greater average volume for both Douglas-fir and western white pine (Figs. 1 and 2). Vegetation control at Priest River affected tree survival during the early years. The hexazinone pellets used at Priest River were better suited for sandy soil conditions (low OM) and a liquid formulation would have likely resulted in less tree mortality (Minogue et al., 1988). Therefore, at Priest River greater survival was found in the plots with all OM (forest floor)

removed (OM2) or on the non-herbicide (NVC) plots. Increased tree biomass in vegetation control treatments was also found at year 20 in mixed-conifer plantations in California and was found to be the most important factor affecting tree growth (Zhang et al., 2017). However, in Washington and Oregon, annual vegetation control resulted in the greatest losses of belowground N and base cations while also contributing to greater volume growth (Littke et al., 2020). For example, vegetation control (VC) and the resulting change in available soil moisture and warmer soil temperatures were critical to tree growth at the Fall River LTSP in western Washington (Ares et al., 2005). Residue retention on the Washington plots played a role in moderating both temperature and moisture (Roberts et al., 2005).

Southeastern British Columbia LTSP sites (the IDF sites discussed above and the Rover-Sedlack and McPhee Creek reported here) also include adjacent mini-plots that are used to examine a range of similar disturbance types on a smaller scale (2.25 m²; Maynard et al., 2014). Miniplots had no vegetation control but included compaction, forest floor (OM) removal, deep gouges, and OM and mineral soil deposits on adjacent plots, that resulted in soil disturbance types similar to the bigger LTSP and amelioration treatment plots. After 10 years, Douglas-fir mortality was high when seedlings were planted on compacted treatments with forest floor intact, while lodgepole pine mortality was high on deposits (Norris et al., 2015). Douglas-fir volume was greatest on the deposit plots that are analogous to the FF + treatment in this study. Ten-year seedling growth was generally negatively affected by planting seedlings in unfavourable (calcareous) subsoils on the IDF sites, and compaction on all sites (Norris et al., 2015). In addition, Norris et al., (2015) noted that high initial mortality at one drier forest site may be attributed to severe drought during the first year.

In general, ameliorative treatments in this study had a positive, although not significant, effect on both survival and tree growth (hypothesis 4). Often, forest sites are slow to recover from compaction (Labelle and Jaeger 2011) and mechanical rehabilitation is necessary to restore soil chemical, physical, and biological functions. Our amelioration plots were designed to restore soil functions that may have been impaired by harvesting, site limitations, or disease. Tree stumps are increasingly being used for bioenergy in many areas of the world or to decrease the incidence of *Armillaria*, *Heterobasidion*, and *Phellinus* (Vasaitis et al., 2008), but data on the long-term consequences of stump removal to tree volume growth and soil properties is scarce (Quesnel and Curran 2000). Stump removal on our sites resulted in a tillage effect on the soil that created some favourable microsite conditions for seedling establishment and early growth. On many stump removal trials, it can be difficult to elucidate the site preparation effect of the disturbance from possible *Armillaria* control benefits (Curran et al., 2000). For example, on three ICH sites Hope (2007) found better growth of lodgepole pine on a stump removal treatment that was combined with scarification of the forest floor. Quesnel and Curran (2000) noted that stump removal creates excessive disturbance under some conditions, including soils that are shallow to unfavourable subsoils such as compact till, or bedrock. In this study, although not significantly different the survival on stumped plots was favourable for Douglas-fir but negative for western white pine. Average tree volume was good for both species, and the resulting total volume was generally higher after stump removal than in core LTSP treatments for Douglas-fir, but similar to the LTSP core treatments for western white pine. Forest areas that have a high incidence of root diseases may benefit from removal of stumps (Thies 1987). Our results for the *Hypholoma* plots suggest potential for beneficial growth effects without the extra soil disturbance of stump removal.

