Chapter 6
Maintaining Adequate Nutrient Supply—Principles, Decision-Support Tools, and Best Management Practices

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Background

Maintaining adequate nutrient supply to maintain or enhance tree vigor and forest growth requires conservation of topsoil and soil organic matter. Sometimes nutrient amendments are also required to supplement inherent nutrient-pool limitations or replenish nutrients removed in harvested material. The goal is to maintain the productive potential of the soil and, when economically feasible and environmentally acceptable, enhance productivity where nutrient supply significantly limits growth. Nitrogen (N) is most frequently the limiting nutrient in Pacific Northwest forests, particularly on soils with low N pools (Gessel and Walker 1956; Heilman 1971; Turner et al. 1988, Chappell et al. 1991).

General principles of nutrient management

Soil N nutrient pools vary across the landscape (figure 6.1), and even across relatively short distances within a stand. Soil N is highly correlated with soil carbon/organic matter (figure 6.2). Nitrogen enters most forest ecosystems by fixation of atmospheric N and subsequent incorporation into organic matter. This organic matter eventually dies, decomposes, and releases mineralized N that becomes available for plant uptake. Nitrogen is maintained in the ecosystem by cycling living plants to soil organic matter and then to mineralized nutrients and then back to living plants, but large amounts of N are often held in dead organic matter and remain unavailable until further decomposition and mineralization.

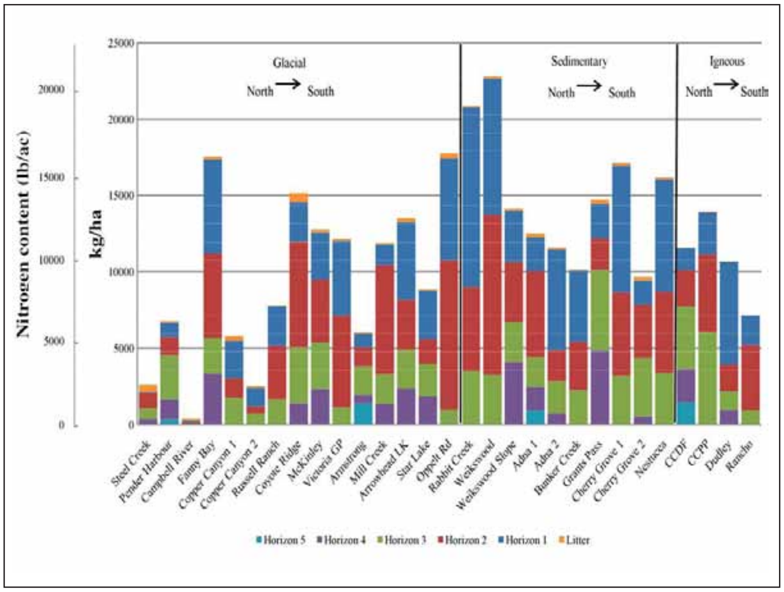

Figure 6.1. Soil nitrogen at selected locations west of the Cascades from Vancouver Island, British Columbia, to southern Oregon with glacial, sedimentary, and igneous parent material.

Graph by author Robert B. Harrison, unpublished data.

Factors affecting levels and retention of soil nutrient pools

Plant nutrients are supplied to the soil from a number of different sources:

- Mineral weathering
- Atmospheric fixation (carbon by photosynthetic tissues, N by N-fixing microorganisms)
- Atmospheric dry and wet deposition
- Organic matter mineralization
- Soil amendments (e.g., fertilizers and biosolids)

Forests growing on soils with large N pools generally have higher productivity than those on soils with small N pools, particularly when soil aeration and temperature are not limiting to decomposition and mineralization. Organic matter and topsoil conservation is critical for nutrient-pool conservation because the forest floor and topsoil horizons are generally higher in organic matter content than subsoil horizons, and the organic matter in surface horizons generally provides a greater proportion of available N than the more decay-resistant organic material in deeper soil horizons.

Soil nutrient pools should be maintained or enhanced rather than depleted (nutrient removals should not exceed inputs over the long term). Nitrogen and other nutrient concentrations vary by tree component. For example, the concentration of N in foliage is greater than that in branches or bole wood (table 6.1). Therefore, the level of nutrient removal is not exactly proportional to the mass of harvested material; rather, it depends on utilization intensity and the type of material removed.

