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Decrease in Sapling Nutrient Concentrations for Six Northern Rocky Mountain Coniferous Species

Theresa B. Jain and Russell T. Graham

In the west, fire exclusion, timber harvest, and last century's climate led to copious regeneration on millions of ha that now need tending. Without treatment, overcrowding increases competition, snow and ice damage potential, and ladder fuels. Limited funding prevents treating all of the affected ha, but by selling small trees for wood pellets, biofuel, or methanol, costs would decrease and more ha could be cleaned. In the northern Rocky Mountains, 8–10 tree species can occur in young forests, and until this study, information on foliage nutrient concentrations and leaching from saplings for all of these species was limited. We use a mixed-model analysis to examine the change in nutrient concentrations (calcium, magnesium, potassium, carbon, and nitrogen) remaining in saplings for 6 tree species (western white pine, ponderosa pine, western hemlock, western redcedar, Douglas-fir, and grand fir) over a 12-month period. Nutrient concentrations and the pattern of nutrient leaching did vary among the species, but we found that nutrient concentrations did not diminish in the first 200 days and western hemlock was the only species for which nutrient concentrations leached substantially in the 12-month period. Results suggest managers may need to use biomass utilization thresholds to ensure sufficient biomass is left on site to maintain soil productivity.

Keywords: soil productivity, young forests, small tree utilization, cleanings and weedings, precommercial thinning

The mission of the US Department of Agriculture (USDA) Forest Service includes producing diverse and disturbance-resilient forests and providing wildlife habitat, recreation opportunities, and forest products on public lands without reducing soil productivity (USDA Forest Service 2014, see also the National Forest Management Act of 1976). Throughout much of the western United States, fire exclusion, timber harvesting, and last century's cool and wet climate led to copious regeneration on millions of ha that now need tending. Without treatment, competition limits the growth of preferred species (Thibodeau et al. 2000). Overcrowding also increases susceptibility to snow or ice damage (Christiansen and Pickford 1991), promotes ladder fuels that favor crown fire during wildfires, and enables soil heating that reduces soil productivity by consuming the forest floor and volatilizing nutrients (Fahnestock 1968, Alexander and Yancik 1977, Graham et al. 2004). Managers cannot meet long-term management objectives without tending these young forests.

Nonetheless, limited funding prevents managers from treating all the affected ha. To help reduce the cost of this thinning, some researchers suggest selling small trees for wood pellets, biofuel, or methanol (Kelkar et al. 2006, Polagye et al. 2007). In Finland, for example, small trees provide wood fuel to local heating plants (Malinen et al. 2001, Siren et al. 2006, Heikkila et al. 2007). Similarly, managers in the western United States have also sold small trees to local heating plants and as hog fuel to produce electricity (Neary and Zieroth 2007). In Canada, analysts predict that thinning of young lodgepole pine (*Pinus contorta* Douglas ex Loudon) could produce an estimated 20–33 10^3 kg of feed stock for biorefineries per year (Mabee et al. 2006). Thus, opportunities to sell small trees and enable managers to thin more ha exist. A constant flow of smallwood might also encourage communities to invest in infrastructure, improving local economies that depend on public forests for their livelihood, another key USDA Forest Service objective (USDA Forest Service 2014).

Yet, removing all the cleaning and weeding residues (slash) produced by such thinning also risks decreasing soil productivity. Residues from cleaning and weeding keep the forest floor cool and moist and thereby enhance nutrient mineralization, and as the

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Affiliations: *Theresa B. Jain (tjain@fs.fed.us), USDA Forest Service, Rocky Mountain Research Station, Moscow, ID. Russell T. Graham (rtgraham@fs.fed.us), USDA Forest Service.*

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; millimeters (mm): 1 mm = 0.039 in.; kilograms (kg): 1 kg = 2.2 lb; grams (g) 1 g = 0.035 oz; milligrams (mg): 1 mg = 0.015 gram; hectares (ha): 1 ha = 2.47 ac.

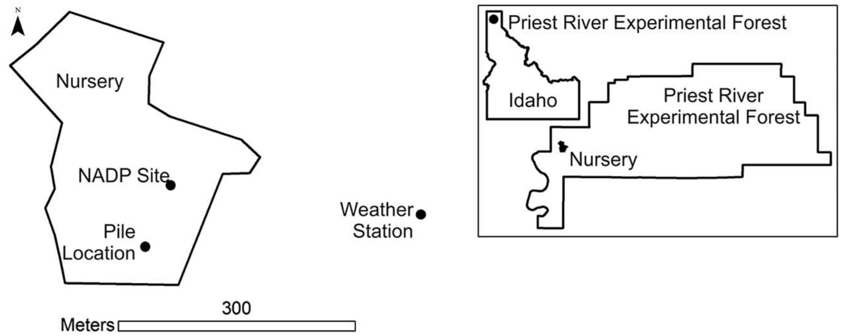

Figure 1. The study area was located on Priest River Experimental Forest (PREF) nursery in northern Idaho. We collected trees from places surrounding the nursery (the outline is the nursery fence) and used the nursery as an open area and common surface to place piles and measure the change in nutrient concentrations over time. The weather station is 350 m east of the pile location and the National Atmospheric Deposition Program site is 80 m north of the pile location.