Stump removal from clear-cut sites has been found to reduce root rot in the next forest stand and increase planted tree survival, growth and stand productivity (Vasaitis et al. 2008; Karlsson and Tamminen 2013). However, our fourth hypothesis, ameliorative treatments would have positive effects on tree survival and growth, is only applicable to some sites. For example, Curran et al., (2005a), in describing soil texture effects in southern BC on disturbance, noted difference in stumping effects

on soils as a function of clay content, and also demonstrated that positive early growth effects on one site reversed by age 15. Smith and Wass (1991) initially reported that Douglas-fir was more sensitive to soil disturbance than lodgepole pine or western larch. Norris et al., (2014), reporting 20 to 31 year results from four stump removal trials in southern BC, including the two described in Smith and Wass (1991) and Curran et al., (2005a), noted that while height data did not show obvious trends, total tree volumes, based on number of planted trees, showed significantly lower volumes in compacted treatments; organic matter removal did not appear to have an effect.

At McPhee Creek there were also survival issues on various treatment halves of the amelioration treatments due to brush competition and blister rust increased, in the case of western white pine (the planted stock used on all sites was considered 68 % resistant). As noted previously, tree survival at the Priest River LTSP were complicated by herbicide remaining active within the forest floor and affecting seedlings on the OM0 and OM1 plots.

On all sites, long-term drought conditions have become exacerbated over the length of this study. As a consequence, we are already observing poorer growth of both species, and increased mortality of Douglas-fir on all forest floor removal (OM2) treatments at the sandier Rover-Sedlack site. While we do not have comprehensive microclimate data for these sites, this is likely associated with reduced soil moisture availability on those plots. This is consistent with data from forest floor removal plots at the neighbouring Mud Creek LTSP (~100 km northeast) where on-site microclimate monitoring demonstrated that forest floor removal plots reached soil permanent wilting point in typical years three weeks earlier than plots with forest floor intact or on Rehab plots with forest floor put back into the soil. During a severe drought year, permanent wilting point started six weeks earlier, with drought occurring on the forest floor removal plots before the end of May (Curran, unpublished data).

Treatments may play a role in the number of species and their efficacy (Sturrock 2000), through influencing the expression of diseases that impact growth and survivorship of trees. For example, at 15 years of age, three Interior Douglas-fir (IDF) sites north of the current study, had higher levels of root disease (*Armillaria ostoyae*) and western gall rust (*Endocronartium harknessii*) associated with treatment combinations that caused greater soil disturbance (Reid et al., 2015). Based on recent field observations on the ICH sites reported in this study, the most common disease agent on western white pine is white pine blister rust (*Cronartium ribicola*), which continues to impact growth and cause mortality.

We continue to observe the root pathogen, *Armillaria ostoyae*, killing a small number of trees annually. The initial 5–20 year period of plantation establishment appears to be the most vulnerable to root disease impacts (Morrison et al., 1988; Murray and Leslie 2021). Cleary et al., (2013), studying mortality due to *Armillaria* on the sandier Phoenix study described by Curran et al., (2007) and Norris et al., (2014), indicated that mortality of Douglas-fir was more frequently caused by other sources, despite the large amounts of inoculum present. The Phoenix study investigated stump treatments to manage *Armillaria* infection in subsequent stand growth. In this study, both Stumped and Hypholoma treatments were used to investigate *Armillaria* infection in subsequent stand growth. Here, *Hypholoma fasciculare* planting at each stump as an experimental biological control resulted in a similar survival and growth to Stumping, without the obvious site preparation effects (e.g., compaction, microsite changes) and subsequent soil disturbance (e.g., mixing subsoil with surface soil) effects which can increase invasive species, remove critical organic matter, and reduce soil C inputs from root decay. Newsome et al., (2010) reported on tree growth on the sites described by Quesnel and Curran (2000) and noted that harvest method had a variable effect on regeneration survival and growth. Where significant responses did occur, they were generally attributed to harvesting (e.g., pushover logging) effects on the characteristics of planting microsites rather than root disease spread. Curran et al., (2007) evaluated various site and soil factors in an attempt to elucidate a relationship with *Armillaria* root disease and noted that, while more study is needed,

thicker ash cap soils historically supported species that are considered more root disease resistant (e.g., western white pine) but, with their mortality due to white pine blister rust, other more susceptible species such as Douglas-fir have become established on these sites, increasing the incidence of *Armillaria*.