Management of nutrition in perennial forest crops such as Douglas-fir has several advantages over managing fertility for annual agricultural crops. In coastal Douglas-fir, nutrient uptake can occur year-round when temperature and moisture conditions permit. Multiple cohorts, or age classes, of needles allow internal translocation of nutrients from older needles before they are shed, facilitating internal conservation of nutrients. Tree growth also builds on a perennial structure accumulated from previous years' nutrient uptake and growth. Finally, the primary tree component removed for commercial use is the stem or bole, which has a relatively low concentration of nutrients compared with tree foliage and fine branches. Of course, this is not the case in whole-tree harvesting, in which limbs and tops may be deposited at the roadside or removed during a biomass harvest. In many agricultural crops, the nutrient-rich foliage or fruiting structures comprise the bulk of the harvest.

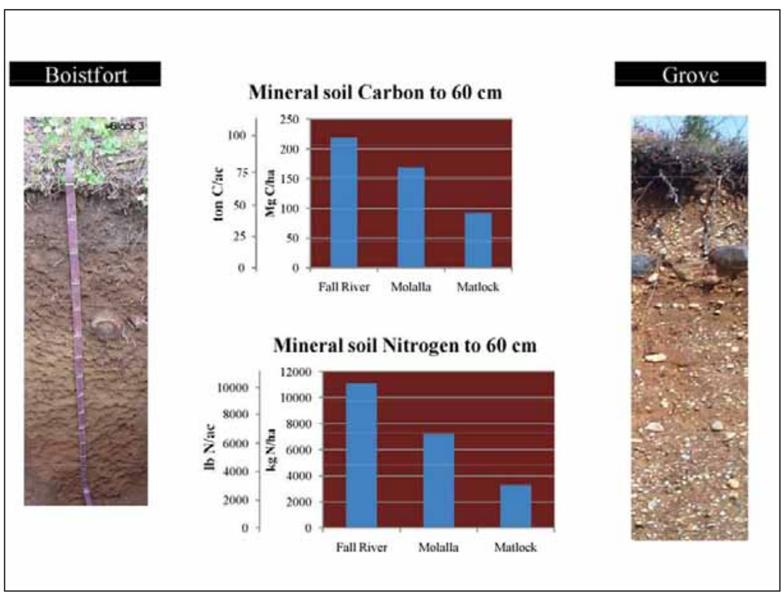

Figure 6.2. Mineral soil carbon and nitrogen to a 0.6-m depth at three regional soil productivity studies (after Ares et al. 2007 and Slesak, Schoenholtz, and Harrington, unpublished data). The Boistfort soil (residual soil derived from basalt) is located at the Fall River, Wash., site; the Kinney soil formed from basic agglomerate residuum (photo not shown) is at the Molalla, Ore., site; and the Grove soil (glacial outwash) is at the Matlock, Wash., site.

Photos by authors Darlene Zabowski (*left*) and Robert B. Harrison (*right*).

Table 6.1. Examples of Douglas-fir tree component nitrogen (N) concentrations for a 47-year-old fertilized stand and a 5-year-old stand on the same site (Fall River Long-Term Soil Productivity Study, a highly productive site in western Washington)

	N concentration (%, dry-mass basis)	
Tree component	**Age 47 years[1]**	**Age 5 years[2]**
Foliage	2.02 (0.07)	1.55 (0.4)
Bark	0.40 (0.05)	…
Live branches	0.26 (0.04)	…
Live branches + bark	…	0.89 (0.3)
Bole wood	0.08 (0.01)	
Bole wood + bark	…	0.42 (0.2)
n (number of samples)	14	12

Note: Values are mean ± one standard error. Standard errors are shown in parentheses.

[1] *Source*: Ares et al. (2007).

[2] *Source*: Peterson et al. (2008).