residues decompose, they release nutrients for residual vegetation (Carlyle 1995). One study revealed that without such residue, the annual growth of Scots pine (*Pinus sylvestris* L.) decreased by 56% over 4 years, and other researchers haves found an 8–13% decrease in annual growth over 10 years (Jacobson et al. 2000, Helmisaari et al. 2011). Although fertilizer can offset productivity losses, the expense can outweigh the economic benefit from selling wood fuel, making this option impractical. Furthermore, managers cannot forego soil productivity to maximize smallwood utilization regardless of the potential economic opportunities (Page-Dumroese et al. 2010).

To properly balance smallwood utilization and soil fertility, scientific information concerning the nutrient dynamics of saplings from various species is needed. In the northern Rocky Mountains, up to 10 tree species can grow on moist mixed-conifer forests, and thus obtaining baseline and decreases in nutrient concentrations of felled saplings over time is a critical first step in gaining this knowledge. Although researchers have determined the total nutrient concentrations of several Rocky Mountain species (Will and Youngberg 1979, Graham 1982, Edmonds 1987, Mandzak and Moore 1994, Garrison et al. 2000, Moore et al. 2004), each of these studies focused on one or just a few species and determined nutrient concentrations from mature trees (>15 cm dbh [1.5 m]) rather than small trees, which may have different physiological and nutrition characteristics (Korol 2001, Steppe et al. 2011). Scientists who have conducted nutrient leaching studies have concentrated on mass and nutrient loss in slash piles created from commercial harvesting, which also have physical characteristics different from those of slash created by cleanings or weedings[1] (e.g., Edmonds 1987, Sánchez et al. 2010).

As the first stage of a proposed three-stage research project, we conducted the following experiment to analyze the change in nutrient concentrations of multiple species over 12 months to determine the possible benefits of delaying tree removal to allow nutrients to leach from freshly cut saplings. The species we selected were western white pine (*Pinus monticola* Douglas ex D. Don), ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), Douglas-fir (*Pseudotsuga menziesii* (Mirb.), grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), western redcedar (*Thuja plicata* Donn ex D. Don), and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). For each species, we evaluated the total nitrogen, carbon, calcium, potassium, and magnesium concentrations immediately after cutting, and then for the following 12 months, we determined the nutrient concentrations remaining in the slash approximately every 28 days. To identify any corollary responses between changes in nutrient concentrations over time, we also examined changes in concentrations related to atmospheric deposition, temperature, relative humidity, and precipitation.

Materials and Methods

Study Area

The saplings were collected at the Priest River Experimental Forest (PREF), and the study took place within a 4-ha nursery inside the PREF compound (Figure 1). The Experimental Forest in northern Idaho, USA, represents the most common forest types and climate of the northern Rocky Mountains. The PREF comprises 2,590 ha and a wide range of elevations (680–1,800 m) and slope aspects and angles (5–70%). Intermittent maritime and continental climates create diverse weather patterns in the forest, favoring dry summers and wet winters. Precipitation averages 817 mm (32 in.), with the greatest accumulation of moisture arriving as snow during the winter (January through March). Summers are usually sunny and dry in July and August, with intermittent rain in the early spring and fall. Average mean temperature is −4° C in January and 18° C in July (Finklin 1983). Soils surrounding the nursery are ashy, glassy, frigid Andic Fragiudalfs with a thick (>30 cm) mantle of volcanic ash overlaying belt series parent material (Soil Survey Staff, Natural Resources Conservation Service 2014). Depending on elevation, aspect, and ash cap depth, five major forest types occur in the PREF, subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), grand fir, western hemlock, Douglas-fir, and western redcedar. Lodgepole pine, ponderosa pine, western larch (*Larix occidentalis* Nutt.), and western white pine are seral species and are abundant and can grow on one or more of these forest types.

Experimental Design and Sampling

We used a replicated (3 replicates) random design to quantify the depletion of carbon, nitrogen, potassium, magnesium, and calcium concentrations for six tree species (western white pine, ponderosa pine, Douglas-fir, grand fir, western hemlock, and western redcedar) during the study. Our sampling was conducted as follows.

Because nutrient concentrations vary by species and by site (Moore et al. 2004), we collected our saplings from the same elevation, soils, ash cap depth (>30 cm), and (with one exception) forest type. All but one of the sampled species came from the western

Table 1. Sampling began at time of cutting on Oct. 26, 2004 and continued monthly during a 12-month period.

