Forest Ecology and Management 256 (2008) 732–740

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Long-term effects of post-harvest stump removal and N-fertilization on understory vegetation in Western USA forests

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ARTICLE INFO

Article history:
Received 2 January 2008
Received in revised form 16 May 2008
Accepted 19 May 2008

Keywords:
Disturbance
Understory
Stump removal
Fertilization
Diversity
Introduced species
Phellinus weirii
Plant species richness

ABSTRACT

Intensive forest management practices often disturb understory vegetation, and the recovery of these plant communities may depend on the type and severity of the disturbance. We examined the effects of stump removal and N-fertilization on understory plant communities and functional group (shrubs, graminoids, forbs, and introduced species) cover and diversity at five study areas in the Pacific Northwest of North America 24–28 years after treatment. Treatments at each study area included stumped and non-stumped controls as well as four levels of broadcast ammonium nitrate (0, 336, 672, and 1345 kg N ha^{-1}) in all combinations. Stumping had significant effects on community composition at all sites, and several plant species were associated ($p < 0.05$) with either controls or stumped plots. Diversity of graminoids, forbs and introduced species increased in stumped areas region wide. Stumping reduced cover and diversity of shrubs at some sites. Cover of graminoids and forbs also increased in stumped plots at some study areas. Forbs like *Viola sempervirens* were often indicators of stump removal while shrubs such as *Acer circinatum* tended to be associated with non-stumped plots. N-fertilization affected community composition at only one study area, and had no effects on cover or richness of functional groups. Stump removal has lasting impacts on plant communities and may make them more vulnerable to colonization by introduced species.

1. Introduction

Intensive forest management practices are widely used and can have substantial positive effects on tree growth and silvicultural productivity (**Fu et al., 2007**) by reducing competition, increasing nutrient availability, improving seedling microclimate, and limiting infection by tree pathogens. But their effects on understory vegetation, especially over the long-term, are often not well documented, even though the greatest proportion of plant species diversity in temperate forest systems is found at or near the ground layer (**Gilliam and Roberts, 2003**). Forest canopy removal, for example, has been shown to reduce species richness, at least initially, and controlled burning to remove debris can result in local loss of some species (**Halpern and Spies, 1995**). Intensive forest management practices appear to affect understory vegetation most when they alter abundance of woody debris (**Harmon et al., 1986**), exposure of mineral soil as a seed bed (**Battles et al., 2001**), and nutrient availability (**Gilliam, 2006**).

Stump removal with heavy machinery after tree harvest has been advocated and applied as a method to increase efficiency in post-harvest site preparation and planting (**Saarinen, 2006**) and reduce recolonization and spread of root diseases caused by fungal pathogens such as *Phellinus weirii* (**Thies and Sturrock, 1995**; **Thies and Westlind, 2005**) and *Armillaria ostoyae* (**Roth et al., 1977, 2000**; **Thies and Russell, 1984**; **Morrison and Mallett, 1996**). Excavating stumps may result in the initial destruction of understory vegetation, burial of seeds, exposure of mineral soil, mixing of soil horizons, and alteration of soil properties such as bulk density, structure, and moisture holding capacity. These factors can have significant impacts on vegetation establishment (**Mou et al., 1993**), tree growth (**Froehlich et al., 1986**; **Alban et al., 1994**), and species diversity in general (**Chapin and Shaver, 1981**) and of specific species groups (**Gondard et al., 2003**). Soil compaction alone is speculated to reduce tree growth for decades (**Wert and Thomas, 1981**). This effect may depend on soil texture, with productivity declining on compacted clay soils and increasing on compacted sandy soils (**Powers et al., 2005**). Heavy machinery in forested

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doi: **10.1016/j.foreco.2008.05.028**

systems can also carry seeds of invasive species which become established on disturbed soils (Evans et al., 2006).

Fertilizer is used in forestry to improve silvicultural productivity (Bengtson, 1979) and has been shown to improve growth of Douglas-fir (*Pseudotsuga menziesii*) in the Pacific Northwest (Jacobs et al., 2005). Laboratory and field tests also suggest that N-application encourages competing soil organisms to displace *P. weirii* (Li et al., 1967; Nelson, 1970, 1975, 1976), and short-term benefits of fertilization to Douglas-fir in areas infected with *P. weirii* have been well documented (Thies and Nelson, 1988; Thies et al., 1994). The effects of fertilization on plant growth have been studied extensively in the greenhouse (Turkington et al., 1993), old-field systems (Bakelaar and Odum, 1978; Mellinger and McNaughton, 1975; Tilman, 1993), and forest plantations (Miller and Fight, 1979; Rose and Ketchum, 2002), but long-term fertilization experiments in forest understory plant communities are uncommon (Abrams and Dickmann, 1983; Thomas et al., 1999; Gilliam, 2006). Nitrogen fertilization can favor a few opportunistic species resulting in a decline in species diversity (e.g., Bakelaar and Odum, 1978) and lead to changes in species composition through resource competition (Wedin and Tilman, 1996). High fertilizer doses could prove to be toxic to some species resulting in low diversity (Olsson and Kellner, 2006). Nitrogen additions can also alter soil microbial populations and affect communities through changes in mycorrhyzal associations (Allen, 1991).