However, despite the low concentrations of N in wood, the large mass of bole wood/ha relative to foliage and live limbs in whole-tree harvested stands can result in N removals in bole wood exceeding removals in foliage and branches. For example, a 47-year-old stand of Douglas-fir and western hemlock at Fall River, Wash., had 39 Mg/ha (17 tons/acre) of foliage plus live limbs and 341 Mg/ha (152 tons/acre) of bole wood plus bark. The corresponding amount of N in these components was 225 kg/ha (200 lb/acre) in foliage and live branches and 359 kg/ha (320 lb/acre) in bole wood and bark (Ares et al. 2007).

The annual N demand of a typical Douglas-fir stand is approximately 45 kg/ha/year (40 lb/acre/year) from age 25 to 50 years (Cole 1986; figure 6.3). Internal recycling of nutrients is a significant source of N for meeting these annual requirements. On average, roughly 20% of annual uptake is retained and accumulated in tree biomass; the rest is shed as fine roots die and senesced foliage and branches fall to the forest floor. This fine root, branch, and foliage material decomposes, and the resulting mineralized N and other nutrients become available again for uptake by trees and other forest vegetation. Soil N supply generally is adequate for seedling growth after regeneration harvesting but can become limiting on N-deficient sites, particularly in the presence of intensely competing vegetation and as nutrient demand increases with accelerating growth and crown expansion (figures 6.3 and 6.4).

The amount of N removed during harvest depends on the yarding procedure and utilization intensity. In whole-tree yarding, all aboveground tree components are yarded to the landing regardless of utilization intensity. However, during this operation, a considerable amount of branches and needles can remain on site as these components are broken off during transport. In contrast, only logs are yarded when the trees are limbed and bucked where they fall (bole-only yarding). Utilization intensity is determined by the proportional amounts of logs and chipped or bundled biomass (e.g., foliage, branches, tops, and cull logs) that are removed from the site for subsequent use. Utilization intensity is also determined by the minimum diameter and length of logs demanded by the market and opportunities for using biomass held in residual bole-wood, branches, and foliage. Bole-only yarding removes about 5% of the total site N pool (the amount of N existing on the site including above- and belowground biomass and mineral soil components). In contrast, whole-tree yarding removes about 10% of the total N pool (Edmonds et al. 1989).

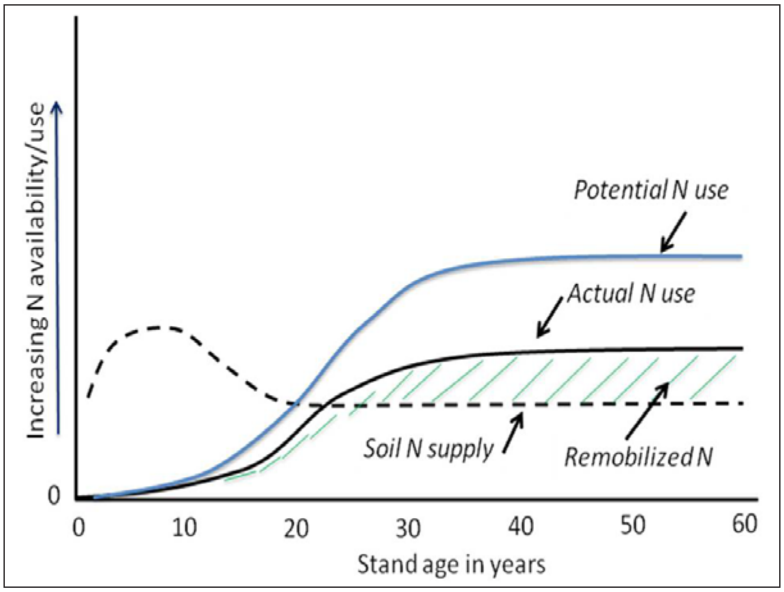

Figure 6.3. Conceptual diagram of soil nitrogen (N) nutrient supply and uptake of a Douglas-fir stand showing the importance of recycling (remobilized N) within the tree. Nutrient availability from the soil is highest when tree demand for nutrients is lowest. The potential N-use curve compared with the actual N-use curve reflects the deficit not available to trees on N-deficient sites during the maximum growth and nutrient uptake period. The difference between potential and actual N use will depend on the degree of N limitation on the site and other factors that may be limiting growth potential.

Graph by author Robert B. Harrison, adapted from the southern pine diagram of Fox et al. (2007).

