Chapter 5

Nutrient Management in Interior Forest Types

R. P. BROCKLEY, R. L. TROWBRIDGE, T. M. BALLARD, and A. M. MACADAM

ABSTRACT. Inadequate nutrition is a characteristic of many forests of the Interior Northwest. Nitrogen deficiencies are widespread and serious enough to dominate nutrient management concerns. On many sites, forest management activities and recurring wildfires may exacerbate existing nutritional problems. Because a large proportion of site nutrients may be contained in the forest floor and surface mineral soil, many Interior forest soils—especially those where organic matter is produced, recycled, or replaced very slowly (e.g., dry, cold, or fire-damaged sites)—are vulnerable to harvesting or site preparation practices that remove or displace surface organic layers and nutrient-rich topsoil. Also, the removal of needles and branches in whole-tree harvesting operations may have a negative impact on soil nutrients and long-term site productivity. Alternative harvesting and site preparation techniques are often available that may satisfy management objectives without sacrificing the future productivity of the site.

Although currently not extensively used, nutrient amendments may become important in future nutrient management strategies for Interior forests. However, the primary approach should be to improve forest management practices to conserve soil nutrient capital rather than to rehabilitate sites after damage has been done. Although nutrient amendments such as inorganic fertilizers, nitrogen-fixing systems, and municipal and industrial sludge or wastewater have great potential for improving forest growth, they may be less important than native organic matter in the maintenance of soil physical, chemical, and biological properties.

Diverse patterns of climate and physiography have contributed to the tremendous variety of soils and forest types throughout the Interior Northwest (i.e., interior of British Columbia and the eastern slopes of the Cascade Mountains in Washington and Oregon, to the forests of Idaho and western Montana). Forest types dominated by climax forests of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are characterized by a very dry climate with large growing-season water deficits resulting in low stand productivity. At the other extreme are very productive forests characterized by climax stands of western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*). This area, often referred to as the Interior Wet Belt, has the best climate for tree growth and the greatest diversity of tree species of any of the forest ecological zones of the Interior Northwest (Krajina 1970; Franklin and Dyrness 1973; Pfister et al. 1977; Cooper et al. 1987). Mature forests containing the climax species Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) cover much of the higher elevation landscapes. Finally, the low to midelevation landscapes of the central and northern interior of British Columbia are dominated by subboreal and boreal climax forests of white spruce (*Picea glauca*) and white x Engelmann spruce, black spruce (*Picea mariana*) and subalpine fir, and vast seral stands of lodgepole pine (*Pinus contorta* var. *latifolia*) and trembling aspen (*Populus tremuloides*). Low soil temperatures and short growing seasons limit the productivity of the subalpine, subboreal, and boreal forests.

Forestry is an important industry in virtually all Interior forest types. In the interior of British Columbia alone, the 55 million m³ of timber harvested in 1988-89 generated revenues to the province of about $90 million (B.C. Ministry of Forests 1990). The future economic stability of many Interior communities depends on a healthy forest industry. However, forest management activities such as harvesting and subsequent site preparation reduce and displace site nutrient capital and have direct and indirect effects on soil physical, chemical, and biological properties. Depending on the degree, extent, and duration of disturbance or nutrient removal, these

---

R.P. Brockley is Research Silviculturist, B.C. Ministry of Forests, Vernon, British Columbia. R.L. Trowbridge is Regional Soil Scientist, B.C. Ministry of Forests, Smithers, British Columbia. T.M. Ballard is Professor, Faculty of Forestry, University of British Columbia, Vancouver. A.M. Macadam is Research Soil Scientist, B.C. Ministry of Forests, Smithers.

activities may degrade soils and decrease site productivity. In addition, natural erosion processes may be accelerated.

It is incorrect to assume that by conserving soil nutrients one can necessarily maintain or enhance site productivity. Many variables affect soil biological processes and influence productivity. For example, soil compaction caused by heavy logging or site preparation machinery may reduce site productivity while having no direct effect on soil nutrient capital. Also, certain harvesting or site preparation activities, while having a negative influence on soil fertility (e.g., by removing or displacing organic material), may result in improved regeneration performance when compared to undisturbed sites. Improvement of other site factors (e.g., soil temperature and vegetation competition) affecting seedling growth may compensate for, or mask, the negative effects on soil nutrients, at least over the short term. In these cases, however, the possibility that performance could have been even better if activities were modified to conserve soil nutrient capital is often ignored.

As outlined by DeBell (1981), the objective of forest nutrient management is to modify stand management practices to conserve, optimize the use of, and add to the soil nutrient capital in order to maintain or enhance site productivity (which, in the narrow sense of this discussion, is defined as wood production). In most cases, nutrient management is synonymous with organic matter management. In addition to its favorable influence on soil water availability, aeration, and aggregation, organic matter plays a critical role in soil nutrient cycling (especially nitrogen, sulfur, and phosphorus), mycorrhizal root development, and regeneration establishment and growth. Stand productivity of Interior forest types increases as the amount of soil organic matter increases (Jurgensen et al. 1990). Boreal and subalpine forest types may be exceptions; organic matter decomposition and tree growth may be limited more by low soil temperatures in these cold forest ecosystems.

Forest soils of the Interior Northwest are often low in organic matter—much of which is contained in the forest floor and upper mineral soil (Harvey et al. 1987). As a result, these surface layers contain a large proportion of site nutrients (especially nitrogen), cation exchange capacity, and soil microbial populations. The forest floor and soil wood, despite their relatively small contribution to soil volume, are also extremely important sites for tree feeder roots, ectomycorrhizal root activity, and nitrogen fixation (Kimmins and Krumlik 1976; Kimmins and Hawkes 1978; Harvey et al. 1986, 1987; Jurgensen et al. 1990). Because of this, many Interior forest soils—especially those where organic matter is produced, recycled, or replaced very slowly (e.g., dry, cold, or fire-damaged sites)—are vulnerable to harvesting or site preparation practices that remove or displace surface organic layers and nutrient-rich topsoil. Also, the removal of nutrients in harvested materials may reduce long-term site productivity, especially on sites where whole-tree harvesting is practiced. Because of the important role played by organic matter in the maintenance of soil physical and biological properties, the addition of inorganic fertilizers to compensate for nutrients removed from the site in harvesting or site preparation may not be wholly effective in maintaining site productivity, especially on sites already low in organic matter.