As growth impacts continue while mortality accumulates, periodic inventories of disease agents will remain useful. Due to increased frequency and intensity of summer droughts (Murdock and Werner 2011), we anticipate that forest health impacts will become amplified in stressed plantations of the Southern Interior of BC (Woods et al., 2010). The LTSP trials can provide valuable insight regarding the interactions of drought, soil disturbance, and forest health and further reporting should occur after the more detailed 20-year measures.

Rehabilitation of the most severe LTSP treatment (OM2C2), with Rehab + FF and without forest floor addition (Rehab; tillage alone) produced similar results on the two BC sites where it was applied. Without the forest floor being incorporated into the site during rehabilitation, the trees on the Rehab only treatment had lower average volumes. This was partially offset at the brushier McPhee Creek site through fairly good survival, but Rehab alone produced lower total volumes. Plotnikoff et al., (2002) in studying 5-year lodgepole pine growth and soil conditions on landing rehabilitation in the ICH zone, found growth similar to surrounding plantations, except on clayey soils. On the landings, which had no topsoil or forest floor replaced, they also found higher soil temperatures, lower soil moisture levels and lower nutrient status than the surrounding plantation conditions. Operationally, organic matter can be retrieved during rehabilitation through accessing topsoil stripped during construction of a road, trail or landing (Curran 1999, Bulmer 2002). Dykstra and Curran (2000) found greater tree growth on recontoured haul and skid roads where the seedlings had access to remaining topsoil, such as in the berm/sidecast locations. Addition of chipped log waste can be a source of organic matter during soil disturbance rehabilitation, but may affect nutrient relations as nitrogen will be required to break down the carbon rich material; however, Sanborn et al., (2004) found improved soil properties and establishment and early growth of white spruce with the addition of chipped log waste in north central BC. Conversely, Bulmer (2000) found the best growth on a till only treatment, with sawdust being a close second and wood chip treatments not as productive, even with fertilization to offset potential nitrogen effects. Closer to the current study, Bulmer et al., (2007), studying landing rehabilitation with wood wastes in the drier IDF zone in the southern BC Okanagan, found that wood wastes improved soil conditions and increased survival, although overall tree growth was similar. In discussing rehabilitation of volcanic ash cap soils, Bulmer et al., (2007) note that restoration of soil organic matter levels can be costly unless locally available topsoil (and/or forest floor) is available.

Forest floor addition (FF +) clearly was beneficial and produced more volume in this study, often far greater than some (McPhee Creek) or most (Rover-Sedlack) of the core LTSP plots, although the difference was not statistically significant. However, non-native, invasive vegetation that had already become established on the sites before the FF + or both Rehab treatments, occurred in greater abundance on these treatments, which resulted in survival and growth challenges on some FF+, Rehab and Rehab + FF (and also stumped) plots. However, in the absence of the competing vegetation, it is clear that forest productivity can be enhanced locally through the application or mixing in of forest floor and topsoil layers that have been removed during the development of permanent access structures such as roads and landings in immediately adjacent areas.

5. Conclusions, management implications and recommendations

Establishing these studies, we had several expectations that are updated based on our study sites:

- (1) organic matter (OM) removal, particularly the forest floor has a negative effect on tree survival and growth.
 - a. Douglas-fir were particularly sensitive to OM (forest floor) removal and this was measured at 15-years.
- (2) Compaction currently has lesser effect on low density, more porous ash-cap soils.
 - a. Compaction significantly influenced Douglas-fir survival, but was not a significant factor affecting tree growth at 15 years; however, examples of poorer growth occurred on heavy compaction treatments, particularly those with forest floor removed and this may affect longer-term growth.
- (3) Vegetation control has a positive effect on tree survival and growth.
 - a. Vegetation control resulted in significantly better 15-year growth for the two tree species across both core LTSP and adjacent amelioration treatments.
- (4) Ameliorative treatments (stump removal, reduced compaction and organic matter additions) would have positive effects on tree survival and growth
 - a. Amelioration currently not significantly different, but some grew better.
 - b. Vegetation competition was more of a problem on treatments that mixed soil.
 - c. Rehabilitation with forest floor replacement showed promise (not significant).
 - d. Soil tillage with extra forest floor addition to the soil increased growth (not significant).