Both stumping and fertilization have been considered as strategies for controlling *P. weirii*, the fungus that causes laminated root-rot disease. In 1976, a study was established (Thies and Westlind, 2005) to assess stump removal alone and in combination, with four dosages of ammonium nitrate, as strategies for reducing the occurrence of laminated root rot in replacement stands on infested sites. To allow a broad area of inference, the study was repeated using the same design in five predominantly Douglas-fir stands in Oregon and Washington. All stands received identical treatments but differed in the number of replicate plots, local site characteristics, and the year in which various activities occurred. The effects of these treatments on laminated root-rot occurrence and tree regeneration were reported in Thies and Westlind (2005) and impacts to soil bulk density and nitrogen content were presented in Zabowski et al. (2008).

In this paper we report an expansion of the 1976 study to examine the effects of stumping in combination with nitrogen fertilization on understory vegetation 24–28 years after treatment. The results from this study have broad relevance since various forest management practices include soil disturbance and fertilization. We evaluated the long-term impacts of the treatments by framing the following hypotheses and testing their corresponding null hypotheses: (1) fertilization and stumping alter plant community composition, (2) individual species can serve as indicators of these treatments, and (3) fertilization and stumping affect abundance and species richness of functional groups such as shrubs, forbs, graminoids, and invasive species.

2. Methods

2.1. Study areas

This study was conducted in coniferous forests at five study areas in Oregon and western Washington (see Thies and Westlind (2005) for a map of study area locations) within a region of North America commonly termed the Pacific Northwest that includes Washington and portions of Oregon, Idaho and Montana and British Columbia (Hitchcock and Cronquist, 1976). The forest stands were cut prior to the initiation of the study. Each study area is identified by the name of a nearby town: *Apiary* – Apiary, OR; *Gates* – Gates, OR; *Hoodsport* – Hoodsport, WA; *La Grande* – La Grande, OR; and *Sweethome* – Sweethome, OR. The *La Grande* site is the only one east of the Cascade Range; the other four are west of the crest of the Cascade Range. In the Pacific Northwest, areas west of the Cascade Range receive precipitation off of the Pacific Ocean and tend to be much more moist than areas to the east, which are in the rain shadow of the Cascade Range (Table 1). Slopes at the study areas were generally gentle (≤16%) and aspects were southwest to southerly (Thies and Westlind, 2005). Together the study areas represent a wide range of site characteristics including elevation, soil type, annual precipitation, and forest canopy composition. More complete descriptions of the study areas and initial experimental methods are described by Thies and Westlind (2005) and Zabowski et al. (2008).

2.2. Study design and treatments

Each study area was established as an independent study with the same experimental design. Each forest stand was selected to be homogeneous for slope, soil, and general stand and understory vegetation characteristics. The number of replicates, and thus the number of plots, was based on the size of each study area and distribution of *P. weirii*. Activities on each study area were conducted independent of the other sites, so the timing of treatments differed somewhat from place to place (Table 1). Treatments consisted of two levels of stumping (all stumps removed and no stumps removed) and four levels of fertilization. The treatments were implemented in all combinations in a 2 × 4 factorial design, with each combination replicated five to seven times depending on the study area (Table 1) in a randomized complete block design. Blocking in each stand was based on relative amount of *P. weirii* inoculum in each plot without regard to site characteristics (see Thies and Westlind (2005) for the

Table 1
Summary of blocks, treatment combinations, total sample sizes, and year of treatment (and other stand activities) and understory sampling, at each site

	Site				
	Apiary	Gates	Hoodsport	La Grande	Sweethome
Study area location	Western Oregon, Coast Range	Western Oregon, Cascade Mountains	Western Washington, Olympic Mountains	Eastern Oregon, Blue Mountains	Western Oregon, Cascade Mountains
Soil texture	Silt loam	Cobbly loam	Gravelly, sandy loam	Silt loam	Silty clay loam
Annual precipitation (cm)	145	200	229	82	127
Blocks	5	7	5	7	6
Treatment combinations per block	8	8	8	8	8
Samples per site	40	56	39	56	47
Cut	1978	1979	1976	1978	1979
Treated	1978	1980	1976	1978	1980
Planted	1979	1981	1977	1986	1981
Thinned	2000	1996	1999	NA	NA
Understory sampled	2004	2004	2004	2003	2004
Years between treatment and sampling	26	24	28	25	24