Time	Collection date	Slash pile no. (per replicate)	No. of saplings per species	Days between sampling	Days since harvested
Time 0	Oct. 26–28, 2004		3		0
Time 1	Nov. 22, 2004	1	3	27	27
Time 2	Dec. 20, 2004	2	3	28	55
Time 3	Jan. 18, 2005	3	3	29	84
Time 4	Feb. 14, 2005	4	3	27	111
Time 5	Mar. 14, 2005	5	3	28	139
Time 6	Apr. 11, 2005	6	3	28	167
Time 7	May 9, 2005	7	3	28	195
Time 8	June 6, 2005	8	3	28	223
Time 9	July 5, 2005	9	3	29	252
Time 10	Aug. 3, 2005	10	3	29	281
Time 11	Aug. 31, 2005	11	3	29	310
Time 12	Sept. 26, 2005	12	3	26	336

Three whorls from each sapling (needles and fine twigs) were taken from western white pine, ponderosa pine, Douglas-fir, grand fir, western hemlock, and western redcedar and placed into one bag for each measurement period, resulting in 18 samples per measurement period.

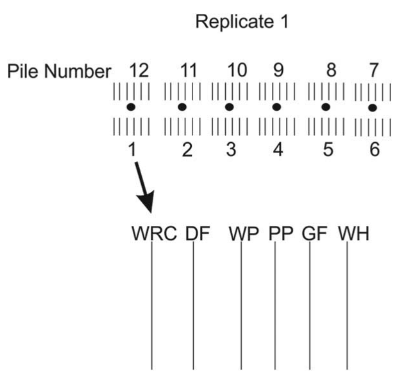

Figure 2. The sampling design was a replicated (3 times) random design and contained six species, western redcedar (WRC), Douglas-fir (DF), western white pine (WP), ponderosa pine (PP), grand fir (GF), and western hemlock (WH). For each replicate, trees were randomly assigned to 1 of 12 piles. Posts labeled with sampling date (indicated by ●) were used to find piles under the snow. This prevented the piles from being disturbed until they were ready to be sampled. The trees were placed parallel to each other in contact with the soil surface within each pile.

hemlock forest; the ponderosa pine (which is not common in western hemlock forests) came from a western redcedar forest. All saplings were similar in size (5 cm dbh and <3 m tall) and age (10–15 years), were open grown, and were transported to the pile location at the time of cutting (Figure 1).

To avoid rain and snow interception from overstory trees, we placed our saplings in the nursery 50 m from the canopy edge. Each of the three replicates included 12 piles (representing 12 measurement periods), for a total of 36 piles. Within each pile, one tree of each species was laid 1 m apart and parallel to the others in contact with the ground (Figure 2; Table 1). We identified the replicate, pile, and sampling date on a tag attached to a post next to each pile.

At the time of cutting and at each designated measurement time, we sampled all six species from one pile within each of the replicates (Table 1). For example, pile 1 from all replicates was sampled on Nov. 22, 2004. To ensure that we obtained a nutrient concentration that reflected the potential variation in the crown, we obtained 3 samples (fine branch with needles attached) per sapling, one each from the lowest branch, the middle of the crown, and the top branches (all trees had >80% crown ratio, and each tree had a minimum of 5 complete whorls of branches [circular arrangement of branches around a point on the stem]). We selected branches that had at least 3 years' needle retention to make sure we had sufficient foliage to conduct the analysis. We combined all three samples from a given sapling in one paper bag with a unique identifier (replicate, species, and measurement period). Each sampling period thus produced 18 bags of twigs with needles attached. In one case (western hemlock), needles detached from the twigs during the study period, and we then collected the detached needles and the twigs.

We obtained daily weather conditions and monthly atmospheric deposition readings during the study period from the National Atmospheric Deposition Program[2] site (80 m from pile location) and weather station at the PREF compound (350 m from the pile location).

Laboratory Procedures

In the laboratory, we prepared the collected samples to analyze their magnesium, calcium, potassium, carbon, and nitrogen concentrations. Samples were dried at 60° C for 48 hours after which magnesium, calcium, and potassium analysis required a coarse-ground sample, and carbon and nitrogen analysis required a fine-ground sample. We used a Thomas Wiley Laboratory Mill (model 4 3375-E 10 series) to obtain the coarse-ground samples. After each sample was ground, we cleaned the mill using a brush and a vacuum to remove the material. When pitch began to build up or when we started grinding a different species, we cleaned the grinder with alcohol (2-propanol). To create a sample for fine grinding, we used the ELE international model CL-280 soil splitter to obtain a subsample from the coarse-ground sample. This representative sample was then fine-ground with a Wiley Mini Mill until it could pass through a 40-mesh screen (0.425 mm).