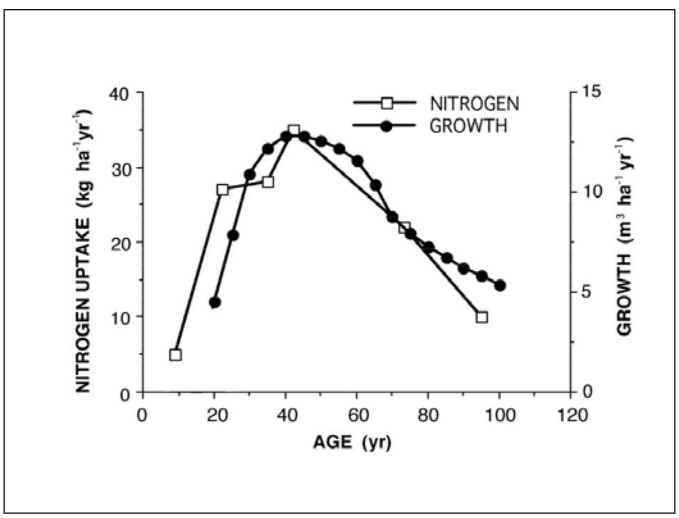

Figure 6.4. Example of nitrogen uptake of a Douglas-fir stand with age compared with the volume growth (tree boles) of the stand.

Graph from Turner (1975).

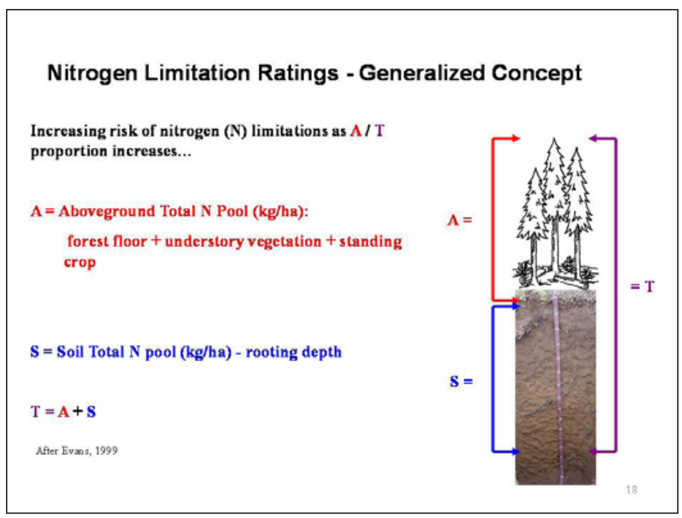

Figure 6.5. The likelihood of having a nutrient supply limitation due to biomass removal increases as the A/T proportion increases (i.e., when a high percentage of the site's nutrient pool is in the standing crop and forest floor) because the aboveground biomass can be removed during harvest and the forest floor can be removed or displaced during site preparation.

Illustration by author Thomas A. Terry, reproduced by permission of Weyerhaeuser Company.
Photo by author Darlene Zabowski.

Removing an increasing proportion of the nutrient pool increases the risk of causing a negative impact on nutrient supply and tree growth. Evans (1999) concluded from a review of the literature that the risk of declining tree productivity was low for 10% removal of an essential nutrient and serious for 30% removal and that imminent decline was likely if nutrient-pool removals approached 50% or greater. One method for assessing the potential impacts of organic matter removal is to estimate the ratio of the aboveground N pool to the total above- and belowground N pool. For example, if the aboveground pool (pool A in figure 6.5) was removed from the Boistfort soil, it would deplete 9% of the N pool, whereas removing this pool on a Grove soil would deplete 16% of the N pool (figure 6.5). The risk of detrimental impacts from whole-tree yarding on the N pool is greater on the Grove soil because it has a relatively small total N pool, and a relatively high proportion of it resides in the aboveground biomass.

