Foliar nutrient levels in Douglas-fir plantations 25 years after stump removal and fertilization to control *Phellinus weirii*

by

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Introduction

Laminated root rot is caused by a basidiomycete fungus, *Phellinus weirii* (Murr.) Gilb. It is a native facultative saprophyte that occurs as a natural part of the ecosystem in most Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests in the Pacific Northwest. This structural root rot strongly influences forest succession, biodiversity, composition, and dynamics (Cook 1982, Holah et al. 1993, Ingersoll et al. 1996, Holah et al. 1997). Trees infected by *P. weirii* can either die standing, be windthrown, or made vulnerable to bark beetles, or other secondary agents (Thies and Sturrock 1995). Its main hosts are Douglas-fir, grand-fir (*Abies grandis*), and mountain hemlock (*Tsuga mertensiana*); pines and cedars are tolerant or resistant while all hardwoods are immune (Thies and Sturrock 1995, Edmonds et al. 2000). It is considered one of the most destructive diseases and difficult root pathogens to manage resulting in average annual timber volume losses of 4.4 million cubic meters (Nelson et al. 1981). *Phellinus weirii* infection reduces timber productivity several years prior to death in second-growth Douglas-fir stands (Bloomberg and Wallis 1979, Thies 1982, 1983, Lawson et al. 1983, Bloomberg and Reynolds 1985, Thies and Sturrock 1995).

Phellinus weirii spreads vegetatively through root-to-root contact by ectotrophic mycelia, rarely produces fruiting bodies, and can survive saprophytically in roots and stumps of dead trees for several decades (Hansen 1979). It establishes large genets in root disease pockets and younger trees appear more susceptible than old-growth. Regeneration of susceptible host species in these pockets is usually unsuccessful.

Infection centers expand at a rate of 0.3 m per year radially and travels less than 1.8 m up the stem base. Roots of infected trees commonly snap off close to the root collar forming characteristic "root balls" (Edmonds et al. 2000). Symptoms include reduced height growth, yellow foliage, slow loss of foliage, distress cones, slow crown decline, rotted roots, downed trees in different directions, and insect galleries under the bark. Setal hyphae, ectotrophic mycelium, and laminated decay with pits on both sides of sheets are signs of laminated root rot (Hatfield et al. 1986).

Two treatments have been recommended as options for control of laminated root (LLR) disease: stump removal and fertilization. Removing stumps and roots from the soil has been prescribed to reduce inoculum (Wallis 1976) and in field tests, the application of urea was shown to reduce survival of *P. weirii* in buried cubes (Nelson 1975). Starting around 1980, these treatments were applied to five sites in Oregon and Washington that were known to be infested with *P. weirii*. Clearcut sites were treated by bulldozing stumps and applying ammonium nitrate (NH_4NO_3), then planting with Douglas-fir seedlings. Growth of Douglas-fir has since been monitored since and final results were reported in Thies and Westlin (2005). In 1990, soil bulk density and soil nitrogen (N) concentrations were measured at Sweethome, one of the five sites. Small increases in soil bulk density and elevated soil N were found at this time (Thies et al. 1994). Questions remained as to the long-term effects of stump removal and fertilization of *Phellinus*, soil bulk density, soil N, and foliar nutrients following this work.

In 2003, trees from all five sites were remeasured for growth and mortality. Foliar and soil samples were collected to examine the long-term ecological effects of stump removal and fertilization. Soil analysis from this work was reported by

Chambreau (2004). This report summarizes the effects of stump removal and fertilization on foliar Ca, K, Mg, N, P, and S and perhaps provide insight into long-term consequences of management efforts to control laminated root rot.

Objectives & Hypotheses

Objective: To determine long term ecosystem effects from stump removal and N fertilization to control laminate root rot by examining foliar Ca, K, Mg, N, P, and S foliar concentrations.

H_o: *There is no significant long-term residual effect in foliar % Ca, K, Mg, N, P, and S concentrations from stump removal and fertilization to control laminated root rot in Douglas-fir plantations*.

H_A: *There is no significant long-term residual effect in foliar % Ca, K, Mg, N, P, and S concentrations from stump removal and fertilization to control laminated root rot in Douglas-fir plantations.*

1.1
H_o: *There is no significant difference in foliar % Ca, K, Mg, N, P, and S between stumping treatments*.
H_A: *There is a significant difference in foliar % Ca, K, Mg, N, P, and S between stumping treatments.*

1.2
H_o: *There is no significant difference in foliar % Ca, K, Mg, N, P, and S among fertilization treatments*.
H_A: *There is a significant difference in foliar % Ca, K, Mg, N, P, and S among fertilization treatments.*

1.3
H_o: *There is no significant difference in foliar % Ca, K, Mg, N, P, and S from the interaction of stumping and fertilization treatments*.
H_A: *There is a significant difference in foliar % Ca, K, Mg, N, P, and S from the interaction of stumping and fertilization treatments.*

Methods

Study Areas

This field study was begun in 1977 to examine treatments for control of *Phellinus weirii* disease and mortality on managed timber stands. Five sites in Oregon and Washington (Fig. 1) were established to investigate preplanting site treatments of fertilization and stump removal at areas with differing soil types and microclimate properties. Each study area was established in a clearcut unit and planted with Douglas-fir seedlings. A 2 x 4 set of factorial treatments of stump removal in combination with N fertilization was applied to 0.04 ha circular plots and replicated five to seven times (Thies & Westlin 2005). The area of the clearcuts ranged between 3.8 - 6.1 ha. All five sites showed documented mortality by *P. weirii* and each stand were considered a complete and separate study. The Oregon sites were located in forests near Apiary, at the western end of the Columbia River Gorge, Gates and Sweethome, on the west slopes of Oregon's Cascade Mountain Range, and LaGrande, in eastern Oregon's Blue Mountains. The Washington site is near the town of Hoodsport and is located in the southeast edge of the Olympic Mountains. Each was established with the cooperation of public and private landholders.

The western sites, Hoodsport, Apiary, Gates, and Sweethome, were composed of characteristic second and third-growth forests of the *Tsuga heterophylla Zone* (Franklin and Dryness 1973). *Tsuga heterophylla* and *Thuja plicata* are the climax species. Early successional species are red alder (*Alnus rubra)*, big-leaf maple, *(Acer macrophyllum)*, and Douglas-fir. Traditional silviculture management of this type of forest has been clear-cutting and replanting with Douglas-fir (*Pseudotsuga menziesii)*. The eastern Oregon site, LaGrande, is in the *Abies Grandis* Zone, characterized by its climax species Grand fir (*Abies grandis*) and the successional species, Douglas-fir, lodgepole pine (*Pinus contorta*), ponderosa pine *(Pinus ponderosa*), and western larch *(Larix occidentalis)*. Silviculture practices tend to be wide-ranging in these forests and root diseases may be mitigated by planting with resistant *Pinus* and *Larix* species on clear-cuts. Further details of site characteristics including geological variations are listed in Table 1.

Plots

Each of the five study areas was subdivided into 30x30 m subunits. The subunits were then systematically searched prehavest and postharvest to locate and map *P. weirii* infested live trees, down trees, and stumps (Thies and Hoopes 1979) for an overall total of 239 plots. For each infested entity, an index of relative inoculum potential (INOC) was assigned based on the presence of incipient or advanced decay typical of that caused by *P. weirii* or characteristic *P. weirii* ectotrophic mycelium near the root collar. The formula used to calculate the extent of infection was INOC=BM x *O* x *Y*, where INOC is the relative biomass of potential inoculum, *O* is the orientation, and *Y* is the years dead.

On a map of infested stumps, 0.04 ha circular, non-overlapping treatment plots were positioned over concentrations of infested stumps. A 0.02 ha circular measurement plot with a 3m buffer was centered in each 0.04 treatment plot. The 0.02 ha plots were rated for inoculum potential using the designated INOC rating of stumps in the plot plus

25% of the INOC in the buffer area (see Thies and Westlind 2005 for INOC index and mortality results). Plots were stratified based on total INOC into treatment blocks of eight plots each. Each plot center on the map was verified in the field for infested stumps and eight plots were placed over areas without infected stumps. After stump removal, plot centers were reestablished and permanently marked (Thies and Hoopes 1979).

Treatments

Factorial treatments of stump removal in combination with N fertilization were applied the next planting season following harvest. Two stump removal levels were used: no stumps removed (B_0) and all stumps removed (B_1). A D-8 crawler tractor with a brush blade removed the stumps and much of the root system using normal bulldozing techniques. Whenever achievable, stumps were left upended where they came to rest. Stump removal also was done when the soil surfaces were dry. Nearly all vegetation on the stumped plots was destroyed (Thies and Nelson 1988).

. Before planting, N fertilization was applied as small prills of NH_4NO_3 evenly broadcasted by a cylone seeder. The four levels of N treatments were: F_0, no fertilizer applied, F_1, 336 kg ha^{-1}, F_2, 672 kg ha^{-1}, and F_3, 1345 kg ha^{-1} applied fertilizer.

Eight possible combinations of stump removal and fertilizing (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).

Douglas-fir was planted the next planting season at all sites. The trees were thinned and interplanted the following seasons to control stocking levels. Seedling height, diameter, or mortality was observed and recorded at intervals of 3- to 5-years as resources allowed (Thies and Nelson 1988). Complete analysis of this data is reported elsewhere (Thies and Westlin 2005).

Soil Measurements

Soil and forest floor samples were collected and analyzed to determine treatment effects (Chambreau 2004). Samples were evaluated for soil bulk density, forest floor and soil N, and forest floor depth, volume, and weight from each treatment plot at all sites.

In 1991, soil samples were collected at the Sweethome site. Total soil N and soil bulk density were analyzed from all treatment plots except treatments with 672 kg ha^{-1} (Thies et al. 1994). The collection methods were done similarly to the 2003 methods except that in 2003, forest floor samples were taken for depth, volume, and weight. These methods, results and comparisons of soil bulk density and soil and forest floor nitrogen 12 years apart are examined elsewhere (Chambreau 2004).

Foliar Nutrients

Pole pruners were used to clip branches from the canopy of each sample tree. There were four sample trees per plot and one at each of the cardinal directions from the plot center. Branches were sampled from the south side and from the upper one-third of the canopy. Previous year’s needles were collected and put into paper bags and labeled. Current year’s needles were avoided because collection across all five sites occurred at different times of the year. Bags were left open to air-dry at room temperature. The collection dates at each site were as follows:

Gates	June 24-25, 2003
Sweethome	July 8-9, 2003
LaGrande	July 10-11, 2002
Hoodsport	October 21-23, 2003
Apiary	October 28-29, 2003

Two hundred and fifty-six Douglas-fir branch samples were debranched of their needles and ground through a Wiley mill using a 2 mm stainless steel screen. After grinding, samples were re-bagged, labeled, and placed in a 70^{o}C oven for 48 hrs. The dried samples were then further ground with a mortar and pestle.

Total N was analyzed using a Perkins-Elmer PE 2400 Series II CHNS/O Analyzer at the University of Washington's College of Forest Resources Lab in Seattle, Washington. A standard (NBS Standard Reference material No. 1575 (pine needles)) was run every 10 samples to monitor % recovery. Duplicates were also run every 10 samples to check for precision. Mean percent recovery and standard deviation for total N (n = 23) was 98% $\pm$ 6%.

For the elemental analysis of Ca, K, Mg, P, and S, four of the eight treatments were sampled from each site. The four treatments included the lowest (F_0, 0 kg ha^{-1}) and highest (F_3, 1345 kg ha^{-1}) levels of fertilization with stump removal (B_1) and no stump removal (B_0) treatments, for a total of 119 samples. A nitric acid digest was used (Vogt et al. 1987*a*, 1987*b*) with an addition of 2mL H_20_2 to the digest solution (Mills 1996) with subsequent elemental analysis for Ca, K, Mg, P and S using a Jarrel-Ash 955 Atomcomp ICP at the UW lab. Mean percent recovery and standard deviation for Ca (n = 7) was 88 $\pm$ 2%, 86 $\pm$ 3% for K (n=7), and 100 $\pm$ 1% for P (n=5). Percent recovery for

Mg and S was not calculated because the standard reference material did not include data for Mg and S.

Data Analysis

Significant effects from stump removal, fertilization, and their interaction on foliar nutrients were analyzed using a two-way ANOVA. For N concentrations, combined total data of all 5 sites (n=5), treatment means from each site (n=40) were used where N was considered the independent variable and where stump removal and fertilization were considered fixed. For individual site differences, plot data was utilized in a two factorial analysis of data (Apiary n=40, Gates n=55, Hoodsport n=39, LaGrande n=56, and Sweethome n=48). Tukey's HSD and least squares were used for comparisons of significant differences for means on the individual five sites for stump removal, fertilization, and treatment effects.

Treatment effects on foliar Ca, K, Mg, P, and S were analyzed by using a two by two-factorial analysis (as opposed to a two-by-four factorial for N). For total combined data of all 5 sites, treatment means from each site (n=20) were used and for the individual sites, plot data (Apiary n=20, Gates n=27, Hoodsport n=20, LaGrande n=28, and Sweethome n=24). Treatment effects were considered significant when p was less than or equal to 0.05. A significant interaction implies that the difference among levels of one factor is not constant at all levels of the second factor (Zar 1999).

