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ScienceDirect

Forest Ecology and Management 255 (2008) 720–727

Forest Ecology and Management

www.elsevier.com/locate/foreco

Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content

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Received 6 July 2007; received in revised form 5 September 2007; accepted 9 September 2007

Abstract

Removal of stumps and fertilization after harvesting have been proposed to reduce root diseases in succeeding stands. Potential impacts such as compaction and loss of soil C or N could limit the use of this technique. This research examined forest soils in five Pacific Northwest stands 22–29 years after stump removal and fertilization with N. Results show that small long-term soil bulk density increases caused by stump removal are not likely to either limit tree growth or discourage the use of stump removal to reduce root rot. However, an extended decrease was noted in mineral soil total N and C and forest floor depth caused by stump removal. The stumped areas show a mineral soil nitrogen concentration that is 20% lower than the non-stumped areas. Mineral soil carbon concentrations were 24% lower and the forest floor depth was 24% lower. A non-significant trend of lower foliar N was also observed with stump removal. These results were consistent in all five soil types. This reduction in the organic component of the soil may be a concern for nutrient cycling and long-term productivity on poor sites.

Keywords: Soil nitrogen; Soil carbon; Laminated root rot; *Phellinus weirii*; Soil bulk density; Douglas-fir root rot; Douglas-fir nitrogen

1. Introduction

Phellinus weirii (Murr.) Gilb is a native pathogen in the forests of the northwestern United States causing laminated root rot and mortality in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and other susceptible conifer species. This facultative saprophyte is a natural part of the ecosystem, present in most Douglas-fir forests of the Pacific Northwest (Thies and Sturrock, 1995). In a natural stand, the tree mortality caused by *P. weirii* creates openings that will be occupied by resistant or early successional plant species, and creates habitat changes that increase overall species diversity in the forest. In a managed forest, *P. weirii* can exist as a saprophyte in the stumps and roots of infested trees that are harvested. Spread of the fungus is usually vegetative and occurs when seedling roots come in contact with infested stumps or roots. Laminated root rot can cause growth reduction, mortality and economic loss, especially in harvested stands that regenerate to Douglas-fir or other susceptible conifer species (Bloomberg and Wallis, 1979; Thies, 1983; Bloomberg and Reynolds, 1988). Spread of the fungus by root contact can create infestations many hectares in size (Thies and Sturrock, 1995).

Clear-cutting followed by planting Douglas-fir has been a widely used silvicultural prescription in the Pacific Northwest, especially west of the Cascade Mountains. Controlling the spread of *P. weirii* in these managed stands has been a concern for forest managers, and removal of *P. weirii* infected stumps and roots before replanting has been shown to reduce the disease in succeeding stands (Thies and Sturrock, 1995).

Heavy equipment used to remove the stumps may have an impact on long- and short-term site productivity and physical soil properties, especially bulk density (Smith and Wass, 1994). Soil displacement and disturbance has been shown to reduce nitrogen levels and site productivity (Vitousek and Matson, 1985).

Addition of nitrogen fertilizer has been suggested to accelerate the displacement of *P. weirii* by *Trichoderma* spp., the main fungal competitor invading *Phellinus* infected root fragments after stump removal. Studies have shown that

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doi:10.1016/j.foreco.2007.09.046

application of urea reduced *P. weirii* survival in buried wood cubes (Nelson, 1967).

A long-term study was established to examine combined effects of stump removal and nitrogen application on laminated root rot persistence in succeeding stands and the effects on tree growth. Replicated treatments with and without stump removal and with four different nitrogen fertilizer treatment levels have been underway at five sites in the Pacific Northwest (Thies and Nelson, 1988; Thies and Westlind, 2005). This paper reports changes in soil bulk density, mineral soil total nitrogen and carbon, and forest floor total nitrogen, carbon and mass 22–29 years after preplant stump removal and nitrogen fertilization.

2. Methods

2.1. Study areas

Five clear-cuts with varying soils and environmental conditions were assessed for long-term stump removal and fertilization effects (see Fig. 1 and Table 1). Sites included: Hoodsport, WA on the southeast edge of Washington's Olympic Mountains; near Apiary, OR at the west end of the Columbia River Gorge; near Sweethome, OR and Gates, OR on the west slopes of Oregon's Cascade Mountain Range and La Grande, OR in eastern Oregon's Blue Mountains. The four stands west of the crest of the Cascade Mountains are typical of second and third-growth forests of the *Tsuga heterophylla* zone (Franklin and Dyrness, 1973). These forests have been managed by clear cutting followed by planting with Douglas-fir. The eastern Oregon site is in the *Abies grandis* zone (Franklin and Dyrness, 1973) and silvicultural methods used in this area are varied. Other tree species found infrequently within the plots include *Pinus contorta* (lodgepole pine), *Pinus ponderosa* (ponderosa pine), *Larix occidentalis* (western larch), *Picea engelmannii* (Engelmann spruce) and *Thuja plicata* (western red cedar).