In addition to the above observations possible at this time, over time the LTSP results, in association with data from other research such as the amelioration and miniplot treatments that are immediately adjacent to the sites studied in the paper, will provide information for validation or revision of the soil disturbance proxy (standards and criteria; e.g., soil disturbance types and cumulative limits, soil disturbance hazard ratings for various soil and climate combinations) and for the assessment of intensive biomass harvesting on productivity and biodiversity (Curran and Maynard 2009). Because the international LTSP sites span a broad climatic range, they also inform our understanding of the effects of climate change on productivity.

5.1. Climate change

Both harvest operations and subsequent soil disturbance can result in changes in the soil carbon pool, and can also alter soil climate by increasing temperature and therefore microbial activity and nutrient cycling (Bekele et al., 2007). However, a more recent meta-analysis by Nave et al., (2010) noted that there were no significant impacts to soil C storage across a wide range of soil and stand types. However, mixing organic horizons into the mineral soil may alter long-term soil aggregation and subsequent loss of soil organic carbon (Balesdent et al., 2000). Forest management under changing climate should consider the effects of more extreme events such as longer, more severe droughts, higher rainfall intensities, and more severe runoff events. It is clear from this study and in subsequent observations leading up to the 20-year measurements, that forest floor removal can have effects on vegetation recovery, seedling establishment and growth, and overall forest productivity. Rehabilitation of disturbance, and tillage of extra topsoil/forest floor into adjacent sites can enhance productivity based on our data and observations to date. However, any soil disturbance can create a brush-field environment due to competing vegetation and invasive species which are becoming increasingly important in light of climate change. Compaction was not currently demonstrated to be clearly detrimental in all cases in this shorter-term study, but there are other reasons for restricting machine traffic such as reduced hydrologic function of the soil that can result in increased runoff, decreased onsite water storage for summer drought, and onsite erosion and off-site,

downslope, or downstream effects during more extreme climatic events (Curran and Maynard 2009).

Treatments designed to reduce Armillaria root disease generally had a beneficial effect on overall growth but require further study regarding their efficacy and long-term effects on not only disease, but also the overall ecosystem response under changing and more variable climatic conditions.

Soil carbon management under changing climate is facilitated by studies on overall productivity and the LTSP and the adjacent ameliorative and miniplot studies are well positioned to answer questions regarding carbon storage above ground (of which the volume results in this paper attest to the importance of maintaining or restoring surface soil organic matter (forest floor), and below ground carbon (for example we are observing the development of deeper, carbon rich soils on the forest floor replacement (Rehab + FF) or addition (FF +) plots).

Overall, results to date on the core LTSP treatments, amelioration treatments, and adjacent miniplots reported elsewhere (Norris et al., 2014), suggest that in some conditions forest floor removal causes negative growth and, combined with heavy compaction, caused both negative growth and poor survival. Therefore, for routine forestry in the Interior Northwest it may be prudent to minimize soil disturbance and leave organic matter onsite unless there is site specific evidence to the contrary, given our more variable and changing climatic cycles. A large amount of data has been collected over the life of these study sites and further monitoring, analysis, reporting, and extension are required to provide critical payback on the large investment made.

5.2. Recommendations

The following recommendations can be made as a result of this study and its relevance under a more variable and changing climate:

- Critical monitoring and reporting work should be completed in the near future before biological evidence is lost to decay,
- Further data analysis and extension is required for the wealth of data already collected,
- Continue LTSP, and adjacent amelioration and miniplot measurements to document ecosystem changes over time in response to the various treatments, and to demonstrate Governments' commitment to sustainable forestry, and
- Incorporate results into the application and revision of current soil disturbance policy, guidance and forest management practices; particularly forest floor removal at this time, and other aspects likely after future reporting of 20 year and longer results.

CRediT authorship contribution statement

Mike P. Curran: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Charlotte E. Norris:** Formal analysis, Writing - review & editing. **Karen E. Hogg:** Formal analysis, Writing - review & editing. **Michael Murray:** Project administration, Writing - review & editing. **Deborah S. Page-Dumroese:** Conceptualization, Methodology, Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2021.119559>.

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