relativization procedure). This blocking structure was maintained in all our data analyses because understory species richness and composition is altered in root-rot disease centers (Holah et al., 1993; Bendel et al., 2006) and may have varied non-randomly across the study areas prior to treatments. The treatment units were 0.04 ha (1/10th acre) circular plots. A crawler tractor weighing between 32,000 and 40,000 kg equipped with a brush blade on the front and a splitting wedge on the back was used to remove stump material. The stumping process removed as much of the stump and root system as possible, leaving the woody remains on the ground within the plot, and no secondary effort was made to remove severed roots from the soil. Stumping was performed in late summer (late August and September), during the regional dry season so that the soil surface was dry. The tractor was confined to the individual plots during treatments resulting in soil compaction as heavy as would be expected on an operational scale; soil mixing occurred primarily between the organic and upper mineral horizons. Fertilizer was applied immediately after stump removal as small granules of ammonium nitrate at rates of 0, 336, 672, and 1345 kg N ha^{-1} (0, 300, 600, and 1200 lb N $acre^{-1}$). It was broadcast by a person using a cyclone-type seed spreader. Treatments were applied the same year the stand was cut or 1 year later. Douglas-fir seedlings were planted the year following treatment. Animal damage to these seedlings necessitated some interplanting the next season to maintain stocking, except at *La Grande*, where interplanting continued for 8 years post-treatment. Tree thinning with chain saws (no heavy machinery) occurred at *Apiary*, *Gates*, and *Hoodsport* 12–23 years after treatment, and we sampled the understory vegetation 24–28 years after treatment (Table 1). We evaluate these treatments as five independent studies with each analyzed separately, except for evaluations of functional groups for which we also conducted region-wide analyses.

2.3. Vegetation sampling

We defined understory vegetation as those vascular plants occurring below the forest canopy including shrubs. Occasional tree species were included when they were small (<1.35 m in height). To measure understory vegetation, we sampled each circular treatment unit with four 0.5 m^2 (0.5 m × 1 m) subplots. To ensure that sampling captured the variation in the understory vegetation, each plot was divided into four quadrants, and one subplot was placed in each quadrant using a randomly selected compass bearing and a distance of 9 m from the center of the plot. This distance allowed us to avoid disturbance concentrated in the center of the plot caused by tree sampling and management actions conducted 1–12 months prior to understory sampling. The percentage cover of each plant species present within each subplot was measured through ocular estimation to the nearest 1%. Cover values for each of the four subplots were averaged to give a single mean cover estimate for each species per plot. The plots were sampled during July of 2003 or 2004, depending on the study area. Plant species nomenclature and functional group (growth habitat) classification follows the USDA PLANTS database (USDA NRCS, 2007).

2.4. Data analysis

2.4.1. Effects on community composition

We used permutation-based non-parametric multivariate analysis of variance (perMANOVA [sometimes referred to as npMANOVA]) (Anderson, 2001) to test for treatment effects on community composition at each study area. PerMANOVA is a multivariate procedure that performs distance-based analysis of variance to test hypotheses with permutation procedures. It avoids the assumption of normal distributions of the response variables which are not met when analyzing some community data (McCune and Grace, 2002), including ours due at least in part to the presence of large numbers of species absences (zero cover values) for infrequent taxa. We used PC-ORD statistical software, version 5.0 (McCune and Mefford, 2006) with Sørensen's distance measure and 10,000 permutations to test the hypothesis that group differences were no larger than expected by chance ($\alpha < 0.05$). Separate analyses were conducted for each area because floristic composition of the plant communities differed substantially across the geographic range of the study areas. PerMANOVA incorporated the 2 × 4 factorial experimental design and allowed us to test for main effects and treatment interactions. Species occurring in ≤5% of the plots (i.e., two or fewer plots per site) were excluded from the analyses to reduce noise and improve the correlation structure of the dataset, as suggested by McCune and Grace (2002). As implemented in PC-ORD, perMANOVA required a completely balanced design. One treatment unit was lost at Hoodsport due to road construction and we were unable to relocate one at Sweethome during vegetation sampling. These two missing values were replaced with the study area-wide average for each species (McCune and Grace, 2002, pp. 58–59), a conservative approach that involves no subjective guessing or investigator bias.

2.4.2. Species-specific responses

PerMANOVA tests for differences between groups in community composition, but does not identify how these groups differ. Therefore, we used Indicator Species Analysis (ISA) to quantify how individual species were distributed among treatment groups and identify those species that were significant indicators of particular treatments. ISA combines the abundance and relative frequency of each individual species within a particular group and assigns an indicator value (Dufrêne and Legendre, 1997). A perfect indicator species always occurs in one group and never occurs in others. Indicator values range from 0 to 100, where zero means that a species is not associated with any particular group and 100 corresponds to exclusive frequent and abundant membership by a species to a particular group. We performed a Monte Carlo randomization with 5000 permutations to determine if an indicator value for a given species was larger than expected by chance ($\alpha < 0.05$) using PC-ORD (McCune and Mefford, 2006). ISA was performed only for sites with treatments identified as having statistically significant community effects in perMANOVA, above. Species occurring in less than 5% of the plots were excluded from the analysis, as recommended by McCune and Mefford (2006).

2.4.3. Effects on functional groups

We used analysis of variance (ANOVA) to test for treatment effects on mean species richness and percentage cover of functional groups. Each of the encountered species was placed into a functional group based on growth-form and taxonomic relationship. Plants with woody stems were categorized as shrubs (tree seedlings that were less than 1.35 m tall were included, as were plants sometimes termed subshrubs and vines); grasses (Poaceae), sedges (Cyperaceae) and rushes (Juncaceae) were grouped as graminoids; and all other herbaceous plants were considered forbs. Non-native, introduced species were additionally placed in a fourth group regardless of their growth-form. Total cover for each functional group was then calculated by summing the individual percentage cover values for each species within the group. Richness was calculated as the total number of species in each group. Our use of functional groups combined all species that played similar roles in the community without omitting species that had low frequency in the plots. This is a useful approach to compare responses of plants among sites from distinct communities or ecoregions (Lawrence and Kaye, 2006). Percentage cover values were log-transformed prior to analysis to meet the

assumptions of normality and equal variance of residuals. We report the back-transformed medians and confidence intervals.