Results

Foliar N Concentrations

Foliar N concentrations combined across all sites and treatments show no significant treatment effects from bulldozing and fertilization. However, trends between treatments are evident and site effects are present. Foliar N concentrations across all sites (n=5) were lower in plots that had stump removal (Fig. 2). N concentrations ranged between 1.44-1.47% on stumped plots and on unstumped plots were N was between 1.48-1.55%. Without stump removal foliage N also increases with increased NH_4NO_3 application. Although statistical analysis reveals no significance ($p \leq 0.05$) between the stump removal, fertilization treatments, or interactions between treatments, foliar N trends appear to be related to both stump removal treatments and fertilizer application.

For each of the eight treatments across our five study sites, foliar N is above the mean of published data for critical and deficient concentrations (Table 2). The cited foliar N concentrations in Table 2 were collected from similarly aged Douglas-fir trees in a variety of soil types, environmental conditions and geographic locations. The critical concentration level is defined as the concentration in the foliage of a particular element that will give 90% of maximum growth when no other element is limiting (Epstein 1972, Walker and Gessel 1991). If foliar nutrient concentrations are below critical levels, it is widely accepted that trees are considered to be deficient in those nutrients (Garrison et al. 2000). In our study sites, collection dates were generally at the end of the growing season as with the data from Table 2.

Foliar N is incrementally higher with each level of N fertilization at all sites combined (n=5, Fig. 3). Although this trend is not statistically significant ($p \leq 0.05$), the average foliar concentration of plots fertilized with 1345 kg ha^{-1} NH_4NO_3 was 0.04% higher than those that received no fertilization. Forest floor and mineral soil N concentrations (Chambreau 2004) did not follow the same pattern as the foliage and remain indistinguishable with increasing NH_4NO_3 applications.

Foliar N concentrations varied according to site. Differences are evident in each study area's overall mean of combined treatments (Fig. 4). Douglas-fir foliar N concentrations are noticeably higher at Hoodsport (n=39) and LaGrande (n=56) from those at the Apiary (n=40), Gates (n=55), and Sweethome (n=48) study areas. In contrast, mineral soil and forest floor N concentrations were considerably lower but not significant at Hoodsport and LaGrande (Chambreau 2004).

No significant treatments effects in foliar N are present between treatments on any of the sites. Combined stump removal and fertilization treatments at each individual site (Fig. 5, n=238) do not show any discernable trend such as seen when all five sites are combined (Fig. 2, n=5).

When all five sites are considered separate studies, the foliar N concentration differences in the combined stump removal and no stump removal treatments can be distinguished (Fig. 6). On all sites except Apiary, there is a decrease of N concentrations on plots that were stumped. However this decrease is not statistically significant ($p \leq 0.05$) at any of the sites with the possible exception of Sweethome ($p=0.06$). Nitrogen means in stumped plots were lower by 9% at Hoodsport, 7% at Sweethome, 6% at Gates, 2% at LaGrande. The only study area with a higher N mean in stumped plots was Apiary by 1%. This increase at Apiary is due to the higher foliar concentrations from one treatment: the 336 kg ha^{-1} N application, yet higher concentrations were not observed with higher rates of N fertilization. However, this isolated increase may likely be a response to site conditions, and not a response to the fertilizer application.

Although insignificant in the foliage, this trend of reduced N in stumped plots at each site is mimicked in the mineral soil concentrations of total N. Lower mineral soil N concentrations were statistically significant as a result of stump removal at all sites except Hoodsport (Chambreau 2004).

Across all five study areas (n=5) Douglas-fir foliage and mineral soil N concentration means are higher in plots without stump removal (Fig. 7). Mineral soil N concentrations are significantly lower in stumped plots ($p \leq 0.05$) while forest floor N slightly decreases (Chambreau 2004). The average difference between stump removal and no stump removal treatments in total N more than twenty years after treatment was 5% in the foliage, 20% in the mineral soil, and 1% in the forest floor.

Although statistically insignificant, foliar N concentrations were generally lower on stumped plots at all sites combined and individually at four of the five study areas (Fig. 6). Approximately 25 years after treatments, the overall combined average foliar N concentration was 7% lower in stumped plots. This reduction of foliar N in plots that received bulldozing treatment corresponds to the N reductions found in the soil part of this study. Chambreau (2004) found a 20% overall decrease in mineral soil N concentrations, a 28% reduction in forest floor N in kg ha^{-1}, and a 22% decline in mineral soil C as a result of the stump removal treatment.

Foliar concentrations of P, K, Ca, Mg, and S

Summed across all study sites, macronutrient concentrations of Ca, K, Mg, and P exceeded critical or deficient levels as reported in the literature (Table 3). Sulfur, however, was below deficient levels at all sites and may indicate regional deficiencies in S availability (Table 4).

Treatment Effects

Across all five sites ($n=5$, $p \leq 0.05$), the fertilization and stump removal treatments did not significantly effect Ca, K, Mg, P, and S concentrations in Douglas-fir needles). Of the two fertilization treatments (0 kg ha-1 and 1345 kg ha-1) with combined stump removal treatment, only Ca concentrations increased with fertilization (Fig. 8, n=5). Potassium and S concentrations remained similar, while Mg and P decreased slightly yet not significantly with fertilization.

Stump removal alone or combined with fertilization treatments (Fig. 9, n=5) did not affect Mg, P, and S foliar concentrations. Slight, yet non-significant effects were seen in Ca and K concentrations in stumped plots. In plots that received the stump removal, Ca was reduced while K was somewhat elevated.

Site Effects on Macronutrients

Significant treatment effects were seen in foliar macronutrient concentrations at the five sites individually. At the Apiary study site, fertilized plots ($n=10$) were significantly higher in Ca ($p=0.02$) while significantly lower in P ($p=0.05$, Fig. 10). With combined fertilization treatments, K was significantly higher (p=0.002) on stumped plots (n=10) than in plots without stump removal.

Although insignificant, foliar K and P increased slightly at Gates with fertilization treatment while declining in non-stumped plots independent of fertilization treatments (Fig. 11, n=20). In addition, there was a small interaction effect between the stump removal and fertilization treatments at this study area.

No treatment effects were significant at Hoodsport (n=20) with any foliar macronutrients. Only slight differences were seen among individual nutrients in the fertilization and stump removal treatments separately yet no clear trends were evident (Fig. 12).

At LaGrande (n=28), significant treatment effects were only seen in Mg concentrations on fertilized and unfertilized plots. Magnesium was higher in fertilized plots than in unfertilized plots (p=0.01, Fig. 13).

Magnesium and S concentrations at the Sweethome study area were both significantly reduced (p=0.03 and p=0.03, respectively) in fertilized plots with the combined stump removal treatment (n=24, Fig. 14). In the combined bulldozing treatments, K and S concentrations were significantly higher in stumped plots (p=0.03 and p=0.001 respectively) than plots without stump removal. In addition, foliar P showed an interaction between bulldozing and fertilization (p=0.01).

All five sites displayed at least one macronutrient concentration mean that falls at or below published critical and deficient levels (Table 4). Foliar S is limited by nearly half the critical deficient S concentration mean (0.2%) at all sites. Potassium at Gates, Mg at LaGrande and Sweethome, and P at Sweethome were all below published mean foliar critical and deficiency levels.

Discussion

Stump removal

At the establishment of our study, the bulldozed treatment plots were considered highly disturbed (Thies and Westlin 2005). The amount of disturbance from stump removal is similar to intensive site preparation. Prior research has documented that heavy equipment used in site preparation generally causes an increase in bulk density and soil compaction which many persist for many years (Hakansson et al. 1987, Soane 1990, McColl 1995, Kozlowski 1999). Poor soil physical conditions as a result of increased bulk density can impair root growth and limit the uptake of nutrients resulting in overall poor tree growth (Whalley et al. 1995, Fisher and Brinkley 2000). Soil compaction impedes root elongation and soil microbial biomass and activity by reducing nutrient availability and modifying rates of N mineralization (Zabowski et al. 1994, Whalley et al. 1995, Breland and Hansen 1996). Intensive site preparation usually involves removal of the forest floor. Removing the forest floor reduces and redistributes organic matter and the associated soil microflora and fauna in the litter (Marshall 2000). This loss has been shown to adversely alter soil physical and biological properties and processes (Miller 1976) which controls forest productivity and sustainability (Fisher and Brinkley 2000). Resulting changes in forest floor C/N ratios influence tree response (Edmonds and Hsiang 1987). Forest floor removal has been linked to increases in soil temperature and reductions of soil moisture (Zabowski et al 1994). Temperature changes adversely affect rates of absorption of mineral nutrients by altering vital plant metabolism (Kozlowski and Pallardy 1997) or decreasing water availability.

Although statistically insignificant, foliar N was generally lower on stump removal plots. This effect was visible at all sites combined and individually at four of the five sites with Apiary as the one exception (see Fig. 6). Approximately 25 years after treatments to control *Phellinus weirii*, the overall combined average foliar N concentration was 7% lower in stumped plots. This overall reduction of N in the needles from stumped plots corresponds to N reductions observed in the soil. Chambreau (2004) found a 20% decrease in mineral soil N concentration, a 28% reduction in forest floor N (kg ha^{-1}), and a 22% decline in mineral soil C from the stumping treatment. This was probably responsible for the lower N concentration of the foliage in this treatment.

Foliar nutrient concentration measurements can indicate tree response to compaction depending on whether or not forest floor removal has taken place. In a study involving factorial combinations of soil compaction and forest floor removal applied to three different soil textures, Gomez et al. (2002) found significant interaction effects with foliar N on one of their sites. Foliar N concentrations were influenced by compaction and forest floor removal in ponderosa pine after four growing seasons. They also observed that foliar ^{15}N uptake under soil compaction and forest floor removal treatment was different throughout a range of soil textures, properties, and site preparation.

The significant losses in mineral soil and forest floor N (Chambreau 2004) together with reductions in foliar N concentrations in bulldozed plots suggest that long-term tree available N has been lost from the system as a result of forest floor removal. Forest floor removal is often associated with the mixing and displacement of mineral soil horizons. Loss of forest floor organic matter can also reduce cation exchange sites, increase temperatures, and reduce soil moisture resulting in adverse effects on biological activity (Zabowski et al. 1994). However, if N leaching is or has occurred from the loss of organic matter due to forest floor removal, it would not necessarily be seen in foliar N concentrations. Previous studies have found N leaching to be positively related with N concentrations in current year needles (Teitema and Beijer 1995, Nohrsted et al. 1996).

While the soil analysis indicates N leaching may well be occurring in our study sites, current literature suggests caution in attempting to make any statistical correlation between foliar and soil nutrient analyses. There is limited information on long-term responses in foliar N from bulldozing and or soil compaction. However, there are numerous studies that show foliar nutrient concentrations are consistently related to growth, site index, and nutrient status within a tree rather than with particular soil variables (Morrison 1974, Turner et al. 1978, Ballard and Carter 1986, Kayahara et al. 1995, Wang 1995, Lambert and Turner 1998). Typically, soil properties and foliar nutrient status are not related using simple linear regression correlations. Plotnikoff et al. (2002) found that reduced levels of total soil C, N, and mineralized N on forest landings relative to plantation soils did not affect the current foliar nutrient status of lodgepole pines. Likewise, in another study, Wang and Klinka (1997) determined that foliar nutrient concentrations in white spruce could be correlated to site index and growth using a quadratic function while soil nutrient amounts were unreliable in diagnosing stand nutrient status. While stump removal had significant negative impacts on both mineral soil N concentration and forest floor N (kg ha^{-1}) (Chambreau 2004) and slight reductions in foliar N concentrations, these trends do not appear to translate to overall negative effects on seedling growth and mortality measured by Thies and Westlin (2005). Since most harvesting practices generally affect soil organisms over the short term (Marshall 2000), our combined results indicate gradual ecosystem recovery in the more than 25 years from the commencement of our study.

Nitrogen fertilization

Pervious studies have suggested that N fertilization may be an effective management strategy to control *Phellinus* infection and mortality (Nelson 1964, Li et al. 1967, Nelson 1970, 1975) and accelerate tree growth (Austin and Strand, 1960, Arnott and Brett 1973). Approximately 25 years after the fertilization treatments in our study, N concentrations in the foliage did not significantly increase from the fertilization applications. This result is consistent with current literature. In a study of biomass and nutrient element dynamics in Douglas-fir, Mitchell et al. (1996) found that neither thinning nor fertilization had any effects on foliar N concentrations after 18 years. Further, indications from foliar ^{15}N-fertilization studies (Preston et al. 1990, Brockley et al. 1992) have shown single applications of fertilizers are sometimes an inefficient way to add nutrients to a forest ecosystem. The growth response of Douglas-fir to single N fertilization application approaches zero after 8-14 years (Stegemoeller and Chappell 1990). Foliar response to applied N varies considerably among locations (Peterson et al. 1984, but it is also noted that in general most analyses suggest that greater benefits N fertilization initially occur on poor sites (Gessel et al. 1965, Radwan and Shumway 1984, Miller et al. 1986). Nevertheless, the poor sites in our study did not show a consistent long-term effect from fertilization.