Two laboratory analyses were conducted. To determine the organic cation concentration, a coarse-ground sample weighing 1.0 g was heated for 5 hours at 475° C (Jones and Case 1990). Through this process, the organic matter combusted, leaving ash. We used 2 N nitric acid to extract the organic cations and added deionized water to produce a 50-ml sample. The extracted samples were analyzed on a PerkinElmer 5100PC atomic absorption spectrophotometer. Results are reported in mg kg^{-1}. To determine carbon and nitrogen levels, fine-ground samples between 0.2000 and 0.2099 g were analyzed on a LECO CHN 2000 (LECO Corporation, St. Joseph, MN). Results are reported in g kg^{-1}.

Statistical Analysis

We conducted three statistical tests ($P \leq 0.05$) using the general linear mixed model (Schabenberger and Pierce 2002, Littell et al. 2006) from the SAS GLIMMIX procedure (SAS 9.3) (SAS Institute, Inc. 2012). In the first test, we determined whether there were statistically significant differences in nutrient concentrations among the species. We conducted multiple comparisons among the means using the Tukey-Kramer approximation (Littell et al. 2006). For the second test, we used a generalized linear model with time as a repeated measure because each tree was measured twice (at time 0 and again at the prespecified sampling date) (Schabenberger and Pierce 2002, Littell et al. 2006). For this repeated-measures analysis, we used the Kenward-Roger method for computing denominator degrees of freedom and used compound symmetry to model our covariance structure. In the third test, we analyzed the relationship

Table 2. Estimated least squares mean and SE using the Tukey-Kramer adjustment for nutrient concentrations at time 0.

Species	Least squares mean (SE)	Significant differences
Magnesium (mg kg^{-1})		
Western hemlock	1,186 (56)	A
Western white pine	1,085 (57)	AB
Ponderosa pine	984 (57)	BC
Western redcedar	923 (57)	C
Douglas-fir	913 (56)	C
Grand fir	891 (56)	C
Potassium (mg kg^{-1})		
Ponderosa pine	5,815 (169)	A
Grand fir	5,602 (168)	A
Douglas-fir	5,242 (168)	AB
Western hemlock	5,220 (168)	AB
Western white pine	4,726 (170)	BC
Western redcedar	4,207 (170)	C
Calcium (mg kg^{-1})		
Western redcedar	11,797 (364)	A
Grand fir	10,104 (360)	A
Douglas-fir	6,431 (360)	B
Western hemlock	4,633 (360)	C
Western white pine	2,449 (365)	D
Ponderosa pine	1,778 (362)	D
Nitrogen (g kg^{-1})		
Ponderosa pine	13.2 (0.2)	A
Douglas-fir	10.8 (0.2)	B
Western white pine	10.7 (0.2)	B
Grand fir	8.4 (0.2)	C
Western hemlock	8.2 (0.2)	C
Western redcedar	7.1 (0.2)	D
Carbon (g kg^{-1})		
Douglas-fir	500.8 (0.8)	A
Western hemlock	497.8 (0.8)	AB
Western white pine	497.5 (0.8)	AB
Ponderosa pine	496.3 (0.8)	B
Grand fir	490.0 (0.9)	C
Western redecear	485.1 (0.8)	C

Depending on the nutrient, the ranking varied among the species (different letters indicate significant differences).

Table 3. Nutrient concentration *P* values.

Nutrient	Species	Time	Time by species
Magnesium	0.0092	0.0005	0.0001
Potassium	<0.0001	<0.0001	<0.0001
Calcium	<0.0001	0.1917	0.4998
Nitrogen	<0.0001	<0.0001	0.0016
Carbon	<0.0001	<0.0001	0.0841

Calcium did not change over the sampling year (time), and thus there was not a significant species × time interaction. However, magnesium, potassium, and nitrogen did significantly change among the species over the sampling year (significant time × species interaction). Although carbon did change over time, the interaction was not statistically significant ($P > 0.05$).

between maximum and minimum temperature, precipitation, and snow accumulation and change in nutrients over time using linear regression where time was the repeated measure. We characterized a nutrient concentration curve associated with each species using a semiparametric regression with Loess smoothing (Schabenberger and Pierce 2002). We report the results of these analyses in days since harvest, with harvest equal to time 0 and our last day of collection 336 days later.