This approach allowed us to test for treatment effects at each site as well as across all sites to increase our scope of inference. However, testing for effects across study areas would be statistically inappropriate if there were significant site by treatment interactions. Therefore, we performed ANOVAs to determine if these interactions were present, and only tested for across-site treatment effects when they were not. In all ANOVAs the 2×4 factorial treatments and within-site blocking were included. We used SAS version 9.1 (SAS, 2000–2004) for these analyses. Differences were considered significant when $p \leq 0.05$.

3. Results

3.1. Effects on community composition

A total of 159 vascular plant species were encountered in our sampling: *Apiary* 53, *Gates* 62, *Hoodsport* 45, *La Grande* 87, and *Sweethome* 65. PerMANOVA indicated that stumping had a significant ($p < 0.05$) effect on understory plant community structure and composition at each of the five study areas (Table 2). Fertilizer application had a significant effect on the plant community only at *Apiary* ($p = 0.0045$). We found no significant interactions to community composition between stumping and fertilizer for any of the study areas (Table 2).

Table 2
Significance results for perMANOVA for treatment effects on community composition at each study area

Treatment	*p*-Values by study area				
	Apiary	Gates	Hoodsport	La Grande	Sweethome
Stumping	**0.021**	**<0.001**	**<0.001**	**0.049**	**<0.001**
Fertilizer	**0.004**	0.618	0.333	0.114	0.056
Interaction	0.161	0.766	0.324	0.556	0.302

Values in bold indicate significant treatment effects at $p < 0.05$.

Table 3
Indicator values[a] and significance by site and treatment for each species with $p < 0.05$

Site	Treatment	Species (functional group)	Indicator Value	*p*-Value
Apiary	Stumped	*Gaultheria shallon* (shrub)	53.9	0.021
		Satureja douglasii (forb)	50.0	0.049
		Viola sempervirens (forb)	60.4	0.003
	No N-addition	*Prosartes hookeri* (forb)	30.0	0.029
		Trientalis latifolia (forb)	36.9	0.026
Gates	Stumped	*Asaurum caudatum* (forb)	56.6	0.001
		Brachypodium sylvaticum (graminoid)[b]	37.8	0.003
		Campanula scouleri (forb)	32.1	0.001
		Fragaria virginiana (forb)	32.1	0.002
		Galium triflorum (forb)	66.9	0.001
		Mycelis muralis (forb)[b]	55.1	0.001
		Osmorhiza chilensis (forb)	57.3	0.001
		Stachys cooleyae (forb)	17.9	0.045
		Trientalis latifolia (forb)	62.5	0.001
		Viola sempervirens (forb)	80.6	0.001
	Not stumped	*Acer circinatum* (shrub)	42.9	0.003
		Mahonia nervosa (shrub)	53.2	0.038
		Gaultheria shallon (shrub)	59.7	0.001
		Rubus armeniacus (shrub)[b]	30.2	0.028
		Vaccinium parviflorum (shrub)	17.5	0.049
Hoodsport	Stumped	*Linnaea borealis* (forb)	50.0	0.026
	Not stumped	*Acer circinatum* (shrub)	62.2	0.006
La Grande	Stumped	*Piperia unalascensis* (forb)	45.6	0.004
		Trifolium aureum (forb)	45.9	0.036
	Not stumped	*Elymus glaucus* (graminoid)	29.5	0.017
		Lonicera ciliosa (shrub)	42.5	0.001
		Rumex acetosella (forb)[b]	19.6	0.046
Sweethome	Stumped	*Campanula scouleri* (forb)	37.2	0.013
		Hieracium albiflorum (forb)	32.2	0.015
		Iris tenax (forb)	29.2	0.008
		Leucanthemum vulgare (forb)[b]	29.2	0.018
		Rubus ursinus (shrub)	52.8	0.001
		Tsuga heterophylla (shrub)	55.6	0.002
		Viola sempervirens (forb)	60.1	0.002
	Not stumped	*Acer circinatum* (shrub)	47.6	0.003
		Polystichum munitum (forb)	53.9	0.037
		Rosa gymnocarpa (shrub)	30.2	0.006

[a] Indicator values are scaled from 0 to 100. A perfect indicator species (indicator value of 100) is always present in a group and never occurs in other groups. This method combines information on species relative abundance and frequency.
[b] Introduced species.