Fig. 1. Location of root rot study sites in Oregon and Washington.

The sites cover a range of soil types (Table 1). Soils at Hoodsport and La Grande are both Andisols, but the Hoodsport soil (Hoodsport soil series) is shallower with restricted drainage. The Lagrande soils (Tolo soil series) are a fine-textured silt loam formed from loess and volcanic ash. Due to geographic location and high elevation, La Grande is the least productive (a site index of 70). Apiary (Bacona soil series) and Sweethome (Honeygrove series) are Ultisols with a high clay content. The soil at Sweethome has the highest productivity rating (DF site index 120). The soil at Gates (Kinney soil series), is a cobbly, loamy Inceptisol.

2.2. Plots

The study areas were divided into 30 m × 30 m subunits that were systematically searched before and after harvest for *Phellinus* infested trees, down trees and stumps. Infection was rated using an index of relative inoculum potential (INOC) based the presence of decay typical of *P. weirii* near the root collar. Infection was identified based on the presence of incipient or advanced decay typical of that caused by *P. weirii* or ectotrophic mycelium typical of *P. weirii* near the root collar of standing trees or on the tops of stumps.

On a map of infected stumps, treatment plots were positioned to cover areas of infected stumps. Plot centers were then located in the field based on the map, and the presence of infected stumps verified. The plots are a 0.02 ha non-overlapping circular measurement and sampling area surrounded by a treated buffer zone for a total plot size of 0.04 ha. The 0.02 ha plots were rated for inoculum potential using the INOC rating of stumps in the plot plus 25% of the INOC of stumps in the buffer area. Plots were then stratifed by INOC ratings into treatment blocks of eight plots each. Eight plots were placed in areas without infected stumps. The number of replicate blocks at each site ranged from 5 to 7. After stump removal, plot centers were reestablished and permanently marked with fiberglass poles and rebar (Thies and Nelson, 1988). An additional forest site was sampled adjacent to each study area to provide reference soils for preharvesting data with the same soil and timber type (Thies et al., 1994).

2.3. Treatments

Treatments were applied in late summer following harvest as a set of factorial treatments of stump removal (two levels) in combination with four levels of N application. The stump removal treatments were: B_0, no stumps removed, and B_1, all stumps removed. Removal of stumps was done under dry conditions using a bulldozer equipped with a brush blade and a rear splitting wedge. Large stumps were split at least once with the wedge before attempting to remove them with the blade.

Table 1
Summary of site characteristics

	Apiary	Gates	Hoodsport	Lagrande	Sweethome
Latitude/longitude[a]	46°0′N, 123°4′W	44°46′N, 122°21′W	47°28 N, 123°12 W	45°32′N, 118°27′W	44°21′N, 122°39′W
Average temperature (°C)[a]	12.2	9.6	10.4	6.4	10
Average rainfall (cm)[a]	101	200	229	81.8	127
Elevation (m)[a]	335	603	268	1198	439
Slope (%, aspect)[a]	15 SW	15 S	15 S	4 S	16 SW
Forest type[a]	Douglas-fir, hemlock	Douglas-fir, hemlock, cedar	Douglas-fir, hemlock, cedar	Grand fir, Douglas-fir, Englemann spruce, larch, P. pine, lodgepole pine	Douglas-fir, hemlock, cedar, grand fir
Site index[b]	125	122	n/a	70	135
Harvest year[a]	1978	1979	1976	1978	1979
Stump removal year[a]	1978	1980	1976	1978	1980
Soil series[b]	Bacona	Kinney	Hoodsport	Tolo	Honeygrove
Taxonomic class[b]	Fine-silty, mixed, mesic Typic Haplohumults	Fine-loamy, mixed, mesic Andic Dystrudepts	Medial-skeletal, mesic Typic Haploxerand	Ashy over loamy, mixed, Frigid Alfic Vitrixerands	Clayey, mixed, mesic Typic Haplohumults
Texture[b]	Silt loam	Cobbly loam	Gravelly Sandy Loam	Silt Loam	Silty clay loam
Parent material[b]	Eolian material and colluvium from sedimentary rock and basalt	Colluvium, residuals from basic igneous tuffaceous agglomerate	Glacial Till	Volcanic ash over loess and colluvium	Colluvium, residuals from sandstone with basalt and siltstone
Average soil temperature (°C)[b]	8.3–12.2	8.3–11.1	8.3–11.7	6.1–8.3	7.7–12.8
CEC (meq/100 g)[b]	10–15	15–30	n/a	15–35	20–25
Clay content (%) 0–20 cm[b]	18–25	18–27	n/a	5–15	30–40
Clay content (%) 20–80 cm[b]	25–35	22–30	n/a	18–35	50–60