Results

Nutrient Concentrations among Species

At time of cutting, nutrient concentrations did differ significantly among species, but the disparity in nutrient concentrations among them varied, depending on the particular nutrient (Table 2). For example, we noted a large disparity in calcium concentrations among the species. Western redcedar and grand fir had >10,000 mg kg^{-1} more calcium than the pines (western white pine and ponderosa pine), which had <2,500 mg kg^{-1}. Western hemlock and Douglas-fir had 6,400 and 4,800 mg kg^{-1}, respectively. Although the differences in potassium and magnesium concentrations were also statistically significant, the disparity among the species was less than the calcium concentrations. For example, there was only a 1,600 mg kg^{-1} difference in potassium concentration between western redcedar (5,815 mg kg^{-1}) and ponderosa pine (4,206 mg kg^{-1}), and magnesium concentrations varied only 295 mg kg^{-1} between western hemlock (1,186 mg kg^{-1}) and grand fir (891 mg kg^{-1}). Nitrogen concentrations were significantly different among the species. The nitrogen concentration of Western redcedar was 7.1 g kg^{-1}, which was close to half the concentration of ponderosa pine (13.2 g kg^{-1}). Carbon concentrations ranged from 485 to 501 g kg^{-1}. The highest carbon concentrations (500 g kg^{-1}) occurred in Douglas-fir and were significantly different from those of western redcedar (485 g kg^{-1}) or grand fir (490 g kg^{-1}). Western white pine, western hemlock, and ponderosa pine had statistically similar carbon concentrations, ranging from 496 to 498 g kg^{-1}.

Change in Nutrient Concentrations

Over the study period, our analysis revealed a significant time × species interaction ($P < 0.05$) for potassium, magnesium, and nitrogen concentrations (Table 3). Although calcium concentrations differences among the species were significant, they did not change over time ($P = 0.19$) nor was there a significant interaction with species ($P = 0.48$). The carbon concentration was significantly different among species and did decrease over time, but this decrease was similar across all species and thus did not show a time × species interaction ($P = 0.08$).

The nutrient concentrations varied among the species over time (Figures 3 and 4). Western hemlock, in particular, appeared more susceptible to decreases in magnesium and potassium concentrations. For example, western hemlock's potassium concentration decreased by 67% over the measurement period, compared with only 12% for western white pine (Figure 3). Magnesium concentrations increased for all species except western hemlock, where its concentration decreased by approximately 528 mg kg^{-1} by the end of the 12 months (Figure 3). For carbon, however, we did identify a notable decrease in concentration in relation to the species' shade tolerance. Carbon concentrations in Western hemlock and western redcedar (the most shade-tolerant species) tend to decrease more rapidly than those in grand fir and Douglas-fir (moderately shade-tolerant), followed by the pines (least shade-tolerant), which had the slowest rate of decrease in carbon concentrations (Figure 4). Total nitrogen concentrations either stayed relatively constant over time or showed a slight increase in the pines, grand fir, and Douglas-fir. Although there was variation over the year, western redcedar had similar nitrogen concentrations at time 0 and 336 days later (Figure 4). Western hemlock again had the greatest decrease in nitrogen concentration, but it was only 0.25%.

