

Nutrient Management of Coastal Douglas-fir and Western Hemlock Stands: The Issues

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ABSTRACT. An attempt is made to review briefly the current understanding of the role of nutrient elements in controlling the productivity of Douglas-fir and western hemlock forests. Information on the uptake and cycling of major nutrients is summarized. Nitrogen and phosphorus availability depends on forest site conditions, particularly moisture availability, humus form, and vegetative competition. Site preparation, slash burning, brush removal, and windthrow have also been found to affect nutrient availability. Coast Douglas-fir forests have shown reliable and consistent response to large-scale operational forest fertilization programs for over 30 years. Douglas-fir plantations in Europe have had nutritional problems. Coastal western hemlock forests, by contrast, have shown inconsistent response to nitrogen additions. The various reasons proposed for this lack of response are reviewed. The main nutrient management issues for Douglas-fir are: fertilizer response prediction, long-term productivity, and the effects of excessive nitrogen input in European plantations. The main issues for hemlock are: sensitivity to vegetative competition for nutrients, chlorosis of regeneration on some sites, the long-term effects of windthrow on fertility, and the erratic response fertilization sometimes produces.

Douglas-fir (*Pseudotsuga menziesii*) is the dominant commercial tree species in Washington and Oregon, with a long history of successful operational fertilization based on detailed study of its nutritional requirements. Current American concerns about Douglas-fir nutrition mainly focus on maintaining stand productivity and predicting fertilizer response. However, the lack of long-term data limits our ability to prove or disprove that current and projected management practices will not impair long-term productivity.

In British Columbia, coast Douglas-fir is relatively unimportant commercially, because of its limited range. The species is locally important on southern Vancouver Island and the southwestern mainland. Approximately 80,000 hectares of second-growth coast Douglas-fir stands have been fertilized since 1963, mostly following juvenile spacing. Current research in Douglas-fir nutrition includes determining the relationships between the growth response to fertilization and the stand and site characteristics of different ecosystem types (Carter and Klinka 1988).

Douglas-fir has been widely planted in central Europe for the last 100 years. Currently, high nitrogen inputs (due to pollution) and acidification are causing concern about nutrient management in that part of the world, attracting considerable scientific attention. Fortunately, these problems do not yet exist in western North America and hopefully can be avoided. However, a high level of nitrogen availability combined with surplus growing season moisture on some Pacific Northwest sites is suspected to be related to distorted growth in off-site Douglas-fir plantations (Carter et al. 1986).

In contrast to Douglas-fir, western hemlock (*Tsuga heterophylla*) is by far the most important commercially valuable species on the coast of British Columbia and becomes increasingly less important as one proceeds south. Also in contrast to Douglas-fir, this species has received little study of its nutritional requirements. Erratic and uncertain responses to nitrogen fertilization have been recorded for western hemlock throughout its range. Understandably, as a result, there has been a reluctance to invest in western hemlock fertilization programs. The primary focus has been stocking control, because it is not uncommon for this species to regenerate naturally at high densities on cutover lands. Recently however, additional problems in western hemlock nu-

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trition, such as chlorosis and stagnation in some young stands, have been recognized and these, coupled with increasing demands to produce more wood from a shrinking land base, have focused more attention on western hemlock nutrition management.

Because of differences in history, forest land-ownership, and land classification systems, approaches to the study of nutrient management have varied between the western United States and British Columbia. In the United States, much of the nutrition work, especially in regard to fertilizer response, has been based on averaged effects of many cooperative plot studies using a soil classification or a site index framework to reflect site fertility differences. The emphasis has been on prediction and understanding based on averaged effects in second-growth forests belonging to many owners. This chapter briefly reviews some of the current nutrient management issues for the two species.

Nutrient Elements Controlling Stand Productivity

Nutrition of Douglas-fir has been intensively studied for over three decades in the Pacific Northwest. Good summaries can be found in Oliver et al. (1986), the contribution on nutrition by Radwan and Brix being particularly useful. Considerably less is known about the nutrition of western hemlock. Useful reviews include van den Driessche (1976) and Gill (1981).

