

Nutrient Management: A summary and review

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Introduction

The Intermountain Forest Tree Nutrition Cooperative has carried out forest fertilization trials and forest nutrition and health monitoring activities in the inland northwest since the early 1980's. Over the course of this time period several trends in forest nutrition have become obvious, some of which are supported by data and some of which are based on observation and are currently being researched. This paper provides a summary of these trends and findings, and also provides an extensive literature review of current and older findings related to forest nutrient management and health. The report is organized into three parts. The first is a general review of nutrients in the environment, and the role of the various nutrients in tree growth and health. The second section provides coverage of basic species nutritional ecology for the major species in the inland northwest. The third part of this document reviews information on silvicultural activities and the effects of biomass removal, slash treatments and site preparation on nutrient pools. Literature citations are included at the end of each section. A short list of additional literature reviews on intensive forest harvesting is included on the final page.

The Nutrient Environment

Nutrients are those elements which are considered essential for plant growth. Three of these elements, carbon (C), hydrogen (H), and oxygen (O), are provided by the air, earth and water, and are not considered limiting factors to plant growth (Mahler 1997). Six elements, nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), sulfur (S), and magnesium (Mg), are considered the macronutrients, which means that plants require these in relatively large quantities (500-14000 ppm) in order to grow and function adequately (Foth and Ellis 1997). A number of other nutrients are required in trace quantities (usually <100 ppm) for plant growth, and these are known as micronutrients. Eight elements are currently considered micronutrients, and more will probably be added to this list over time as equipment detection levels and research techniques improve. Tables 1a and 1b respectively list the macro and micronutrients, their principal functions in higher plants, and their sources.

The nutrient sources listed in Tables 1a and 1b indicate that most elements derive from rocks. The knowledge that most nutrients derive from rocks, which form the soil parent materials, allows us to get a landscape-level view of nutrients in the forest environment. Geologic maps are available for all of the inland northwest (Washington DNR, Idaho Geologic Survey, Montana Bureau of Mines and Geology, U.S. Geologic Survey). Geologists commonly identify and classify rocks based on their chemical composition, or their geochemistry. Rocks may also be classified based on their mineral content, or their petrography. These two diagnostic procedures provide information on the elemental content of rocks (geochemistry) and the mineral form the elements are in (petrography). The three broad rock types most common in our area are granites, basalts, and metasedimentary rocks.

Tables 1(a): The macronutrients -- their function and source, and 1(b): The micronutrients -- their function and source All information on nutrient function is taken from Marschner (1995) except for those indicated by (1) which are based on IFTNC research. An asterisk indicates that this nutrient is available in fertilizer form.

Table 1(a): The macronutrients -- their function and source

Symbol	Element	Function	Source
N*	Nitrogen	Biomass production ¹ Photosynthesis (proteins) ¹	Organic matter N-cycle
K*	Potassium	Disease resistance ¹ Osmotic potential, turgor Enzymatic transfer of glucose to starch Nitrate synthesis Photosynthesis and CO ₂ fixation	Parent material
P*	Phosphorus	Structural constituent of DNA and RNA Basal metabolism (ATP and energy transfer) Photosynthesis (carbon partitioning)	Parent material
S*	Sulfur	Photosynthesis (proteins) Membrane structure Some defense substances	Atmosphere Parent material
Ca*	Calcium	Structural component (cell walls, membranes)	Parent material
Mg*	Magnesium	Chlorophyll Protein synthesis Enzymes and enzymatic reactions Carbohydrate partitioning	Parent material

Table 1(b): The micronutrients -- their function and source

Symbol	Element	Function	Source
Fe*	Iron	Chloroplast development, photorespiration Enzymatic reactions	Parent material
Mn*	Manganese	Enzymatic reactions Photosynthetic O ₂ evolution	Parent material
Cu*	Copper	Nitrogen metabolism (NOTE: High N rates can induce Cu deficiency!) Cell wall lignification Pollen formation and fertilization Carbohydrate and lipid content Enzymatic reactions	Parent material
Zn*	Zinc	Metabolic functions Complexes with N, O and S DNA replication Regulation of gene expression (NOTE: High P rates can induce Zn deficiency!)	Parent material
Ni	Nickel	N metabolism	Parent material
Mo*	Molybdenum	N metabolism N ₂ -fixation May affect pollen formation/fruit formation Critical level increases with increasing N supply	Parent material
B*	Boron	Cell wall biosynthesis and structure Plasma membrane integrity Root elongation, apical dominance Deficient B associated with <i>Eucosma</i> sp. borer ¹	Parent material
Cl*	Chlorine	Photosynthetic O ₂ evolution Stomatal regulation	Parent material Atmosphere

The following charts show both the geochemistry and the petrography for sample rock types in our area. The first two charts (Figures 1a and 1b) show major and trace element geochemistry, the third (Fig 1c) indicates which minerals contain which elements, and the fourth (Fig 1d) shows petrography for the same rocks. Essentially, the basalts tend to have the lowest silica (SiO_2) content and greater quantities of important cations, as well as greater quantities of the trace elements Fe, Cu and Zn (Figures 1a and 1b). Furthermore, these nutrients tend to be held in minerals which are somewhat more susceptible to weathering than the minerals which comprise granites and metasedimentary rocks (Figure 1d). Generally speaking, the metasedimentary rocks have very little in the way of macro or micronutrients, tending to be comprised largely of silica and little else. The silica in the metasedimentary rocks is primarily in the form of quartz, a mineral extremely resistant to weathering.

Figure 1a: Geochemical averages for major elements for three common northwest rock types. Geochemical values for six major elements were averaged for three rock types common to the inland northwest. Basalts generally showed the lowest amount of SiO_2 and the greatest amount of other elements. Generally, the less SiO_2 is present, the more of the other elements are present.

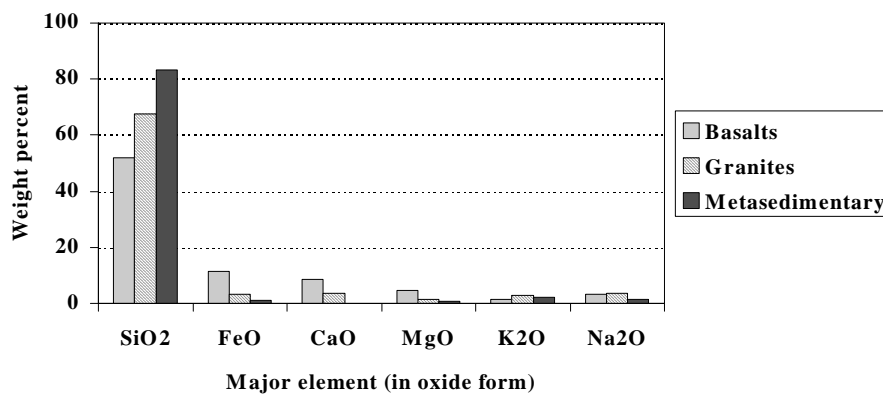


Figure 1b: Geochemical averages for trace elements for three common northwest rock types. Geochemical values for two trace elements were averaged for three rock types common to the inland northwest. Basalts generally showed the greatest amounts of both elements by weight, followed by granite and metasedimentary rocks, respectively.

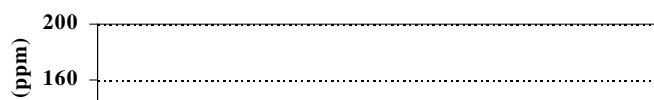
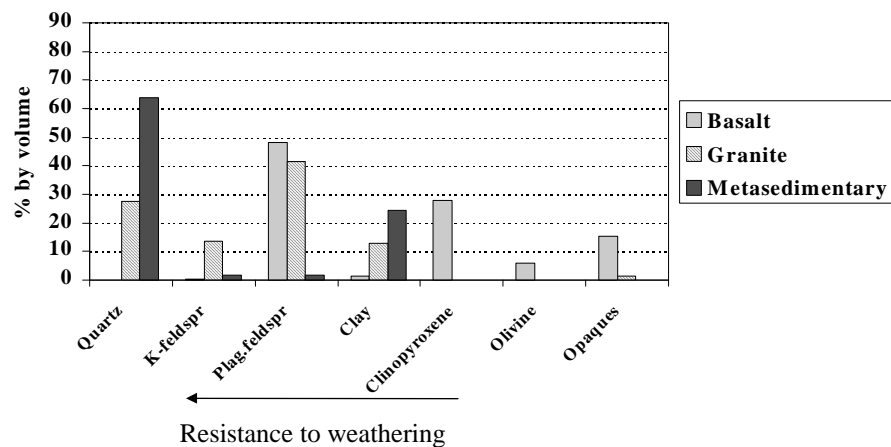


Figure 1c: Common minerals and their possible constituents. Minerals commonly found in rocks of the inland northwest are listed on the left, and their chemical components are listed on the right. Oxygen is a component of all these minerals and is not listed. Most of the following minerals always contain aluminum (Al) and silicon (Si), however the proportions and quantities of the other elements listed can be variable.

- | | |
|------------------------|------------------------------|
| • Quartz | • Si |
| • K-feldspar | • K, Al, Si |
| • Plagioclase feldspar | • Na, Ca, Al, Si |
| • Clays (variable) | • K, Mg, Ca, Fe, Al, Si |
| • Oxyhornblende | • Ca, K, Na, Mg, Fe, Al, Si |
| • Clinopyroxene | • Ca, Mg, Fe, Al, Si |
| • Olivine | • Mg, Fe, Si |
| • Carbonate | • Ca, Mg, Mn, Fe |
| • Opaques | • weathered products, metals |

Figure 1d: Average petrography of three rock types common to the inland northwest, with minerals listed in order of decreasing resistance to weathering. Generally, basalts tend to be composed of more weatherable minerals than the granites and metasedimentary rocks.