Table 4
Effects of stumping on richness and cover by functional group at the study areas as estimated by ANOVA

Species group	*p*-Values by study area					
	Across all sites	Apiary	Gates	Hoodsport	La Grande	Sweethome
Species richness						
Shrub	–	0.105	**0.002**	0.078	**0.019**	0.167
Graminoid	**0.0009**	0.780	**0.001**	0.182	**0.037**	**0.005**
Forb	**<.0001**	0.064	**<.0001**	0.099	0.156	**0.000**
Introduced	**0.0178**	0.502	**0.001**	0.309	0.496	0.143
Cover						
Shrub	–	0.065	**<.0001**	**0.001**	0.155	0.061
Graminoid	–	0.319	**0.001**	0.309	0.429	0.101
Forb	0.8392	0.497	0.741	**0.008**	0.504	0.243
Introduced	0.1284	0.374	0.624	0.855	0.056	0.141
Total vegetation	**0.0097**	0.237	**<.0001**	0.396	0.550	**0.022**

Values in bold indicate significant effects at $p < 0.05$. No *p*-values are reported for across-site effects where significant site by treatment interactions were detected (indicated with "–").

3.2. Species-specific responses

ISA found statistically significant indicator species at all sites where PerMANOVA found treatment effects (Table 3). Three species at *Apiary* were associated with stumping, the shrub *Gaultheria shallon*, and the forbs *Satureja douglasii* and *Viola sempervirens* (Table 3). Two forbs were indicators of no N-fertilization, *Prosartes hookeri* and *Trientalis latifolia*. At *Apiary* no species indicated a lack of stumping. At *Gates*, nine forbs and one grass were significant indicators of stumping; the grass, *Brachypodium sylvaticum*, and one forb, *Mycelis muralis*, were introduced species. Five shrub species were significant indicators of non-stumped habitat at *Gates*, including *Acer circinatum*, *Mahonia nervosa*, *G. shallon*, *Rubus armeniacus*, and *Vaccinium parviflorum* (Table 3). One forb, *Linnaea borealis*, was a significant indicator of stumped habitat at *Hoodsport*, and one shrub, *A. circinatum*, was an indicator of no stumping. At *La Grande*, two forbs, *Piperia unalascensis* and *Trifolium aureum*, were indicators of stumping, while a forb (*Rumex acetosella*), a grass (*Elymus glaucus*), and a shrub (*Lonicera ciliosa*) were indicators of the no stumping treatment. There were seven indicators of stumping at *Sweethome*, including five forbs, and the shrubs *Rubus ursinus* and *Tsuga heterophylla* (hemlock tree seedlings). One of the forbs associated with stumping was the invasive exotic, *Leucanthemum vulgare*. Indicators of no stumping at *Sweethome* were two shrubs, *A. circinatum* and *Rosa gymnocarpa*, and one forb, *Polystichum munitum*.

3.3. Effects on functional groups

Stumping had significant effects on species richness and cover of some functional groups both regionally and within individual study areas. Stumping resulted in significantly lower species richness of forbs and graminoids, and higher richness of introduced species when tested with ANOVA across all study areas (Table 4). Total vegetative cover was significantly lower in stumped plots when examined region wide (Table 4). There was a significant site by treatment interaction for shrub species richness ($p = 0.045$) and cover ($p = 0.007$), as well as graminoid cover ($p = 0.034$), so no across-site treatment effects were tested for these variables (Table 4). N-fertilization had no significant effects on any functional group in across-site ANOVAs.

Treatment effects varied somewhat among study areas. At *Apiary*, for example, no significant effects of stumping or N-fertilization were detected for any functional group. But at *Gates*, stumping significantly reduced mean species richness of shrubs, and increased richness of forbs, graminoid, and invasive species by at least one species per 0.5 m^2 plot in all cases (Fig. 1). Median shrub cover in stumped plots was less than half of that in non-stumped plots (Fig. 2) and total vegetative cover was less than a third (Fig. 3), while graminoid cover, though very low overall, was higher in stumped areas (Fig. 2). At *Hoodsport*, median shrub cover was about one third higher in non-stumped plots, while forb cover was about 40% higher in stumped plots (Fig. 2). At *La Grande*, stumped plots had about one less shrub species than non-stumped plots (Fig. 1), but there were no other significant treatment effects. Graminoid and forb richness were about 1 and 2 species greater, respectively, in stumped plots at *Sweethome* (Fig. 2), while median total vegetative cover was lower (Fig. 3).

At all study areas, N-fertilization had no significant effects on any functional group, and no significant interactions between stumping and fertilization were detected (all $p > 0.05$).

4. Discussion

We found that stump removal to control laminated root rot had substantial impacts on forest understory community composition and functional groups of species across a range of sites 24–28 years after treatment. After stump removal, all three of our hypotheses about effects to entire communities, individual species, and functional groups were supported. In contrast, a one-time application of nitrogen fertilizer, even at very high rates (up to 1345 kg N ha^{-1}), had only small effects at one study area.

4.1. Stump removal

In this study, stump removal involved the use of heavy machinery that resulted in substantial soil disturbance. The resulting understory plant community was significantly different in stumped plots compared to non-stumped plots at all five areas examined in this study (Table 2).