In this chapter we: (1) generally describe the soil and site factors that influence the nutrient status of Interior forest types, (2) summarize the likely impacts of forest harvesting, site preparation, and nutrient amendment practices that are commonly used in the Interior Northwest, and (3) describe how these practices may be modified to conserve and improve soil nutrient capital and availability.

Site-Soil Characteristics and Nutrient Status

Priorities for nutrient management in forests of the Interior Northwest generally focus on those nutrients most likely to limit tree growth. Some growth-limiting problems are quite pervasive over the region; some are associated with particular parent materials; a few occur over a range of materials; and some appear related to management and fire. In this section, we examine nutrient management problems associated with particular soil characteristics and subregions of the Interior Northwest.

Nitrogen deficiencies are sufficiently widespread and serious that they have tended to dominate nutrient management concerns. Fertilization experiments have repeatedly demonstrated response to nitrogen application. Reports by van Cleve and Zasada (1976), Moore (1988), Powers et al. (1988), and Weetman (1988) illustrate the extensive geographical range of nitrogen nutrition problems throughout the Interior Northwest. Apart from fertilizer application, nitrogen management considerations have included cycling rates (van Cleve et al. 1983), particularly where management might enhance utilization of stored nitrogen in forest floor and humus. Management-induced loss of available and stored nitrogen has been another concern, whether such losses result from fire, mechanical site preparation, or soil displacement during harvesting (Utzig and Walmsley 1988).

Low sulfur status has been observed widely in the Interior Northwest. Work in central and eastern Washington and Oregon found low sulfur levels associated particularly with soils derived from volcanic ash (Will and Youngberg 1978; Klock et al. 1975). Sulfur has been found lacking in forest soils in most interior areas of British Columbia (Beaton and Soper 1986). Low sulfur in tree foliage (Brockley, unpublished data) has been found over a wide range of soil materials, and growth responses to sulfur fertilization have been indicated (Cochran et al. 1981; Yang 1985*b*; Powers et al. 1988; Brockley and Swift 1990; Mika et al., this volume). Commonly, response to sulfur addition is expected only after nitrogen deficiency has been overcome by nitrogen fertilizer application. However, Will and Youngberg (1978) observed some response to gypsum addition alone, on some pumiceous soils of central Oregon. Like nitrogen, sulfur is subject to volatilization loss during burning. However, whereas rhizobial or actinorhizal nitrogen fixation may replenish nitrogen on some sites, restoration of available sulfur by natural processes (e.g., atmospheric inputs, weathering) may be slow. Another consideration is that available sulfur in some soils may be concentrated in near-surface horizons, so that scalping during site preparation might result in microsite sulfur deficiencies (Will and Youngberg 1978).

Boron deficiency occurs in several scattered locations in Interior forests. Extremely low foliar boron levels (Ballard, unpublished data) occur in a few stands in the vicinity of McBride, B.C., east of Prince George. Near Burns Lake, B.C., Brockley (1990) has found low foliar boron levels, classic visual symptoms of boron deficiency, and responsiveness to boron application in lodgepole pine. Low foliar boron levels (Brockley, unpublished data) and top dieback in lodgepole pine near Golden, B.C., indicate that boron deficiency was induced by nitrogen fertilization.

In interior Alaska, data of van Cleve et al. (1983) are suggestive of inadequate phosphorus status, and Weetman et al. (1988) observed a response to phosphorus application in two out of seventeen lodgepole pine stands tested in interior British Columbia.

Soils of high pH occur in some interior forests. Limestone and calcareous shale bedrock and calcareous tills are common in the Rockies of the United States and Canada, and in the interior ranges and interior plateaus of British Columbia. High evapotranspiration and low rainfall tend to favor high soil pH, so that acidification of near-surface soils in dry subregions of the Interior is less pronounced than in humid coastal environments. Fire also contributes to high pH near the surface, because wetting of base oxides, which dominate the ash, results in hydroxide formation. With the history of frequent fires over much of the forested Interior, nutritional problems associated with high pH can be observed. In particular, deficiencies of iron and copper (confirmed by response to micronutrient application in foliar sprays) have been seen on some burned sites and on some calcareous soils (Majid 1984; Ballard and Majid 1985). From a management standpoint, two considerations seem particularly important. First, mechanical site preparation should be undertaken cautiously, if at all, where calcareous materials lie close to the surface. The preservation of somewhat acidified surface horizons may be important for tree micronutrient status. Second, slash burning should be undertaken cautiously, if at all, on soils characterized by high base status. Particularly in drier interior environments, re-acidification may be slow after surface soil pH is raised by ash.

Soils derived from ultramafic materials occur in several Interior locations, from California to northern British Columbia and beyond. These "serpentine" soils are characterized by low calcium, high magnesium, and high levels of nickel and chromium; nitrogen status is commonly poor. Other nutritional problems may also occur, as described in a recent review by Schreier (1989). Tree foliage samples reflect many of these characteristics; however, while foliar nickel is often quite high, chromium is not necessarily much elevated. From a nutrient management standpoint, great care during site preparation may be desirable. Displacement of forest floor and organic-enriched A horizons, characterized by less extreme chemical composition than the parent material, may be nutritionally detrimental. Also, in some cases, near-surface soils may originate from other parent materials such as loess and ash. For example, on soils of the Shulaps Range, northwest of Lillooet, B.C., tree growth is faster and stands are better stocked where a layer of the Bridge River volcanic ash is at the surface than where the ultramafic materials are exposed. Although the effect has not yet been measured, it seems likely that local displacement of the ash layer would impair tree nutrition.

Nutrient deficiencies are widespread throughout the Interior Northwest, and forest management activities may exacerbate existing nutritional problems on many sites. The following sections summarize the impacts that these activities may have on soil nutrient capital and site productivity, and describe ways to conserve or replace soil nutrients.

Management Effects and Alternatives

Harvesting

Soil disturbance and nutrient removals are unavoidable consequences of forest harvesting. Displacement of surface organic layers and nutrient-rich topsoil, soil compaction, exposure of unfavorable substrates, and removal of nutrients in harvested material all occur to varying degrees in Interior harvesting operations. Forest harvesting may also accelerate soil erosion and mass wasting (Megahan et al. 1979; Froehlich 1979). The presence of fresh logging residue, changes in soil temperature and moisture, and decreased nutrient uptake by crop and noncrop vegetation generally result in a period of greater nutrient availability following harvesting (Tamm and Pettersson 1969). Although some nutrient leaching losses do occur following the harvest of Interior forests, the losses are negligible relative to other harvest-related losses (Stark 1979).