Rock weatherability is also important in determining soil texture and nutrient availability. Table 2 shows soil properties expected from various parent material types. The granitic and metasedimentary rocks tend to weather to sandy soils, with low cation-exchange holding capacities and low base status (Buol et al. 1989). Basaltic soils, on the other hand, tend to be richer in clay minerals and have a higher nutrient-holding capacity. Therefore, while basalts start out relatively low in certain nutrients (such as K), they tend to form a rich soil capable of retaining those nutrients in the system. Hence, basalts get a 'good' rating for nutrient status. Granites, which start out fairly high in nutrients, typically form a sandy soil with less capability of holding those nutrients, so granites usually produce a site of 'medium' fertility. The metasediments start out low in nutrients and then weather to soils with a low nutrient-holding-capacity, and as such these soils are generally considered to be nutritionally 'poor.' Some surficial deposits, such as ash layers common in the region, improve soil

Table 2. Rock weathering characteristics of several rock types common to the inland northwest. Rock nutrient status from Garrison (1996). Expected soil characteristics from Buol et al. (1989).

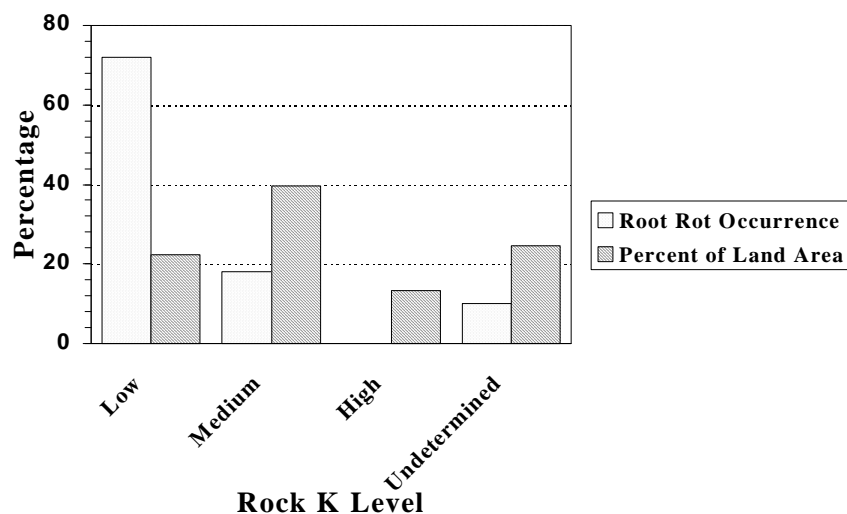
Rock Type	Rock Nutrient Status	Expected Soil Particle Size	Expected Soil Nutrient (Base) Status
Plutonic (granites)	Good	coarse - sandy	medium to low
Volcanic (basalts)	Medium	fine - clayey	high
Metamorphic * Schists * Gneisses * Metasedimentary	Medium to Poor Medium to Poor Poor	fine - silty coarse - sandy variable	medium to low medium to low low
Mixed (unconsolidated) * Glacial Till * Loess	Medium Medium	variable fine - silty	variable medium to high
Sedimentary (consolidated) * Shales * Sandstones	Medium to Poor Medium to Poor	fine - clayey variable	medium to low variable

physical properties, but not fertility. In some cases, surficial deposits such as glacial till, alluvial deposits, and loess can be so deep that they become the soil parent material and mask the

nutritional characteristics of the underlying bedrock. Oftentimes, these deep deposits are mapped as such on bedrock geology maps, and surficial geology maps are often available which show locations of these deposits. By using geologic maps in combination with information on rock geochemistry and soil-forming processes, we can get an idea of nutrient availability across the landscape.

Current developments using GIS technology support a growing body of evidence that forest health conditions across the landscape are affected by rock type. The Idaho Department of Lands gathered input from foresters throughout north Idaho to create a coverage of locations of known root rot "hot spots" in the region. The IFTNC took this information, and used digital geology maps to develop a K-content map based on rock type for the same region (Avila et al. 1996). Figure 2 shows the results of overlaying these two GIS coverages. While only

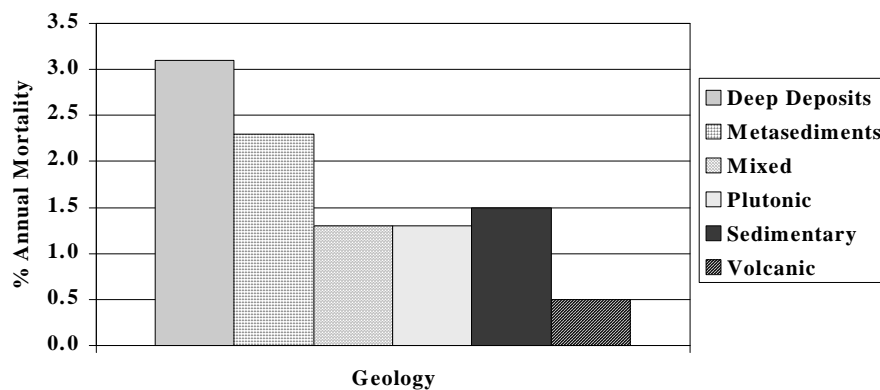
Figure 2: Root rot occurrence on Idaho Department of Lands properties in the north Idaho region. IDL root rot "hot spots" were located on a K-classification geology map for north Idaho and categorized according to rock K level. The resulting percentages are reported below as "Root Rot Occurrence." Total land area for north Idaho was also categorized by rock K level, and these percentages are reported below as "Percent of Land Area." Most (72%) of the root rot problem areas occurred on the 23% of land classified as low K status.



22% of the land in north Idaho is comprised of 'bad' rock, about 70% of IDL's root rot problem areas occur on the bad rock, and virtually no problems are reported on good-rock sites. In other words, root rot problems occur much more frequently on the low K rocks.

Rock type is also being recognized as an important contributor to forest growth modeling. Forest Service workers compiled data and identified rock types on hundreds of long-term forest monitoring plots throughout the northwest in order to evaluate mortality by rock type. Figure 3a shows that rock type was a significant predictor of mortality losses, with plots on deep deposits

Figure 3a: Tree mortality and geology. Annual mortality by rock type, based on long term Forest Service inventory plot data. Deep deposits refer to deep surficial deposits. Deep deposits and metasediments had 2-3% mortality per year, while volcanic rocks (basalts) had only 0.5% annual mortality.



and metasediments (bad rocks) showing 2-3% annual mortality, while volcanic rocks (good rocks) showed only about 0.5% (Hamilton and Byrne 1998). From the same data, yield predictions were made for white pine plantations on good and bad rocks, and the resulting projections are shown in Figure 3b. This figure shows that significantly better yields can be expected from white pine grown on good rock sites over white pine grown on bad rock sites. Similar results were found for Douglas-fir grown under the same conditions.

Figure 3b: FVS predicted yields for white pine based on good and bad rock projections. Predicted yield for white pine plantations growing on good rock sites versus bad rock sites. Projections made using the Forest Vegetation Simulation model (Hamilton and Byrne 1998).

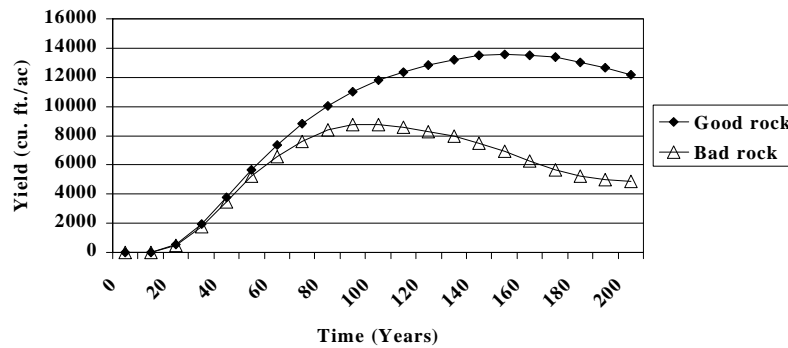
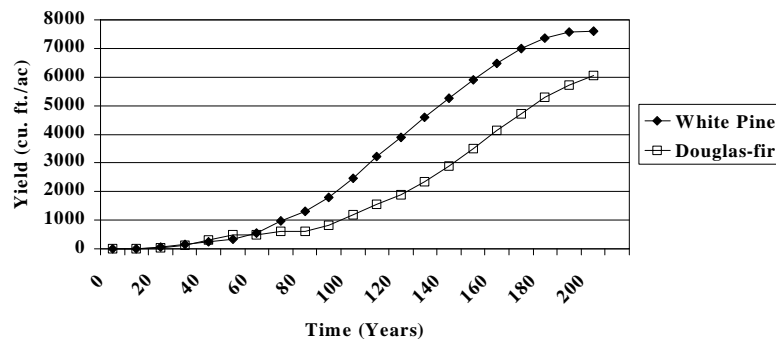


Figure 3c shows the differences between good-rock and bad-rock yield projections for both white pine and Douglas-fir. In both cases greater yields were predicted on good rock than on bad rock sites. The white pine shows a greater difference, probably due to the larger size attained by the white pine than the Douglas-fir over the same time period. In other words, the removal of a few large white pine from the stand has more effect on the per-acre yield than does the mortality of an equal number of smaller Douglas-fir. These findings of yield differences by rock type are further evidence that stand growth and death patterns at the landscape level are predictable by rock type.