Some individual species were strongly associated with stumped or non-stumped plots, but the species affected generally differed from area to area (Table 3). In general, ISA found forbs and grasses to be indicators of stumped plots, while shrubs tended to indicate lack of stumping. At *Gates*, *Hoodsport*, and *La Grande*, all indicators of stumping were forbs or grasses. At *Gates* and *Hoodsport* shrubs were the only indicators of non-stumped plots. *V. sempervirens*, a widespread forb, was strongly associated (indicator values: 60.1–80.6) with stumped plots at three out of four study areas west of the Cascade Range (the species was absent from the study area east of the Cascade Range). This forb responds favorably to forest disturbances such as forest thinning (**Thomas et al., 1999**) and increases slightly after timber harvest (**Dyrness, 1973**) in western

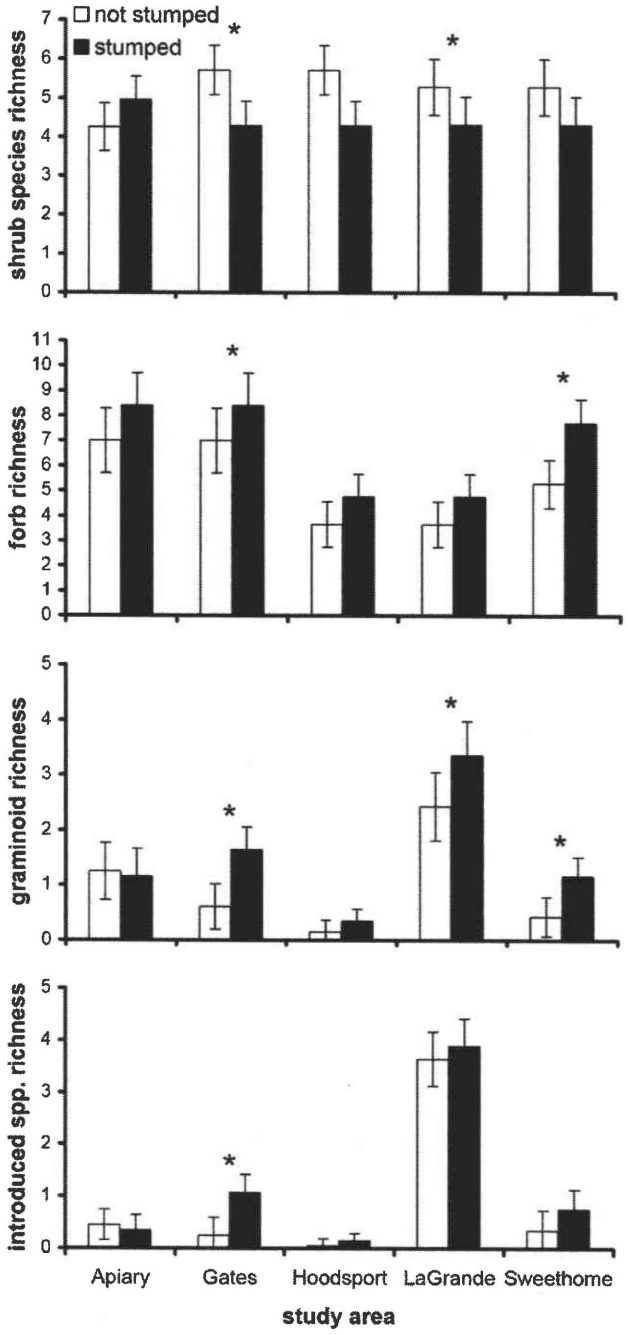

Fig. 1. Mean species richness of shrubs, forbs, graminoids and introduced species in 0.5 m^2 plots at each site. Error bars represent 95% confidence intervals. Asterisks above pairs of bars indicate significant differences of $p \leq 0.05$.