The effects of harvesting disturbance range from beneficial to detrimental depending on the severity and extent of disturbance and the nature of the site (Lewis 1991). Disturbance that exposes mineral soil and promotes shallow mixing of organic and mineral layers may provide favorable conditions for the establishment and growth of natural regeneration and planted seedlings without causing long-term productivity losses. However, excessive disturbance or nutrient removals may degrade soil physical, chemical, and biological properties to the extent that crop production and long-term site productivity are adversely affected. Utzig and Walmsley (1988) estimated that 277,000 hectares of forest land were degraded as a result of harvesting practices and subsequent harvest-related erosion in the interior of British Columbia between 1976 and 1986 (19% of the total area harvested during this period). No consideration was given to possible site degradation caused by nutrient leaching and the removal of nutrients in harvested material. By taking this estimate and combining it with published reports on growth reductions associated with degradation and known mean annual increments for Interior forest types, the authors estimated current annual growth losses occurring on degraded soils as a result of harvesting activities during this period to be about 245,000 m^3/yr.

Although site degradation involves many factors, soil displacement and loss of nutrients in harvested material may be the two most important nutrient management issues associated with harvesting in Interior forest types. The effects of soil surface erosion and mass movement tend to be localized and, despite possible negative impacts on other resources, generally have limited impact on the extent of degraded forest soils (Utzig and Walmsley 1988). Although soil compaction caused by heavy logging equipment can seriously impair tree nutrition and growth (Smith and Wass 1979; Wert and Thomas 1981; Cochran and Brock 1985; Froehlich et al. 1986; Clayton et al. 1987), the effects are largely indirect since they are generally not caused by displacement or removal of nutrients from the site.

Soil Displacement. Major sites of soil displacement during timber harvesting are landings, bladed skid roads, and heavily used skid trails. When these areas are constructed and used, surface organic layers and upper mineral layers of the soil are scalped or buried. Exposed subsoils generally have unfavorable chemical, physical, and biological properties that may adversely affect regeneration (Clayton et al. 1987; Smith and Wass 1979, 1985). In Interior forest types, marked adverse effects can result from the exposure of dense glacial till or glaciolacustrine parent material, dense clay-enriched horizons, and coarse-textured, glaciofluvial deposits. The exposure of parent materials that contain high levels of calcium carbonate and other salts results in very alkaline soil conditions that offer an especially poor substrate for seedling establishment and growth.

Ground-based harvesting systems using crawler tractors or rubber-tired skidders generally cause considerably more soil disturbance than cable methods (i.e., highlead, grapple), due largely to the absence of skid-road development in the latter systems (Table 1). Ground skidding also generally causes deeper soil disturbance than cable-logging systems (Krag et al. 1986; Smith and

Table 1—Comparison of soil disturbance (%) caused by ground-skidding and cable-logging systems in British Columbia.

Ground Skidding	Cable Logging		Reference
	Highlead	Grapple	
45(s)		12	
49(w)			Schwab and Watt (1981)[1]
46(s)	17(s)	29(s)	
29(w)	17(w)	22(w)	Smith and Wass (1976)
45(s)	31(s)	27(s)	
40(w)	26(w)	20(w)	Krag et al. (1986)
20(s)	10(s)		
16(w)	7(w)		Watt and Krag (1988)[2]
16	5		Utzig and Herring (1975)[3]

Note: s = summer; w = winter.

[1] Does not include haul roads and landings.

[2] Ground skidding conducted with small crawler tractor.

[3] Recorded only disturbance deeper than 25 cm.

Wass 1976). This information is especially relevant to Interior forest types where the vast majority of harvesting is done by ground-skidding methods (Utzig and Walmsley 1988). The proportion of logged areas affected by various logging methods is apparently similar whether the harvesting system is clearcutting or selection (Cromack et al. 1979; Froehlich 1976).

The amount and severity of soil disturbance depend largely on steepness of slope and terrain complexity (Garrison and Rummel 1951; Smith and Wass 1976; Krag et al. 1986). For ground-skidding systems, the amount of soil displacement is determined largely by the extent of cuts required to construct the required bladed skid-road network. On simple slopes up to 30% (40-45% with tracked skidders), unbladed skid trails may suffice, so soil displacement is confined to that caused by the actual skidding operation (Lewis 1991). On steeper slopes, the extent of disturbance is determined by the spacing of skid roads, equipment size, and slope gradient. Despite widespread steeply sloping, complex terrain, ground-skidding systems are commonly used in many subalpine forest types and the highly productive forest sites in the Interior Wet Belt. Conventional ground-skidding systems operating on steep slopes within the Interior Wet Belt have caused, and continue to cause, severe site degradation and productivity losses (Smith 1988; Smith and Wass 1979, 1980). Although soil displacement should be less of a problem on gentler slopes, factors such as terrain complexity, equipment size, and operator care must also be considered. Even shallow disturbance can be deleterious on sites with high water tables and where calcareous or dense parent material is close to the surface.

The use of alternative logging systems and the modification of existing systems are two of the options for reducing soil disturbance. Greater use of cable systems in Interior forest types, especially those on steeper terrain, could reduce damage considerably. Although cable systems are being used with increasing regularity in the Interior Northwest, they may be 50 to 100% more expensive than ground-skidding systems (Wellburn 1975). Because of this, modification of existing systems may be an attractive alternative to reducing soil disturbance. Winter logging often, but not always, causes less soil disturbance than summer logging (Smith and Wass 1976; Schwab and Watt 1981; Krag et al. 1986). Under certain conditions, compacted snow may comprise a large portion of the skid road cut. However, the effect of season may be confounded by variables such as the depth of snow and depth of soil freezing. The use of smaller equipment will reduce the width of skid roads and can result in less total soil disturbance in some situations (McMorland 1980; Watt and Krag 1988). There has also been a recent trend toward roadside processing, especially in large clearcuts, thus reducing the need for landings.