Figure 3c: Differences between good and bad rock FVS yield projections for western white pine and Douglas-fir. Each of the curves below represents the difference between the yield projection for that species grown on good rock and on bad rock. In both cases growth is greater on good rock than on the bad rock. White pine shows a greater difference than Douglas-fir, probably because the white pine plantations tend to be composed of larger individuals than the Douglas-fir plantations. Therefore when one white pine dies, it has a greater effect on the yield per acre than does the death of a single, smaller Douglas-fir.



Visual observations indicate that stand types and health conditions often change at rock type boundaries. Since these visual observations often translate into diagnosable nutrient conditions and deficiencies, it is important to be able to quantify the nutrient status of trees and forest stands. Soil analysis and plant tissue analysis are commonly-used tools for quantification of nutrient status. Past experience of the IFTNC indicates that soil analysis is not always a good indicator of the nutritional status of the trees on a site. Much better success has been obtained by use of plant tissue analysis, primarily of foliage. Foliar samples are collected from the upper third of the crown of dominant or codominant trees in late fall, after dormancy has set in (Everard 1973). These samples are iced for transport to the lab, where they are dried, weighed and ground. Chemical analysis of the foliage is performed at an outside laboratory, and results are compiled by tree species. The results are then compared to critical foliar nutrient levels, which have been determined for many tree species in the inland northwest. Compared to soil testing, the foliar nutrient levels are a much better indicator of which nutrients are being taken up into trees, and whether the nutrients are present in sufficient quantities for tree growth and health.

In addition to critical foliar nutrient levels, nutrient ratios are used to assess nutrient status of forest trees. The concept behind nutrient ratios is that nutrients must be present not only at minimum levels but also in optimal proportion with the other nutrients, particularly N, in order for the tree to grow and function properly (Ingestad 1971). Foliar nutrient ratios of interest are given in Table 3. Foliar K/N ratios are of particular interest as indicators of disease susceptibility of the tree. Entry (1991) found that the K/N ratio correlated with the phenolic/sugar ratio of the tree, influencing susceptibility to *Armillaria* root disease (Figure 4).

Table 3. Foliar nutrient ratios are thought to be important for proper tree functioning and health. Critical levels indicate the minimum suggested ratio, while optimal levels indicate the preferred ratio. Values for all ratios except for N/S determined by Ingestaad and are not species-specific (from van den Driessche 1974). Values for N/S determined for Douglas-fir and radiata pine by Turner and Lambert (1978) and Kelly and Lambert (1972).

Ratio	Critical	Optimal
K/N	50%	65%
P/N	8%	15%
Ca/N	5%	10%
Mg/N	5%	10%
N/S		14.7%

Figure 5 shows the results of IFTNC Douglas-fir trials, indicating that sites low in K had significantly greater mortality than good-K sites, particularly on N-fertilized plots (IFTNC 1993). Similarly, Figure 6 shows the results of subsequent Montana trials which included both N and N+K fertilization, indicating that mortality was much lower on N+K plots than on N-alone plots (IFTNC 1992). While in the Montana trials the mortality was due to beetles rather than root disease, it does appear that the N-fertilized trees were somehow more attractive to the beetles, perhaps due to higher sugar content. Generally speaking, the K/N ratio might be a better indicator of disease resistance than K or N alone. While less work has been performed on the other nutrient ratios suggested by Ingestaad, these ratios should be examined as well to ensure a nutritionally balanced site and stand.

Figure 4: Armillaria infection rate and its relationship to the thermochemical budget. Phenol:sugar ratios are closely related to foliar K:N ratios of forest tree species. In this study from Entry et al. (1991), Armillaria infection rates increased sharply once the phenol:sugar ratio dropped below the critical level of 15:1.

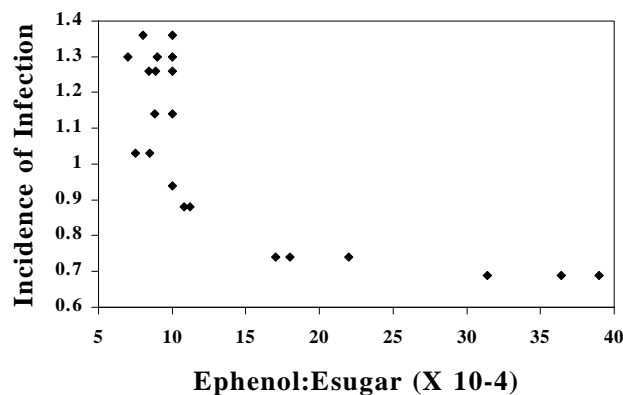


Figure 5: Ten-year net volume response by initial potassium condition. Results of the original IFTNC Douglas-fir trials were analyzed according to initial foliar K status. On the poor-K sites, mortality increased significantly when fertilizer rates were increased from 200#N/ac to 400#N/ac. On the good-K sites, however, volume response increased when fertilization rates were doubled. Mortality on the poor-K sites was due primarily to root rot.

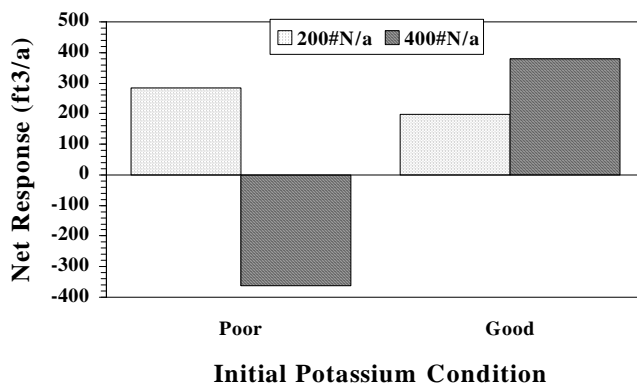
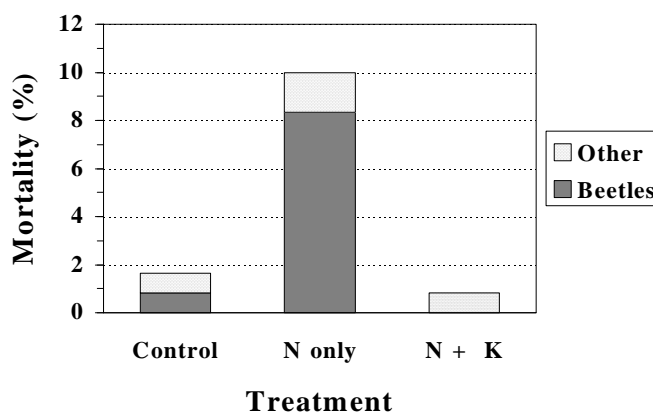


Figure 6. Four-year mortality rates for 1987 ponderosa pine sites. This figure shows the mortality rates by cause for the 1987 IFTNC ponderosa pine study in Montana. The percent mortality by cause is given for control plots (no fertilization), N-only (200#N/ac), and N+ K (200#N/ac + 170#K/ac). Where N-only was applied, beetle mortality increased significantly over the control plots, and where N+ K was applied, no beetle mortality was reported.



In summary, the nutrient environment is a function of parent material type, soil characteristics, and nutrient demand by trees and plants growing on a site. Parent material type plays a critical role in determining nutrient availability on forest sites. Nutritional status may be diagnosed at a stand and at a landscape level based on parent material and soil characteristics, and at the tree level using foliar diagnostics. Both parent material assessment and foliar

diagnostic techniques are very important to determining overall nutrient status of a site, and to determining the type and timing of management activities to be implemented on that site.

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Species Nutrient Requirements

Critical foliar nutrient levels have been established in order to evaluate nutrient status for many tree species in the northwest. As noted in the previous section, the critical nutrient level is the minimum concentration of a nutrient needed by a plant in order to function efficiently.

Species-specific critical foliar nutrient concentrations for several northwest tree species are shown in Table 4. Sources for these values are also included in the table. While foliar analysis is the most definitive method of determining nutrient deficiencies, visual symptoms may also be diagnostic. Tables 5a through 5d list some common visual deficiency symptoms for four conifer species (Walker and Gessel 1990).

The differences in critical foliar nutrient concentrations for the various tree species shown in Table 4 is indicative of the varying nutritional needs of those species. Particularly in mixed-conifer forests, these needs may translate into nutrient imbalances at the stand level, as some species out-compete others for available nutrients. The results of several IFTNC studies were compiled in order to examine foliar nutrient levels of several species, with special emphasis on mixed-conifer stands. Figure 7a shows foliar N concentrations on control (untreated) plots for four species across five different IFTNC studies. Generally, N concentrations on untreated plots were about the same for all species studied. This probably indicates that without fertilization, N is so limiting that species differentiation for N is unlikely, in other words none of the species studied were getting sufficient N. Figures 7b and 7c show concentrations of K and B for the same species and studies. Concentrations of these and most other nutrients tended to be highest in grand fir and Douglas-fir, and lower for ponderosa and

Table 4. Critical foliar nutrient concentrations for several conifer species in the inland northwest.