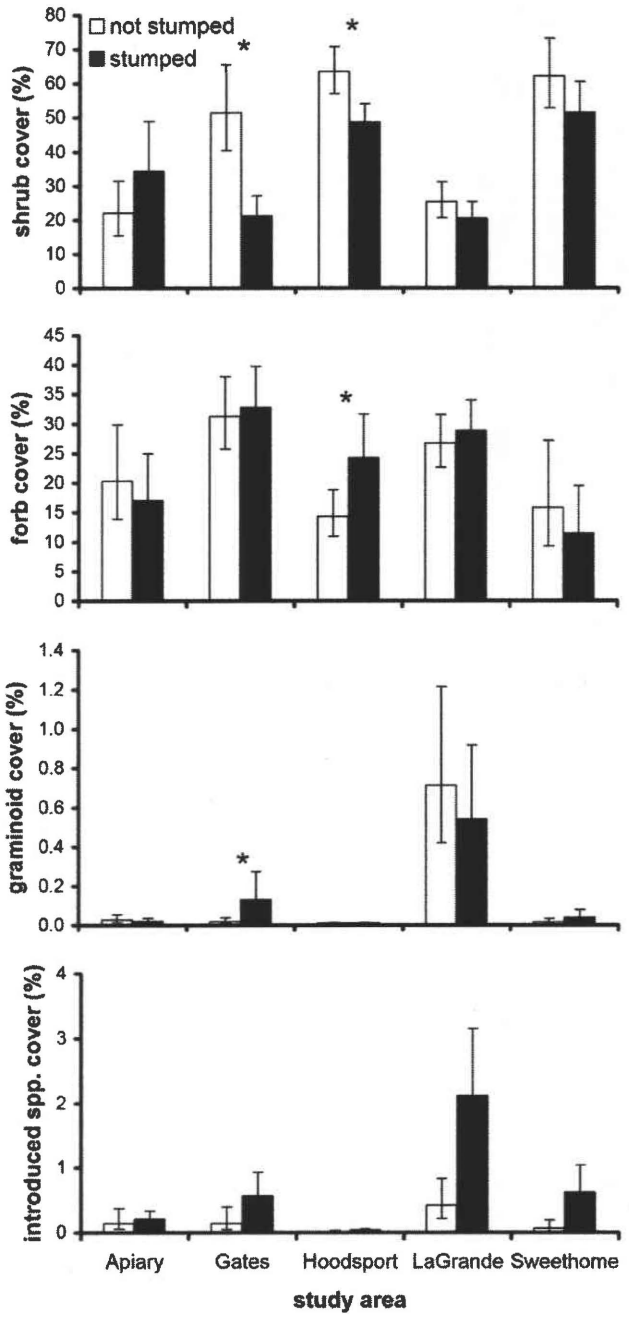

Fig. 2. Mean vegetative cover of shrubs, forbs, graminoids, introduced species and all species combined at each site. Error bars represent 95% confidence intervals. Asterisks above pairs of bars indicate significant differences of $p \leq 0.05$.

Douglas-fir forests. One regionally common shrub, *A. circinatum*, was an indicator of non-stumped plots at three study areas (indicator values: 42.9–62.2). This species of habitats west of the Cascade Range appears to be relatively intolerant of severe disturbances. It has been found to be more abundant in undisturbed forests than in intensively managed sites that were logged and/or burned (**Dyrness, 1973; Halpern, 1988; Halpern and Spies, 1995; O'dea et al., 1995**).

These species-specific trends are consistent with our results with functional groups. For example, forb and graminoid diversity were higher in stumped plots than non-stumped plots at *Gates* and *Sweethome* (**Table 4, Fig. 1**). When analyzed regionally this was also true across all study areas. Forb cover was also higher in stumped plots at *Hoodsport* and graminoid cover was greater with stumping at *Gates* (**Fig. 2**). In contrast, shrub diversity was significantly lower in stumped plots at *Gates* and *La Grande*, and shrub cover was less at *Gates* and *Hoodsport*. Introduced plant diversity was significantly higher in stumped plots across all sites and at *Gates* individually. The noxious weed *B. sylvaticum* was present at *Gates* and accounted for much of this increase at that site. There were no effects unique to one climatic zone (east or west of the Cascade Range).

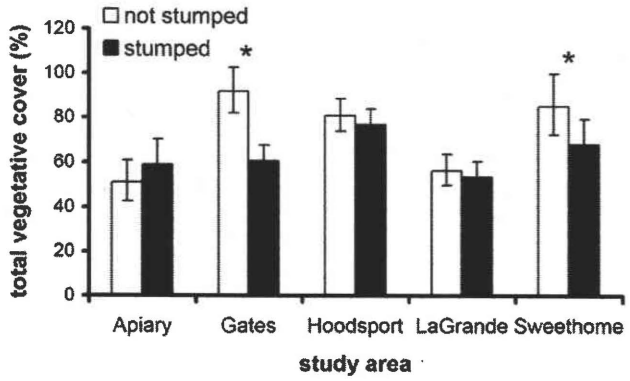

Fig. 3. Mean total cover of understory vegetation at each site. Error bars represent 95% confidence intervals. Asterisks above pairs of bars indicate significant differences of $p \leq 0.05$.

We believe the decline of woody plants in favor of herbaceous species at our study areas is the result of slow recovery of shrubs and changes in soils after stumping. Woody species in general appear to recover more slowly than herbaceous vegetation after forest disturbance, possibly because of reduced establishment and slower growth. For example, when Mou et al. (1993) followed forest succession after harvest for 6 years at the Hubbard Brook Experimental Forest in areas where soils were undisturbed, scarified, or severely disturbed (mineral soil exposed and vegetation removed), they found that woody vegetation was lowest in the most severely disturbed sites. Alban et al. (1994) also found substantial losses of woody vegetation after experimental removal of organic material from the forest floor and soil compaction in harvested forests, despite increased overall species richness. Reduced shrub dominance in forest systems may in turn release herbaceous species from competition. Both Halpern and Spies (1995) and Long (1977) report that during succession after forest canopy disturbance, shrub re-growth had a strong competitive exclusion effect on herbaceous plants resulting in loss of species diversity. The disturbance associated with stumping appears to set back shrubs for decades and allow forbs and graminoids to recover, colonize, and persist with greater diversity and abundance.

It is also possible that the reduction in shrub abundance contributed to increase in tree growth observed in stumped plots at some sites as reported in Thies and Westlind (2005). Shrubs are well known to compete with trees during reforestation in Pacific Northwest USA forests (e.g., Minore and Weatherly, 1994; Erickson and Harrington, 2006).