Diagnosis of nutrient deficiency may be done by visual inspection, soil analysis, soil bioassay, fertilization trials, and foliar analysis. Interpretation of foliar analysis by "vector analysis" has proved to be quite a useful method for conifers with determinate needle growth, such as Douglas-fir (Weetman and Wells 1990), and may be useful for species with indeterminate needle growth, such as western hemlock (Weetman et al. 1989). Procedures for diagnosing nutrient deficiencies are covered in detail in this volume by Carter.

The nutrient requirements of Douglas-fir and western hemlock are not known with precision. Although the requirements are likely to change with age (Miller et

al. 1981) and may vary with site conditions, they appear to be similar to the known requirements for higher plants. Estimates of adequate foliar macronutrient concentrations for plant growth in general and for Douglas-fir and western hemlock specifically are given in Table 1. While van den Burg's (1985) compiled data do not suggest much difference between Douglas-fir and western hemlock in nutrient requirements, Ballard and Carter's (1986) work in the Pacific Northwest suggests a higher phosphorus requirement for hemlock and a higher calcium requirement for Douglas-fir.

The critical level for a foliar nutrient is the concentration that is just adequate for maximum growth. In interpreting critical levels, one should recognize that nutrient requirements are not absolute; they depend in part on the relative amounts of other nutrient elements available, and they vary with age and reproductive activity (Radwan and Brix 1986). The critical foliar N level for Douglas-fir is generally agreed to be 1.5% (Radwan and Brix 1986). While there is no general agreement on critical foliar levels for other nutrients, Peterson et al. (1986) give the following: phosphorus 0.15%, potassium 0.80%, sulfur 0.14%, and boron 15 ppm. Critical foliar nutrient levels remain to be determined for western hemlock.

Mohren (1987) estimated from published literature that the growth rate of Douglas-fir is positively correlated with foliar N concentration over the range 0.8 to 2.0%. Similarly, for young western hemlock on poor sites on northern Vancouver Island, growth rates were found to be positively correlated with foliar N over the range 0.7 to 1.9% (Thompson and Weetman, unpublished data). However, Gill and Lavender (1983) found no association of growth rate of fertilized hemlock stands with foliar N over the range 1.3 to 1.9% on medium sites in Oregon.

Ratios of nutrients can be useful for predicting whether fertilization with an element may induce a deficiency of another element (van der Driessche 1981). For example, Turner et al. (1977) suggested that the N:S ratio be examined prior to fertilization of coastal Douglas-fir. Nitrogen fertilization of Douglas-fir can depress foliar concentrations of phosphorus (Radwan et

Table 1—Adequate foliar macronutrient requirements for growth (%), estimated and compiled for plants in general and for Douglas-fir and western hemlock specifically.

	N	P	K	Ca	Mg	S	Reference
Plants	1.5	0.2	1.0	0.5	0.2	0.1	Epstein (1972)
Douglas-fir	1.45	0.15	0.80	0.25	0.12	—	Ballard and Carter (1986)
	0.9 - 2.4	0.10 - 0.31	0.40 - 1.55	0.20 - 0.57	0.04 - 0.22	0.10 - 0.27	van den Burg (1985)
Western hemlock	1.45	0.35	0.80	0.10	0.10	—	Ballard and Carter (1986)
	0.86 - 2.10	0.09 - 0.35	0.30 - 1.0	0.09 - 0.65	0.06 - 0.19	0.08 - 0.17	van den Burg (1985)

al. 1984; Radwan and Shumway 1984) and sulfur (Humphreys et al. 1975).

There is recognition in Europe that Douglas-fir is a fairly nutrient demanding species; it cannot be planted successfully on poorer sandy soils that previously grew satisfactory Scots pine (*Pinus sylvestris*) crops. However, there is a danger that large repeated annual nitrogen inputs due to pollution, which initially improve site class, may lead to saturation acidification of forest soils (van Breemen et al. 1982), nitrogen leaching, increased drought, frost and disease sensitivity, and nutrient imbalances (van den Burg and Kiewiet 1989). Some Dutch plantations have foliar N concentrations of up to 4.00%, imbalanced N:P ratios, distorted growth, top dieback, needles covered in green slime, and changes in mushroom populations. There are no Pacific Northwest precedents in natural Douglas-fir forests for these effects seen in Europe.