Sources of data include: [a]Thies and Westlind (2005) and [b]Soil Survey Staff (2004).

Normal bulldozing techniques were used to remove as much of the stump and root system as possible. No effort was made to remove severed roots. Upended stumps were left where they came to rest whenever possible.

Nitrogen fertilizer was applied before planting using ammonium nitrate as small prills. Fertilizer was broadcast with a cyclone seeder, crossing the treatment area in perpendicular directions to assure even coverage. The four levels of treatment were: F_0, none applied; F_1, 336 kg N ha^{-1}; F_2, 672 kg N ha^{-1} and F_3, 1345 kg N ha^{-1}.

The eight possible treatment combinations (B_0F_0, B_0F_1, B_0F_2, B_0F_3, B_1F_0, B_1F_1, B_1F_2, B_1F_3) were randomly assigned within each block of eight plots (Thies and Nelson, 1988). All sites were planted with Douglas-fir seedlings the next planting season after treatment, and in subsequent years were interplanted and thinned to control stocking levels and brush competition.

2.4. Soil measurements

Bulk density (D_b) measurements, mineral soil samples and forest floor samples (total O horizon) were collected in 2003 at each plot at three randomly selected subplots created by division of each circular plot into 360 subplots of equal area. Subplots were defined by 10 concentric rings of equal area and 36 10° sectors. The subplot locations were generated by selecting random pairs of numbers: 1–10 (ring) and 1–36 (sector). If an obstruction, such as a stump or downed log, prevented sampling of a subplot, a new subplot was selected. All subplot measures were averaged to give a plot mean.

Soil bulk density was measured at each subplot to a depth of 20 cm with a Troxler 3411B moisture/density neutron probe. Rousseva et al. (1988) found that field calibration of the neutron probe rather than factory calibration is necessary for matching results. The neutron probe results were validated by collecting bulk density core samples directly from some of the probe sites with a bulk density corer or by the displacement method. These samples were oven dried, and weighed for comparison with the probe readings. Eight validation samples were taken at each site. Bulk density measurements taken with the neutron probe were consistently higher (by an average of 0.13 g cm^{-3}) than the validation samples across all sites and treatments and between methods. These results were considered consistent enough to use the neutron probe readings for comparing bulk density across treatments.

Mineral soil and forest floor samples were collected and analyzed for total N and C. Forest floor samples were separated from mineral soil and collected from a 187 cm^2 area with depth averaged from four measurements. Each of the three subplot samples were oven dried, weighed to determine D_b, composited and analyzed for total N and C using a Perkin-Elmer 2400 CHN Analyzer. Mineral soil samples were collected from the upper 15 cm of mineral soil directly beneath the forest floor sample and air dried. The three subplots samples from each plot were sieved to 2 mm, composited, ground and also analyzed for total N and C. Subsamples were used to determine moisture content corrections. The Sweethome site had previously been sampled for bulk density and total nitrogen in the mineral soil (A horizon) in 1991 for all treatments except the 672 kg ha^{-1} N applications (Thies et al., 1994). All sites were remeasured similarly in 2003 with the addition of forest floor sampling. To separate the effects of harvesting from the treatments, soil and forest floor samples were also collected and analyzed from the adjacent unharvested stand as described above.

2.5. Foliar nitrogen

Douglas-fir foliage samples were collected from all plots in 2002 at Lagrande and in 2003 from all other sites. Foliar samples were not collected from adjacent forest areas. Pole pruners were used to collect samples from the south side and upper 1/3 of the canopy from four trees randomly sampled in each plot, for a total of 256 foliage samples. Previous year's growth was used for N analysis. Samples were air dried, ground and analyzed for N using a Perkin-Elmer PE 2400 Series II CHNS/O analyzer. Percent recovery was verified using a standard reference material (NBS No. 1575, pine needles) and was determined to be $98 \pm 6\%$ ($n = 25$).