Foliar Conc.	Douglas-Fir ^a	True Fir ^b	Lodgepole ^c Pine	Ponderosa ^d Pine	White Pine ^e	Englemann ^f Spruce	Western ^g Red Cedar	Western ^h Hemlock
N (%)	1.40 ¹	1.15 ³	1.20 ¹	1.10 ³	1.00 ³	1.50	1.50 ¹	1.20 ¹
P (%)	0.12 ¹	0.15 ³	0.12 ¹	0.08 ³	0.15 ³	0.18	0.13 ¹	.13 ¹
K (%)	0.60 ¹	0.58 ²	0.50 ¹	0.48 ²	0.70 ³	0.60	0.60 ¹	.75 ¹
S (%)	0.11 ²	0.08 ⁴	0.09 ⁴	0.08 ⁴	0.20 ³		0.40 ¹	
Ca (%)	0.15 ¹	0.12 ²	0.08 ¹	0.05 ²	0.30 ³	0.15	0.20 ¹	.08 ¹
Mg (%)	0.08 ¹	0.06 ²	0.09 ¹	0.05 ²	0.10 ³	0.10	0.12 ¹	.09 ¹
Mn (ppm)	15 ¹	100 ¹	293 ¹	60 ³	400 ³	15 ⁵	15 ⁵	15 ⁵
Fe (ppm)	25 ¹	50 ¹	58 ¹	50 ³	40 ³	100	25 ⁵	25 ⁵
Zn (ppm)	10 ¹	10 ¹	52 ¹	30 ³	15 ³	10 ⁵	10 ⁵	10 ⁵
Cu (ppm)	2 ¹	3 ¹	2.7 ¹	3 ³	5 ³	2.6 ⁵	2.6 ⁵	2.6 ⁵
B (ppm)	10 ¹	10 ⁵	4.3 ¹	20 ³	10 ³	5	15 ¹	10 ⁵

Values obtained by:

- ¹ Best estimate by cited author based on literature review and personal experience
- ² Derived by cited author using optimal proportions
- ³ Derived by cited author experimentally
- ⁴ Critical S values derived for this paper using an N:S ratio of 14.7 in conjunction with the given critical N values (Blake et al. 1990, Turner and Lambert 1978)
- ⁵ General value established for all conifer species, not yet species-specific (Ballard and Carter 1986)

^a From Webster and Dobkowski (1983), these values are considered inadequate for growth, critical values would be somewhat higher.

^b All values except S from Powers (1983). S value calculated as noted above.

^c All values except S from Ballard and Carter (1986), based on Everard (1973) and Swan (1972). S value calculated as noted above. Micronutrient values from Van den Driessche (1979)

^d Value for N from Powers et al. (1985), values for P, K, Ca and Mg from Powers (1983). S value calculated as noted above. Micronutrients from Boyer (1984, unpublished)

^e All values from Boyer (1984, unpublished)

^f All values except S from Van den Driessche (1974), value for S from Cole and Gessel (1992)

^g All values from Cole and Gessel (1992)

^h Values from Ballard and Carter (1986)

Table 5. Summary of mineral deficiency symptoms for (a) Douglas-fir, (b) Sitka spruce, (c) western hemlock, and (d) western red cedar are shown here. From Walker and Gessel (1990). The term "necrotic" means light brown, and "chlorotic" means yellow.

a. Douglas-fir

<i>Nutrient</i>	<i>Symptoms</i>
Nitrogen (N)	Light green foliage; in severe deficiency needles small and yellow, terminal growth restricted, and older foliage turning brown and shedding prematurely
Phosphorus (P)	Unspecific symptoms characteristic of a mobile element -- browning and dying of older needles
Potassium (K)	Tips of needles become brown, starting in the older foliage; this necrosis progresses back from the tips with severe deficiency.
Calcium (Ca)	Dying of terminal buds and some lateral buds
Magnesium (Mg)	Beginning with the older needles, the tips turn brown and there is a yellow region between the brown tip and the green basal portion; this progresses until the entire needle is brown.
Sulfur (S)	Upper needles yellowish; older needles still green
Boron (B)	Terminal buds dying, foliage exceptionally dark green
Iron (Fe)	Upper (younger) foliage bright yellow; older foliage remains green

b. Sitka spruce

<i>Nutrient</i>	<i>Symptoms</i>
Nitrogen (N)	Pale yellow-green foliage; in severe deficiency needles short, especially in new flushes
Phosphorus (P)	Older foliage reddish, later becoming necrotic and dying; younger foliage green
Potassium (K)	In mild deficiency, tips of some needles yellowish, then browning; in severe deficiency, older foliage necrotic and dying
Calcium (Ca)	Youngest needles become pale green, then browning at the tips or even in the whole needle
Magnesium (Mg)	Older branches yellowish-brown and necrotic at the ends; youngest foliage yellowish; in severe deficiency the entire plant necrotic
Sulfur (S)	younger foliage yellowish, then entire plant becoming yellowish as deficiency progresses
Boron (B)	Youngest needles curled closely together into a rosette, and dark gray-green in color; roots stubby
Iron (Fe)	Youngest foliage chlorotic, but older needles green
Manganese (Mn)	Younger needles pale green or yellowish, becoming necrotic at the tips; older needles dark green; in severe deficiency the shoot tip dies.
Zinc (Zn)	Youngest needles pale green, then becoming chlorotic or necrotic
Copper (Cu)	Tips of young needles become necrotic
Molybdenum (Mo)	Younger needles turn pale green or yellow, then brown

c. Western hemlock

<i>Nutrient</i>	<i>Symptoms</i>
Nitrogen (N)	Light green foliage; reduced extension growth
Phosphorus (P)	Foliage darker green than normal; limited branching and reduced extension growth
Calcium (Ca)	Dying of terminal buds
Magnesium (Mg)	Needles pale green
Boron (B)	Foliage dark green; youngest needles of the leader and branches clustered together in rosettes
Iron (Fe)	Youngest needles chlorotic; older needles remain green

d. Western red cedar

<i>Nutrient</i>	<i>Symptoms</i>
Nitrogen (N)	Foliage yellow-green and sparse; stems reddish in young plants; necrosis and dying of

	older foliage but little shedding
Phosphorus (P)	Youngest foliage retains good green color; stems and older foliage reddish or purplish initially, turning to reddish brown; oldest foliage necrotic and dying but does not shatter
Potassium (K)	Terminal foliage a good green, but older branchlets necrotic or dying and burning brown; foliage sparse with 4th order branches not elongating; stems limber, causing drooping of foliage
Calcium (Ca)	Browning and dying at the tips of the leader and branch shoots; good green color maintained in lower foliage; roots browning and dying
Magnesium (Mg)	Youngest foliage remains green; older branchlets turn yellow or white, then brown, progressing from tip to base; older branchlets tend to shatter and shed, leaving lower parts of stems bare
Sulfur (S)	Younger foliage becomes yellowish; older foliage is paler green than normal, but distinctly greener than the younger parts
Boron (B)	Elongation restricted; youngest needles closely bunched, resembling rosettes; stems weak, so branches lop down; older foliage near normal, upper foliage finally bronzing; roots stubby
Iron (Fe)	Youngest foliage quite yellow, but older foliage remaining normal green; this difference is more striking as the plants become older
Manganese (Mn)	Younger foliage yellowish, then slowly becoming necrotic and dying; older foliage retains a good green color

lodgepole pine. This indicates that besides N, most nutrients were taken up in greatest quantity by shade tolerant species, followed by the shade intolerants. Therefore, in mixed-conifer stands, the potential exists for shade-tolerants to out-compete the intolerants for nutrients, particularly where the nutrient supply is limited.

Differences in nutrient uptake rates among species are also reflected in their disease resistance characteristics. As mentioned in the previous section, foliar K/N ratios are representative of the biochemical status of the trees, particularly the phenolic/sugar ratios. The phenolic/sugar ratios, in turn, correlate strongly with resistance to *Armillaria ostoyae*, a root disease causing widespread mortality in the inland northwest. Figure 8 shows root chemistry of five north Idaho conifers from a study by Entry et al. (1992). Where western larch and

Figure 7a: Average foliar nitrogen concentrations for four conifer species across five IFTNC studies. GF= Grand fir, DF= Douglas-fir, LP= lodgepole pine, PP= ponderosa pine. Difference by species across

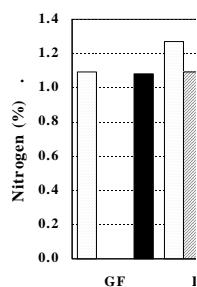


Figure 7c: Average foliar boron concentrations for four conifer species across five IFTNC studies. GF= Grand fir, DF= Douglas-fir, LP= lodgepole pine, PP= ponderosa pine. Boron tends to get taken up in greater amounts by the shade-tolerant grand fir and Douglas-fir.

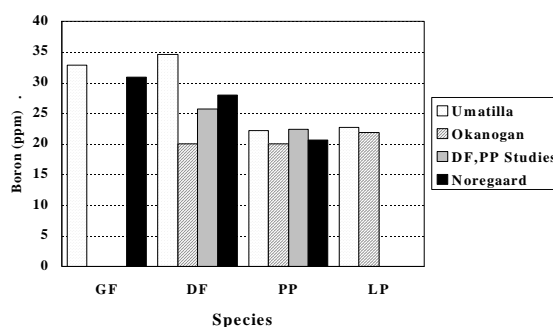
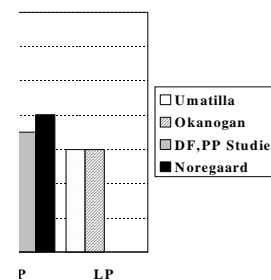


Figure 7b: Average foliar potassium concentrations for four conifer species across five IFTNC studies. GF= Grand fir, DF= Douglas-fir, LP= lodgepole pine, PP= ponderosa pine. Potassium tends to get taken up in greater amounts by the shade-tolerant grand fir and Douglas-fir.



conifer species for root disease resistance. Western larch and white pine were found to be the most resistant species to root infection, while the more shade-tolerant Douglas-fir and grand fir were most susceptible. Field observations support these findings. In natural stands infected by root rot, it is not uncommon to see larch and pines remaining relatively unaffected. Although not included in the Entry et al. (1992) study, cedar and hemlock also tend to be resistant to root rot and may dominate sites where root rot infection risk is high. These results indicate that the shade tolerant not only take up nutrients at higher rates than intolerants, but are also the most likely to suffer nutrient imbalances, leading to root chemistry imbalances and increased susceptibility to root disease. This implies that a species composition shift towards shade intolerants would be advisable on sites where root disease has been a problem.