Intensive forest management practices using heavy machinery for harvest or stump removal can have substantial and lasting effects on forest soil organic (Snider and Miller, 1985) and nutrient (e.g., C, N, S, and P) content for at least a decade (Hope, 2007). Soil evaluations conducted at our study areas show that in stumped plots mineral soil N and carbon concentrations were 20% and 22% lower, forest floor organic horizon depth was reduced by 24%, while soil bulk density (a measure of compaction) was only slightly increased compared to non-stumped areas across all sites (Zabowski et al., 2008). These soil results were generally consistent across all study areas, with the exception of *Hoodsport*, at which only mineral soil N concentrations were reduced by stump removal (Zabowski et al., 2008). In our analyses, the understory vegetation at *Hoodsport* did not stand out as distinct in its response to stumping, but *Hoodsport* along with *Apiary* both displayed no effect of stumping on species richness (Table 4). Differences in soil conditions may have contributed to the slow recovery of shrubs after stumping, and the lower total vegetative cover we observed at *Gates* and *Sweethome* and in analyses across all sites (Fig. 3). Lower soil fertility may also favor greater diversity of herbaceous plants in stumped areas; diversity of herbaceous plants is generally higher when nutrients are less available at the forest floor (Gilliam, 2006).

The effect of soil compaction on tree growth can depend on soil texture. Powers et al. (2005) reported that compaction of clayey textured soils reduced tree biomass, while compaction of sandy soils increased tree growth relative to uncompacted soils in California forests. The effects of compaction on loamy soils was intermediate, with no overall change in tree biomass. The soils at all of our study areas were loamy, and those at *Hoodsport* were sandy loam while those at *Sweethome* were silty clay loam (Table 1). We found no evidence that differences among study areas in soil texture explained the variation in understory response to stump removal.

4.2. N-fertilization

N-fertilization had a significant effect on plant community composition only at *Apiary* (Table 2). At this study area, *P. hookeri* (indicator value: 30) and *T. latifolia* (indicator value: 36.9) were significant indicators of unfertilized plots, while no species were associated with N-fertilization (Table 3). We failed to detect any significant changes in functional group cover, diversity, or total vegetative cover associated with N-fertilization (Table 5). This weak effect of fertilization is consistent with soil analyses at our study areas, which found no significant differences in N or C concentrations between fertilized plots and controls at any of the study areas (Zabowski et al., 2008).

In a review of N-fertilization studies in temperate forests of North America and Europe, Gilliam (2006) noted declines in herbaceous diversity, cover, or biomass after fertilization in four of nine studies. Similarly, herb-layer cover and diversity were lower at sites receiving N compared to controls in one study in an Oregon forest (Thomas et al., 1999). These studies observed vegetation responses 1–9 years after fertilization, which typically occurred multiple times over several years. Olsson and Kellner (2006) measured vegetation in three Swedish forests 15–18 years after multiple N-fertilizations and 5–12 years after clear felling. They found persistent differences in total vegetative cover compared to unfertilized controls at only one site, which was primarily due to changes in moss and lichen abundance, and concluded that the long-term effects of N-fertilization on vegetation were moderate because overall community-types were not altered. Our study included very high doses of N compared to concentrations reported in most studies, but our observations were conducted 22–26 years after application – a longer time period after disturbance than most studies. Our study suggests the effect of fertilization on plant communities may fade with time if additional applications are not made, which may explain why we did not detect changes in vegetation associated with fertilizer.

5. Conclusions

Stump removal to reduce infection of trees by *P. weirii* and slow the spread of laminated root-rot disease had lasting effects on understory vegetation in Northwest USA forests. This intensive forest management practice affected plant community composition over two decades later, but unequally across species groups. Abundance and biological diversity of shrubs were reduced at some sites, but cover and richness of forbs and graminoids increased in stumped areas. Introduced species also invaded stumped plots disproportionately. We found no effects of N-fertilization on forest understory species diversity and abundance,

despite numerous studies showing short-term negative effects. This difference is possibly due to the relatively long period of time that elapsed between N-fertilization and our observations. Stump removal has been shown to reduce tree seedling mortality due to laminated root rot at our study areas, and N-fertilization can increase seedling growth at some sites (Thies and Westlind, 2005). When stump removal is used as a tool to control root-rot diseases in the Pacific Northwest, forest managers should also expect some long-term shifts in local understory plant community composition, diversity and total cover. While increases in introduced species associated with stumping were relatively small, they were widespread. We caution managers that equipment for stump removal should be cleaned prior to use to remove seeds of invasive species, and follow-up control of invasive plants may be necessary in some cases.

Acknowledgments

We thank the landowners and managers who established and maintained this study, provided access to their property, and supported this study by providing land and in some cases funds, road building, stump removal, planting, vegetation control, fencing and thinning. In some cases the land owners and managers changed but the commitment to this long-term study continued: *Apiary* – Started by International Paper Company, continued by Stimpson Timber Company, and subsequently by Weyerhauser Corp.; *Gates* – USDI Bureau of Land Management; *Hoodsport* – Started by Simpson Timber Company and continued by the state of Washington, Department of Natural Resources; *La Grande* – Boise Cascade Corporation; *Sweethome* – Hill Interests (managed by Cascade Timber Consulting). Thanks also to the Sustainable Forestry component of Agenda 2020, a joint effort of the USDA Forest Service Research and the American Forest and Paper Association for funds to complete final data collection and analysis for this paper. We are grateful for statistical assistance by Manuela Huso and Bruce McCune of Oregon State University. This manuscript was improved by careful and useful comments from Robin Rose and Andrea Thorpe, as well as anonymous reviewers.

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