2.6. Data analysis

Analysis of the total data was done by two-way ANOVA, utilizing treatment means from each site ($n = 40$, 5 sites $\times$ 8 treatments). Two-factor analysis of variance was used to examine data from individual sites for significant effects of stumping, fertilization and interaction effects of stumping and fertilization ($n = 39$–56 for each of the 5 sites; 1 treatment plot flooded and was dropped at the Hoodsport site reducing the plot number from 40). Variables analyzed were bulk density, total mineral soil N and C, forest floor total N and C, forest floor mass, forest floor depth and forest floor and total kg of N to a depth of 15 cm per hectare and foliar N concentration. Comparisons of significant differences of means for stumping, fertilizer and treatment effects were done utilizing Tukey's HSD and least squares. The factors of stumping and fertilization are considered fixed. The application of the treatment blocks in the five separate sites introduced a random factor when considering total data. Differences in p-values were considered significant when $p < 0.05$.

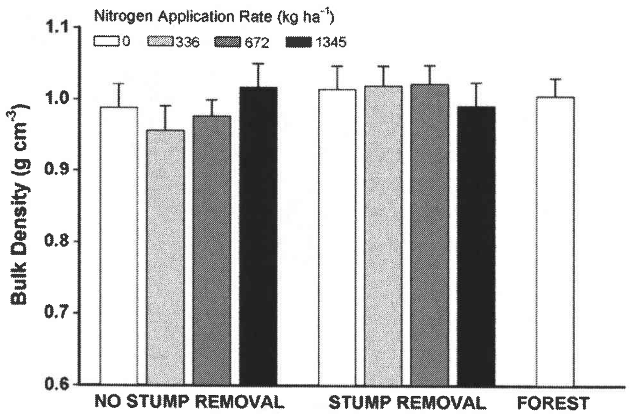

Fig. 2. Average D_b with standard error across all sites by treatment more than 20 years after stump removal and fertilization to control root rot.

3. Results and discussion

3.1. Soil bulk density

More than 20 years after the fertilization and stump removal treatments were applied, their is no significant difference in soil D_b among treatments (Fig. 2). Overall, there is a non-significant 3% increase in D_b with stump removal at all sites. When the sites are considered separately, Gates was the only site that had a lower D_b with stump removal (Fig. 3). After 20 years there was little difference in bulk density due to treatments (Fig. 2). Only Apiary showed a statistically significant ($p = 0.0022$) increase in bulk density (stump removal and nitrogen application) with the two-factor ANOVA. When the main