Figure 8: Root chemistries of five north Idaho conifers. Root phenolics:sugar ratios of five conifer species in north Idaho are given. The greater the phenolics:sugar ratio, the greater the tree's resistance to Armillaria root disease. Grand fir is the least resistant, and western larch the most resistant. From Entry et al. (1992).

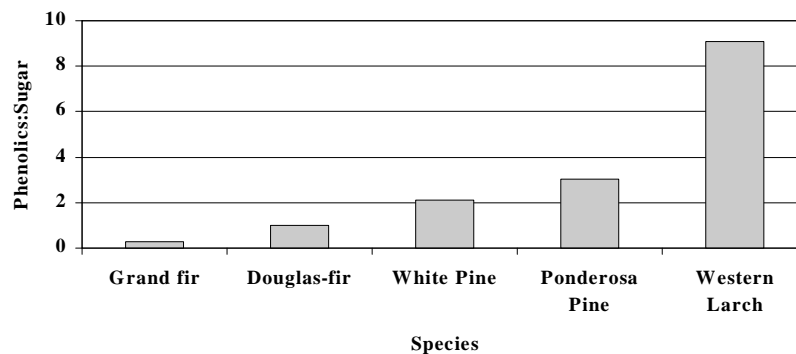


Table 6. Ranking of north Idaho conifer species in order of resistance to Armillaria root disease. The species are listed in order of greatest to least resistance. From Entry et al. (1992).

Ranking	Species
1	Western larch
2	Ponderosa pine
3	White pine
4	Douglas-fir

5	Grand fir
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The variation in nutrient demand and disease susceptibility among species is important at the stand level, particularly in mixed conifer stands. In addition to being aware of nutrient demands by individual species, it is also important to be aware of the shifts in nutrient demand by the stand as a whole throughout the growing season. Several studies have been performed on nutrient retranslocation over the course of the year. Recent work by Kiiskila (1996) on coastal Douglas-fir indicates a high demand for nutrients in early spring, and a second peak demand in late summer. Similar results have been shown for Scots pine (Helmisaari 1992). Gower et al. (1989) showed that in mixed stands of western larch and lodgepole pine, larch demand for N was highest in early spring, probably because of foliage construction costs. While the demand by larch for N gradually decreased until fall needle loss, the lodgepole pine in the same stand showed peak N demands both in spring and late fall. Most species (larch is probably different) show similar patterns in nutrient demand over the course of the growing season. Given that some species have greater nutrient demands than others, we can expect that the spring and fall peaks in nutrient demand will be amplified in stands dominated by these more demanding species.

Also important are changes in a stand's nutrient demand over the course of the rotation. Nutrient demand is high in young trees, and generally decreases as trees age (Fife and Nambiar 1997, Helmisaari 1992, Miller et al. 1981, van den Driessche 1974). Nutrient demand follows periodic annual increment, with the time soon after crown closure coinciding with the time of maximum nutrient demand. Cole and Gessel (1992) show a strong relationship between N uptake and growth expressed as periodic annual increment per acre (Figure 9a). Miller (1981)

uses periodic annual increment to describe three stages of nutrient demand as a function of stand development (Figure 9b). According to Miller (1981), Stage I represents early stand growth, where trees are not yet competing, but highly dependent on available nutrients and likely to respond well to fertilization. Stage II is the period after crown closure when the trees concentrate on stemwood production. Fertilizer responses are not likely here unless the stand is opened up, such as by thinning. Stage III represents maximum density, and nutrient demands in this stage decrease as tree growth rates decrease. This decadent type of stand would not be an appropriate stand to fertilize, however thinning or harvesting might be wise. Interestingly, Miller (1981) also points out that on nutrient-poor sites, stage III may set in very soon after crown closure. Thus, on 'bad rock' sites we may expect to see nutrient deficiencies, decreased growth, and mortality setting in soon after crown closure with very little additional stand development. This situation would be exacerbated on sites revegetated with shade-tolerant, nutrient-demanding species.

Figure 9a: Relationship between periodic annual increment and N uptake. The relationship between growth as periodic annual increment (Curtis et al. 1982) and N uptake (Turner 1975) for site IV Douglas-fir during stand development is shown. Graph from Cole and Gessel (1992).

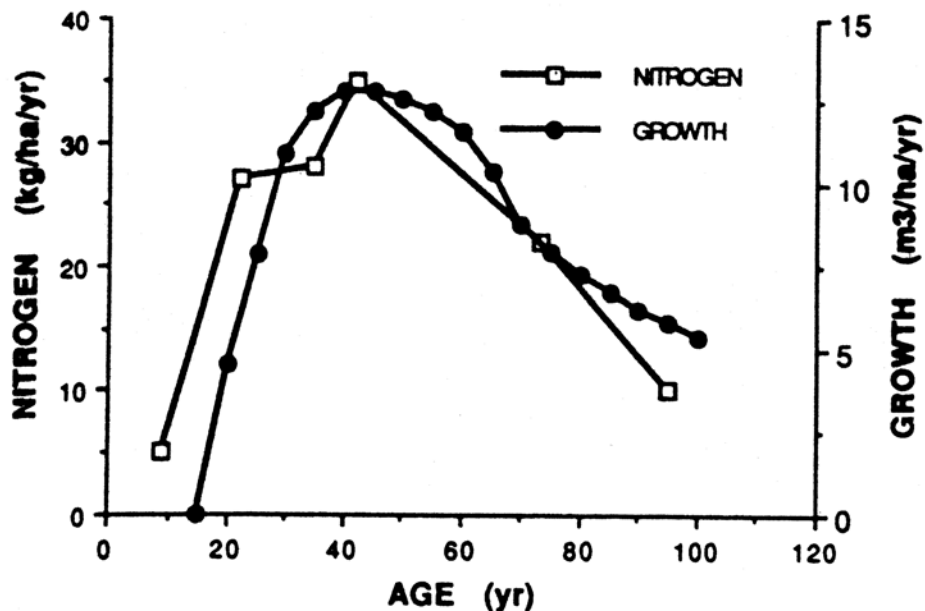
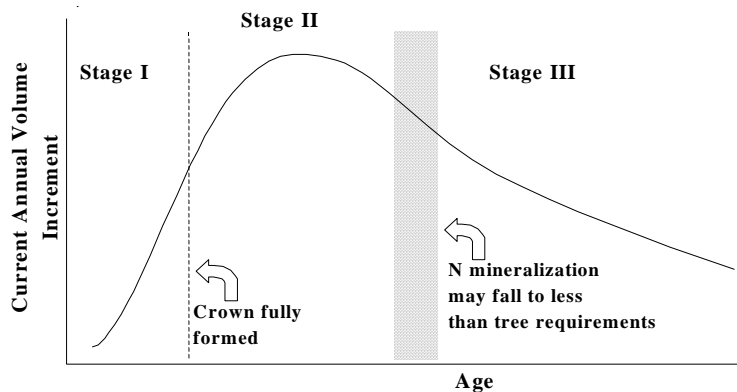


Figure 9b: Three nutritional stages in the life of a forest stand. Conceptual diagram created by Miller (1981) to illustrate the critical stages in the life of a forest stand. Stage I represents pre-crown closure, open-growing stand, Stage II represents crown closure and the onset of competition, and Stage III represents mature or over-mature stands in which growth and nutrient requirements begin to decrease.



In summary, stand-level nutrient demand varies with tree species, time of year, and stage of growth. Shade-tolerant species are more nutrient demanding than shade intolerant species. Symptoms of nutrient deficiencies are most likely to show up in the spring and late fall, times of peak demand. At a stand level, visual symptoms of nutrient stress are most likely to appear just after crown-closure, however nutrient demand remains high from seedling establishment through maturity. Nutrient stress may be partially controlled through selection of appropriate species composition and regulation of stand density levels, and through using other techniques to be covered in the following section on Nutrient Management.

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Nutrient Management

Understanding the nutritional environment of inland northwest forests and the specific nutritional needs of trees and stands is an important first step in creating nutrient management plans for our forests. The next step is to determine techniques for managing those nutrients to the best advantage for forest health and productivity. One of the most important aspects of nutrient management is knowing where the nutrients are located, both within the ecosystem and within the trees. With this information, decisions may be made regarding what to remove during intermediate or final harvest operations, as well as when and how to perform these and other operations so as to minimize negative impacts on nutrient pools.

Numerous studies provide estimates of nutrient budgets at the ecosystem level. These studies are usually performed for an entire watershed or a portion thereof, and nutrients are commonly reported as percentages held in various pools. Several of these studies provide estimates of nutrients being held in the standing crop, or in the tree portion of the stand. Cole et al. (1967) found that for a forested Douglas-fir ecosystem on glacial outwash soils, about 10% of the N, 2% of the P and 45% of the K was being held in the trees, with the remainder being held in subordinate vegetation, forest floor and soil pools (Figure 10a). Gordon (1982) reported similar values for several different stand and parent material types, except that he reported exchangeable soil P rather than total soil P values (Figure 10b). Based on Gordon's (1982) values, about half of the total K and Mg and exchangeable P in forest ecosystems was held in the above-ground vegetation. Nitrogen and Ca varied by parent material and stand type, but generally seemed to be held in equal or greater proportions in the soil and organic matter reserves than in the standing crop.