Foliar analyses and tree nutrient status

In the present study, foliar analysis was used as a method in conjunction with soil, growth, mortality, and inoculum data to identify long-term ecosystem effects from efforts to control laminated root rot. Foliar analysis is recommended and widely used as a tool for identifying forest nutrient status and for predictions of growth response to fertilizer treatments in conifer stands (Morrison 1974; van den Driesessche 1974). Its advantages among other methods are that it is closely correlated with growth, relatively easy to sample, and may be more accurate than soil nutrient levels (Hinckley et al. 1992). Its disadvantages are, like most methods of ecosystem measurement, subject to many variables.

In literature reviews interpreting foliar nutrient variations, van den Driesessche (1974), Morrison (1974) and Turner et al. (1978), pointed out that mineral concentrations in the foliage are affected by many variables other than nutrient supply from the soil to the tree. Factors that could be relevant to variations in the current study that were not entirely factored in include leaf and tree age, variation during the year (seasonal) and between years, and occurrence and extent of infection of pathogens. Other variables that have been reported to influence foliar concentrations such as needle age, position on whorl and crown, light regime, slope, aspect, and soil moisture were accounted for by blocking and replicating according to published methods (Thies and Westlin 2005).

Geographic and soil differences are fundamental factors that can influence needle nutrient concentrations (Turner et al. 1978). Our current study was designed to not only account for these influences by treating each of the five study sites as a pseudo separate study, but to also provide a broader ecosystem perspective of long term management techniques.

The occurrence of pathogens is an important factor that may have influenced our foliar nutrient status results. In a study of the influence of *Armillaria* on nutrients of current foliage in six coniferous species aged 12-14 years old, Singh and Bhure (1974) found a reduction in the foliar concentrations of N, P, K, Mg, and Na with increased levels of Ca, Mn, Fe, and Zn. An *Armillaria* attack can cause the gradual interruption of absorption of some elements. Rykowski (1981) studied Scots Pine (*Pinus sylvestris*) infected with *Armillaria* and found reduced N and Mg and increased K and Ca in current foliage. Entry et al. (1990) was also able to demonstrate that *Armillaria* infected Douglas-fir trees had a significantly lower foliar N and S concentrations in than non-infected trees even though they conceded that their measurements may not be a reliable method to determine the extent of the pathogen infection. Further research by Thomson et al. (1996) reported that reductions in foliage moisture, chlorophyll *a* and N were consistently associated with *Phellinus* infection on all their plots. However, due to the normal high variability in foliage chemistry, demonstration of statistically significance was slight. In our study, the INOC measurements to determine the amount of inoculum of *Phellinus* were inconclusive and not reliable enough to make correlations in our long-term study between foliar mineral concentrations and infection.

Sulfur deficiencies

Noteworthy results from the foliar nutrient concentrations other than N show mean foliar S concentrations well below published deficiency levels on all the five study sites (Table 4). Sulfur is involved in many of the same photosynthetic processes as N in the needles (Kelly and Lambert 1972) and biochemically related (Dijkshoorn and Van Wijk 1967). Nitrogen application, particularly in the form of NH_4NO_3 has been shown to interfere with S uptake in conifers (measured as reduced foliar S concentrations) (Brockley 1991). In theory this suggests these factors could account for foliar S deficiencies in our study. However, it is unlikely due to the amount of time that has passed since pre-plant fertilization in the late 1970s and that there were no significant effects on foliar N between the fertilized and unfertilized plots. Foliar sulfate, SO_4-S, has been reported to be a better indication of overall foliar S status than S concentration alone (Freney and Spencer 1967). Further foliar S testing may provide our study with a more accurate picture of total needle S and explain the S deficiencies. Turner et al. (1980) found when researching S cycling in Douglas-fir that foliar SO_4-S should be low when S is deficient and N is adequate whilst SO_4-S should be high when S is abundant and N is deficient. Until SO_4-S tests are done, our ability to explain S deficiencies across all five of our study areas is limited. It may possible that S is low in the soils throughout the Pacific Northwest region. Brady & Weil (2000) reported that soils in the Pacific Northwest are among the most S deficient in the United States.

Site Effects

The Hoodsport study area is a good example of the inconsistent relationship between soil and foliar variables. Chambreau (2004) reported that the soil N levels at Hoodsport were very low compared to other sites whereas this same study area also had the highest concentrations of N in the foliage. These higher foliar N concentrations were not expected because the trees at this site at the end of this study appeared weak, exhibited signs of chlorosis, thin foliage, and high *Phellinus* mortality was evident.

Excess water (Walker 1962), retranslocation (Leaf 1973), and pathogens (Singh and Bhure 1974, Rykowski 1981, Entry et al. 1990, Thomson et al. 1996) influence foliar N concentrations. Further research would be needed to determine to what extent these may have influenced our foliar results.

Located next to the Olympic Mountains, Hoodsport is saturated with water most of the year, the soil is coarse-textured, and site productivity is low. Excess moisture and restricted drainage can significantly interfere with N movement in surface and ground water (Chappell et al. 1992). Blackstain root rot caused by *Leptographium wageneri* was observed throughout the Hoodsport plots (Thies 1988). Previous studies have shown that Blackstain root rot and Annosus root disease caused by *Heterbasidion annosum* can affect water conductivity and increase ethanol concentrations in the roots and sapwood of the root collar (Joseph et al. 1998, Thies 1998). These reported pathogenic influences might also contribute to high N concentrations we observed in the foliage.

The needles at Hoodsport were also collected at the very end of the growing season in late October when retranslocation of N may factor into the higher foliar N concentrations at this site. Nason and Myrold (1992) reported 15N studies that showed retranslocation of recent foliar N is considerable: estimates ranging from 50% annually to over 100% in one month.

Due to geographical location and elevation, LaGrande is considered one of the least productive sites since it lies at the edge of the Douglas-fir growing zone. It has a short growing season, snow covers it much of the year, and shows signs of signs of heavy animal grazing (Chambreau and Zabowski, personal communication 2004). Like Hoodsport, it was puzzling to find that the LaGrande study area had the second highest foliar N concentrations yet the lowest mineral soil and forest floor N. This observed pattern may be influenced by microsite variability or some other interaction is occurring. These results could be due to some other unexplored factors and further study could indicate interactions among them.

The Gates study area is considered the most productive site of the five (Zabowski personal communication 2004). It was the only site where soil bulk density was not higher for stumped plots (Chambreau 2004) yet the foliar N concentrations were smaller in bulldozed plots. Potassium and S deficiencies were also present in the foliage. The mechanism for these results is unclear.

Sweethome, with the highest productivity rating, had significantly higher K concentrations and reductions of foliar N in the needles from bulldozing. Magnesium, P, and S were all deficient in the needles across all plots.

The lowest concentrations of foliar N were at Apiary. This was also the only site that foliage N did not decrease with stumping and increased instead. Similar to Sweethome, foliar K was significantly higher on bulldozed plots. This pattern may be attributed to similar clay soil types.

Conclusions

Although insignificant, foliar N concentrations combined across all 5 study sites were higher in plots that were not bulldozed and incrementally greater with increasing N applications. Approximately 25 years after treatments, the overall combined average foliar N was 7% lower in stumped plots. For each of the eight treatments, foliar N was above critical and deficient concentrations.

Foliage N varied among sites and soil types. No significant treatment effects were present between treatments on any of the individual study areas. On all sites except Apiary, foliar N was lower on bulldozed plots. Hoodsport had the highest concentrations of N and the greatest difference between stump removal and no stump removal.

The macronutrient concentrations of Ca, K, Mg, and P at the 5 sites combined exceeded critical deficient levels. Sulfur was below deficient levels at each site and at all sites combined. Stump removal and fertilization treatments had no significant effect on macronutrient concentrations other than N when n=5 but some significant effects were seen individually at some of the 5 sites (n=238).

Combined with the 2004 soil and the 2005 growth and mortality data, these results provide the foundation for continuing evaluation of long-term ecosystem effects of forestry activities to mitigate laminated root rot on *P. weirii* infested sites.

References

Arnott, J. T., Brett, C.P., 1973. Container grown trees show response to fertilization at time of planting. Tree Planters Notes 24, 15-19.

Austin, R.C., Strand, R.C. 1960. The use of slowly soluble fertilizers in forest planting in the Pacific Northwest. J. Forest 58, 619-627.

Ballard, T.M., Carter, R.E., 1986. Evaluating forest stand nutrient status. Land Management Report **20**. BC Ministry of Forestry, Victoria, BC.

Beaton, J.D., Moss, A., MacRae, I., Konkin, J.W., McGhee, W.P.T., and Kosick, R. 1965. Observations on foliage nutrient content of several coniferous tree species in British Columbia. Forestry Chronicle 41(2): 222-236

Brady, N.C., Weil, R.R. 2000. Elements of the Nature and Properties of Soils. 12^{th} ed. Prentice-Hall, Inc. Upper Saddle River, New Jersey. 559p.

Breland, T.A., Hansen, S. 1996. Nitrogen mineralization and microbial biomass as affected by soil compaction. Soil Biol. Biochem. 28, pp. 655-663.

Brockley, R.P. 1991. Response of thinned, immature lodgepole pine to nitrogen fertilization: six-year growth response. B.C. Ministry of Forests, Victoria. For. Resour. Dev. Agree. Rep. 184.

Brockley, R.P., Trowbridge, R.L., Ballard, T.M., and Macadam, A.M. 1992. Nutrient management in interior Forest types. *In*: Chappell, H.N., Weetman, G.F., Miller, R.E. (Eds.), Forest Fertilization: Sustaining and Improving Nutrition and Growth of Western Forests, Contribution No. 73, College of Forest Resources, University of Washington, Seattle, pp.43-63.

Chambreau, D. 2004. Soil effects twenty years after stump removal and fertilization to control *Phellinus weirii* in Douglas-fir plantations. Masters Thesis, College of Forest Resources, University of Washington. Seatttle, Washington.

Chappell, H.N., Omule, S.A.Y., and Gessel, S.P. 1992. Fertilization in coastal northwest forests: using response information in developing stand-level tactics. *In*: Chappell, H.N., Weetman, G.F., Miller, R.E. (Eds.), Forest Fertilization: Sustaining and Improving Nutrition and Growth of Western Forests, Contribution No. 73, College of Forest Resources, University of Washington, Seattle, pp.98-112.

Cook, S.A. 1982. Stand development in the presence of a pathogen, *Phellinus weirii*. *In*: Means, J.E. (Ed.), Forest Sucession and Stand Development research in the Northwest. Forest Research Laboratory/Oregon State University, Corvallis, OR: pp. 159-163.

Dijkshoorn, W., and Van Wijk, A.L. 1967. The sulphur requirements of plants as evidenced by the sulphur-nitrogen ratio in the organic matter. A review of published data. Plant and Soil, 26: 129-157.

Edmonds, R.L., and Hsiang, T. 1987. Forest floor and soil influence on response of Douglas-fir to urea. Soil Sci. Soc. Am. J. 51: 1332-1337.

Edmonds, R.L., Agee, J.K., and Gara, R.I. 2000. Forest Health and Protection. 1st ed. McGraw-Hill. Boston, MA. 630p.

Entry, J.A., Hagle, S.K., and Cromack, K., Jr. 1990. The effect of *Armillaria* attack on the nutrient status of inland Douglas-fir. Eur. J. For. Pathol. 20: 269-274.

Epstein E. 1972. Mineral nutrition of plants: principles and perspectives. N.Y.: John Wiley and Sons.

Fisher, R.F. and Binkley, D. 2000. Ecology and Management of Forest Soils. 3rd ed. John Wiley & Sons, New York. 489 p.

Freney, J.R., and Spencer, K. 1967. Diagnosis of sulphur deficiency in plants by soil and plant analysis. J. Aust. Inst. Agric. Sci. 33: 284-288.

Garrison, M.T., Moore, J.A., Shaw, T.M, Mika, P.G. 2000. Foliar nutrient and tree growth response of mixed-conifer stands to three fertilization treatments in northeast Oregon and north central Washington. For. Eco. Manage. 132: 183-198.

Gessel, S.P., Stoate, T.N., and Turnbull, K.J. 1965. The growth behavior of Douglas-fir with nitrogenous fertilizer in western Washington. Institute of Forest Resources Contrib. 1, Univ. of Washington, Seattle. 204 p

Gomez, A.G., Powers, R.F., Singer, M.J., and Horwath, W.R. 2002. N uptake and N status in ponderosa pine as affected by soil compaction and forest floor removal. Plant and Soil, 242: 263-275.

Hadfield, F.S., Goheen, D.J., Filip, G.M., Schmitt, C.L., and Harvey, R.D. 1986. Root diseases in Oregon and Washington Conifers. USDA Forest Service, State and Private Forestry, forest Pest Management, R66-FPM-250-86, Portland, OR.

Hansen, E.M. 1979. Survival of *Phellinus weirii* in Douglas-fir stumps after logging. Can. J. Forest Res. 9: 484-488.

Heilman, P.E., and Gessel, S.P. 1963. Nitrogen requirements and the biological cycling of nitrogen in Douglas-fir stands in relationship to the effects of nitrogen fertilization. Plant and Soil 18: 386-402.

Holah, J.C., Wilson, M.V., and Hansen, E.M. 1993. Effects of a native forest pathogen, *Phellinus weirii*, on Douglas-fir forest composition in western Oregon. Can. J. Forest Res. 23: 2473-2480.

Holah, J.C., Wilson, M.V., and Hansen, E.M. 1997. Impacts of a native root-rotting pathogen on successional development of old-growth Douglas-fir forests. Oecologia 111: 429-433.