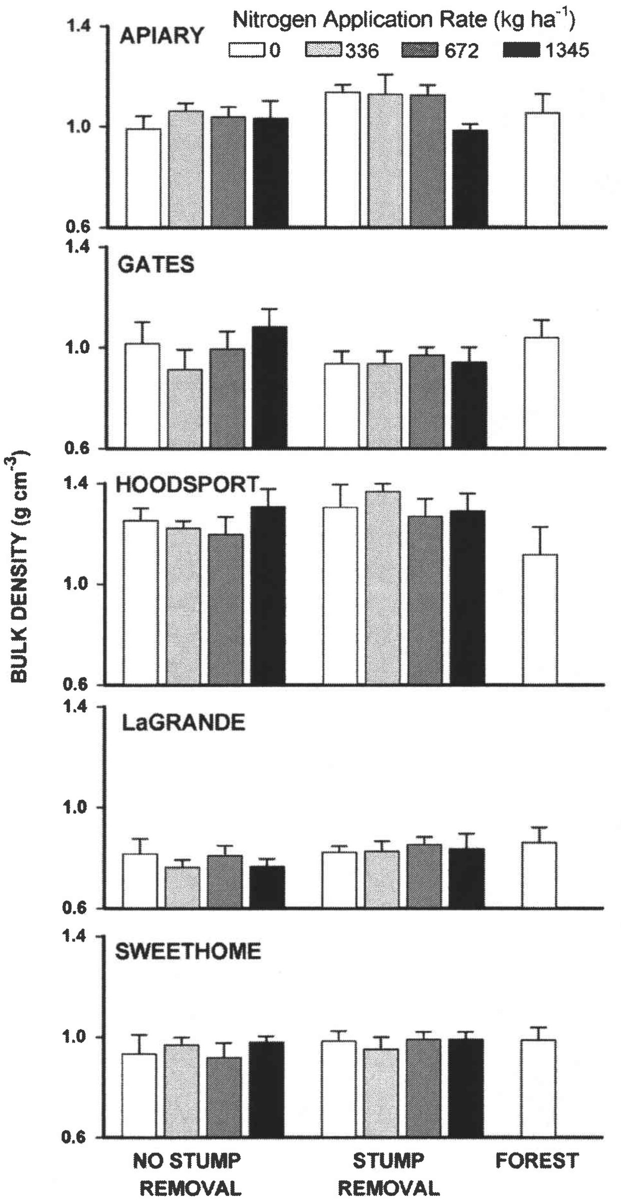

Fig. 3. Average soil D_b with standard error for all sites and all treatments more than 20 years after stump removal and fertilization to control root rot.

effect of stump removal is considered separately, Apiary and LaGrande show a small but statistically significant ($p = 0.0060$; $p = 0.0413$, respectively) increase in bulk density with stump removal (6.0; 5.8% increases, respectively) (Table 2), but at La Grande, D_b is low due to the presence of volcanic ash, and D_b at Apiary is still within densities typical of unimpacted forest soils. The small changes found here are unlikely to affect tree growth (Wass and Smith, 1997; Heninger et al., 2002). There is no region-wide evidence of fertilizer effect on bulk density ($p = 0.9998$).

The higher bulk densities measured on the no-stump removal plots at Gates may be the result of the chance grouping of these randomly assigned plots into one area that has higher density or that was the center of activity during stump removal or logging. The soils at Gates also contained many large decomposing logs. The variability in D_b in the no-stump removal plots at Gates was the highest of the study areas. The statistically significant increase at La Grande and Apiary caused by the stump removal may be due to the finer texture of these soils. Apiary especially has a high clay content and heavy rains occurred the month before the bulldozing took place.

While stump removal can lower D_b by mixing forest floor material into mineral soil and loosening soil around extracted roots as well as increase it from compaction, we found little increase in variability after 25 years. Interestingly, stump removal treatments reduced within plot D_b variability (among subplots) at all sites except Apiary. Coefficients of variation for bulk density were lower in stump removal plots at Gates, Sweethome and LaGrande, but region-wide the coefficients of variation for bulk density measures were not different between stump removal and no-stump removal.

The soil D_b at Sweethome showed recovery from increases caused by stump removal in the first decade after treatments. The data taken in 1991 (Thies et al., 1994) and in 2003 (this study) show a decrease in the bulk density of the stump removal plots by 7%, while the results from the no-stump removal plots are almost the same (−1%). The 2003 results show that the stump removal and no-stump removal plots are now similar (0.97 and 0.96 g cm^{-3}, respectively). The Sweethome no-stump removal plots have returned to the bulk densities measured in the unharvested forest plots in 1991 (0.96 g cm^{-3}). These recovery rates for surface soils are faster than those found in studies which examined compaction on skid trails (Wert and Thomas, 1981; Froehlich et al., 1985), possibly due to less compaction from the stump removal, or lifting of the soil by the stump removal that counteracted the compaction.

Although these results show no long-term increases in D_b, it should be noted that care was taken during the bulldozing to have equipment on the site when soils were drier. If soils are only dry at the surface and moist at depth, compaction could occur at depth and not within the top 20 cm. Additionally, if stump removal is not done with dry soils, there could be short-term compaction that could affect early seedling root development (Page-Dumroese et al., 1998). It should also be noted that stump removal on these sites was done in 1978–1980 by pushing with a bulldozer. Today stump removal would most