Figure 10a: Nutrients in the ecosystem: west-side Douglas-fir. This figure shows the percentage of N, P and K in the forest ecosystem being held in the tree portion of the stand. From Cole et al. 1967.

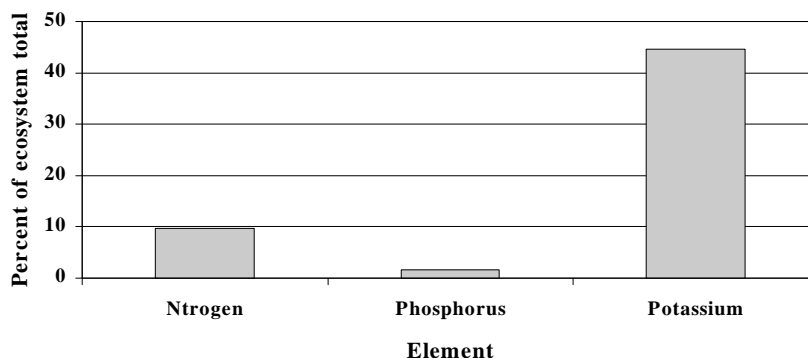
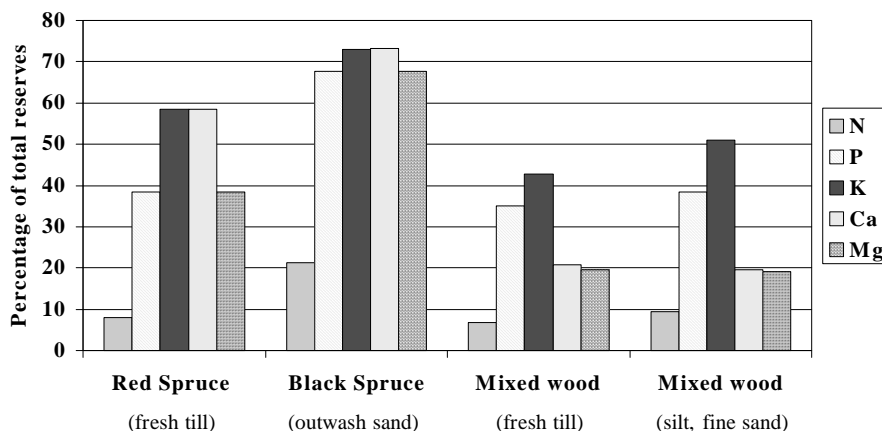


Figure 10b: Bioelement stores in standing crop of forest stands in Ontario. Bioelement stores in standing crop as a percentage of total nutrient reserves for spruce and upland mixed wood stands on typical parent material types in Ontario. From Gordon (1982).



It is interesting to note the difference between the spruce sites and mixed-wood (spruce-fir-birch-aspen) sites as reported by Gordon (1982) in Figure 10b. Spruce has been reported to be a very nutrient demanding species (Gordon 1982, Miller et. al 1993, Proe et al. 1996). On both parent material types reported by Gordon (1982) for spruce stands, most of the nutrient capital of the stands was being held in the tree component. On the mixed-wood sites, however, a proportionally smaller percentage of the total nutrients was held in the trees, with more nutrients remaining in the soil and organic matter pools. One possible explanation for this is that the

species on the mixed wood site are overall less nutrient demanding, and that the hardwood components of the mix are returning nutrients to the organic matter and soil pools on a regular basis. The parent material types may also be affecting these figures. The outwash sand under the black spruce probably results in a nutritionally poorer site than the till and silty materials supporting the red spruce and mixed stands. This is further evidence of how important both parent material type and species mix are to understanding the nutrient dynamics of a site.

As shown in Figures 10a and 10b, half or more of the total nutrient budget for several important nutrients is held in the standing crop. Since so much of the total nutrient pool is held in the standing crop, it is important for forest managers to know how those nutrients are distributed within individual trees. Nutrient distributions among various tree components for 34-year-old Douglas-fir trees are shown in Figures 11a through 11e (Pang et al. 1987). While these estimates are for Douglas-fir, most coniferous evergreens show a similar pattern of nutrient distribution within the above-ground tree components. These figures indicate that about 10-15% of the total amount of any given nutrient is held in the bole and bark, and the other 85-90% is held in the branches, twigs and foliage. Anywhere from 40% to 75% of the nutrients are held in the foliage alone. We can expect a shift in these figures as trees age, with older trees having a somewhat greater proportion (up to 50%) allocated to stemwood and bark. Mitchell et al. (1996) studied the effects of thinning and fertilization on nutrient allocation, and found that both

Figure 11c: Potas
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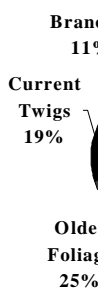
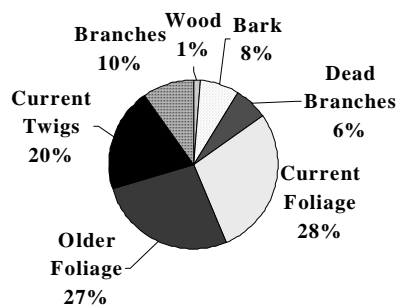


Figure 11e: Magnesium in Douglas-fir. Estimated allocation of magnesium to various tree components in 34-year-old Douglas-fir. From Pang et al. (1987).



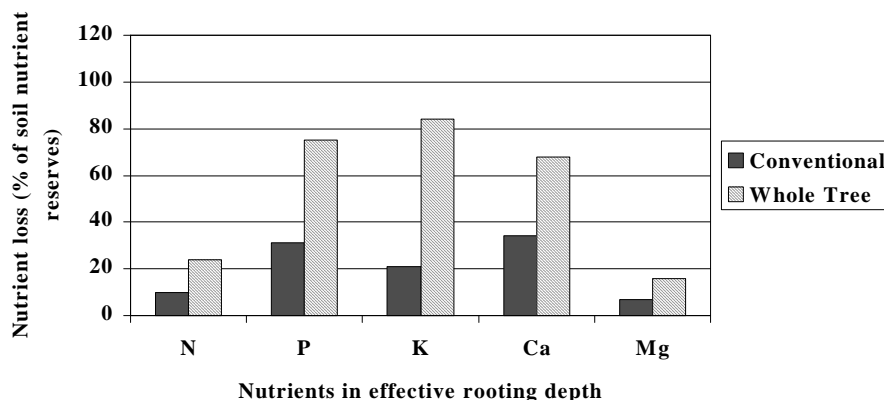
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Given where nutrients are located within the trees, it is clear that to conserve nutrients during harvest activities, every effort should be made to leave the branches, twigs and foliage on site, and remove only the stems (conventional harvest), which contain a smaller proportion of the stand's nutrients. However, due to both decreased cost and increased biomass extraction associated with mechanized systems, whole-tree harvesting techniques are being practiced in many areas. Many studies have been performed which assess the effects of different harvesting activities on forest nutrients. Most studies focus on losses from soil nutrient pools and increased losses in stream water following harvesting. One example is a study by Timmer et al. (1982) performed on spruce stands in Ontario. Figures 12a and 12b show the effects of both conventional and whole-tree harvesting on soil nutrient reserves for stands of two different age classes. In both cases, whole-tree harvesting had tremendously greater effects on nutrient pools than did conventional harvesting. On the younger stand, whole-tree harvesting resulted in K removal of more than 100%, indicating that more K was removed from the site than was left in soil reserves. The Ca, P and Mg pools were also greatly affected. Biomass and nutrient extraction from the site increased for whole tree versus conventional harvesting, with about 56-110% more biomass removed. However, corresponding nutrient removals were significantly greater, in the range of 83-224%. Similar results have been reported by many researchers

(Freedman et al. 1982)

Figure 12b: Nutrient losses from a 126-yr old stand following two harvesting regimes. Losses of N, P, K, Ca and Mg in an older spruce-fir stand on outwash gravels in Ontario, following both conventional and whole-tree harvesting. Nutrient losses are represented as a percentage of soil nutrient reserves. From Timmer et al. (1982).



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stands varies not only by harvest technique, but by site quality. Bigger and Cole (1983) studied nutrient losses and growth of second-rotation Douglas-fir on high- and low- quality sites

Figure 13a: Losses of three elements following conventional vs. whole-tree harvesting on high and low quality Douglas-fir sites. Nitrogen, phosphorus and potassium losses are represented kg/ha following conventional harvesting (CH) and whole-tree harvesting (WTH) on high and low quality Douglas-fir sites. From Bigger and Cole (1983).