Nutrient requirements can also be expressed¹ on a stand basis. These requirements can be partly satisfied by internal redistribution (Sollins et al. 1980), with the remainder coming from the soil. For example, annual nutrient uptake in old-growth Douglas-fir has been measured (kg/ha) as nitrogen 42.0, phosphorus 9.1, potassium 26.9, and calcium 44.2 (Sollins et al. 1980) on a site where net primary production (NPP) was 8 Mg (tonnes) dry matter per hectare. In contrast, Mohren (1987) estimated nutrient requirements for Douglas-fir growing under Dutch conditions. Assuming an annual growth rate of 20 Mg dry matter/ha (foliage 4, branches 1, stems 10, and roots 5) for a closed canopy stand with no water shortage, he calculated that 120 kg N/ha and 6.5 kg P/ha would be supplied annually by retranslocation and that 87.5 kg N/ha and 12.3 kg P/ha would be required annually from the soil. These large differences in nutrient requirements are explained by the differences in growth rate. Both sets of figures fit the

linear relationship between NPP and nitrogen uptake shown by Miller (1984) for forest plantations worldwide.

Marshall (1991) stated that nitrogen is the main element of nutritional interest in the Pacific Northwest but identified seven other elements (phosphorus, potassium, sulfur, boron, copper, iron, and zinc) that are expected to receive more attention as areas deficient in these nutrients are targeted for treatment. Nutrient deficiencies in Douglas-fir stands have been clearly and consistently demonstrated only for nitrogen. This has been done by recording positive responses in numerous nitrogen fertilizer trials (RFNFP 1989; Omule 1990; Gardner 1990; Miller et al. 1986). Peterson et al. (1986) noted: "Economically important growth-limiting deficiencies of nutrients other than N have not generally been found." However, systematic testing has not been done. Some evidence exists for deficiencies of other nutrients, particularly following nitrogen fertilization. These include: boron (Carter et al. 1984; Carter and Brockley 1990; Peterson et al. 1986), sulfur (Turner et al. 1977; Peterson et al. 1986), and phosphorus (Shumway 1983).

Nutrient Uptake, Cycling, and Transfers

For general information on the cycling of nutrient elements see Bonneau and Souchier (1982), Tisdale et al. (1985), and Stevenson (1986). As shown in Table 2, major nutrient inputs to the soil and some estimated values for coastal forest ecosystems of the Pacific Northwest are quite varied depending on the presence or absence of nitrogen-fixing species and the rate and quality of litterfall.

Many nutrient cycling studies have been done in the Pacific Northwest over the past 30 years, particularly on Douglas-fir. Hemlock has been studied much less extensively. For both these and other conifers, Cole

Table 2—Major nutrient inputs (kg/ha/yr) to the soil and some estimated values for coastal forest ecosystems of the Pacific Northwest.

Input	N	P	K	Ca	Mg	Reference
Weathering of rocks and minerals	—	—	4-15	8-24	8	Zasoski (1981)
Litterfall	19.2	0.05	12.0	47.4	5.4	Gessel and Turner (1974)
Root turnover	—	—	—	—	—	None for PNW ¹
Biological fixation						
Red alder (<i>Alnus rubra</i>)	27	—	—	—	—	DeBell et al. (1983)
	300	—	—	—	—	Newton et al. (1968)
Snowbrush (<i>Ceanothus velutinus</i>)	20	—	—	—	—	Zavitkovski and Newton (1968)
	100	—	—	—	—	Youngberg and Wollum (1976); Binkley et al. (1982)

¹Joslin and Hendersen (1987) reported annual inputs of 14.6 kg/ha for N, 0.7 for P, 4.1 for K, 10.3 for Ca, and 2.0 for Mg for a white oak stand in Missouri.