Table 2
Factorial ANOVA results

	All sites	Apiary	Gates	Hoodsport	Lagrande	Sweethome
Probabilities for differences caused by treatments (stump removal and nitrogen application)						
n	40	40	56	39	56	48
Bulk density	0.9985	**0.0022***	0.1279	0.4432	0.4053	0.5391
Mineral N	0.3556	0.0721	**0.0014***	0.2589	0.1964	**0.0086***
Mineral C	0.2180	0.1690	**0.0042***	0.2905	0.1396	**0.0345***
Forest floor depth	0.1796	0.1456	**0.0012***	0.1512	0.3820	0.2430
Forest floor N kg ha^{-1}	0.1866	0.1549	0.6880	0.0960	0.1088	**0.0484***
Total N kg ha^{-1}	0.2072	0.0929	**0.0003***	0.4907	0.2030	**0.0082***
Probabilities for differences caused by main effect of stump removal						
n	40	40	56	39	56	48
Bulk density	0.6018	**0.0060***	0.0790	0.1056	**0.0413***	0.1710
Mineral N	**0.0128***	**0.0010***	**<0.0001***	0.2110	**0.0088***	**0.0002***
Mineral C	**0.0072***	**0.0050***	**0.0002***	0.1842	**0.0054***	**0.0015***
Forest floor depth	**0.0084***	0.2665	**<0.0001***	0.0754	0.1845	**0.0197***
Forest floor N kg ha^{-1}	**0.0195***	0.6502	0.2158	**0.0138***	**0.0222***	**0.0033***
Total N kg ha^{-1}	**0.0056***	**0.0086***	**<0.0001***	0.1877	**0.0294***	**0.0004***
Probabilities for differences caused by main effect of nitrogen application						
n	40	40	56	39	56	48
Bulk density	0.9998	**0.0331***	0.2819	0.5887	0.6298	0.7268
Mineral N	0.8775	0.9136	0.0586	0.5610	0.6784	0.6840
Mineral C	0.7735	0.7987	**0.0472***	0.5514	0.5923	0.6747
Forest floor depth	0.4942	0.1128	0.2147	0.3900	0.1775	0.5518
Forest floor N kg ha^{-1}	0.3495	0.0792	0.5608	0.2826	0.2586	0.2992
Total N kg ha^{-1}	0.8598	0.8205	0.1159	0.6571	0.7625	0.7424

Probabilities of differences among treatments and main effects at all sites and at individual sites for bulk density, mineral soil total N and C, forest floor depth, total forest floor N and total N in the forest floor and top 20 cm of mineral soil. No interactions were found between treatments. Bold fonts and '*' indicate significant difference when $p \leq 0.05$.

likely be done with an excavator, which should cause less soil disturbance (Wass and Smith, 1997). If stump removal is done with care, it is not likely to result in long-term increases in soil bulk density.

3.2. Soil and foliar nitrogen

Despite more than 20 years having passed since root rot treatments were applied, mineral soil N concentration was consistently lower in the stump removal plots among all sites (Fig. 4). The mean reduction in mineral soil total nitrogen after 20 years was 20%. The stump removal treatments showed a statistically significant ($p = 0.0128$) reduction in mineral soil nitrogen compared to the no stump removal plots and the adjacent forest at Gates and Sweethome ($p = 0.0014$, $p = 0.0086$, respectively) (Fig. 5 and Table 2). Comparing main ANOVA effects shows that the lower N is caused by the stump removal treatment and not affected by the fertilizer application. Lower nitrogen concentrations are a statistically significant result of stump removal at all sites except Hoodsport. At all sites except Hoodsport, the reduced N concentration declines from the undisturbed forest to no-stump removal (clearcut) to stump removal (clearcut and stump removal).

Although foliar N analysis showed no significant effect from either stump removal or fertilization, there was a consistently lower foliar N content with stump removal (Fig. 6). Fertilization showed no trends with stump removal, but increasing fertilization did somewhat increase foliar N although the large variability made all results non-significant. This trend of lower foliar N with stump removal may be related to decreases in soil nitrogen and organic matter. Stump removal, but not fertilizing, decreased the soil carbon region-wide by 22% ($p = 0.0072$) (Fig. 4). A reduction in mineral soil carbon is significant at all sites except Hoodsport (Table 2).

There was a reduction in forest floor depth and total forest floor carbon at all sites in the stump removal plots compared to the no stump removal plots. The mean reduction in forest floor depth region-wide was 24% ($p = 0.0084$), and the mean