Timber harvesting prescriptions to minimize site degradation have recently been developed for the British Columbia Interior (Carr et al. 1991; Lewis 1991). They provide an objective process to assess the sensitivity of a site to degradation and present a range of strategies to modify logging practices to suit this sensitivity. Interim soil disturbance ground rules that set provincial standards for maximum allowable disturbance for various sensitivity classes have been adopted by the B.C. Ministry of Forests. Policies and legislation are being prepared to accompany these guidelines.

Nutrient Removals in Harvested Material. Site nutrient capital is depleted following harvesting because nutrients are contained in the harvested material. Until recently, however, the use of previously unharvested sites and the low utilization of aboveground biomass have meant that nutrient removals were generally small in relation to total site nutrient capital and rates of nutrient additions from natural processes (i.e., mineral weathering, dust, precipitation, biological nitrogen fixation) in Interior forest types. However, multiple-rotation forestry and increased fiber utilization, with concomitant increases in nutrient removal in harvested material, have led to concerns regarding long-term site productivity (Kimmins 1977; Harvey et al. 1980; Stark 1979; Jurgensen et al. 1990).

In conventional harvesting systems, trees are felled and delimbed at the stump prior to yarding the bole to the landing. Merchantable stemwood, although about 80% of the total aboveground biomass, contains only about 50% (or less) of the aboveground nutrients (Kimmins et al. 1985; Smith et al. 1986; Mann et al. 1988; Maliondo et al. 1990). This is due to the disproportionately larger amount of nutrients in the relatively nutrient-rich branches, twigs, and foliage (Maliondo et al. 1990). In conventional harvests, appreciable amounts of fresh residue are added to the forest floor for subsequent decomposition. Even though protection or silvicultural objectives may necessitate mechanical removal and/or burning of the slash, a portion of the nutrients contained in the slash will be released into the soil. In most cases, nutrients removed in conventional harvests from Interior forests will be restored to the soil over normal stand rotations (Stark 1979; Clayton and Kennedy 1985; Kimmins et al. 1985). Long-term maintenance of site nutrient status, therefore, should not be adversely affected so long as rotations are not shorter than this ecological rotation (Kimmins 1974). However, whole-tree harvesting, which involves yarding the entire aboveground portion of the tree to the landing where unmerchantable portions (i.e., branches and foliage) are removed and disposed of prior to transporting the bole to the mill, has become the standard method of harvesting in most Interior forest types. Although no deliberate effort is made to remove branches, there is generally at least some breakage during the skidding operation. These portions of the tree, in addition to unmerchantable trees that are cut and left, remain on the site. Breakage is generally higher during the winter, when branches are brittle. Reasons for adopting whole-tree practices include reduction of logging costs and decreased slash loading, resulting in less need for slash disposal to meet protection and silvicultural objectives. However, the removal of nutrients in the harvested biomass reduces site nutrient capital, with possible negative impacts on site productivity.

Determination of what effect whole-tree harvesting will have on future site productivity requires information on the amount of nutrients that are removed in harvested material relative to the total and "available" amounts of site nutrient capital, the rate at which remaining site nutrient capital recycles, the rate at which site nutrients are replenished by natural processes, the nutrient requirements of the next crop, the magnitude of other harvest-related losses (e.g., slash burning, leaching), and the anticipated rotation length (Kimmins 1977). Unfortunately, most of these are complex issues for which little quantitative information exists. However, calculation of the amount of nutrients removed in harvested material is a fairly straightforward procedure. As shown in Table 2, whole-tree harvesting may result in large relative increases in nutrient removals over those lost in conventional harvests. Of the nutrients shown, nitrogen and phosphorus removals generally show the largest relative increases. Table 2 also illustrates the considerable variability between and among species. The relative distribution of biomass and nutrients in the tree varies according to species, stand age, and site quality (Kimmins 1977; Hendrickson et al. 1987; Maliondo 1988). Those species with higher foliar nutrient concentrations and/or large percentage of nutrients and biomass in foliage and fine branches, such as spruce and fir, will have a higher increase in losses with whole-tree harvesting than species with low foliar concentrations and small crowns, such as pine. Because the distribution of nutrients between crown and stem changes with age, whole-tree harvesting of younger stands will result in greater nutrient losses. In addition to having a higher proportion of aboveground biomass in crown

Table 2—Increases in biomass and nutrient removal due to whole-tree harvesting, expressed as percentage of quantity removed via conventional harvesting.

Forest Type	Aboveground Biomass	N	P	K	Ca	Reference
Hemlock and cedar	43	165	117	77	95	Kimmins and Krumlik (1976)
Lodgepole pine	15	53	54	14	15	Kimmins and Krumlik (1976)
White spruce and subalpine fir	25	116	163	32	50	Kimmins and Krumlik (1976)
Jack pine	29	133	183	80	65	Foster and Morrison (1989)
Black spruce	53	143	121	175	72	Foster and Morrison (1989)
Aspen	26	94	100	60	58	Foster and Morrison (1989)
Black spruce	99	288	367	236	179	Weetman and Webber (1972)
Black spruce	48	300	533	206	91	Weetman and Algar (1983)
Jack pine	73	326	400	54	48	Weetman and Algar (1983)
Red spruce and balsam fir	38	232	283	103	97	Smith et al. (1986)
Mixed conifer and hardwood	29	111	85	82	69	Hendrickson et al. (1987)
Black spruce	77	381	657	286	171	Maliondo et al. (1990)
White spruce	65	319	396	266	169	Maliondo et al. (1990)
Balsam fir	80	401	620	221	222	Maliondo et al. (1990)
Jack pine	27	158	288	131	74	Maliondo et al. (1990)
Aspen	38	164	200	117	89	Maliondo et al. (1990)

components, younger stands also have higher nutrient concentrations (Madgwick et al. 1977). Crown development is also promoted by silvicultural treatments such as thinning and fertilization. Therefore, the difference in nutrient removals between conventional and whole-tree harvests will undoubtedly be greater in future intensively managed stands where crown components will make up a greater portion of the aboveground biomass.

In British Columbia, the harvest of lodgepole pine stands characterized by small piece size and low merchantable volumes per hectare is done exclusively with whole-tree methods. These stands have generally been perpetuated through repeated fire disturbance, and therefore often occupy sites of low nutrient status. Vast areas of unmanaged, fire-origin lodgepole pine are widely distributed throughout Interior regions. Due to high stand densities characterized by trees with very small live crowns, the extra nutrient losses associated with whole-tree harvesting of lodgepole pine are low compared with other species (see Table 2). However, these losses may be high relative to total site nutrient capital, and therefore may have a much greater negative impact on future site productivity than losses in other forest types. Studies elsewhere have indicated that repeated whole-tree harvesting could potentially cause nutrient depletion problems on poorer quality sites (Morrison and Foster 1979; Weetman and Webber 1972; Weetman and Algar 1983).