(1981a) concluded that their ecosystems were basically stable; that is, they had no net nutrient gains or losses. While there is considerable variation in rates of transfer and specific processes between different coniferous ecosystems, there is little nutrient loss. In some areas, windthrow may play a major role in maintaining site productivity of western hemlock. For example, in the Tongass western hemlock forests of Alaska, where podzolization may reduce soil fertility in as little as three years, windthrow is considered to be the principal mechanism of reversing the effects of podzolization (Bormann 1990).

We do not know in detail the annual pattern of nutrient uptake. The periods of maximum uptake are probably the fall, late winter, and spring, corresponding to the periods of maximum root extension and cambial and meristematic activity (Radwan and Brix 1986). It is generally observed that over the life of the stand, uptake rates are greatest at the time of or soon after canopy closure (Cole 1981b).

Clearcutting and slash burning have minimal effects on leaching losses alone (Gessel and Cole 1965; Cole et al. 1975). There are, however, important exceptions to these general observations, which are discussed below under management practices.

Control of Nutrient Availability

Moisture Availability

Nutrient availability and moisture availability are interdependent. A deficiency of soil moisture can limit nutrient availability, but improved soil nutrition can also increase plant water-use efficiency (Brix 1981b). Growth response to fertilization can be significantly enhanced by irrigation. This was found by Brix (1972) working with Douglas-fir on southern Vancouver Island and by Khanna and Raison (1990) working with radiata pine (*Pinus radiata*) in Australia. Fertilization on dry sites can potentially induce water stress, due to increased transpiration from a larger canopy. This has been demonstrated for radiata pine in Australia (Landsberg 1986). Whether or not this can happen to coastal western hemlock has yet to be conclusively demonstrated. Mortality of unfertilized and fertilized hemlock on dry sites may be caused by seasonal moisture deficits (Brix 1991). Hemlock usually roots in the humus layer and is thus more sensitive to drought conditions. However, hemlock forests in the Coastal Western Hemlock Zone usually have adequate growing season moisture supplies. But moisture does appear to be limiting for hemlock growing in coastal Douglas-fir

regions that experience drought. Fertilization of hemlock on these dry sites is not recommended.

In contrast, on southern Vancouver Island, fertilization of Douglas-fir at the Shawnigan Lake trial did not have any significant effect on the soil and tree water stress (Brix and Mitchell 1986). Similarly, apparently shallow sites on south-facing slopes at Pack Forest, Washington, which would appear to be moisture limited, have responded well to sludge additions. Gessel et al. (1990), in assessing the relative importance of water and nutrients for Douglas-fir growth in the Pacific Northwest, concluded that compared to nutrition, moisture does not seem to be a major limiting factor for growth in the region. However, Green et al. (1989) and Klinka and Carter (1990) indicate that soil moisture does significantly limit the productivity of coastal Douglas-fir in coastal British Columbia.

Evidence of the sensitivity of Douglas-fir to moisture stress following fertilization is available from The Netherlands. Annual runoff from agricultural sources of up to 100 kg N/ha to Douglas-fir plantations has raised fears that root growth will be reduced and that stands will become unstable to wind and subject to drought stress. The Dutch ACIFORM project, which intensively monitors and studies Douglas-fir plantation development, indicates that high levels of ammonium deposition reduce root densities and root uptake capacity. The transpiration of the forest stand may increase, and on dry soils this will lead to larger water deficits (Olsthoorn et al. 1991).

Humus Form

The shallow rooting of hemlock in the humus layer suggests, but does not prove, that the supply of nitrogen and phosphorus for hemlock may be related to the restricted availability of the two nutrients from organically bound forms in humus. While British Columbia has a taxonomic classification of humus forms (Klinka et al. 1981), it has not been possible to correlate humus form to nitrogen and phosphorus supply problems for hemlock in a useful way. Conventional wisdom about richer and more productive sites being associated with mull or moder forms rather than mor forms seems to apply to both Douglas-fir and hemlock. In virgin old-growth coastal hemlock forests, it is relatively easy to identify rich, medium, and poor sites through associated humus forms and plant associations (Haeussler et al. 1984; Klinka and Carter 1980). However, it has proved difficult to relate directly the well-established and known site characteristics of the hemlock forests to their nutrient regime in a causative and quantitative way. Unfor-

tunately, little experimental work has been done. In contrast, relationships between site quality and environmental factors have been successfully quantified for Douglas-fir (Klinka and Carter 1990).