Ingersoll, C.A., Wilson, M.V., and Thies, W.G. 1996. Effects of Phellinus weirii gaps on early successional vegetation following timber harvest. Can. J. Forest Res. 26, 322-326.

Joseph, G., Kelsey, R.G. and Thies, W.G. 1998. Hydraulic conductivity in roots of pondersosa pine infected with blackstain (*Leptographium wageneri*) or annosus (*Heterbasidion annosum*) root disease. Tree Physiol. 18(5): 333-339.

Kayahara, G.J., Carter, R.E, and Klinka, K. 1995. Site index of western hemlock (*Tsuga heterophylla*) in relation to soil nutrient and foliar chemical measures. For. Ecol. Manage. 170: 161-169.

Kelly, J., Lambert, M.J. 1972. The relationship between sulphur and nitrogen in the foliage of *Pinus radiata*. Plant and Soil. 37: 395-408.

Kozlowski, T.T. and Pallardy, S.G. 1997. Physiology of Woody Plants, 2nd ed. Academic Press, San Diego, CA.

Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. Scan. J. For. Res. 14: 596-619.

Lambert, M.J., and Turner, J. 1988. Interpretation of nutrient concentrations in *Pinus radiata* foliage at Belanglo state forest. Plant and Soil. 108: 237-244.

Leaf, A.L 1973. Plant analysis as an aid in fertilizing forests. *In* Soil testing and plant analysis. *Ed.* L. M. Walsh and J.D. Beaton. Soil Science Society of America Inc. Madison, Wisconsin, U.S.A. pp. 427-454.

Li, C.Y., Lu, K.C., Trappe, J.M., and Bollen, W.B. 1967. Selective nitrogen assimilation by *Poria weirii*. Nature (London) 213, 814.

Marshall, V.G. 2000. Impacts of forest harvesting on biological processes in northern forest soils. For. Ecol. Manage. 133 (1-2): 43-60.

McColl, J.G. 1995. Forest clear-cutting, soil response. *In* Nierenberg, W.A. (ed). Encyclopedia of Environmental Biology. Vol. 2, pp. 95-103. Academic Press, San Diego, CA.

Miller, R.E., Lavender, D.P., and Grier, C.C. 1976. Nutrient cycling in the Douglas-fir type – silvicultural implications. Proceedings, 1975 Annual Convention. Soc. Am. For. pp. 359-390.

Miller, R.E., Barker, P.R., Peterson, C.E., and Webster, S.R. 1986. Using nitrogen fertilizers in management of coast Douglas-fir: I. Regional trends of response. pp. 290-303 *In* Oliver, C.D., Hanley, D.P., and Johnson, J.A., eds. Douglas-fir: stand management for the future. Institute of Forest Resources, Univ. of Washington, Seattle.

Mitchell, A.K., Barclay, H.J., Brix, H., Pollard, D.F.W., Benton, R., and deJong, R. 1996. Biomass and nutrient element dynamics in Douglas-fir: Effects of thinning and nitrogen fertilization over 18 years. Can. J. For. Res. 26 (3): 376-388.

Morrison, I.K. 1974. Mineral nutrition of conifers with special reference to nutrient status interpretation: A review of literature. Canadian Forest Serv. Publ. 1343. 74pp.

Nason, G.E, and D. D. Myrold. 1992. Nitrogen fertilizers: fates and environmental effects in forests. In: Chappell, H.N., Weetman, G.F., Miller, R.E. (Eds.), Forest Fertilization: Sustaining and Improving Nutrition and Growth of Western Forests, Contribution No. 73, College of Forest Resources, University of Washington, Seattle, pp.67-81.

Nelson, E.E. 1964. Some probable relationships of soil fungi and zone lines to survival of *Poria weirii* in buried wood blocks. Phytopathol. 54: 120-121.

Nelson, E.E. 1975. Survival of *Poria weirii* in wood buried in urea amended forest soil. Phytopathology 65: 501-502.

Nelson, E.E., and T. Hartman. 1975. Estimating spread of *Poria weirii* in a high-elevation mixed conifer stand. J. For. 73: 141-142.

Nelson, E.E., Martin, N.E., and Williams, R.E. 1981. Laminated root rot of western conifers. For. Insect Disease Leafl. 159. Washington, DC: U.S. Department of Agriculture. 6 p.

Nohrstedt, H., Arnebrant, K., Baath, E., and Soderstrom, B. 1989. Changes in carbon content, respiration rate, ATP content and microbial biomass in nitrogen-fertilized pine forest soils in Sweden. Can. J. For. Res. 19: 323-328.

Nohrstedt, H-O, Silkstrom, U, Ring, E., Nasholm, T., Hogberg, P., Persson, T. 1996. Nitrate in soil water in three Norway spruce stands as related to N-deposition and soil, stand, and foliage properties. Can. J. For. Res. 26: 836-848.

Peterson, C.E., Ryan, P.J., and Gessel, S.P. 1984. Response of Northwest Douglas-fir stands to urea: correlations with forest soil properties. Soil Sci. Soc. Am. J. 48: 162-169.

Plotnikoff, M.R., C.E. Bulmer, and M.G. Schmidt. 2002. Soil properties and tree growth on rehabilitated forest landings in the interior cedar hemlock biogeoclimatic zone: British Columbia. Forest Ecol. Manage. 170: 199-215.

Preston, C.M., Marshall, V.G., MuCullough, K., and Mead, D.J. 1990. Fate of 15N-labelled fertilizer applied on snow at two forest sites in British Columbia. Can. J. For. Res. 20: 1583-1592.

Radwan, M.A. and Shumway, J.S. 1984. Site index and selected soil properties in relation to response of Douglas-fir and western hemlock to nitrogen fertilizers. P. 89-104 *In* Stone, E.L., ed. Forest soils and treatment impacts. Proc 6th North American Forest Soils Conf., 1983. Univ. of Tennessee, Knoxville.

Rykowski, K. 1981. The influence of fertilizers on the occurrence of *Armillaria mellea* in Scotch pine plantations. II. The influence of *Armillaria mellea* on chemical changes in needles and wood of roots under mineral fertilization. Eur. J. For. Pathol. 11: 178-186

Singh, P., and Bhure, N.D. 1974. Influence of *Armillaria* root rot on the foliar nutrients and growth of some coniferous species. Eur. J. For. Pathol. 4: 20-26.

Soan, B. D. 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil Tillage Res. 16: 179-202.

Stegemoeller, K.A. and Chappell, H.N. 1990. Growth response of unthinned and thinned Douglas-fir stands to single and multiple applications of nitrogen. Can. J. For. Res. 20: 343-349.

Thies, W.G. and Hoopes 1979. Computer mapping of laminated root rot epicenters. *In* Forest insect and disease survey methods, Sect. 3.2.1, USDA Forest Service, Methods Application Group, Davis, Calif. pp. 1-7.

Thies, W.G. and Nelson, E.E. 1988. Bulldozing stumps and nitrogen fertilization affect growth of Douglas-fir seedlings. Can. J. For. Res. 18: 801-804.

Thies, W.G., Nelson, E.E., and Zabowski, D. 1994. Removal of stumps from a *Phellinus weirii* infested site and fertilization affect mortality and growth of planted Douglas-fir. Can. J. For. Res. 24: 234-239.

Thies, W.G and Westlin, D.J. 2005. Stump removal and fertilization of five *Phellinus weirii*-infested stands in Washington and Oregon affect mortality and growth of planted Douglas-fir 25 years after treatment. For. Ecol. and Manage. 219: 242-258.

Thomson, A.J., Goodenough, D.G., Barclay, H.J., Lee, Y.J., and Sturrock, R.N. 1996. Effects of laminated root rot (*Phellinus weirii*) on Douglas-fir foliar chemistry. Can. J. For. Res., 26: 1440-1445.

Tietema A. Beijer C. 1995. A correlative evaluation of nitrogen cycling in the forest ecosystems of the EC projects NITREX and EXMAN. For. Ecol. Manage 71:143-151.

Turner, J., Cole, D.W., and Gessel, S.P. 1976. Mineral nutrient accumulation and cycling in a stand of red alder (*Alnus rubra*). J. Ecol. 64(3): 965-974.

Turner, J., Dice, S.F., Cole, D.W., and Gessel, S.P. 1978. Variation of nutrient in forest tree foliage – a review. Institute of Forest Products Contribution Number 35. College of Forest Resources, University of Washington, Seattle, WA.

Turner, J., Johnson, D.W., and Lambert, M.J. 1980. Sulphur cycling in a Douglas-fir forest and its modification by nitrogen application. Ecol. Plant. 1(15)1: 27-35.

van den Driessche, R. 1974. Prediction of mineral nutrient status of trees by foliar analysis. Bot Rev. 40: 347-395.

Vogt, K.A., Dahlgren, R., Ugolini, F., Zabowski, D., Moore, E.E., and Zasoski, R. 1987a. Aluminum, Fe, Ca, Mg, K, Mn, Cu, Zn, and P in aboveground and belowground biomass. 1. *Abies amabilis* and *Tsuga mertensiana*. Soil Biogeochem. 4(3): 277-294.

Vogt, K.A., Dahlgren, R., Ugolini, F., Zabowski, D., Moore, E.E., and Zasoski, R. 1987b. Aluminum, Fe, Ca, Mg, K, Mn, Cu, Zn, and P in aboveground and belowground biomass. 2. Pools and circulation in a sub-alpine *Abies-amabilis* stand. Soil Biogeochemistry. 4(3): 295-311.

Walker, L.C. 1962. The effects of water and fertilizer on loblolly and slash pine seedlings. Soil Sci. Soc. Amer. Proc. 26(2): 197-200.

Wallis, G.W., 1976. Phellinus (Poria) weirii Root Rot: Detection and Management Proposals in Douglas-fir stands. Tech. Rep. 12, Can. For. Serv., Victoria, BC.

Wang, G.G., 1995. White spruce site index in relation to soil, understory vegetation, and foliar nutrients. Can. Jor. For. Res. 25 (1): 29-38.

Wang, G.G., and Klinka, K. 1997. White spruce foliar nutrient concentrations in relation to tree growth and soil nutrient amounts. For. Ecol. Mgmt. 98(1): 89-99

Webster, S.R., and Dobkowski, A. 1983. Concentrations of foliar nutrients for trees and dosage frequency of fertilizer trials. Weyerhaeuser Res. Rep. No. 1, Project 050-3920/3. 25p.

Whalley, W.R., Dumitru, E. and Dexter, A.R. 1995. Biological effects of soil compaction. Soil Tillage Res., 35: 53-68.

Zabowski, D., Skinner, M.F. and Rygiewicz, P.T. 1994. Timber harvesting and long-term productivity: Weathering processes and soil disturbance. For. Ecol. Manage. 66: 55-68.

Zabowski, D., Chambreau, D., Rotramel, N., Thies, W.G. 2008. Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. For. Ecol. Manage. 255: 720-727.

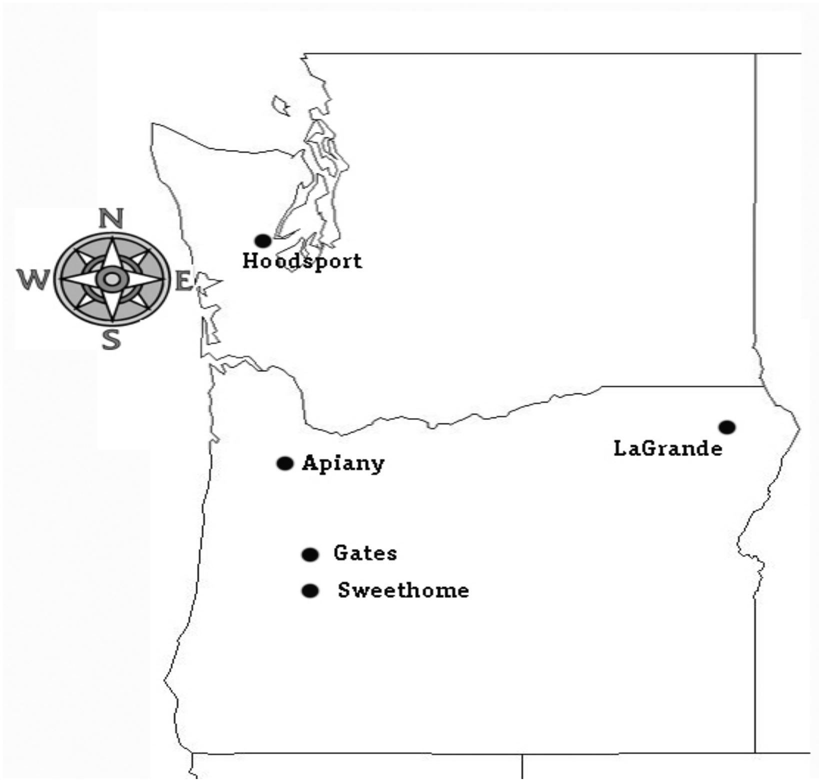

Figure 1. Location of Washington and Oregon study areas. The study was done with the cooperation of the following public and private landholders: Hoodsport – Washington Department of Natural Resources; Apiary – Weyerhaeuser Corporation; Sweethome – Cascade Timber Consulting; Gates – Bureau of Land Management; and LaGrande – Boise Cascade Corporation.