Best management practices (BMPs) implemented for biomass retention and removal during harvest and site preparation depend on trade-offs among several risk factors, including potential adverse effects of wildfire, erosion, and invasive weeds, and the implications for planting quality. Nutrient limitations or shifts in nutrient availability that may affect long-term productivity should also be considered. Key BMPs include the following:

- **Take extra precaution during harvest activities in or around ecologically sensitive areas, riparian zones, and areas characterized by organic or shallow soils with low nutrient pools.** Intensive biomass harvesting should not be conducted in these areas.
- **Conservation of large woody debris (figure 6.6) is important from a wildlife and biotic diversity perspective and also must be considered when retention guidelines are specified during harvest (Bull 2002).** Retain all large legacy wood that exists on the forest floor and large standing snags where it is safe to do so. Wildlife reserve trees or green recruitment trees should also be identified and left in areas where they will not become a safety hazard. These trees will produce large woody debris with time. Large woody debris (>7 inches [18 cm] in diameter) functions as habitat for a variety of organisms (e.g., fungi, mosses, insects, and amphibians). Retention of both large and fine woody debris can protect a site from erosion, soil compaction and rutting, and surface runoff. Forest practice regulations in some states (e.g., Washington and Oregon) have specific requirements for large woody debris and recruitment tree retention.

Figure 6.6. Conserve a range of woody debris sizes to meet wildlife, soil biology, and biodiversity objectives.

Photo by author Thomas A. Terry, reproduced by permission of Weyerhaeuser Company.

- **Removing only logs (bole-only harvest) presents a relatively low risk of loss in productivity, whereas whole-tree yarding may create a greater risk depending on how much of the nutrient pool is removed relative to the total pool before harvest.** Fox (2000) emphasized that productivity losses caused by nutrient losses in harvested material are likely to be highly dependent on specific site characteristics, particularly available nutrients. Evans (1999) concluded from a review of the available literature that removing less than 10% of the nutrient pool presented a low risk of productivity losses on many soils.

- **Retain at least 30% of the fine woody debris on slopes conducive to ground-based harvesting and 50% or more on steeper slopes.**
- **When removing logging residuals for biomass harvest or fuel reduction, or when piling slash to create planting spaces, it is best to wait until the residuals dry so that needles and fine branches can fall off and remain distributed as uniformly as possible across the site.** Slash piles created for site preparation should be small and located such that the site can be planted in a manner that maintains the desired spatial distribution of planted trees.
- **Some displacement of the forest floor to create planting spots can improve planting quality and subsequent root growth (increased soil temperatures in the spring), but too much mineral soil exposure (displacement) can reduce water available to seedlings as a result of increased weed competition and increased evaporation from the surface soil.** Logging slash removal or slash piling that exposes mineral soil can significantly increase invasive weeds such as Scotch broom (Harrington and Schoenholtz 2010). High levels of competing vegetation can reduce planted seedling survival and early growth.

Nutrient deficiencies—diagnosis and correction

On the majority of sites in the Pacific Northwest, N is most frequently the limiting nutrient to Douglas-fir growth. In general, response to N fertilization tends to be greatest in stands with a below-average site index and least on highly productive sites. Our ability to predict the degree to which a specific site will respond to N fertilization, however, is still weak.

Use of foliar diagnosis for identifying deficient stands is problematic because foliage is difficult to sample in older stands, nutrient concentration can vary from year to year depending on weather conditions (e.g., amount and timing of rainfall and many other factors), and nutrients from older needles can be recycled to younger tissue. In addition, the limited evidence to date suggests that the total amount of N and other nutrients in the forest canopy (determined largely by total foliage mass) is more important than the concentration of nutrients in the foliage.

Nitrogen-deficient foliage tends to be yellowish green, and leader growth on branch terminals and lateral branches tends to be less vigorous than that on trees with adequate concentrations of N (figure 6.7). Needle size and needle density per unit length of shoot also decline under N-deficient conditions.

Swiss needle cast (SNC), a foliar disease caused by a fungus that grows within intercellular spaces of needles, causes yellowing and premature loss of foliage in Douglas-fir (Hansen et al. 2000). Foliage is retained on the most severely impacted trees for only 1 year or less (figure 6.8). Although SNC symptoms can appear similar to those of N deficiency, foliar N concentrations are actually highest in trees with the lowest foliage retention. It is still unclear whether relatively high N concentrations cause the disease by providing a N-rich feeding substrate or represent an effect associated with translocation of foliar N to surviving foliage. The key distinguishing characteristics of SNC include progressive yellowing and browning of infected foliage through winter and spring; sparse crowns caused by premature foliage loss, particularly in the spring just prior to bud break; and tiny black fruiting bodies (pseudothecia) that plug stomatal openings on the underside of needles and inhibit photosynthesis (Scharpf 1993 ; Filip et al. 2000).