Competing Vegetation

Western hemlock tends to root in the humus layer, while Douglas-fir roots more deeply. When grown together in the presence of competing vegetation, such as *Vaccinium*, hemlock tends to be more sensitive than Douglas-fir to the vegetative competition. In such a situation in the Coastal Western Hemlock Zone on northern Vancouver Island, nitrogen and phosphorus deficiencies were noted in the dense hemlock regeneration, while the Douglas-fir regeneration was not deficient (Quesnel 1990).

While nitrogen and phosphorus supply problems are not evident on most cutover areas with vegetative competition in the Coastal Western Hemlock Zone, nitrogen and phosphorus deficiencies and growth check of western hemlock have been found in both natural regenerations and planted seedlings growing in competition with dense salal (*Gaultheria shallon*) on northern Vancouver Island on deep mor-humus folisolic podzols. Removal of the vegetation by chemical means or by mechanical removal with a backhoe has led to partial nutritional recovery. A full recovery of growth rate for a 4 to 5 year period has been obtained by experimental N+P fertilizer additions. These have been followed by operational N+P aerial fertilization of young, second-growth western hemlock plantations. This is the first operational use of nitrogen and phosphorus together in the Pacific Northwest. The nitrogen and phosphorus supply problem may be due to the salal, to the kind of humus, or to both. The Salal Cedar Hemlock Integrated Research Project (SCHIRP), involving several scientific disciplines, has been organized to study the problem (Weetman et al. 1990).

In contrast to hemlock, Douglas-fir growth is not restricted by competing salal. On poorer and drier sites in the coastal Douglas-fir zone, Douglas-fir stands usually have salal understories. A study of the effects of salal removal on Douglas-fir growth at Shawnigan Lake indicated no effects on soil or shoot water potential over the first 10 years after treatment (Brix and Mitchell 1986), nor did salal removal affect basal area growth response in the thinned and fertilized plot after the first 15 years of posttreatment.

Douglas-fir also grows in competition with red alder (*Alnus rubra*). Higher soil nitrogen status of prior alder sites increased nitrogen concentration in Douglas-fir

needles, but not four-year height growth, at Thompson Experimental Forest. Symbiotic nitrogen fixation by alder increased nitrogen in the aboveground biomass and soil by 34 to 96 kg/ha annually (Van Miegroet et al. 1990). Since 70% of the Douglas-fir sites in the Pacific Northwest are limited by low levels of soil nitrogen (Miller et al. 1986), alder is currently recommended as desirable in crop rotations and in mixture with other species such as Douglas-fir; alder is also resistant to *Phellinus weirii*, laminated root rot (Miner 1990). However, successive rotations of red alder have decreasing productivity and can increase soil acidity (Cole et al. 1990).

Effects of Management Practices

Stand management practices including slash burning, harvesting, and fertilization can greatly influence nutrient cycling and availability (e.g., Leaf 1979; Ballard and Gessel 1983).

Slash Burning

Nutrient cycling is altered by slash burning via changes in the form, distribution, and amount of nutrients (McNabb and Cromack 1990). Most studies have focused on the immediate and short-term effects on site productivity. Little work has been done to quantify the long-term effects on stand growth and yield, and what information has been obtained indicates a high dependence on local conditions. Research in this area is difficult because of variability in fire severity, initial site tolerance, and subsequent ability to recover after prescribed burning (Miller and Seidel 1990; Curran and Ballard 1990). Nevertheless, Johnson et al. (1982) estimated nitrogen losses from clearcutting at 3.8%, from clearcutting and burning at 9.5%, and from clearcutting and intensive burning at 27% of a total N capital of 3,200 kg/ha.

One study by Miller and Bigley (1990) compared paired burned and unburned plots, established 35-42 years earlier, at 44 locations on the western side of the Cascade Mountains in Washington and Oregon. In analyzing species composition and volume growth, they concluded that slash burning altered species composition by increasing the proportion of Douglas-fir and hardwoods. However, it did not alter the stem volume production of all species combined over the first 40 years after burning.