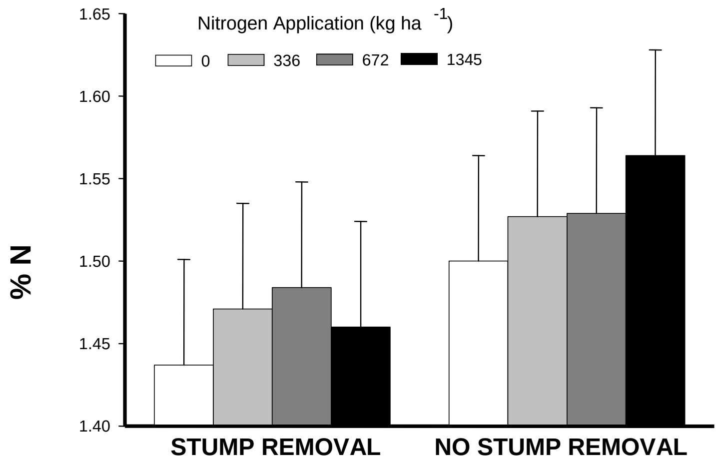

Figure 2. Mean Douglas-fir foliar N concentrations of all sites (n=5) 23-27 years after stump removal and NH_4NO_3 treatments. Error bars represent one standard error.

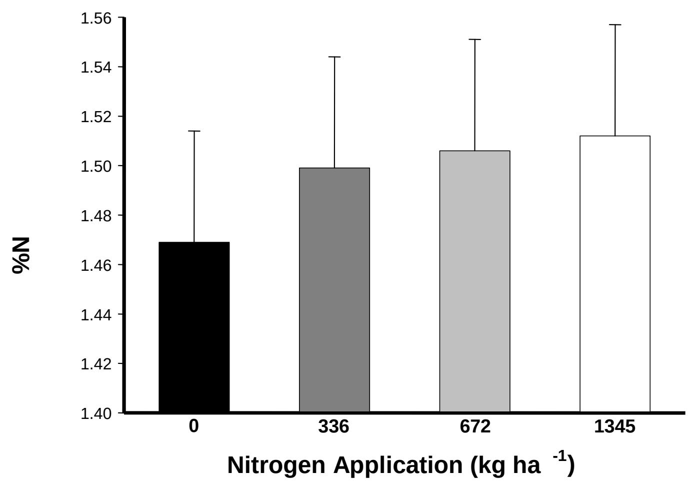

Figure 3. Combined mean Douglas-fir foliar N concentrations 23-27 years after NH_4NO_3 application for all sites (n=5). Error bars represent one standard error.

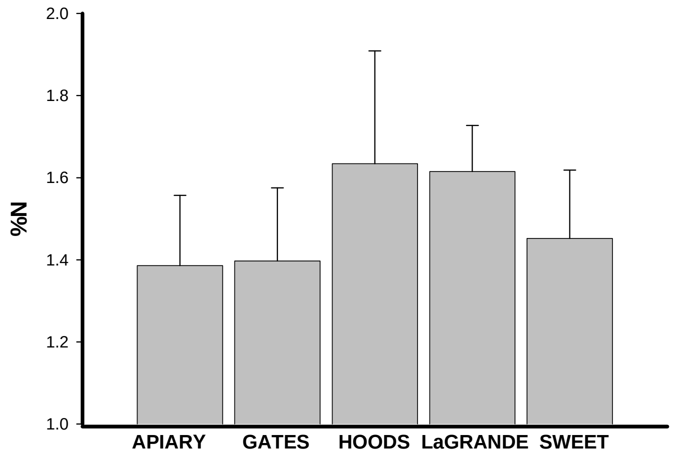

Figure 4. Combined means of Douglas-fir foliar N concentrations at individual sites 23-27 years after stump removal and fertilization treatments. Error bars represent one standard deviation.

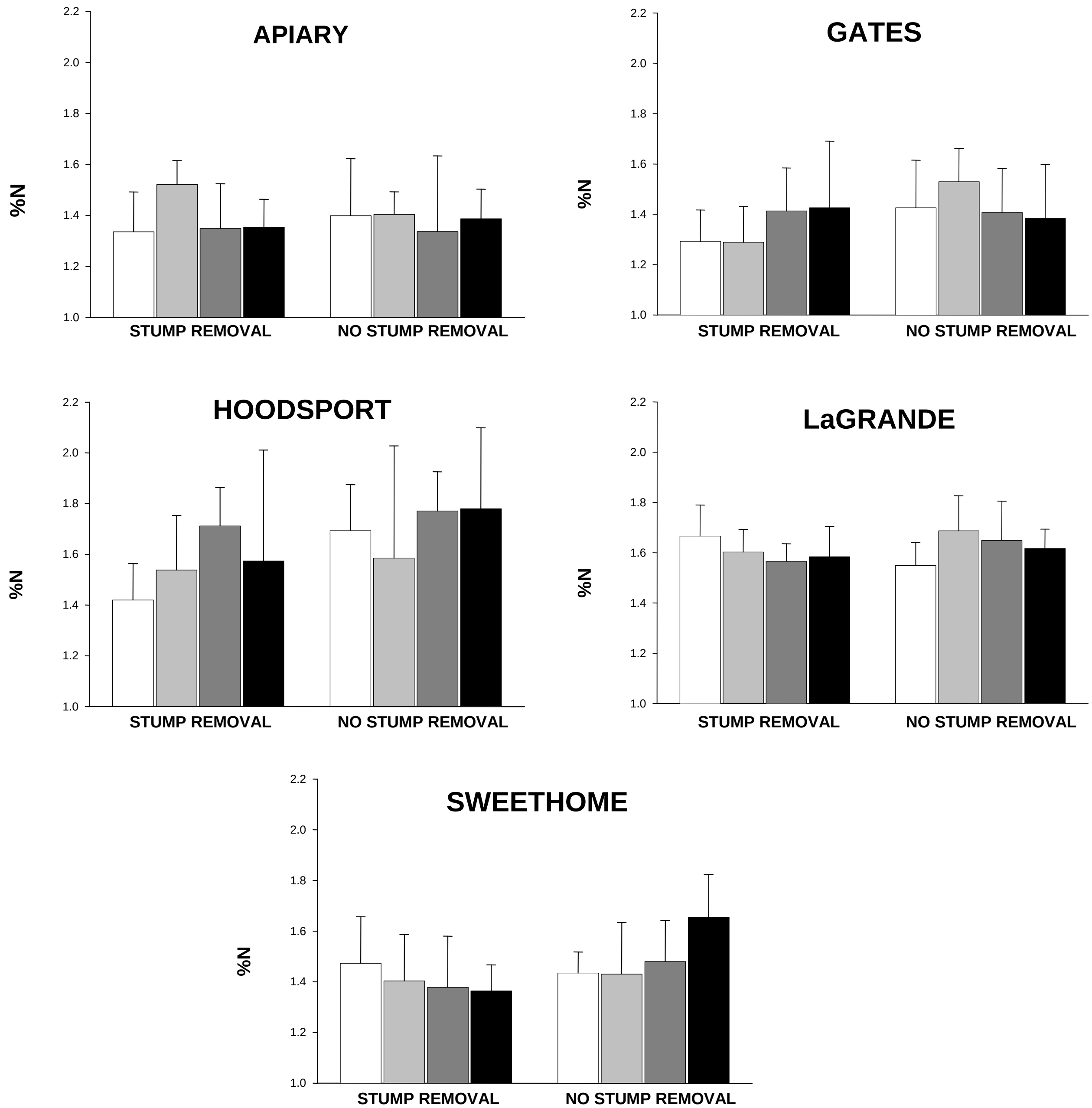

Figure 5. Mean Douglas-fir foliar N concentrations for each stump removal and fertilization treatment at each study site 23-27 years after treatments. Error bars represent one standard deviation.

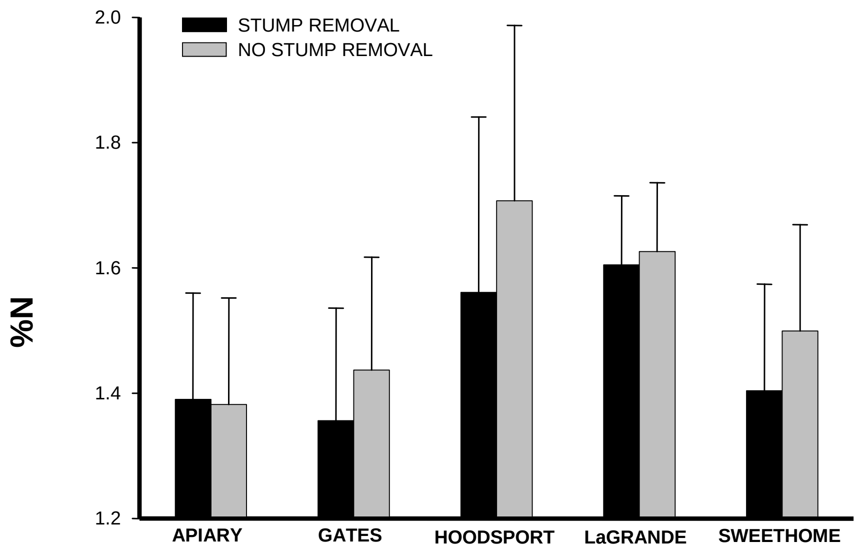

Figure 6. Mean Douglas-fir foliar N concentrations 23-27 years after stump removal at each study site. Error bars represent one standard deviation.

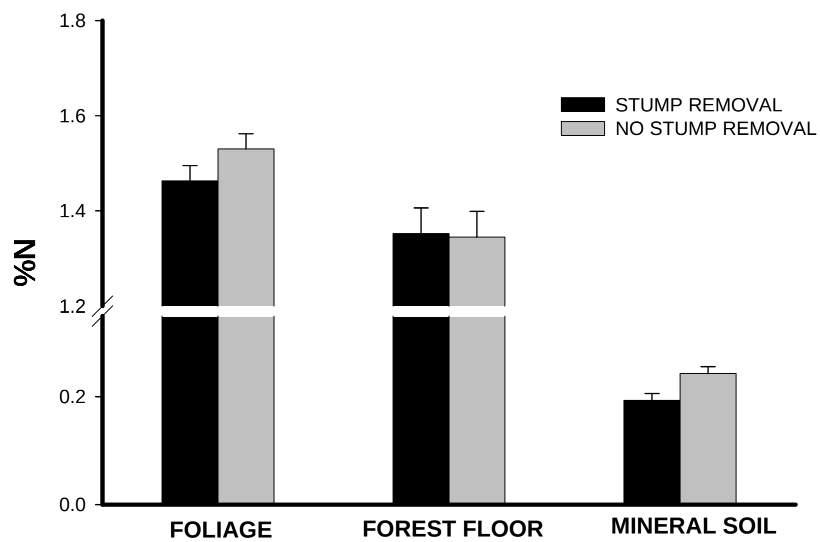

Figure 7. Mean foliar, forest floor, and mineral soil N concentrations across all sites (n=5) 23-27 years after stump removal treatments. Mineral soil and forest floor concentrations are from Chambreau (2004). Error bars represent one standard error.

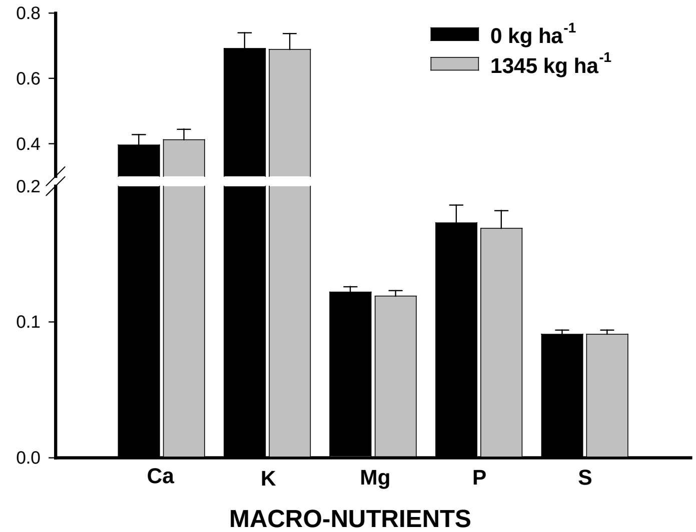

Figure 8. Mean Douglas-fir foliar concentrations for Ca, K, Mg, K, P, and S across all sites 23-27 years after fertilization treatments. The data shown is for two levels of NH_4NO_3 fertilization, 0 kg ha^{-1} and 1345 kg ha^{-1}, (n=5). Error bars represent one standard error.