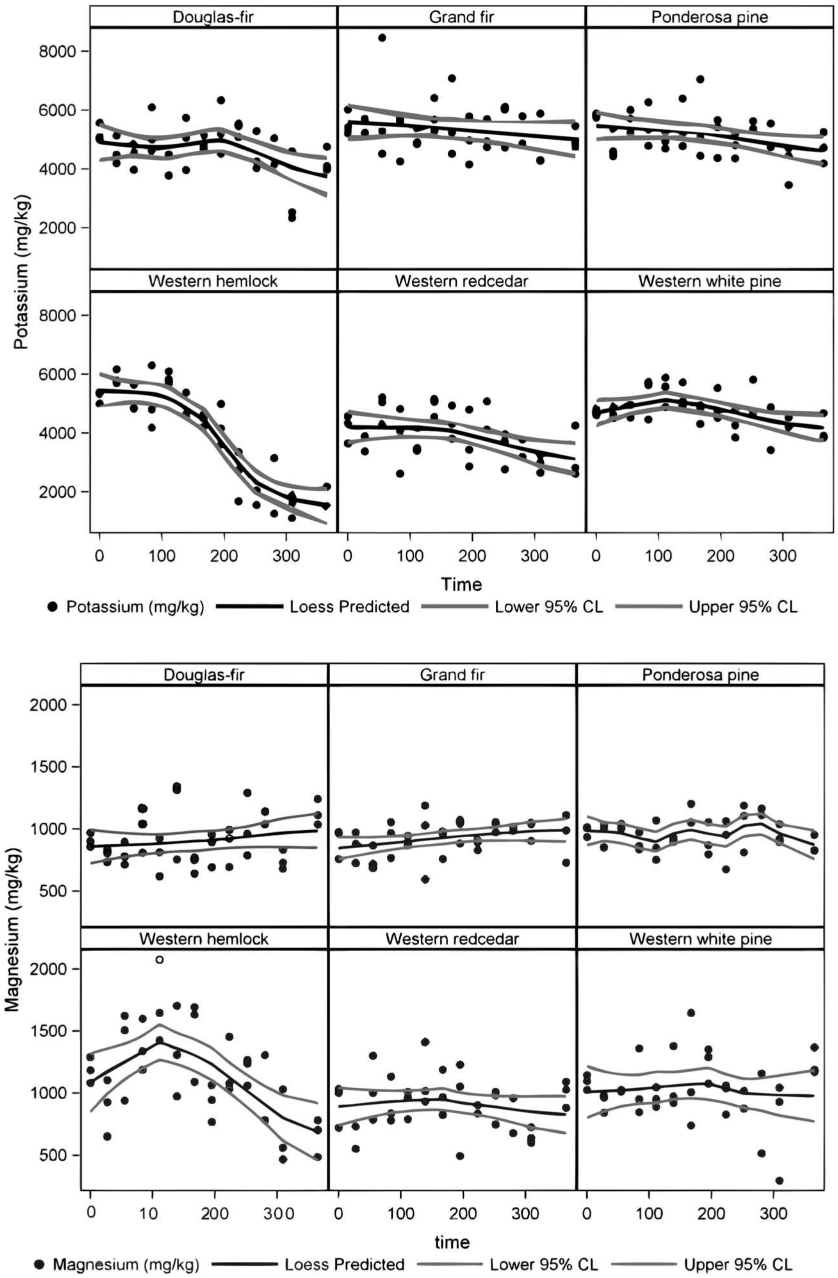

Figure 3. Changes in potassium and magnesium concentrations over time (days since harvest). These are the results of loess smoothing (predicted and confidence intervals) showing the change in concentrations over time. Magnesium and potassium concentrations begin to decrease in Western hemlock, western redcedar, and Douglas-fir begin to decrease after approximately 100, 150, and 200 days, respectively. Although the other species also showed a negative slope, their concentrations did not diminish as substantially as those in the other three species. CL, confidence limits.

The effects of weather variables on nutrient concentrations varied among the species, although atmospheric deposition did not appear to influence foliage nutrient concentrations. Over the period of study, only the potassium levels in the western hemlock were related significantly ($P < 0.0001$) to changes in maximum temperature, decreasing as temperatures increased during the summer months. The other species did not demonstrate any changes related to temperature. Interestingly, precipitation, snow, and snow accumulation did not have any relation to the amount of nutrients remaining in the slash. Although nutrient concentrations from atmospheric deposition during our study period contributed an average of 0.06 mg liter^{-1} of calcium and 0.009 mg liter^{-1} of magnesium per month, this input did not significantly influence the nutrient concentrations.

Discussion

Nutrient concentrations of forests vary as a function of their soil, stand age, and species composition (Johnson et al. 1982, Radwan and Brix 1986). The samples in this study were obtained from one of the more productive sites in the northern Rocky Mountains, but one with a deep ash cap that contains its own mineralogical characteristics (McDaniel et al. 2005); our sampled trees were also young (<15 years old) and growing in stands that have yet to reach complete canopy closure (Johnson et al. 1982). These factors may help explain