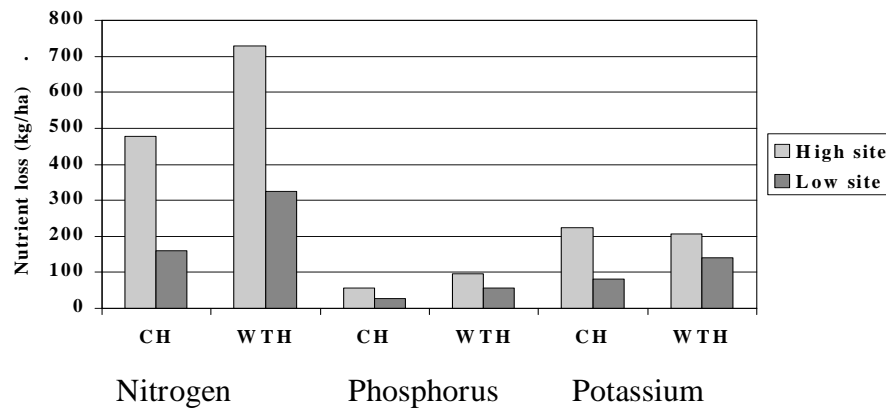
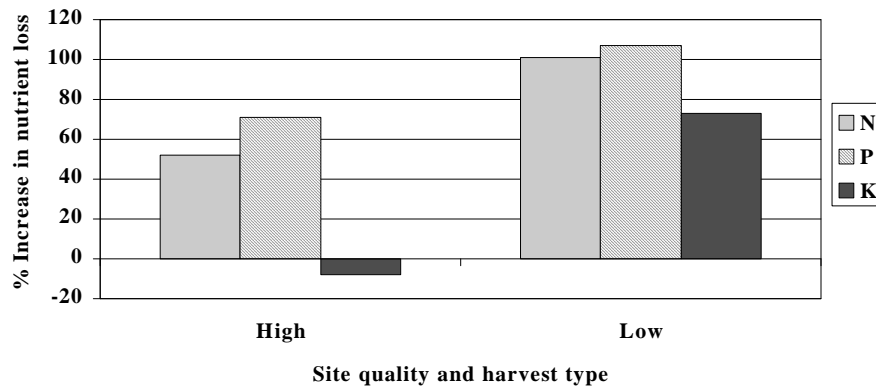


Figure 13b: Percent increase in nutrient losses following whole-tree versus conventional harvesting on high and low quality Douglas-fir sites. Losses of nitrogen (N), phosphorus (P) and potassium (K) represented as a percentage of remaining soil reserves. Losses exceeding 100% mean that more of that nutrient was removed than remains in current soil reserves. From Bigger and Cole (1983).



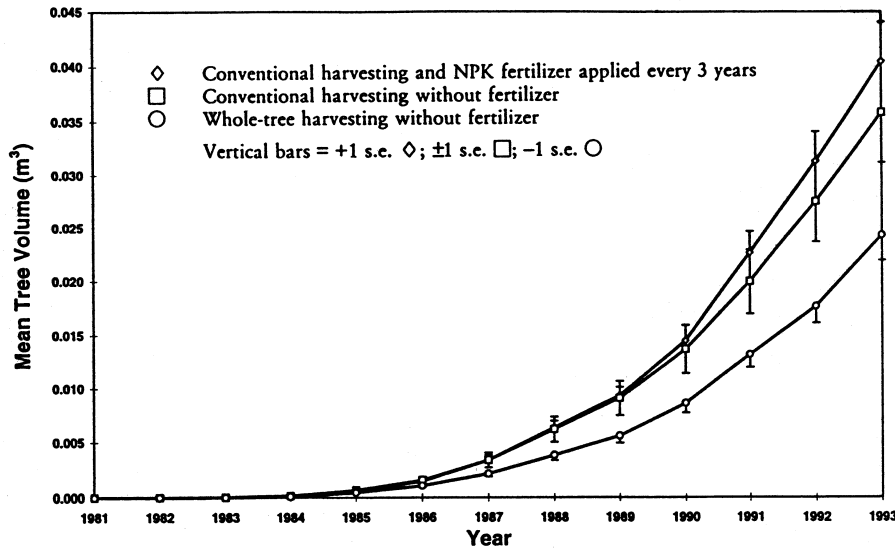
following conventional and whole-tree harvesting. Their results are summarized in Figures 13a-
b. They found that actual amounts of nutrients removed were greater on the

high-quality than low-quality sites, indicating that the high-quality sites initially had the better nutritional status. However, nutrient pools of low-quality sites were even more negatively impacted by harvesting than high quality sites because the percentage of nutrients removed was greater. This depletion was reflected in the growth of the subsequently planted Douglas-fir stand. Height growth after only two seasons showed that the high-productivity site had almost twice the height growth and less than half the mortality as compared to the low-productivity sites, with no significant differences yet appearing by harvest treatment. On the low productivity sites, however, there were already significant differences in seedling height between harvesting treatments, with the whole-tree harvested sites showing 20% less height growth than the conventionally-harvested sites, and the complete biomass removal sites showing a 40% reduction in height growth. This emphasizes the idea that whole-tree harvesting on low nutrient-status sites (such as bad rock sites!) can be even more detrimental than on sites with better nutrient status.

Further supporting evidence for this notion is provided by the work of Proe et al. (1993), who examined the effects of harvest activity and fertilization on the growth of second-rotation Sitka spruce. In their study, tree growth was monitored on both conventionally harvested and whole-tree harvested sites. Their study also included the effect of fertilization on the conventionally harvested site. Their results for the first 12 years of the study are shown in Figure 14. They found that for the second-growth stand, whole-tree harvesting reduced mean tree volume by 32% compared to the conventionally harvested plots. The addition of fertilizer to the conventionally harvested site resulted in a 13% increase in volume growth compared to the unfertilized plots. While this fertilizer effect was not statistically significant as of year 12, a distinct trend is shown in Figure 14 indicating that the fertilization response may shortly become

significant. The authors point out that conventional harvesting procedures with residue left on site have been found to leave a sufficient nutrient supply to support a second-growth stand for approximately 8-10 years.

Figure 14: Effect of whole-tree harvesting and conventional harvesting (with and without fertilizer) on the mean tree volume of second-rotation Sitka spruce. From Proe et al. (1996).



Site preparation also plays an important role in the growth and survival of second-rotation stands. Tew et al. (1996) studied the effects of two types of harvest and two types of site preparation on a loblolly pine stand in North Carolina. Nutrient and biomass removals were compared for whole-tree and conventional harvesting of a 22-year old pine stand, followed by either chopping and broadcast burning or plowing and discing as site preparation treatments. Marginally greater biomass removal was obtained from the whole tree harvested site over the conventionally harvested site (Figure 15a). However, site preparation was a significant factor affecting mineral soil, with the chopping and burning technique leaving most soil on site, while plowing and discing resulted in hundreds of tons of soil per hectare being displaced (Figure 15b). Nutrient removal generally reflected both the soil displacement and

Figure 15a: Biomass removal, loss and displacement during harvest and regeneration of a 22-yr old *Pinus taeda* plantation. Biomass removals and losses (tons/ha) following two harvesting procedures (conventional (C) and whole-tree harvest (W)), and two site preparation procedures (chopping and burning (CB), and plowing and discing (PD)). From Tew et al. (1996).

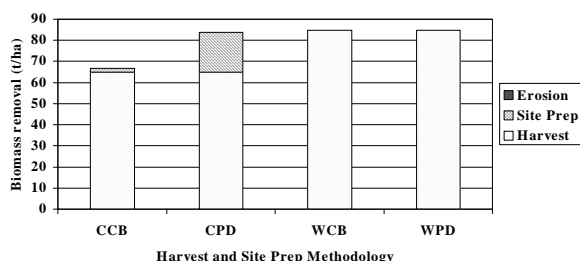


Figure 15b: Mineral soil removal, loss and displacement during harvest and regeneration of a 22-yr old *Pinus taeda* plantation. Mineral soil removals and losses (tons/ha) following two harvesting procedures (conventional (C) and whole-tree harvest (W)), and two site preparation procedures (chopping and burning (CB), and plowing and discing (PD)). From Tew et al. (1996).

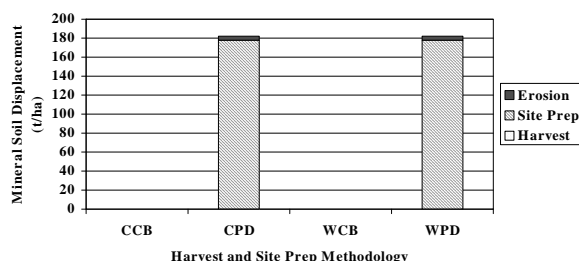


Figure 15c: Nitrogen removal, loss and displacement during harvest and regeneration of a 22-yr old *Pinus taeda* plantation. Nitrogen removals and losses (kg/ha) following two harvesting procedures (conventional (C) and whole-tree harvest (W)), and two site preparation procedures (chopping and burning (CB), and plowing and discing (PD)). From Tew et al. (1996).

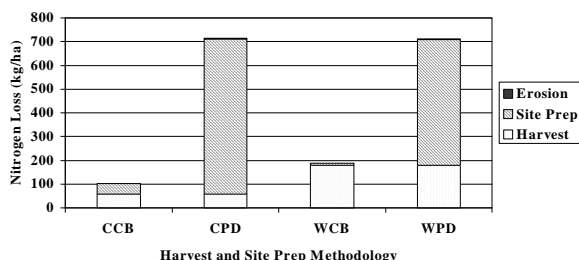


Figure 15d: Potassium removal, loss and displacement during harvest and regeneration of a 22-yr old *Pinus taeda* plantation. Potassium removals and losses (kg/ha) following two harvesting procedures (conventional (C) and whole-tree harvest (W)), and two site preparation procedures (chopping and burning (CB), and plowing and discing (PD)). From Tew et al. (1996).

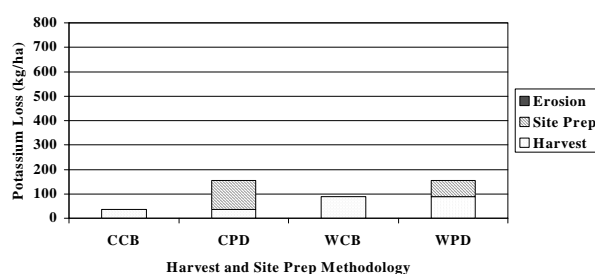


Figure 15e: Calcium removal, loss and displacement during harvest and regeneration of a 22-yr old *Pinus taeda* plantation. Calcium removals and losses (kg/ha) following two harvesting procedures (conventional (C) and whole-tree harvest (W)), and two site preparation procedures (chopping and burning (CB), and plowing and discing (PD)). From Tew et al. (1996).