Slash burning of salal-dominated ecosystems on eastern Vancouver Island was found to improve the subsequent survival, and height and diameter growth, of Douglas-fir (Vihnanek and Ballard 1988). Measure-

ments taken in 5 to 15-year-old stands also showed that foliar phosphorus, potassium, calcium, iron, and boron concentrations were increased as a result of burning, while concentrations of nitrogen, magnesium, sulfur, zinc, and copper were unaffected. The only foliar concentration reduced was that of manganese, but this was not below the critical level.

Convection, volatilization, leaching, and erosion are the primary mechanisms by which nutrients are lost during or after a fire. All of these can be lessened by reducing the intensity of the slash burn. Volatilization has the biggest impact, with nitrogen, and to a lesser degree sulfur and phosphorus, most susceptible to this form of loss. The amounts of nitrogen lost during slash burning via volatilization vary a great deal, with the highest losses occurring on sites where the fire consumes a thick forest floor. Loss estimates for nitrogen via volatilization range from about 100 to 1,000 kg/ha (Feller et al. 1983).

Prescribed fire also usually results in short-term decreases in the populations of several soil organisms, in turn disrupting the roles these organisms play in nutrient cycling and uptake by plants (Borchers and Perry 1990). Comparing paired burned and unburned plots in the western Cascade Mountains approximately 25 years after broadcast burning, Kraemer and Hermann (1979) found no significant differences between soil organic matter, total N, extractable P, exchangeable K and Ca, and soil permeability and wettability.

Harvesting

Any removal of biomass will result in an immediate reduction in the nutrient status of the site, but the long-term effects of biomass removal on future site productivity are not well established. Turner (1981) estimated that removal of branches and foliage during harvest would double the removal of nitrogen, phosphorus, potassium, calcium, and magnesium from 95-year-old Douglas-fir. Cromack et al. (1979) indicate that harvesting removes 12% of the nitrogen from the ecosystem.

A study was initiated in 1979 at the University of Washington's Pack Forest to address the question of impact of various harvesting intensities on the growth of the next stand (Compton and Cole 1992). This study included three levels of harvesting—bole only, whole tree, and whole tree plus understory and forest floor removal—in high and low site stands of 55-year-old Douglas-fir. On both the high and low sites, the more biomass removed, the less the subsequent growth of the new stand, and these differences become more pronounced over the 10-year study period.

In the same study, fertilization of half the plots with 200 kg N/ha as urea in the spring of 1984 resulted in much smaller decreases in growth, suggesting that fertilization may be used to offset the negative impacts of harvesting on nutrient status. In addition, further results of this study agree with results from a study of spruce (Weetman and Webber 1972) that indicated harvesting on poor sites removes a higher proportion of the nutrient capital than harvesting on good sites. This is because a greater fraction of the (smaller) nutrient capital on poor sites is contained in the aboveground biomass.

An associated study reported by Van Miegroet et al. (1990) examined not only the impact of various harvest intensities, but also looked at the effect on site productivity of conversion of alder stands to Douglas-fir stands. Removal of alder resulted in a greater nutrient loss per unit of biomass harvested compared to Douglas-fir. When harvesting included foliage, a substantial portion of the site nutrient capital was removed, strongly suggesting that harvesting of alder (or any species) should not include removal of branches and foliage. Alder, with its symbiotic N-fixing ability, increases the available soil nitrogen. This was found to stimulate nitrification, which in turn resulted in nitrate-mediated leaching of base nutrients. Removal of alder reduced this process of cation leaching and partly offset the nutrient losses resulting from harvesting. In contrast, the harvesting of Douglas-fir had no measured effect on soil chemistry.

Fertilization

Fertilizers are applied with the objective of producing more usable wood. Provided that the target crop is deficient in the applied nutrient(s), the objective will be met if (1) the applied fertilizer reaches the crop trees, (2) no deficiencies or imbalances of other nutrients are induced, (3) the crop remains healthy, and (4) in conjunction with nutrient additions, sufficient water, temperature, light, and space are available for growth. Obviously, fertilizers should not be applied without considering all of these factors.