Soil texture can have important implications for whole-tree harvesting, even in soils of mixed mineralogy. This is of particular concern with regard to potassium. Gravelly sandy soils can have specific surface two orders of magnitude below that of silty soils. Since weathering release of available nutrients from primary minerals occurs at particle surfaces, the rate of potassium weathering from coarse-grained soils is likely to be especially slow. Weathering rate is only one part of the sustainability issue; another is the limited reserve of exchangeable K in many coarse-textured soils. For example, the Ramsey series, which occurs in the central interior of British Columbia, commonly contains less than 250 kg of exchangeable K/ha in the entire root zone (Lord 1982). From tables published by Young et al. (1965), it can be estimated that the potassium contained in a harvestable interior timber stand may exceed 200 kg/ha, of which about half is in bole wood and bark. While recycling of potassium prevents detectable deficiencies in natural stands and some plantations, the risk of longer-term deficiency induced by harvesting is serious. Although the Ramsey series is a rather extreme example, there are many coarse-textured soils in the Interior with less than 500 kg of exchangeable K/ha in the root zone. Even conventional harvesting might raise some concerns about long-term sustainability on such soils. Because whole-tree harvesting approximately doubles the rate of potassium depletion, its indiscriminate application without regard to site nutrient capital deserves to be questioned. Similar concerns have been expressed in other regions of the world. Goulding and Stevens (1988) focused on potassium depletion with regard to whole-tree versus conventional harvesting on a soil in Great Britain. Research on such problems with regard to soils of the Interior Northwest is needed; in particular, to quantify weathering rates and evaluate long-term sustainability on high priority soils identified from soil survey information.

In addition to the direct nutrient losses in harvested material, more subtle impacts on soil fertility may result from whole-tree harvesting for it removes a large amount of coarse woody debris that is an important source of soil wood (Spies et al. 1988). In the Interior Northwest, soil wood can comprise greater than 15% of the organic matter in the forest floor and upper 30 cm of mineral soil (Jurgensen et al. 1990). Soil wood provides efficient storage for nutrients and moisture as well as a favorable medium for the growth and function of tree roots and microbial populations (Larsen et al. 1980; Harvey et al. 1987; Jurgensen et al. 1990). Soil wood is an important site for mycorrhizal activity and biological nitrogen fixation, especially during periods of drought when other materials are too dry (Harvey et al. 1978, 1988).

There is little quantitative information to determine the effects of whole-tree harvesting on future site productivity of Interior forest types. However, European studies show that annual litter raking results in large reductions in the growth increment of pine and spruce growing in sandy soils (see Powers et al. 1990). In New Zealand, "second-rotation decline" in forest productivity has been extensively reported (Dyck and Skinner 1990). Given the shallow rooting of many Interior forests, it is apparent that many stands depend on a relatively small volume of soil to satisfy their nutrient requirements. On sites with shallow surface organic layers, the tree canopy may contain a large portion of the circulating site nutrient capital. On these relatively dry, infertile sites, consideration should be given to implementing residue management practices that leave a larger proportion of logging slash scattered on the site.

Site Preparation

Many harvested areas in the Interior Northwest require site preparation, either by mechanical means or by prescribed burning, for the successful establishment of a new crop (Jurgensen et al. 1990). The primary objectives include fire hazard abatement, improved planter access, and the creation of favorable microsites for natural regeneration or the survival and growth of planted seedlings. Besides removing logging debris, site preparation often involves the deliberate reduction or displacement of surface organic matter to improve soil temperature regimes or reduce vegetation competition. Some disturbance may be especially beneficial on subalpine, subboreal, and boreal sites where microbial decomposition of organic material and tree growth are slowed by low soil temperatures, and on dry sites where grass may vigorously compete for soil moisture. On some sites, thick mor-humus accumulations may offer an undesirable seedbed for regeneration and may effectively tie up site nutrient capital.

Although site preparation is often beneficial to the establishment and early growth of the next crop, it may cause site degradation through loss of soil nutrients and soil compaction if poorly planned or implemented. The impacts are generally evaluated in terms of effects on survival and early growth, since there is little information on the long-term effects. On some sites, however, short-term benefits may be more than offset by long-term losses in productivity. Due to the potential for site degradation, site preparation treatments must be developed that will ensure successful regeneration without sacrificing long-term site productivity.

Mechanical Site Preparation. Mechanical site preparation (MSP) is extensively used in the Interior Northwest following clearcutting to improve plantability and microsite conditions for seedling establishment. Based on B.C. Ministry of Forests estimates, approximately 57,000 ha/yr of recently harvested forest land and 32,000 ha/yr of backlog forest land will be treated in the B.C. interior between 1988 and 1992 (Breadon 1987).

A wide variety of MSP treatments are in use (McMinn and Hedin 1990), but windrowing and piling have accounted for close to half of the area treated in the B.C. interior during recent years (Breadon 1987). These treatments involve the rearrangement of slash using brush rakes and blades, primarily to improve planter access and wildfire hazard abatement, and are often followed by burning or other mechanical treatments. In backlog reforestation operations, blading treatments (using straight blades, brush blades, and V blades) may be used to remove dense vegetation to permit the establishment of conifers. If only slash materials are moved and the forest floor is left relatively intact, the impact on site nutrients may be minimal. However, where forest floor and surface mineral soil layers are extensively scalped and displaced during blading operations, short- and long-term impacts on site productivity may be profoundly negative, since a large proportion of site nutrients are concentrated in these materials. Losses amounting to as much as 834 kg/ha of nitrogen have been reported from boreal sites following windrowing (Foster and Morrison 1989). In the subboreal region of north-central British Columbia, Ballard and Hawkes (1989) estimated nitrogen losses of 475 kg/ha from a windrowing operation that removed essentially all forest floor material from between windrows. In addition, the removal of the forest floor exposes underlying mineral soils to structural damage and can greatly accelerate rates of surface erosion. The exposure of subsoil materials with unfavorable physical and chemical properties is another problem associated with scalping, particularly in soils with very high clay or gravel contents, those with strongly compacted layers of basal till occurring at shallow depths, and calcareous soils. This can be a problem on backlog sites where soils are often intentionally scalped to slow the resprouting of noncrop vegetation and on sites where windrowing is combined with stumping or root raking for the control of root diseases.