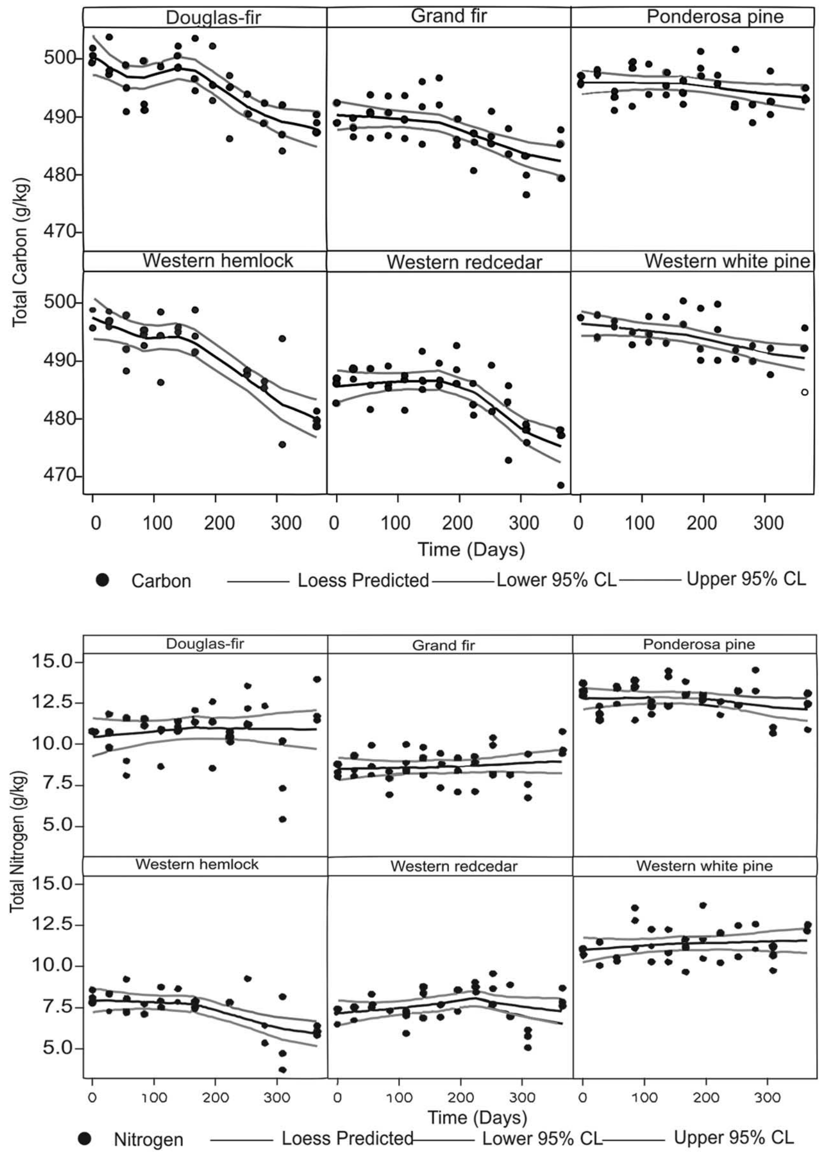

Figure 4. Changes in total carbon and nitrogen concentrations over time (days since harvest). Total carbon concentrations decrease in western hemlock, western redcedar, Douglas-fir, and grand fir after 120–150 days, whereas western white pine and ponderosa pine showed very small changes in total carbon concentrations over the year we sampled. The nitrogen concentration increased or stayed the same in all of the species but western hemlock. CL, confidence limits.

Table 4. Foliar nutrient concentrations reported by other scientists from mature trees and from different locations.

Nutrient concentration	Douglas-fir*†	Grand fir*†	Ponderosa pine†‡	Western hemlock†‡	Western redcedar†‡	Western white pine†§
Magnesium (mg kg^{-1})	2,350	1,520	1,114	1,440	1,460	1,100
Potassium (mg kg^{-1})	10,510	13,790	9,580	7,700	7,700	6,000
Calcium (mg kg^{-1})	5,310	10,860	1,640	2,800	6,800	3,500
Nitrogen (g kg^{-1})	13	12	14	13	17	15
Carbon (g kg^{-1})	475	478	499	473	466	473

* Western redcedar and western hemlock concentrations obtained from productive sites (western redcedar/devils club [*Oplopanax horridus*] were obtained from Kranabetter et al. (2003).
† Carbon concentrations were obtained from Jain et al. (2010).
‡ Grand fir, Douglas-fir, and ponderosa pine nutrient concentrations growing on productive sites were obtained from Moore et al. (2004).
§ Western white pine nutrient concentrations for calcium and potassium were obtained from Larkin et al. (2012); magnesium concentrations were obtained from Will and Youngberg (1979); and nitrogen concentrations were obtained from Cernusak and Marshall (2001).

the differences between our results and those reported in other studies (Table 4). Most notably our saplings tended to have higher calcium concentrations for western redcedar, western hemlock, grand fir, and Douglas-fir than the values reported by Kranabetter et al. (2003) and Moore et al. (2004) (Table 4). However, our saplings had lower potassium, magnesium, and nitrogen concentrations than those reported by several other researchers (Cernusak and Marshall 2001, Kranabetter et al. 2003, Moore et al. 2004, Larkin et al.

2012). These differences, which therefore appear to be based on factors other than species, suggest that forest managers will need to develop site-specific and not merely species-specific recommendations for biomass utilization across sites.

Our results indicate not only that nutrient concentrations vary among species, but also, more importantly, that their nutrient concentration-specific rankings also varied (Table 2). For example, grand fir had calcium concentrations of $>$12,000 mg kg^{-1}, whereas white pine had $<$2,500 mg kg^{-1}, but grand fir had significantly lower magnesium concentrations than western white pine. Other researchers who observed only one or a small number of species typically have not identified the different nutrient concentration levels of various tree species. Furthermore, our cross-species nutrient concentrations were not consistent with those of previous research (Table 4). For example, whereas Moore et al. (2004) noted that grand fir and Douglas-fir tended to contain high potassium concentrations and ponderosa pine had relatively low potassium concentrations, we found that ponderosa pine ranked higher in potassium concentrations than Douglas-fir and grand fir. Moore et al. (2004), by collecting foliage from trees across different site and tree ages, demonstrated the broad range in nutrient concentrations across sites. In addition to these differences across sites, our study also suggests that the ranking phenomenon among species can be identified and verified only by obtaining data from the full suite of potential species at one site.