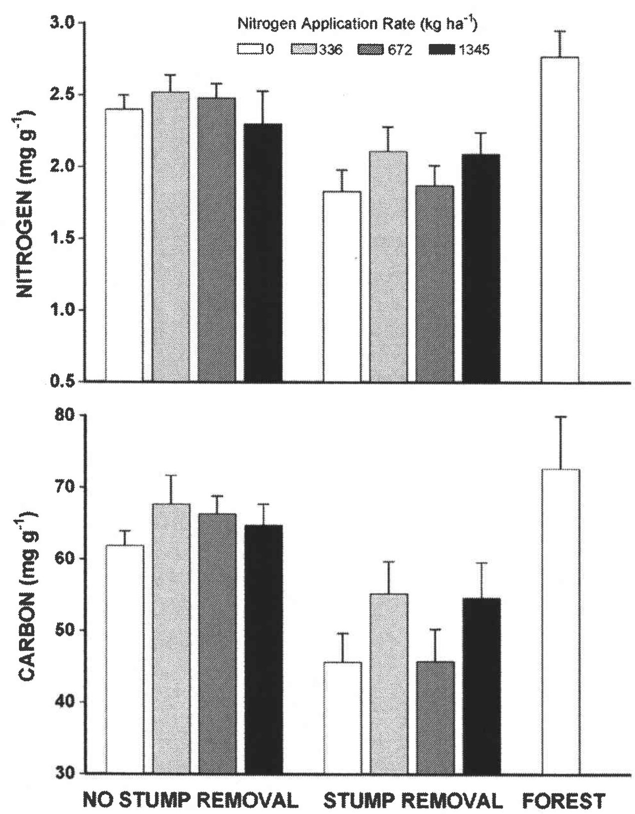

Fig. 4. Average mineral soil N and C concentrations with standard errors across all sites more than 20 years after stump removal and fertilization to control root rot.

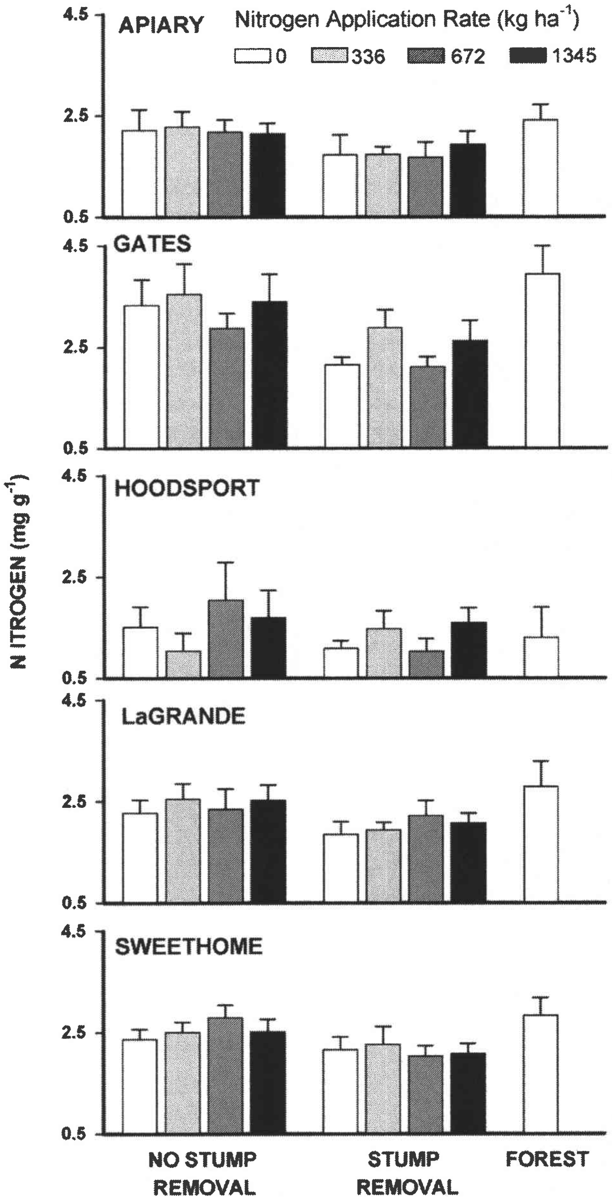

Fig. 5. Average total N and total C concentration in the top 15 cm of mineral soil for individual sites by treatment more than 20 years after treatment to control root rot.

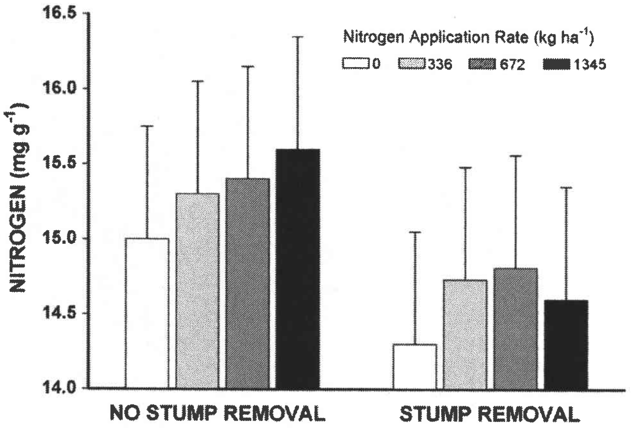

Fig. 6. Average foliar N concentration of 1-year-old Douglas-fir needles more than 20 years after stump removal and fertilization to control root rot.

reduction in forest floor total carbon was 6% ($p = 0.0130$). Despite forest floor total N concentrations that are similar in the stump removal and no stump removal plots, forest floor N in kilograms per hectare declines at all sites from no stump removal to stump removal. The average decline is 28%. This is a statistically significant result of stump removal overall ($n = 40$), and individually at Hoodsport, La Grande and Sweethome.