Numerous studies in the Pacific Northwest have illustrated positive responses of Douglas-fir to nitrogen fertilization. Several, but fewer, studies have shown extremely variable responses of western hemlock. Results of these studies and an interpretation of the factors influencing the responses are presented elsewhere in this volume by Chappell et al.

To trace the movement of urea fertilizer, Preston et al. (1990) applied ¹⁵N-labeled urea (on snow) at a rate of

200 kg N/ha to a 13-year-old Douglas-fir stand. After one growing season, the mean fertilizer recovery was 5.5% in tree biomass, 10.8% in understory vegetation, and 33.4% in soil, for a total of 49.7%. An undetermined additional amount may have been present as extractable inorganic N. It was proposed that the remainder of the nitrogen was lost to a combination of leaching of unhydrolyzed urea and delayed nitrification followed by leaching. In a similar study on Douglas-fir, with both fall and spring application of ^{15}N -labeled urea at 224 kg/ha, Heilman et al. (1982) found 25-36% of the ^{15}N in the trees after two growing seasons. Recovery of ^{15}N from soils and vegetation totaled 68% of that applied.

Given the relatively small portion of applied nitrogen (5-36%) that is taken up by crop trees in the first two growing seasons following fertilization, it is important to understand the reasons for immobilization of nitrogen within the soil organic matter and for losses from the system via volatilization, leaching, erosion, runoff, and biological and chemical denitrification (Marshall 1991).

Addition of nitrogen as urea or secondary effluent has not led to accelerated leaching losses (Crane 1972). While nitrogen cycling is fairly tight in forest ecosystems in the Pacific Northwest, substantial losses of fertilizer nitrogen may occur prior to uptake by the vegetation or incorporation into the soil. Marshall (1991) discusses a number of these losses, including volatilization (up to 25% loss from urea, little from ammonium nitrate), denitrification (up to 25%), and leaching, which accounted for small losses from urea except at very high application rates—for example, though not in the Pacific Northwest, Overrein (1972) found 30% leaching loss from 1,000 kg/ha applications—but large and variable losses from ammonium nitrate, depending on application rate, soil conditions, and precipitation.

In most cases in the Pacific Northwest, fertilization of Douglas-fir with nitrogen has not induced growth-limiting deficiencies or imbalances of other nutrients (Peterson et al. 1986). The Shawnigan Lake thinning and fertilization trials of Douglas-fir have shown a significant increase in growth due to nitrogen fertilization (Gardner 1990). Since the beginning of the project in 1971, foliar nutrient concentrations have been monitored in a subset of the plots. In the untreated plots only nitrogen was found to be deficient. However, in both thinned and unthinned plots that were fertilized twice with 448 kg N/ha, concentrations of phosphorus were reduced from 0.22% to 0.17% and concentrations of sulfur were reduced from 0.14% to 0.10%. To investigate potential effects of phosphorus and sulfur additions on the growth

response to nitrogen fertilization, eight new plots were established at the Shawnigan Lake site in 1987. All plots were thinned to approximately 900 stems per hectare and then four fertilizer treatments were applied to two plots each. These treatments were a control, 224 kg N/ha, 224 kg N/ha plus 100 kg P/ha, and 224 kg N/ha plus 100 kg P/ha plus 100 kg S/ha (Brix et al. 1988). Preliminary results based on three-year basal growth response indicate that all levels of fertilization have increased growth over the control. However, the addition of P alone or P+S has not increased basal area growth over that obtained with nitrogen alone (unpublished data).

Douglas-fir can use either nitrate or ammonium. However, studies of which produced more growth have conflicting conclusions (e.g., van den Driessche 1971; Radwan et al. 1971; Krajina et al. 1973; van den Driessche and Webber 1975). The growth response of Douglas-fir to nitrogen fertilization is caused primarily by an increase in production of foliage and secondarily by an increase in photosynthesis rate (Brix 1971, 1972, 1981a).