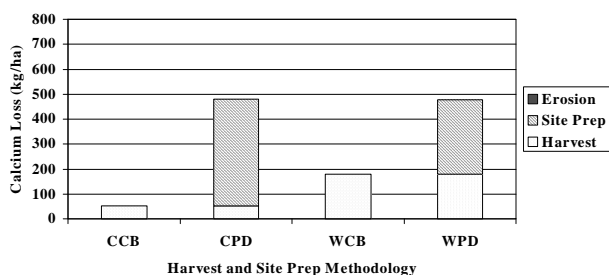
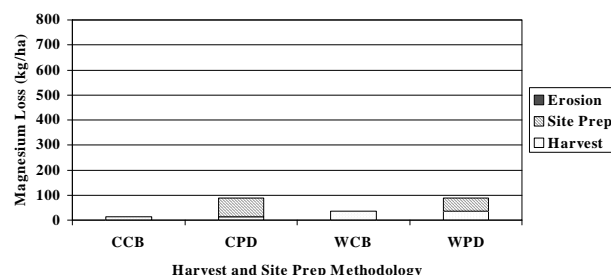


Figure 15f: Magnesium removal, loss and displacement during harvest and regeneration of a 22-yr old *Pinus taeda* plantation. Magnesium removals and losses (kg/ha) following two harvesting procedures (conventional (C) and whole-tree harvest (W)), and two site preparation procedures (chopping and burning (CB), and plowing and discing (PD)). From Tew et al. (1996).



the harvesting technique (Figures 15c-f). Where chopping and burning were used, whole-tree harvesting resulted in about twice as much nutrient removal as conventional harvesting, with most of the loss due to harvesting rather than site preparation or erosion effects. On the plowed and disced sites, however, while nutrient removals were still about double for whole-tree

removal, nutrient losses due to mechanical site preparation far surpassed those due to harvesting, making differences in losses by harvesting technique virtually irrelevant. In other words, while whole-tree harvesting was more detrimental to nutrient pools than conventional harvesting, mechanical site preparation was overwhelmingly more detrimental than either harvesting technique. This suggests that from a nutrient conservation standpoint, it would be wise to avoid mechanical site preparation that displaces the topsoil.

Additional evidence exists that various site preparation techniques significantly affect growth and survival of seedlings in the inland northwest. The Forest Service is currently undertaking a national long-term productivity study, which includes assessment of the effects of soil disturbance on nutrient use and other processes (USDA 1995). Page-Dumroese et al. (1998) found that where site preparation techniques caused severe soil compaction, 3-year old seedlings displayed significantly lower root weights, root collar diameters and total N content than on the non-compacted sites. Douglas-fir and white pine generally grew best when planted in soil mounds with competing vegetation removed, and performed worst following scalping (Page-Dumroese et al. 1997). Jurgensen et al. (1997) also reported on the effects of timber harvesting and extensive site preparation on surface organic matter, and the implications of the removal of organic matter on soil chemical, biological and physical properties.

The results of Tew et al. (1996) indicated that chopping and burning were effective tools for keeping nutrients on site and available for next-rotation growth. Fire is an important process by which nutrients are released and cycled back through the ecosystem. Litter acts as a nutrient sink; that is, nutrients accumulate and are held in woody and organic debris (Entry et al. 1987, Marschner 1995). Shade tolerant species aggressively take up available nutrients as well. Fires

effectively cycle the nutrients held in litter and subordinate vegetation back into the ecosystem. This is particularly important for pine stands, whose lower nutrient requirements probably reflect their evolution with frequent fires. Several studies have been performed on the effects of underburning on litter decomposition and nutrient release in ponderosa pine stands. Monleon and Cromack (1996) found that low-intensity burns were important to the release of N and P from litter in ponderosa pine stands in central Oregon. Covington and Sackett (1984) reported that for southwestern ponderosa pine stands, nutrient storage in woody debris was significantly lower for N, P, Ca, Mg and K following burning, indicating that these nutrients were released back into the system. Some studies, however, do report elevated nutrient losses from the ecosystem following burning. Feller and Kimmins (1984) found that clearcutting and broadcast burning caused greater nutrient losses than clearcutting alone, particularly for N. Jurgensen et al. (1997) also pointed out that nitrogen is often lost through volatilization when prescribed fires are used. There is certainly ample evidence that hot burns can be detrimental to nutrient status, as they can have the effect of volatilizing elements, physically removing elements as particulate matter in ash in the smoke column, and creating an impermeable and sterile layer under extremely hot burn conditions (Waring and Schlesinger 1985, Aber and Melillo 1991). These extremely hot conditions are likely to form under piles in the event that slash is piled prior to burning. Regularly-occurring fires have the effect of reducing fuel loads, resulting in fires that are less intense when they do occur (Waring and Schlesinger 1985). Broadcast burning is preferable to piling-and-burning where prescribed fires are used, from both a temperature and nutrient distribution standpoint.

Thinning and fertilization activities should also be viewed in terms of nutrient status and stand dynamics. As discussed in the previous section on species requirements, nutrient demand

changes over the course of a rotation. Miller's (1981) diagram (Figure 9b) shows three stages of stand development, which relate to growth rates and potential fertilizer response. Growth rates are greatest prior to and just after crown closure, that is during Stage I and the first half of Stage II in Figure 9b. Growth in the second half of Stage II and into Stage III steadily declines. In order to retain the initial high growth rates, thinning may be used to maintain the early (Stage I-II) stand conditions. However, as shown by Cole and Gessel (1992) in Figure 9a, nutrient demand closely follows periodic annual increment. Therefore, by using thinning to maintain an open, fast-growing stand, we are also maintaining a high nutrient demand on the site.

Site quality is reflected in nutrient availability, in other words better sites have more nutrients, and will probably respond better to thinning. However, fertilization is another option which may be used to increase nutrient availability, particularly on sites where past harvesting practices have severely impacted the site's nutrient budget. Miller (1981) points out that after crown closure, the best growth response to fertilization will occur following thinning. This is supported by a number of other studies which show strong growth responses to fertilization in thinned stands for many conifer species (Cochran 1977, Cochran 1979, Strand and DeBell 1979, Scanlin and Loewenstein 1979, Cochran et al. 1986, Cochran 1991, Powers 1992, Mika et al. 1992, Chappell and Bennett 1993, Carlyle 1995, Mitchell et al. 1996). Since the application of fertilizer, particularly nitrogen fertilizer, has been shown to increase biomass production and growth rates, a stand which is to be subsequently fertilized could receive a heavier thinning than one which is not being fertilized. Thinning slash should be treated the same as harvesting slash, that is left on site when possible to maintain nutrient and organic matter status.

In mixed-conifer stands, differences in nutrient requirements for different species may also be an important consideration for fertilization. Fertilization response in mixed-conifer

stands was studied in the Okanogan and Umatilla National Forests by the IFTNC (Garrison et al. 1998). Four species were examined, including Douglas-fir, grand fir, lodgepole pine and ponderosa pine. The fertilization treatments were N, N+S, and N+K. Fertilization resulted in increased foliar N concentrations for all species and increased growth for most species. Nutrient balances, particularly N/S and K/N, were important indicators of growth response to fertilization. Douglas-fir responded well to N fertilization only where S was not limiting growth, while grand fir responded well to N fertilization even when S levels were deficient. Lodgepole pine responded well to N and N+K fertilization, but the response to N+S fertilization varied widely depending on site-specific factors. Ponderosa pine, the least nutrient-demanding of the four species, did not tend to respond to fertilization when foliar nutrient analysis indicated that nutrient levels were adequate for growth.

In summary, a large portion of the ecosystem total of many important nutrients is held in the standing crop of trees. Within the trees, well over half of these nutrients are held in the branches, twigs and foliage. Because of this, whole-tree harvesting is much more detrimental to the nutrient pool than conventional harvesting. Site preparation techniques which remove slash and/or disturb the soil are also detrimental to a site's nutrient status. Second-rotation stands perform better following conventional harvesting than whole-tree harvesting, particularly where logging residue is left on site. Fire plays an important role in nutrient cycling. Cool broadcast burns are particularly useful in returning nutrients to the site, while high-intensity fires can cause nutrient volatilization and can physically remove nutrient-bearing ash from the site. Piling-and-burning is not a desirable nutrient management technique, as it involves the transport and concentration of nutrients into a small area. Thinning to maintain open crowns is useful for maintaining growth rates and minimizing nutrient competition. Fertilization is also a useful tool

for maintaining growth rates and increasing nutrient supply, particularly when used in combination with other silvicultural activities.

MANAGEMENT RECOMMENDATIONS

1. Practice density management. Thin stands in a timely manner in order to maintain high growth rates, and to encourage nutrient allocation to foliar biomass.
2. Practice conventional removal (lop and scatter) rather than whole-tree removal. The lop and scatter technique should be practiced during intermediate operations (thinning) as well as final harvest operations.
3. Let slash remain on site over winter for most mobile nutrients to leach from fine materials back to the soil.
4. Light broadcast burn or underburn for N release, and release of other nutrients from larger materials. It would be good to leave some large woody materials on site as habitat for forest soil biota and to provide organic matter and a future nutrient source.
5. Avoid mechanical site preparation.
6. Plant species appropriate to site, using genetically suitable stock when possible.
7. Apply herbicides to plantations to reduce competition for nutrients from other vegetation.
8. Consult the latest forest fertilization guidelines.

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