There have been many reports of negative impacts on soil properties and tree growth in Interior forests associated with scalping (Herring and McMinn 1980; McMinn 1982; Cole and Schmidt 1986; Page-Dumroese et al. 1986; Ross et al. 1986; Graham et al. 1989; Ball 1990). In central British Columbia, Ballard (1985) found serious nitrogen, iron, and copper deficiencies in planted white spruce substantially more frequently, and with greater severity, on clearcuts that had been scalped or burned than on those that had not been site prepared (Table 3). In a growth chamber study, Dobbs and McMinn (1977) found that foliar nitrogen was more than three times as high and phosphorus twice as high in white spruce seedlings grown in untreated soils than in those grown in scalped soils. However, in field experiments they found that early growth of white spruce was greater in scalped than in untreated soils, and attributed it to increased soil temperatures and reduced competition from noncrop vegetation.

Use of appropriate equipment and techniques can help to minimize some of the negative impacts of windrowing operations. Toothed brush blades or flex-

Table 3—Frequency and severity of nutrient deficiencies in relation to site preparation, for sampled white spruce plantations in central British Columbia. From Ballard (1985).

	Percentage of Plantations with Class 4 and 5 Deficiency[1]			Nutrient Status Class (averaged for plantations)[1]		
Nutrient	NSP	MECH	BURN	NSP	MECH	BURN
Nitrogen	0	30	64	2.73	2.96	3.65
Iron	8	20	59	2.16	2.80	3.44
Copper	0	50	45	2.12	2.90	3.24
Magnesium	20	10	31	3.12	2.90	3.24

[1] Nutrient status classes range from 1 (ample) to 5 (extremely deficient). Nutrient deficiency criteria are from Ballard and Carter (1986).

Note: NSP: no site preparation (n = 5); MECH: scalping of surface soil horizons, but no burning (n = 5); BURN: slash burning (n = 11).

ible tooth rakes generally cause less soil disturbance than standard straight or angled brush blades (Coates and Haeussler 1987), and nutrient displacement can be minimized by shortening the distance between windrows and decreasing their size (Morris et al. 1983; White and Harvey 1979).

In regions with seasonal snow or frozen soil conditions, winter operations may reduce soil displacement. However, windrowing and related "harsh" site preparation methods should be avoided on nutrient-poor sites with thin surface organic layers.

Other MSP treatments such as drag or patch scarification, disk trenching, mounding, and bedding tend to be used where slash accumulations are lighter, and are more often undertaken with the aim of improving microsite conditions as well as plantability. Disk trenching and mounding, in particular, are gaining popularity in the central interior of British Columbia, to some extent in response to increasing public resistance to the use of broadcast burning. Since these treatments generally result in localized rather than continuous soil disturbance, the scale of potential nutrient displacement tends to be less than that associated with blading treatments.

Low soil temperatures are recognized as a major growth-limiting factor in subalpine, subboreal, and boreal forests. Mechanical treatments can often, but not always, result in substantial improvements in growing season soil temperatures as well as the temporary suppression of competing vegetation. Macadam (1990) found higher soil temperatures in scarified patches relative to untreated spots in a well-drained soil, but no significant differences in moist or wet sites. In the central interior of British Columbia, the greatest improvements in soil temperatures and seedling growth have consistently been observed in mounding treatments (Bassman 1989; Draper et al. 1985; Macadam 1990). Root growth, in particular, appears to be greatly enhanced by mounding. On moist and wet sites, poor soil aeration due to excess soil moisture is another important growth-limiting factor that can be alleviated by mounding.

In areas with drier climates, mounding may exacerbate existing moisture deficit problems, particularly on well-drained sites. However, although soil moisture availability was observed to be significantly lower during dry periods in mounds than in scarified patches, superior seedling growth was observed in mounds by the third growing season by both Bassman (1989) in the high elevation Engelmann Spruce Subalpine Fir Zone and Macadam (1990) in the Subboreal Spruce Zone.

Studies in Sweden and Finland cited by Örlander et al. (1990) have demonstrated increased rates of nutrient mineralization (including nitrogen, phosphorus, and potassium) for at least three years under mounds and plow- and disk-trench berms (Rosén and Lundmark-Thelin 1986; Mälkönen 1986). There is often a lag period of a year or more following treatment before this "compost" effect appears. Sites in cold climates with mor-humus forms are most likely to benefit from improvements in soil fertility gained through the stimulation of biological activity in this manner.

The potential for nutrient depletion associated with MSP treatments depends mostly on the extent to which soils are disturbed, but also on climate and soil properties. The degree of soil disturbance may vary widely, even for a given treatment, depending on site and soil factors, the equipment used, and the skill of the operator. Although nutrients are not physically removed from the site during many of these treatments, there is some danger of causing accelerated leaching losses if rates of nutrient mineralization are much greater than the nutrient demands of the vegetation occupying the site. According to Örlander et al. (1990), several Swedish researchers have expressed concerns regarding the long-term effect of treatments such as disk-trenching and plowing for this reason.

Prescribed Fire. Fire is a tool of major importance in the management of Interior forests. Both broadcast burning and the burning of piled and windrowed logging slash are commonly used for silvicultural purposes and for wildfire hazard abatement following clearcutting. In addition, prescribed fire is increasingly being used for the management of rangelands and wildlife habitat.

In British Columbia, the area broadcast burned for silvicultural purposes increased steadily during the mid-1980s, but recently it has begun to decline (Figure 1). Unfavorable weather conditions were a major limiting factor in 1990, but increasing treatment costs and public concern regarding negative impacts on air quality and on site productivity are contributing to a decrease in the use of broadcast burning for site preparation.