Cleaning and weeding can reduce tree densities by 98% in some forest types. For example, in northern Rocky Mountain moist mixed-conifer forests and productive ponderosa pine forests such as those located in the Black Hills, South Dakota, plantations can exceed 50,000 trees ha^{-1} (Haig et al. 1941, Boldt et al. 1983). It is also not uncommon to have $>$750 trees per ha^{-1} growing on less productive ponderosa pine forests in the southwestern United States (Covington and Moore 1994). Typical residual tree densities after cleanings range from 250 to 1,000 trees ha^{-1}, depending on the forest productivity, species, and objectives (e.g., Deitschman 1966, Reukema 1975, Curtis 2008). In the southwestern United States, if the objective was to reduce tree density to reflect historical densities (before Euro-American settlement) of approximately 250 trees ha^{-1}, a cleaning could potentially remove 60% of the trees (Covington and Moore 1994). In the northern Rocky Mountains and Black Hills, even with target tree densities of 1,000 trees ha^{-1}, 98% of the trees are cut. Currently the biomass from such cleanings is left on site, but if the trees are harvested for biofuel, then biomass utilization decisions would need to consider the potential effects on soil nutrition. Our results suggest that managers may need to consider specific species' nutrient concentrations and comparative rankings and tailor their cleaning and weeding prescriptions to incorporate species-specific biomass utilization thresholds to ensure that sufficient soil nutrients are available for residual tree growth and productivity.

Previous findings have indicated that except for Douglas-fir, carbon concentrations are rarely greater than 50%, and scientists currently estimate that carbon makes up 500 g kg^{-1} of total biomass (Linder and Axelsson 1982, Hendrickson 1990, Grigal and Ohmann 1992, Lamlom and Savidge 2003). Our results, while generally consistent with these assumptions, also indicate that there are significant differences among species and that growing conditions of saplings support our earlier finding that subtle changes in concentrations can influence the content and distribution of carbon in forests (Jain et al. 2010). The average carbon concentrations in our open-grown saplings ranged from 48.5 to 50.1 g kg^{-1}, which tended to be greater than previously reported carbon concentrations from similar trees growing underneath the canopy (Jain et al. 2010).

Our findings also seem consistent with the hypothesis of Swift et al. (1979) and Staaf and Berg (1982) that nutrient concentration increases and decreases are a function of the immobilization and mobilization cycle that occurs during decomposition and are dependent on the molecular form of the needles, foliar age, crown position, and season of year. Over the course of the 12 months of our study, none of the species except western hemlock showed substantial decreases in fine branch and needle nutrient concentrations, seemingly indicating a period of immobilization. Even with the western hemlock, nutrient concentrations did not begin to decrease until the needles detached from the stem 100 days after harvest and only then did nutrient concentrations begin to significantly decrease in our samples. In contrast, the needles on the other species never detached from the stem during this period. Previous researchers have argued that calcium concentrations in particular appears to be resistant to mobilization because it is locked in cell walls and therefore takes more time to decompose (Swift et al. 1979, Staaf and Berg 1982).

Our results complicate future biomass utilization opportunities. If biomass utilization is to be an option, nutrient management thresholds for the minimum amount of biomass that should remain to avoid nutrient depletion will have to incorporate species composition and match site productivity requirements for certain nutrients. In some cases, removing biomass may actually prove counterproductive. Another option may be to delay biomass utilization of conifer trees until the needles fall from the stems and remain on site, although this strategy may also diminish the quality of the material for fuel stocks (Nurmi and Hillebrand 2007).

This study is but the first stage of a three-stage research project. Our proposed second stage will focus on quantifying smallwood biomass as a function of species composition across a soil productivity gradient. Biomass estimates subsampled from multiple sites coupled with our current results could provide an estimate of the nutrient capital as a function of variation in biomass. The third stage of this investigation will subsample a set of sites from stage two and vary the levels of residue to identify biomass utilization thresholds. Strategically, this approach would seem a useful and practical middle ground between addressing all three objectives on one site, which limits a study's scope and relevance, and attempting to gather all the required data (nutrient, leaching, decomposition, and biomass) from many sites, which can become too expensive and logistically difficult to implement.

Conclusion

Smallwood biomass utilization potentially offers many benefits to society and may provide funding that can be used to increase the tending of young forests, but we should not ignore the importance of understanding and maintaining nutrient levels in management activities. Although the results of this first stage of our proposed research highlight the variation in nutrient concentrations among different species, our findings that nutrients do not leach from small trees quickly and that the most likely leaching of nutrients occurs when needles detach from the branches raises questions about the viability and wisdom of small tree utilization. Thus, we will need scientists to investigate and develop biomass utilization parameters based on species composition and abundance that will most likely vary depending on the soil and the productivity of a given site. Although smallwood biomass removal is still a viable option, species composition and abundance coupled with site productivity and nutrient limitations must be considered to identify an optimal balance between nutrient management and biomass utilization.

Endnotes

1. Weeding eliminates or suppresses undesirable vegetation regardless of crown position and a cleaning favors individual trees by eliminating or suppressing undesirable individuals of the same age class (Society of American Foresters 1998).
2. For more information, see nadp.sws.uiuc.edu/nadp/.

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