Walker and Gessel (1990) developed nutrient deficiency levels for seedlings by using the solution culture method (table 6.2). These values should be used with caution when examining foliage from older stands. Ballard and Carter (1985) identified three N-deficiency levels in Douglas-fir on the basis of foliar N concentration (%, dry-mass basis):

1. Very severe: <1.05%
2. Severe: >1.05 to 1.3%
3. Slight-moderate: >1.3 to 1.45%

When implementing foliage sampling in established stands, collect foliage from the upper third of crowns on dominant and codominant trees. Foliage sampling should be limited to the dormant season, preferably between October and February, to avoid seasonal changes. Always collect needles that were formed in the most recently completed growing season.

Figure 6.9 shows a generalized relationship between nutrient concentration and tree growth that illustrates the range from deficiency to luxury consumption to toxicity. The goal of any nutrient amendment is to reduce deficiency levels and improve growth rates while achieving an acceptable rate of return on the investment.

Figure 6.7. Douglas-fir branches to the right of the black line show typical symptoms of nitrogen deficiency; the branch on the left shows no nitrogen-deficiency symptoms.

Photo by author Thomas A. Terry, reproduced by permission of Weyerhaeuser Company.

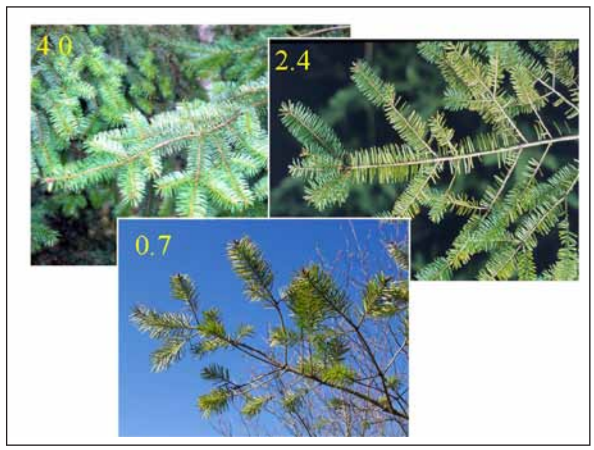

Figure 6.8. Douglas-fir branches with various levels of foliage loss and yellowing due to Swiss needle cast, a foliar disease caused by the fungus *Phaeocryptopus gaeumannii*. The number in upper left corner of each photo indicates foliage retention in years.

Photos by Alan Kanaskie, Oregon Department of Forestry, reproduced by permission.

Table 6.2. Seedling nutrient deficiency levels (foliar concentrations, %, dry-mass basis) developed using the solution culture method

Element	Douglas-fir	Hemlock	Western red cedar	Sitka spruce	True firs
Nitrogen	1.25	1.80	1.50	1.80	1.15
Phosphorus	0.16	0.25	0.13	0.09	0.15
Potassium	0.60	1.10	0.60	0.40	0.50
Calcium	0.25	0.18	0.20	0.06	0.12
Magnesium	0.17		0.12	0.06	0.07
Sulfur	0.35		0.4	0.15	

Source: Walker and Gessel (1990).