Prescribed fire research in British Columbia was accelerated during the early 1980s in response to the increasing use of fire and the lack of knowledge about fire behavior and the long-term impacts on specific forest sites and crop species. Many of these studies focused on the impacts of silvicultural burning on conifer establishment and site productivity (Trowbridge 1986). Several earlier studies focused on the effects of prescribed fire on site nutrients (Ahlgren and Ahlgren 1960; Wells et al. 1979; Feller 1982). However, results cited in review papers are often extremely varied, and at times seemingly inconsistent, largely because researchers tend to describe the ecosystems in broad terms, and usually fail to quantify burning conditions and fire impacts. Reviewers, in turn, tend to discuss research results and their implications in general terms rather than from an ecosystem-specific perspective. To assess the probable impact of burning on site nutrition, it is essential to compare sites based on their inherent nutrient status and the ability of the ecosystem to retain and replenish nutrients following disturbance. In addition, it must be acknowledged that fire is a tool that can be used in many ways, with the potential of bringing about widely varying degrees of change in site properties.

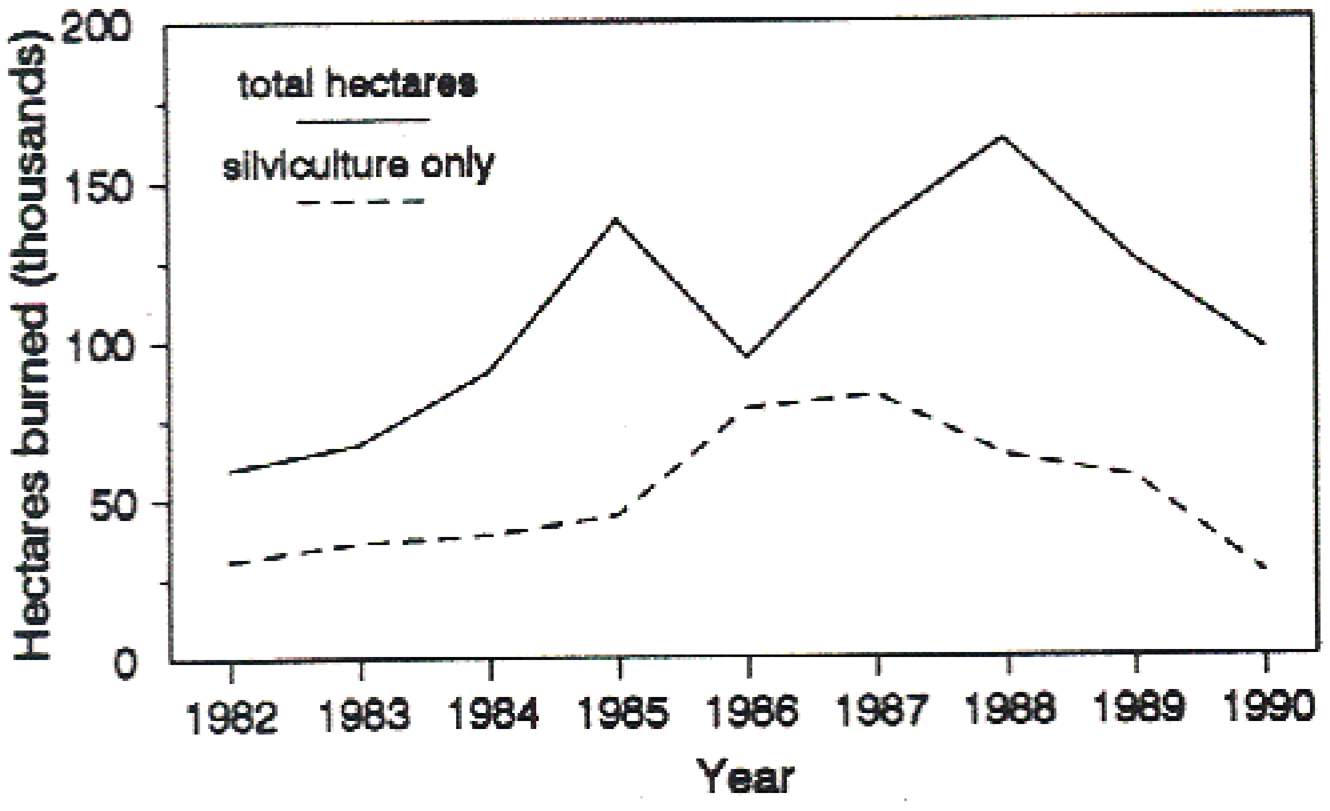

Figure 1. Trend over time of prescribed burned areas (total and for silviculture only) in British Columbia.

Long-term impacts (>20 years) of prescribed burning on forest nutrition have not yet been reported for interior British Columbia. However, review papers (Ahlgren and Ahlgren 1960; Wells et al. 1979; Feller 1982) and recent field research in interior British Columbia (Macadam 1987; Taylor and Feller 1987; Blackwell 1989) indicate some general agreement regarding the kinds of short-term changes in soil chemical properties that occur as a result of the broadcast burning of logging slash.

In general, forest floor materials tend to be most strongly affected by burning, while changes in mineral soil properties are often minimal following light to moderate impact broadcast burns. Some frequently observed effects are: (1) increases in soil pH; (2) increases in the availability of phosphorus, calcium, and magnesium; and (3) decreases in total amounts of nitrogen and sulfur.

The magnitude of these changes, their persistence, and their implications for site nutrient management will vary in a site-specific manner depending on fire severity (dependent primarily on fuel loading, fuel moisture conditions, and weather conditions during burning) and site and soil characteristics (particularly forest floor depth, soil texture, coarse fragment content, organic matter content, and total soil depth).

Fire intensity and duration, reflected in the quantity of slash and forest floor materials consumed, largely determines the absolute amounts of nutrients lost as a result of burning. An important mechanism for the loss of some nutrients is volatilization, which occurs when an element is heated to a critical temperature at which it is converted to its gaseous forms. This is the primary mechanism for the loss of nitrogen and sulfur, because they become vaporized at relatively low temperatures (200-500°C). During intense burns, phosphorus and potassium, and to a much lesser extent some forms of calcium and magnesium, are also vulnerable to loss through volatilization; however, the convection of ash is considered to be a more important mechanism of loss for these nutrients during prescribed burns (Grier 1975; Raison et al. 1985). Convection losses increase with fire intensity and with increasing wind speed. Nutrient losses may also occur following burning, through surface erosion by wind and water, and through the leaching of nutrients made soluble by burning. Leaching losses have in general been found to be small relative to losses via convection and volatilization (Feller 1982).