Marshall (1991) suggests several research questions that need addressing with regard to nitrogen fertilization: When should thinned stands be fertilized? At what rate does immobilized N become available following fertilization? What is the effect of repeated fertilization on nitrifying capacity of the soil? How much fertilizer nitrogen is lost through denitrification? How much urea becomes nitrified, and what is its potential as a water contaminant?

Despite inconsistent responses of western hemlock to nitrogen fertilization, it is generally agreed that nitrogen is limiting growth of many hemlock stands. Several reasons for lack of response to nitrogen fertilization have been proposed, including a deficiency of phosphorus (Radwan and Shumway 1983, 1984) and adverse effects on root growth and mycorrhizae associations inhibiting uptake of nutrients (Gill and Laverder 1983). Evidence was provided by Everard (1973) that western hemlock has a higher foliar P requirement (0.33%) than Douglas-fir (0.20%). A positive correlation between foliar P concentration and height growth was found for western hemlock growing in a moorland plantation (Leyton 1958). Height growth increased over a foliar P range of 0.24 to 0.54%.

Other potential reasons for poor response of western hemlock to nitrogen fertilization include: unfavorable nitrogen application rate; unfavorable nitrogen source; other limiting nutrients; induced deficiency of other nutrients; imbalanced nutrition; large pH shift in the forest floor following fertilization affecting nutrient

availability and soil fauna and flora; other growth limiting factors such as water, temperature, light, and soil physical properties; and induced water stress as found in radiata pine (Landsberg 1986). For example, unthinned stands of western hemlock on fresh and moist sites (no growing season water deficit) responded better to fertilization than unthinned stands on moderately dry sites (growing season water deficit of 1 to 2 months) (Omule and Britton 1991).

Widespread tests of stands for fertilizer response can produce results with small or large mean response and small or large variance. Binkley (1986) has pointed out that where the mean and variance of response are small, fertilization is likely to be unprofitable. And in contrast, where the mean is large and the variance small, all stands can be fertilized without too much concern over predictions of response. But if the mean response is small and variance large, an assessment program might increase the profitability of fertilization; and if both mean and variance are large, substantial investment in an assessment program is probably justified.

Douglas-fir in some regions best fits the large mean/small variance category and in other regions the large mean/large variance one. Western hemlock fertilization may fit into any of these categories; it is uncertain whether there are any consistent patterns. The evidence for chlorosis in some stands, erratic response in others, and a possible trend toward greater response in more northerly forests all point to a much more site-specific control of nitrogen and phosphorus nutrition in hemlock than in Douglas-fir.

In coastal British Columbia, where hemlock is the dominant tree species, there is a need to relate fertilizer response to recognized ecological units (i.e., site associations or combinations of soil moisture and nutrient regimes used by B.C. foresters). A large-scale test using small plot screening trials and foliar vector analyses is under way at 44 installations. One year after the application of 225 kg N/ha or N plus 100 kg P/ha, 60 kg K/ha, 100 kg S/ha, 40 kg Mg/ha, 10 kg Cu/ha, 20 kg S/ha, and 2 kg B/ha, foliar analysis parameters were not related to site index, soil moisture, or nutrient regimes. Significant positive responses to the N alone treatment were found in only two installations and to the blend treatment in fourteen installations (Carter et al. 1992). There is, however, a well-established problem of nitrogen and phosphorus supply associated with poor nutrient regime areas (CH sites) on northern Vancouver Island and the Queen Charlotte Islands (Weetman et al. 1989).

Conclusions

The main issues in Douglas-fir nutrient management are: fertilizer response prediction, long-term productivity, and the effects of excessive nitrogen input in European plantations. For western hemlock the main nutrient management issues are: sensitivity to vegetative competition for nutrients in young stands, chlorosis of regeneration on some sites, the long-term effects of windthrow on fertility, and the erratic response fertilization sometimes produces. For both species there are also nutrient management issues not covered in this chapter, including thinning and fertilizer response interactions, old-growth stability and fertility relationships, the effect of forest nutrient manipulations on aquatic ecosystems, and the calibration of stand-level biometric and ecosystem models for nutrient management effects.

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