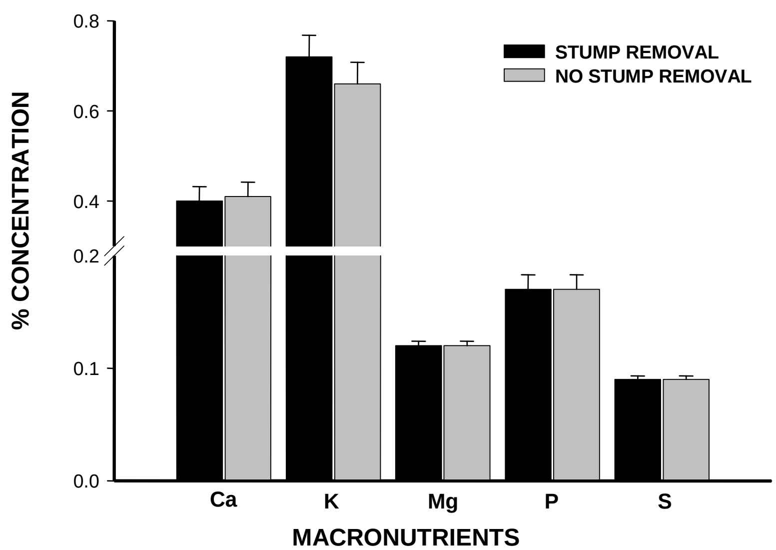

Figure 9. Mean Douglas-fir foliar concentrations for Ca, K, Mg, P, and S across all sites 23-27 years after stump removal treatments. The data shown is for stump removal and no stump removal treatments, (n=5). Error bars represent one standard error.

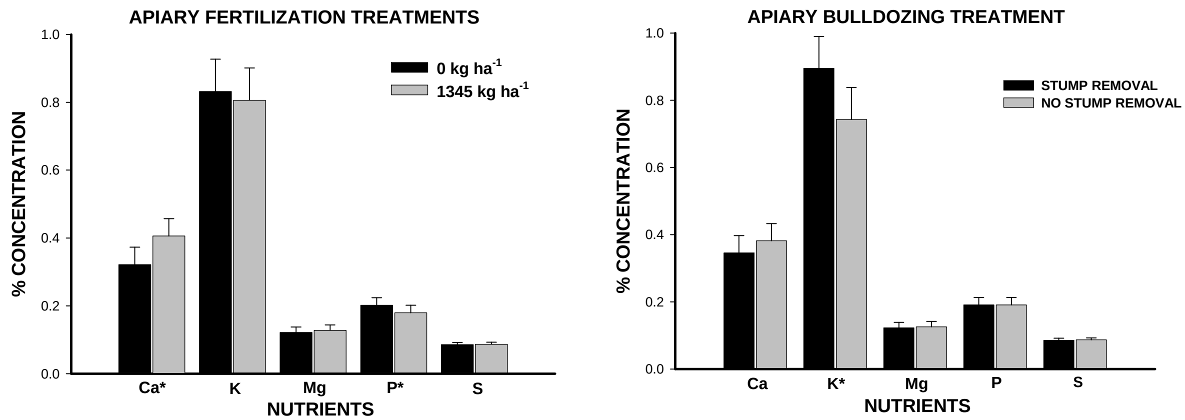

Figure 10. Mean Douglas-fir foliar concentrations for Ca, K, Mg, P, and S at Apiary, OR (n=20). The graph on the left shows NH_4NO_3 fertilization treatments while the right-hand graph shows stump removal treatments. Error bars represent one standard deviation. An * indicates significance at $p \leq 0.05$.

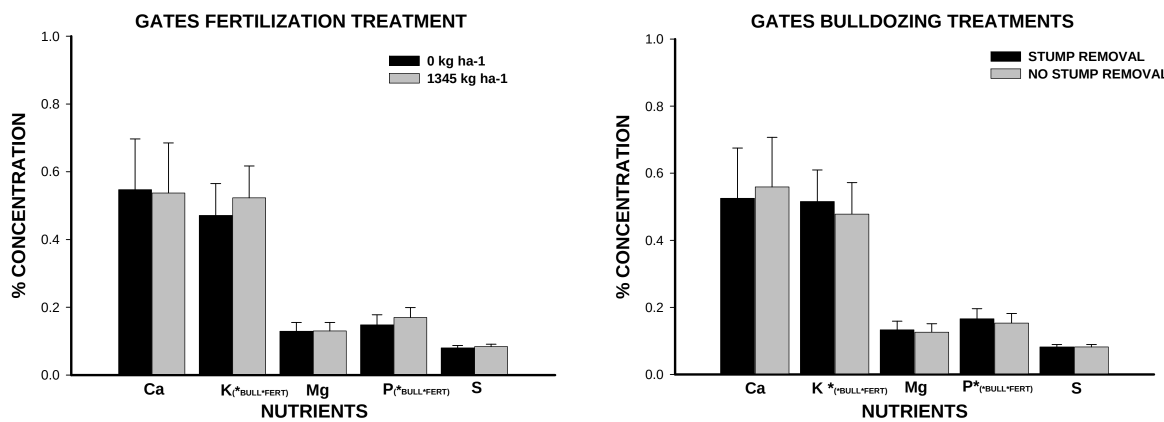

Figure 11. Mean Douglas-fir foliar concentrations for Ca, K, Mg, P, and S at Gates, OR (n=20). The graph on the left shows NH_4NO_3 fertilization treatments while the right-hand graph shows stump removal treatments. Error bars represent one standard deviation. An * indicates significance at $p \leq 0.05$.

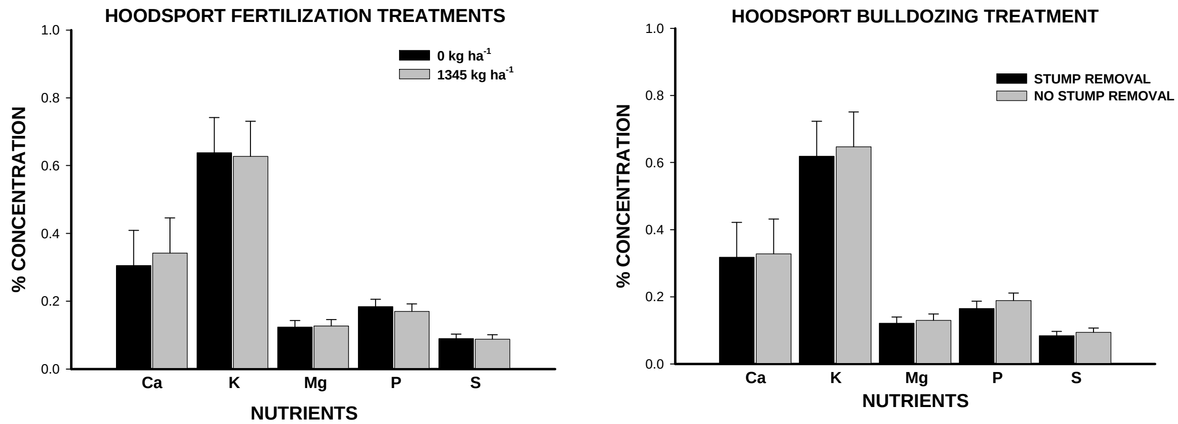

Figure 12. Mean Douglas-fir foliar concentrations for Ca, K, Mg, P, and S at Hoodsport, WA (n=20). The graph on the left shows NH_4NO_3 fertilization treatments while the right-hand graph shows stump removal treatments. Error bars represent one standard deviation.

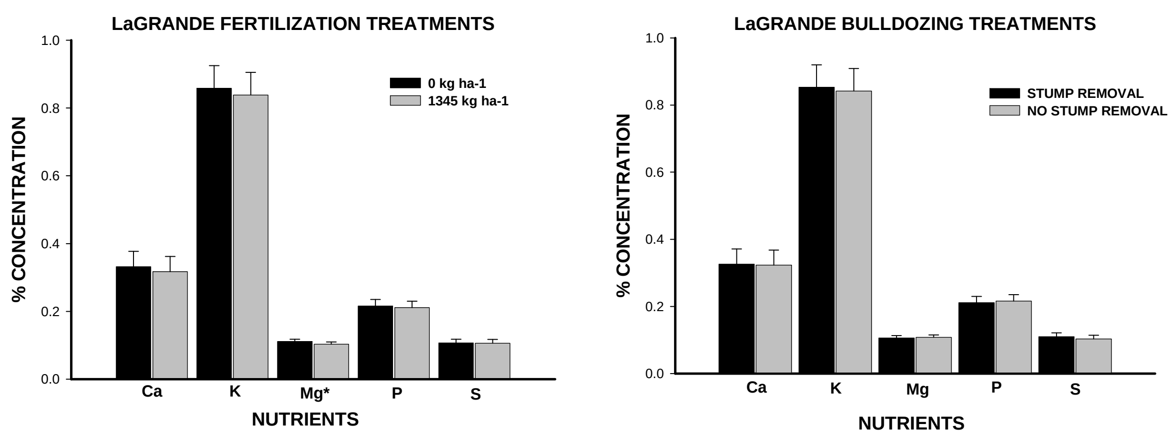

Figure 13. Mean Douglas-fir foliar concentrations for Ca, K, Mg, P, and S at LaGrande, OR (n=28). The graph on the left shows NH_4NO_3 fertilization treatments while the right-hand graph shows stump removal treatments. Error bars represent one standard deviation. An * indicates significance at $p \leq 0.05$.

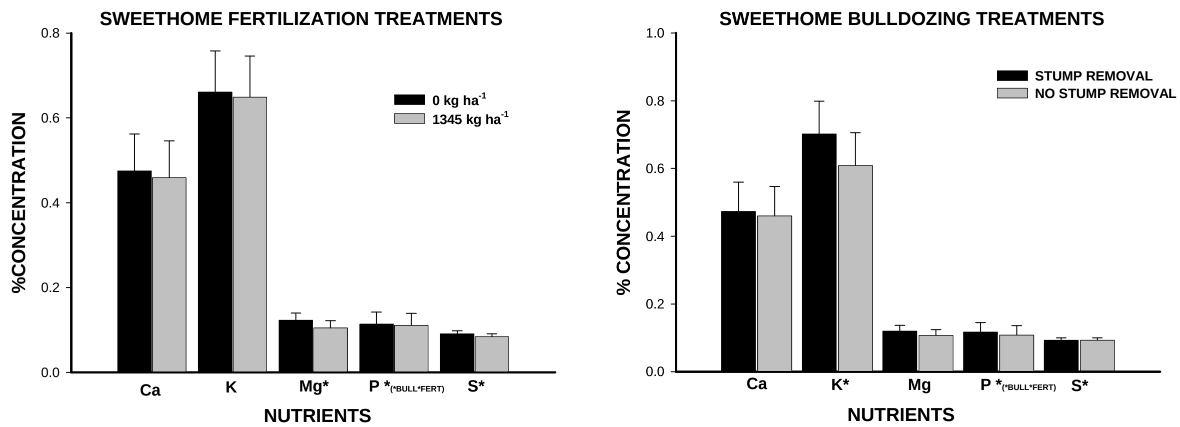

Figure 14. Mean Douglas-fir foliar concentrations for Ca, K, Mg, P, and S at Sweethome, OR (n=24). The graph on the left shows NH_4NO_3 fertilization treatments while the right-hand graph shows stump removal treatments. Error bars represent one standard deviation. An * indicates significance at $p \leq 0.05$.

Table 1. Laminated root rot study site characteristics.

	APIARY	GATES	HOODSPORT	LAGRANDE	SWEETHOME
Latitude/Longitude	46°00N, 123°4′W	44°46′N, 122°21′W	47°20′N, 123°10′ W	45°32′N, 118°27′W	44°21′N, 122°39′W
Avg. Rainfall	101cm	200cm	229cm	81.8cm	127cm
Avg. Temp	12.2°C	9.6°C	10.4°C	6.4°C	10°C
Elevation	335m	603m	268m	1198m	439m
Slope	15%SW	15%S	15%S	4%S	16%SW
Forest Type	Douglas-fir, hemlock	Douglas-fir, hemlock, cedar	Douglas-fir, hemlock, cedar	Grand fir, Douglas-fir, Englemann spruce, larch, P. pine, lodgepolepine	Douglas-fir, hemlock, cedar, grand fir
Site Index (DF)	125	122	N/A	70	135
Soil Series	Bacona	Kinney	Hoodsport	Tolo	Honeygrove
Taxonomic Class	Fine-silty, mixed, active mesic Typic Palehumults	Fine-loamy, isotic, mesic Andic Dystrudepts	Medial-skeletal, mesic Typic Haploxerand	Ashy over loamy, glassy over isotic, frigid Alfic vitrixerands	Fine, mixed active, mesic Typic Palehumults
Texture	Silt Loam	Cobbly Loam	Gravelly Sandy Loam	Silt Loam	Silty Clay Loam
Parent Material	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
Harvest Year	1978	1979	1976	1978	1979
Stumping Year	1978	1980	1976	1978	1980

Table 1 (cont.)	APIARY	GATES	HOODSPORT	LaGRANDE	SWEETHOME
Stocking and Thinning Notes	Closed canopy. Volunteer hemlock regeneration. Precommercially thinned in 2000 to approx. 3.7 x 3.7 m.	Precommercially thinned in 1996 to a 12' x112' spacing.	Precommercially thinned in 1999. The remaining trees look weak with thin foliage, though growth continues. Many *Phellinus* kills in stand.	Consists of Douglas-fir planted in 1980, 1983, and 1987. Some volunteer ponderosa & lodgepole pines, larch, and grand fir. Poor survival due to ungulate browsing sloed establishment and required replanting. Stand is open with little canopy closure.	Dominated by planted Douglas-fir with a few volunteer hemlock and alder. Canopy is closed at 10m. Most pioneering species are declining. At time of harvest site was enclosed within 2nd growth forest. 1993 adjacent areas had been clearcut and planted with Douglas-fir.

Table 2. Douglas-fir foliar nitrogen concentrations from published data. Trees in these studies ranged from ages 10-50 years old, were from a range of soil types, geographic locations, and environmental conditions. Collection dates were generally at the end of the growing season.