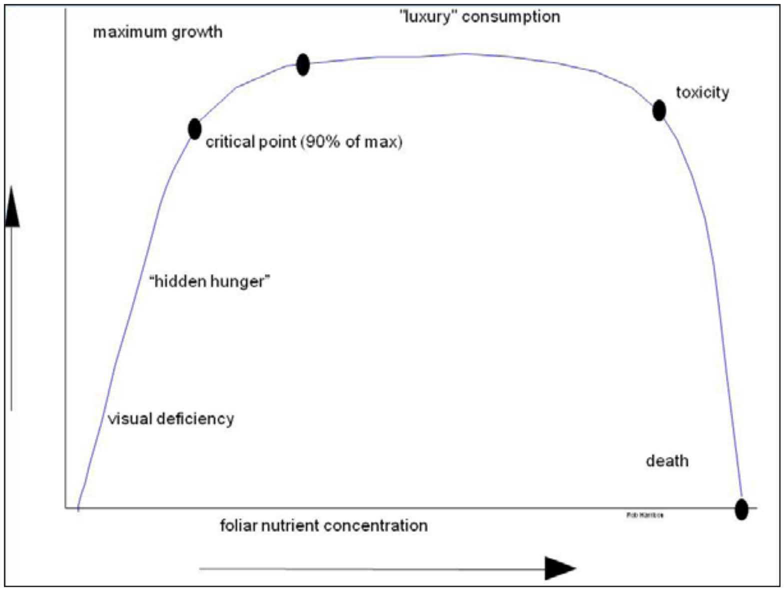

Figure 6.9. Generalized relationship between nutrient concentration (*x-axis*) and tree growth and vigor (*y-axis*).

Graph by author Robert B. Harrison.

Fertilization to maintain and enhance fertility and productivity

The Regional Forest Nutrition Research Project (now the Nutrition Project within the Stand Management Cooperative at the University of Washington) established several sets of regional fertilization trials in coastal Douglas-fir zones of Washington, Oregon, and British Columbia. In one large set of field trials, N was applied as urea at the rate of 224 kg/ha (200 lb/acre) of N in unthinned and thinned stands of Douglas-fir. Four-year N responses averaged 18% for unthinned stands and 29% for thinned stands (Peterson and Heath 1986; Opalach et al. 1987), but large differences in response were observed among stands. These early studies were designed to test the average response to N fertilization across the region rather than site-specific responses. The Stand Management Cooperative has installed a new set of replicated single-tree fertilization trials to develop better site-specific fertilization guidelines for Douglas-fir stands in the region.

On sites where Douglas-fir has responded to N fertilization with accelerated growth, it is unclear how long the added N is retained in the system, particularly with respect to its availability to the subsequent tree crop. Recent analysis of trees planted on old Regional Forest Nutrition Project research plots has demonstrated that growth is significantly greater on fertilized plots than on unfertilized plots (Footen et al. 2009). This carryover effect of N added 30 years before in the previous rotation suggests that this type of soil amendment may increase the labile pool of N available for growth of the succeeding stand. How long this effect lasts needs to be determined.

The timing of fertilization is largely an economic decision but also must be considered in the context of the long-term stand density regime (e.g., growth gains from fertilization in dense or unthinned stands can be lost to increased suppression mortality). Miller and Fight (1979) noted that applying 492 kg/ha (440 lb/acre) of urea prills (approximately 224 kg/ha [200 lb N/acre]) 10 years prior to harvest is an appealing strategy for addressing N deficiency in Douglas-fir stands because

- stand growth responses last about 10 years,
- increased growth goes into trees most likely to be marketed, and
- investment costs are recovered sooner than when fertilizer is applied earlier.

Application of treated biosolids is another option for increasing the N status of soils (Harrison et al. 2002).

With successive harvest of Douglas-fir crops from intensively managed forestlands in the Pacific Northwest, the appearance of other nutrient deficiencies becomes an increasing possibility (Walker and Gessel 1990). Three-year results from a recent set of trials suggest that Douglas-fir growth can show a significant response to applications of calcium and phosphorus (Mainwaring et al. in review). However, as was found in the case of N fertilization, significantly positive growth responses were limited to only a subset of the sites.

Alternative species for improving soil fertility levels

Red alder (*Alnus rubra*) is a N-fixing species that has often been suggested as a component of an alternating crop system (Douglas-fir/alder/Douglas-fir…) or of mixed alder/Douglas-fir plantations. Results from mixed-species trials suggest that red alder offsets Douglas-fir productivity by direct competition (Miller et al. 1999, 2005), and the differential growth rates of the two species require careful planning and management of stand density and spatial arrangement of the species mix. However, red alder should not be overlooked as a species with which to build soil N pools and/or produce a valuable crop on sites where Douglas-fir may not be suitable (e.g., laminated root-rot pockets).

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