The total N content of the forest floor and mineral soil to a depth of 15 cm (in kg ha^{-1}) shows a decrease of 19% N. This is a statistically significant result of stump removal at all sites with the exception of Hoodsport (Table 2). Combining mineral soil and forest floor carbon data shows an average decrease in kg C ha^{-1} of 21% as a result of stump removal. Neither N or C content was increased in the long-term by the preplanting fertilization.

The decreased mineral soil N and C concentration, and forest floor depth and weight caused by the disturbance of stump removal indicates a reduction in soil organic matter. Soil organic matter has been shown to have an important role in forest ecosystems, acting as a reservoir for nutrients (Weber et al., 1984), as well as enhancing moisture holding capability and contributing to soil structure. Soil biota necessary for nutrient cycling are dependent on soil organic matter, and alterations in organic matter can have large effects on soil and site properties (Harvey et al., 1994; Jurgensen et al., 1997). Nitrogen is generally the most limiting nutrient in Pacific Northwest forests. The largest reservoir of nitrogen in these temperate conifer forest ecosystems is soil organic matter. The portion of the N pool in the upper 30 cm of mineral soil may be 50% or greater with another 5 or 10% in the forest floor (Dyck and Beets, 1987; Page-Dumroese et al., 2000; Klopatek, 2002; Finer et al., 2003). Ross et al. (1995) reported 5–7% of forest ecosystem N was found in soil microbes. The 20% reduction in total N in the top 20 cm of mineral soil and the 28% reduction in forest floor kg N ha^{-1} resulting from the stump removal treatments may be a concern to managers for long- and short-term productivity. Tuttle et al. (1985) found increases in N 3 years after site prep treatments. The results from Sweethome from 1991 and 2003 indicate that losses of soil N have stopped, but the deficit remains. While the 2003 mean for total N in the no stump removal plots is 6% lower than the 1991 mean (Thies et al., 1994), the stump removal plot total N has increased 8%. This shows that some recovery is underway, but the reduction in N is still statistically significant in 2003 ($p = 0.0002$). One factor that may lead to the slow recovery of the stump removal plots is the young age of the stand. The trees and other vegetation are accumulating nutrients during this period of recovery and fast growth. Inputs into this system may be accumulating in above ground vegetation at the expense of the soil pool, while additions from litterfall may be lower.

4. Conclusions

Increased soil bulk density caused by stump removal does not seem to be a long-term concern when stumps are pulled to control root rot. The small increases in bulk density seen on some sites are unlikely to impact tree growth in the long term. The recovery seen at Sweethome indicates that surface soils can recover fairly rapidly from increased bulk density resulting from using heavy equipment for stump removal. Stump removal did decrease soil N probably due to a loss of soil organic matter. Decreases in foliar N were also seen with stump removal, but were not significant. These decreases were unaffected by the preplant N fertilization, and have persisted for more than 20 years after treatment. If stump removal is done carefully and shown to be effective for a particular site, then additions of N or organic matter should be applied to ameliorate any long-term losses of soil N.

Acknowledgements

Our thanks to the landowners and managers who have supported this study by providing land, funds, stump removal, planting, vegetation control, fencing and thinning. In some cases the landowners and managers changed, but the commitment to this long-term study continued: *Apiary*, started by International Paper Co., continued by Stimpson Timber Co. and Weyerheauser Corp.; *Gates*, USDI Bureau of Land Management; *Hoodsport*, started by Simpson Timber Co. and continued by the Washington St. Dept. of Natural Resources; *La Grande*, Boise Cascade Corp. and *Sweethome*, Hill Interests (managed by Cascade Timber Consulting). We also thank the USDA-FS and American Forest and Paper Assoc. Agenda 2020 for funding and all of the field crews who established and helped maintain these plots over 25 years. Special recognition is given to Earl Nelson who participated in establishing the study.

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