Author	*Morrison 1974 Heilman & Gessel 1963*	*Garrison et al. 2000*	*Walker & Gessel 1991*	*Ballard & Carter 1986*		*Ballard & Carter 1986*	*Beaton 1965*	*Turner, Dice, Cole, & Gessel 1976*	
	Critical	Critical	Deficient	Deficiency Range	**Mean of Critical & Deficient Concentrations**	Adequate	Typical Range	Typical	**LRR study mean foliar concentration**
Conc. Level (%)	1.00	1.40	1.25	1.10-1.50	**1.24**	1.5	.88-1.40	1.11	**1.54**

Table 3. Douglas-fir foliar macronutrient concentrations from published data. Trees in these studies ranged from ages 10-50 years, were from a range of soil types, geographic locations, and environmental conditions. Collection dates were generally at the end of the growing season.

Author	*Garrison et al. 2000 Webster & Dobkowski 1983*	*Walker & Gessel 1991*	*Ballard & Carter 1986*		*Ballard & Carter 1986*	*Beaton 1965*	*Turner, Dice, Cole, & Gessel 1976*	
	Critical	Deficient	Deficiency Range	**Mean of Critical & Deficient Concentrations**	Adequate	Typical Range	Typical	**LRR study mean foliar concentration**
Nutrient								
Ca	0.15	0.25	.1-.25	.19	0.25	.16-.44	0.68	0.4
K	0.6	0.6	.35-.8	.6	0.8	.38-.70	0.66	0.69
Mg	0.08	0.17	.06-.12	.11	0.12	.07-.18	0.153	0.12
P	0.12	0.16	.08-.15	.13	0.15	.12-.22	0.195	0.17
S	0.11	0.35	.12-.14*	.2	.16*	.14-.25		0.09

*For most conifers

Table 4. Mean Douglas-fir overall mean foliar concentrations for Ca, K, Mg, P, and S at each study site 23-27 years after fertilization and stump removal treatments.

	APIARY n=20	**GATES** n=27	**HOODSPORT** n=20	**LaGRANDE** n=28	**SWEETHOME** n=24
Nutrient	**% Concentration *(std. dev.)***				
Ca	.36 *(.07)*	.54 *(.14)*	.32 *(.10)*	.32 *(.04)*	.47 *(.08)*
K	.82 *(.12)*	*.50 *(.10)*	.63 *(.10)*	.85 *(.06)*	.66 *(.10)*
Mg	.12 *(.01)*	.13 *(.02)*	.13 *(.02)*	*.11 *(.01)*	*.11 *(.02)*
P	.19 *(.02)*	.16 *(.03)*	.18 *(.03)*	.21 *(.02)*	*.11 *(.03)*
S	*.09 *(.01)*	*.08 *(.01)*	*.09 *(.01)*	*.11 *(.01)*	*.09 *(.01)*

*Below published mean of critical and deficient concentrations (Table 3).

APPENDIX A

MEANS FOR COMBINED DATA (5 Sites):

n=Number of Replicates
%N=Foliar Nitrogen Percentage

ALL TREATMENT MEANS		
	n	% N *(std. error)*
	40	1.50 *(.02)*

STUMPING TREATMENT MEANS		
	n	% N *(std. error)*
NO STUMPING	20	1.53 *(.03)*
STUMPING	20	1.46 *(.03)*

FERTILIZATION TREATMENT MEANS		
LEVEL (kg ha^{-1})	n	% N *(std. error)*
0	10	1.47 *(.04)*
336	10	1.50 *(.04)*
672	10	1.50 *(.05)*
1345	10	1.51 *(.05)*

COMBINED FERTILIZATION & STUMPING TREATMENT MEANS		
	n	% N *(std. error)*
BFO	5	1.44 *(.07)*
BF1	5	1.47 *(.05)*
BF2	5	1.48 *(.07)*
BF3	5	1.47 *(.05)*
NFO	5	1.50 *(.05)*
NF1	5	1.53 *(.05)*
NF2	5	1.53 *(.08)*
NF3	5	1.56 *(.08)*

BF0=Bulldoze, Fertilization Level 0 kg ha^{-1}
BF1=Bulldoze, Fertilization Level 336 kg ha^{-1}
BF2=Bulldoze, Fertilization Level 672 kg ha^{-1}
BF3=Bulldoze, Fertilization Level 1345 kg ha^{-1}

NF0=No Bulldozing, Fertilization Level 0 kg ha^{-1}
NF1=No Bulldozing, Fertilization Level 336 kg ha^{-1}
NF2=No Bulldozing, Fertilization Level 672 kg ha^{-1}
NF3=No Bulldozing, Fertilization Level 1345 kg ha^{-1}

APPENDIX B

MEANS BY SITE:

n=Number of Replicates
%N=Foliar Nitrogen Percentage

TOTAL SITE MEANS		
	n	% N *(std. dev.)*
APIARY	40	1.39 *(.17)*
GATES	55	1.40 *(.18)*
HOODSPORT	39	1.64 *(.28)*
LaGRANDE	56	1.62 *(.11)*
SWEETHOME	48	1.45 *(.18)*

SITE MEANS BY STUMPING TREATMENT				
	STUMPING		NO STUMPING	
	n	% N *(std. error)*	n	% N *(std. dev.)*
APIARY	20	1.39 *(.15)*	20	1.38 *(.19)*
GATES	27	1.35 *(.18)*	28	1.44 *(.18)*
HOODSPORT	20	1.56 *(.27)*	19	1.71 *(.27)*
LaGRANDE	28	1.60 *(.10)*	28	1.63 *(.13)*
SWEETHOME	24	1.40 *(.17)*	24	1.50 *(.18)*

FERTILIZATION MEANS BY SITE			
LEVEL (kg ha^{-1})		n	% N *(std. dev.)*
0	APIARY	10	1.37 *(.19)*
336	APIARY	10	1.46 *(.11)*
672	APIARY	10	1.34 *(.23)*
1345	APIARY	10	1.37 *(.11)*
0	GATES	14	1.36 *(.17)*
336	GATES	14	1.41 *(.18)*
672	GATES	14	1.41 *(.17)*
1345	GATES	13	1.41 *(.23)*
0	HOODSPORT	10	1.56 *(.21)*
336	HOODSPORT	9	1.56 *(.23)*
672	HOODSPORT	10	1.74 *(.15)*
1345	HOODSPORT	10	1.68 *(.38)*

0	LaGRANDE	14	1.61 *(.1)*
336	LaGRANDE	14	1.64 *(.1)*
672	LaGRANDE	14	1.61 *(.2)*
1345	LaGRANDE	14	1.60 *(.1)*
0	SWEETHOME	12	1.45 *(.14)*
336	SWEETHOME	12	1.42 *(.19)*
672	SWEETHOME	12	1.43 *(.18)*
1345	SWEETHOME	12	1.51 *(.20)*

TREATMENT MEANS BY SITE			
SITE	TREATMENT	n	% N *(std. dev.)*
APIARY	BF0	5	1.34 *(.16)*
APIARY	BF1	5	1.52 *(.09)*
APIARY	BF2	5	1.35 *(.18)*
APIARY	BF3	5	1.35 *(.11)*
APIARY	NF0	5	1.40 *(.22)*
APIARY	NF1	5	1.40 *(.09)*
APIARY	NF2	5	1.34 *(.30)*
APIARY	NF3	5	1.39 *(.12)*
GATES	BF0	7	1.29 *(.13)*
GATES	BF1	7	1.29 *(.14)*
GATES	BF2	7	1.41 *(.17)*
GATES	BF3	6	1.43 *(.26)*
GATES	NF0	7	1.43 *(.19)*
GATES	NF1	7	1.53 *(.13)*
GATES	NF2	7	1.41 *(.17)*
GATES	NF3	7	1.38 *(.21)*
HOODSPORT	BF0	5	1.42 *(.14)*
HOODSPORT	BF1	5	1.54 *(.22)*
HOODSPORT	BF2	5	1.71 *(.15)*
HOODSPORT	BF3	5	1.57 *(.44)*
HOODSPORT	NF0	5	1.69 *(.18)*
HOODSPORT	NF1	4	1.59 *(.44)*
HOODSPORT	NF2	5	1.77 *(.15)*
HOODSPORT	NF3	5	1.78 *(.32)*
LaGRANDE	BF0	7	1.67 *(.12)*
LaGRANDE	BF1	7	1.60 *(.09)*
LaGRANDE	BF2	7	1.57 *(.07)*
LaGRANDE	BF3	7	1.58 *(.12)*

LaGRANDE	NF0	7	1.55 *(.09)*
LaGRANDE	NF1	7	1.69 *(.14)*
LaGRANDE	NF2	7	1.65 *(.16)*
LaGRANDE	NF3	7	1.62 *(.08)*
SWEETHOME	BF0	6	1.47 *(.18)*
SWEETHOME	BF1	6	1.40 *(.18)*
SWEETHOME	BF2	6	1.38 *(.20)*
SWEETHOME	BF3	6	1.36 *(.10)*
SWEETHOME	NF0	6	1.43 *(.08)*
SWEETHOME	NF1	6	1.43 *(.20)*
SWEETHOME	NF2	6	1.48 *(.16)*
SWEETHOME	NF3	6	1.65 *(.17)*

BF0=Bulldoze, Fertilization Level 0 kg ha^{-1}
BF1=Bulldoze, Fertilization Level 336 kg ha^{-1}
BF2=Bulldoze, Fertilization Level 672 kg ha^{-1}
BF3=Bulldoze, Fertilization Level 1345 kg ha^{-1}

NF0=No Bulldozing, Fertilization Level 0 kg ha^{-1}
NF1=No Bulldozing, Fertilization Level 336 kg ha^{-1}
NF2=No Bulldozing, Fertilization Level 672 kg ha^{-1}
NF3=No Bulldozing, Fertilization Level 1345 kg ha^{-1}

APPENDIX C

MEANS FOR COMBINED DATA (5 Sites):

n=Number of Replicates
%=Foliar Nutrient Percentage

ALL TREATMENT MEANS		
NUTRIENT	n	% *(std. error)*
Ca	20	.40 *(.02)*
K	20	. 69 *(.03)*
Mg	20	.12 *(.002)*
P	20	.17 *(.01)*
S	20	.09 *(.002)*

STUMPING TREATMENT MEANS				
	STUMPING		NO STUMPING	
	n	% *(std. error)*	n	% *(std. error)*
Ca	10	.40 *(.03)*	10	.41 *(.03)*
K	10	.72 *(.05)*	10	.66 *(.04)*
Mg	10	.12 *(.003)*	10	.12 *(.003)*
P	10	.17 *(.01)*	10	.17 *(.01)*
S	10	.09 *(.003)*	10	.09 *(.003)*

FERTILIZATION TREATMENT MEANS				
NUTRIENT	0 kg ha^{-1}		1345 kg ha^{-1}	
	n	% *(std. error)*	n	% *(std. error)*
Ca	10	.40 *(.03)*	10	.41 *(.04)*
K	10	.69 *(.05)*	10	.69 *(.05)*
Mg	10	.12 *(.003)*	10	.12 *(.003)*
P	10	.17 *(.01)*	10	.17 *(.01)*
S	10	.09 *(.003)*	10	.09 *(.003)*

COMBINED FERTILIZATION & STUMPING TREATMENT MEANS Ca		
	n	% Ca *(std. error)*
BFO	5	.39 *(.05)*
BF3	5	.41 *(.04)*
NFO	5	.40 *(.04)*
NF3	5	.42 *(.05)*

COMBINED FERTILIZATION & STUMPING TREATMENT MEANS K		
	n	% K *(std. error)*
BFO	5	.71 *(.09)*
BF3	5	.72 *(.05)*
NFO	5	.67 *(.06)*
NF3	5	.66 *(.06)*

COMBINED FERTILIZATION & STUMPING TREATMENT MEANS Mg		
	n	% Mg *(std. error)*
BFO	5	.12 *(.004)*
BF3	5	.12 *(.004)*
NFO	5	.12 *(.004)*
NF3	5	.12 *(.004)*

COMBINED FERTILIZATION & STUMPING TREATMENT MEANS P		
	n	% P *(std. error)*
BFO	5	.17 *(.01)*
BF3	5	.17 *(.02)*
NFO	5	.18 *(.02)*
NF3	5	.17 *(.02)*

COMBINED FERTILIZATION & STUMPING TREATMENT MEANS S		
	n	% S *(std. error)*
BFO	5	.09 *(.004)*
BF3	5	.09 *(.004)*
NFO	5	.09 *(.004)*
NF3	5	.09 *(.004)*

BF0=Bulldoze, Fertilization Level 0 kg ha^{-1}
BF3=Bulldoze, Fertilization Level 1345 kg ha^{-1}
NF0=No Bulldozing, Fertilization Level 0 kg ha^{-1}
NF3=No Bulldozing, Fertilization Level 1345 kg ha^{-1}

APPENDIX D

MEANS BY SITE:

n=Number of Replicates
%N=Foliar Nutrient Percentage

TOTAL SITE MEANS: Ca		
	N	% Ca *(std. dev.)*
APIARY	20	.36 *(.07)*
GATES	27	.54 *(.14)*
HOODSPORT	20	.32 *(.10)*
LaGRANDE	28	.32 *(.04)*
SWEETHOME	24	.47 *(.09)*

TOTAL SITE MEANS: K		
	N	% K *(std. dev.)*
APIARY	20	.82 *(.12)*
GATES	27	.50 *(.10)*
HOODSPORT	20	.63 *(.10)*
LaGRANDE	28	.85 *(.07)*
SWEETHOME	24	.66 *(.10)*

TOTAL SITE MEANS: Mg		
	N	% Mg *(std. dev.)*
APIARY	20	.12 *(.01)*
GATES	27	.13 *(.02)*
HOODSPORT	20	.13 *(.02)*
LaGRANDE	28	.11 *(.01)*
SWEETHOME	24	.11 *(.02)*

TOTAL SITE MEANS: P		
	N	% P *(std. dev.)*
APIARY	20	.19 *(.02)*
GATES	27	.16 *(.03)*
HOODSPORT	20	.18 *(.03)*
LaGRANDE	28	.21 *(.02)*
SWEETHOME	24	.11 *(.03)*

TOTAL SITE MEANS: S		
	n	% S *(std. dev.)*
APIARY	20	.09 *(.01)*
GATES	27	.08 *(.01)*
HOODSPORT	20	.09 *(.01)*
LaGRANDE	28	.11 *(.01)*
SWEETHOME	24	.09 *(.01)*

SITE MEANS BY STUMPING TREATMENT: Ca				
	STUMPING		NO STUMPING	
	n	% Ca *(std. dev.)*	n	% Ca *(std. dev.)*
APIARY	10	.35. *(.04)*	10	.38 *(.09)*
GATES	14	.52 *(.18)*	13	.56 *(.10)*
HOODSPORT	10	.32 *(.13)*	10	.33 *(.06)*
LaGRANDE	14	.33 *(.04)*	14	.32 *(.05)*
SWEETHOME	12	.47 *(.06)*	12	.46 *(.11)*

SITE MEANS BY STUMPING TREATMENT: K				
	STUMPING		NO STUMPING	
	n	% K *(std. dev.)*	n	% K *(std. dev.)*
APIARY	10	.90 *(.06)*	10	.74 *(.12)*
GATES	14	.52 *(.11)*	13	.48 *(.09)*
HOODSPORT	10	.62 *(.12)*	10	.65 *(.08)*
LaGRANDE	14	.85 *(.06)*	14	.84 *(.07)*
SWEETHOME	12	.70 *(.11)*	12	.61 *(.08)*

SITE MEANS BY STUMPING TREATMENT: Mg				
	STUMPING		NO STUMPING	
	n	% Mg *(std. dev.)*	n	% Mg *(std. dev.)*
APIARY	10	.12 *(.01)*	10	.13 *(.02)*
GATES	14	.13 *(.03)*	13	.13 *(.02)*
HOODSPORT	10	.12 *(.02)*	10	.13 *(.01)*
LaGRANDE	14	.11 *(.01)*	14	.11 *(.01)*
SWEETHOME	12	.12 *(.02)*	12	.11 *(.02)*

SITE MEANS BY STUMPING TREATMENT: P				
	STUMPING		NO STUMPING	
	n	% P *(std. dev.)*	n	% P *(std. dev.)*
APIARY	10	.19 *(.01)*	10	.19 *(.04)*
GATES	14	.17 *(.04)*	13	.15 *(.03)*
HOODSPORT	10	.17 *(.02)*	10	.19 *(.03)*
LaGRANDE	14	.21 *(.02)*	14	.22 *(.01)*
SWEETHOME	12	.12 *(.03)*	12	.11 *(.04)*

SITE MEANS BY STUMPING TREATMENT: S				
	STUMPING		NO STUMPING	
	n	% S *(std. dev.)*	n	% S *(std. dev.)*
APIARY	10	.09 *(.01)*	10	.09 *(.01)*
GATES	14	.08 *(.01)*	13	.08 *(.01)*
HOODSPORT	10	.08 *(.01)*	10	.09 *(.01)*
LaGRANDE	14	.11 *(.01)*	14	.10 *(.01)*
SWEETHOME	12	.09 *(.01)*	12	.08 *(.01)*

SITE MEANS BY FERTILIZATION TREATMENT: Ca				
	0 kg ha^{-1}		1345 kg ha^{-1}	
	n	% Ca *(std. dev.)*	n	% Ca *(std. dev.)*
APIARY	10	.32 *(03.)*	10	.41 *(.07)*
GATES	14	.55 *(.17)*	13	.53 *(.11)*
HOODSPORT	10	.30 *(.07)*	10	.34 *(.13)*
LaGRANDE	14	.33 *(.04)*	14	. 32 *(.04)*
SWEETHOME	12	.47 *(.08)*	12	. 46 *(.09)*

SITE MEANS BY FERTILIZATION TREATMENT: K				
	0 kg ha^{-1}		1345 kg ha^{-1}	
	n	% K *(std. dev.)*	n	% K *(std. dev.)*
APIARY	10	.83 *(.13)*	10	.81 *(.11)*
GATES	14	.47 *(.09)*	13	.52 *(.11)*
HOODSPORT	10	.64 *(.10)*	10	.62 *(.11)*
LaGRANDE	14	.86 *(.07)*	14	.84 *(.06)*
SWEETHOME	12	.66 *(.12)*	12	.65 *(.09)*

SITE MEANS BY FERTILIZATION TREATMENT: **Mg**				
	0 kg ha^{-1}		1345 kg ha^{-1}	
	n	% Mg *(std. dev.)*	n	% Mg *(std. dev.)*
APIARY	10	.12 *(.02)*	10	.13 *(.01)*
GATES	14	.13 *(.03)*	13	.13 *(.02)*
HOODSPORT	10	.12 *(.02)*	10	.13 *(.02)*
LaGRANDE	14	.11 *(.01)*	14	.10 *(.01)*
SWEETHOME	12	.12 *(.02)*	12	.10 *(.02)*

SITE MEANS BY FERTILIZATION TREATMENT: **P**				
	0 kg ha^{-1}		1345 kg ha^{-1}	
	n	% P *(std. dev.)*	n	% P *(std. dev.)*
APIARY	10	.20 *(.03)*	10	.18 *(.02)*
GATES	14	. 15*(.04)*	13	.17 *(.03)*
HOODSPORT	10	.18 *(.03)*	10	.17 *(.02)*
LaGRANDE	14	.22 *(.02)*	14	.21 *(.02)*
SWEETHOME	12	.11 *(.03)*	12	.11 *(.01)*

SITE MEANS BY FERTILIZATION TREATMENT: **S**				
	0 kg ha^{-1}		1345 kg ha^{-1}	
	n	% S *(std. dev.)*	n	% S *(std. dev.)*
APIARY	10	.09 *(.01)*	10	.09 *(.005)*
GATES	14	.08 *(.01)*	13	.08 *(.01)*
HOODSPORT	10	.09 *(.01)*	10	.09 *(.01)*
LaGRANDE	14	.11 *(.01)*	14	.11 *(.01)*
SWEETHOME	12	.09 *(.01)*	12	.08 *(.01)*

TREATMENT MEANS BY SITE: **Ca**			
SITE	TREATMENT	n	% Ca *(std. dev.)*
APIARY	BF0	5	.33 *(.02)*
APIARY	BF3	5	.37 *(.05)*
APIARY	NF0	5	.32 *(.04)*
APIARY	NF3	5	.45 *(.07)*
GATES	BF0	7	.55 *(.23)*
GATES	BF3	7	.50 *(.12)*
GATES	NF0	7	.55 *(.11)*
GATES	NF3	6	.57 *(.10)*

HOODSPORT	BF0	5	.27 *(.04)*
HOODSPORT	BF3	5	.37 *(.18)*
HOODSPORT	NF0	5	.34 *(.08)*
HOODSPORT	NF3	5	.31 *(.05)*
LaGRANDE	BF0	7	.34 *(.04)*
LaGRANDE	BF3	7	.31 *(.04)*
LaGRANDE	NF0	7	.33 *(.05)*
LaGRANDE	NF3	7	.32 *(.05)*
SWEETHOME	BF0	6	.47 *(.07)*
SWEETHOME	BF3	6	.48 *(.05)*
SWEETHOME	NF0	6	.48 *(.10)*
SWEETHOME	NF3	6	.44 *(.11)*

TREATMENT MEANS BY SITE: K			
SITE	TREATMENT	n	% K *(std. dev.)*
APIARY	BF0	5	.93 *(.07)*
APIARY	BF3	5	.86 *(.02)*
APIARY	NF0	5	.73 *(.09)*
APIARY	NF3	5	.75 *(.15)*
GATES	BF0	7	.45 *(.10)*
GATES	BF3	7	.58 *(.08)*
GATES	NF0	7	.49 *(.09)*
GATES	NF3	6	.46 *(.10)*
HOODSPORT	BF0	5	.59 *(.12)*
HOODSPORT	BF3	5	.64 *(.14)*
HOODSPORT	NF0	5	.68 *(.05)*
HOODSPORT	NF3	5	.61 *(.08)*
LaGRANDE	BF0	7	.86 *(.05)*
LaGRANDE	BF3	7	.84 *(.07)*
LaGRANDE	NF0	7	.85 *(.09)*
LaGRANDE	NF3	7	.83 *(.05)*
SWEETHOME	BF0	6	.72 *(.13)*
SWEETHOME	BF3	6	.69 *(.09)*
SWEETHOME	NF0	6	.61 *(.09)*
SWEETHOME	NF3	6	.61 *(.07)*

TREATMENT MEANS BY SITE: Mg			
SITE	TREATMENT	n	% Mg *(std. dev.)*
APIARY	BF0	5	.12 *(.01)*
APIARY	BF3	5	.13 *(.01)*
APIARY	NF0	5	.12 *(.02)*
APIARY	NF3	5	.13 *(.01)*
GATES	BF0	7	.13 *(.04)*
GATES	BF3	7	.13 *(.02)*
GATES	NF0	7	.13 *(.02)*
GATES	NF3	6	.13 *(.02)*
HOODSPORT	BF0	5	.12 *(.02)*
HOODSPORT	BF3	5	.12 *(.02)*
HOODSPORT	NF0	5	.13 *(.01)*
HOODSPORT	NF3	5	.13 *(.01)*
LaGRANDE	BF0	7	.11 *(.01)*
LaGRANDE	BF3	7	.10 *(.01)*
LaGRANDE	NF0	7	.11 *(.01)*
LaGRANDE	NF3	7	.11 *(.01)*
SWEETHOME	BF0	6	.13 *(.02)*
SWEETHOME	BF3	6	.11 *(.02)*
SWEETHOME	NF0	6	.12 *(.02)*
SWEETHOME	NF3	6	.10 *(.01)*

TREATMENT MEANS BY SITE: P			
SITE	TREATMENT	n	% P *(std. dev.)*
APIARY	BF0	5	. 19*(.)*
APIARY	BF3	5	. 19*(.)*
APIARY	NF0	5	. 21*(.)*
APIARY	NF3	5	. 17*(.)*
GATES	BF0	7	.14 *(.)*
GATES	BF3	7	.19 *(.)*
GATES	NF0	7	.15 *(.)*
GATES	NF3	6	.15 *(.)*
HOODSPORT	BF0	5	.17 *(.)*

HOODSPORT	BF3	5	.16 *(.)*
HOODSPORT	NF0	5	.20 *(.)*
HOODSPORT	NF3	5	.18 *(.)*
LaGRANDE	BF0	7	.21 *(.)*
LaGRANDE	BF3	7	.21 *(.)*
LaGRANDE	NF0	7	.22 *(.)*
LaGRANDE	NF3	7	.21 *(.)*
SWEETHOME	BF0	6	.14 *(.)*
SWEETHOME	BF3	6	.10 *(.)*
SWEETHOME	NF0	6	.09 *(.)*
SWEETHOME	NF3	6	.13 *(.)*

TREATMENT MEANS BY SITE: S			
SITE	TREATMENT	N	% S *(std. dev.)*
APIARY	BF0	5	.09 *(.01)*
APIARY	BF3	5	.09 *(.003)*
APIARY	NF0	5	.09 *(.01)*
APIARY	NF3	5	.09 *(.01)*
GATES	BF0	7	.08 *(.01)*
GATES	BF3	7	.08 *(.01)*
GATES	NF0	7	.08 *(.01)*
GATES	NF3	7	.08 *(.01)*
HOODSPORT	BF0	5	.08 *(.01)*
HOODSPORT	BF3	5	.08 *(.01)*
HOODSPORT	NF0	5	.10 *(.02)*
HOODSPORT	NF3	5	.09 *(.01)*
LaGRANDE	BF0	7	.11 *(.01)*
LaGRANDE	BF3	7	.11 *(.01)*
LaGRANDE	NF0	7	.10 *(.01)*
LaGRANDE	NF3	7	.11 *(.01)*
SWEETHOME	BF0	6	.10 *(.01)*
SWEETHOME	BF3	6	.09 *(.01)*
SWEETHOME	NF0	6	.09 *(.01)*
SWEETHOME	NF3	6	.08 *(.01)*

BF0=Bulldoze, Fertilization Level 0 kg ha^{-1} NF0=No Bulldozing, Fertilization Level 0 kg ha^{-1}
BF3=Bulldoze, Fertilization Level 1345 kg ha^{-1} NF3=No Bulldozing, Fertilization Level 1345 kg