The relative proportion of site nutrients that are lost as a result of burning, and the consequences to the site of nutrient losses, are strongly influenced by site and soil characteristics. Nitrogen is the nutrient most at risk during burning, because it is present almost exclusively in organic materials and because of its low vaporization temperature. As already noted, it is regarded as the primary nutrient limiting productivity in forest ecosystems. If site nitrogen is concentrated in a relatively thin forest floor, and the underlying mineral soil is low in organic matter (and therefore low in nitrogen), then a large fraction of site nitrogen is highly vulnerable to loss as a result of burning. In such cases, fire must be excluded or fire intensity kept extremely low if nutrients are to be conserved. Conversely, if a large proportion of site nitrogen is concentrated in organic matter-enriched mineral soil (which is relatively immune from combustion), or in an extremely deep forest floor layer, the odds of sustaining losses of nitrogen that are significant in practical terms are much less, assuming a burn of light to moderate severity.

Nitrogen losses during broadcast burning on sites with mor-humus forms (Klinka et al. 1981) in interior British Columbia can be roughly estimated, based on forest floor consumption, as 100-150 kg/ha for each centimeter of F horizon consumed (Figure 2) (Macadam 1989). Examples of nitrogen losses from Subboreal Spruce Zone ecosystems in north-central British Columbia as a result of broadcast burning are given in Table 4. Whether or not the ecosystems will replace these losses within the plantation rotation is unknown. However, analyses of foliar nitrogen in natural forest stands in the interior of British Columbia have consistently shown moderate to severe nitrogen deficiencies (Brockley 1989; Yole et al. 1991) relative to diagnostic levels cited by Ballard and Carter (1986). Further depletion of site nitrogen through forestry practices, including prescribed burning, must be recognized as a major nutrient management concern. On average and less productive interior ecosystems, moderate to light severity burning prescriptions, respectively, should be applied where burning is needed to meet other necessary forest management objectives. It may be appropriate to prescribe amelioration treatments to replace nitrogen in ecosystems thought to be adversely affected by prescribed fire.

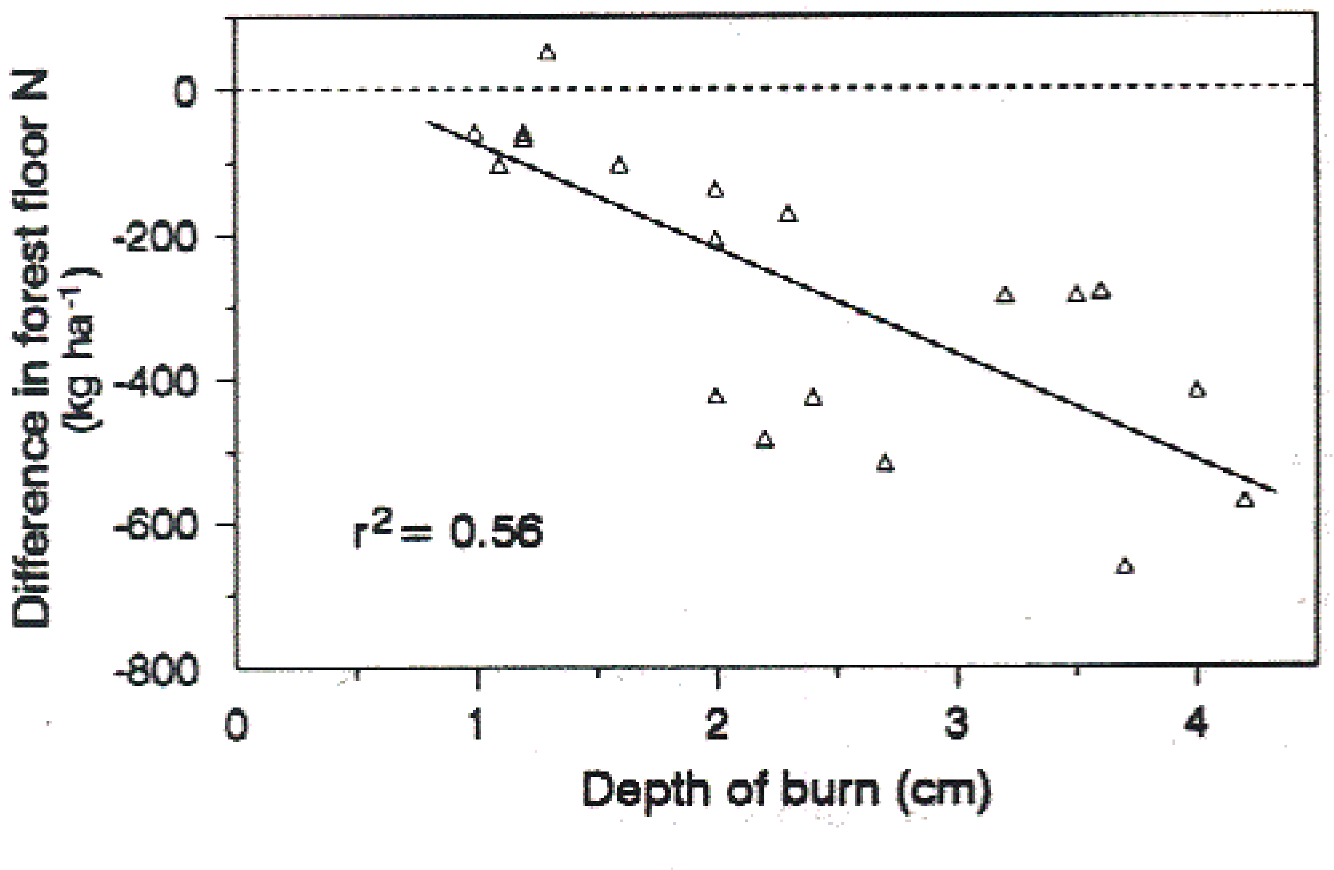

Figure 2. Relationship of forest floor consumption to differences in forest floor nitrogen content. From Macadam (1987).

The deposition of ash on the soil surface can have significant effects on soil chemistry and nutrient availability, at least over the short term. Increases in soil pH, and increased concentrations of available calcium, magnesium, and potassium are frequently observed following burning. The quantity of fuels consumed by the fire determines the amount of ash deposited on the soil surface, and the chemical composition of the ash depends on the nature of the fuels and temperatures achieved during combustion. The hotter the fire, the more nitrogen, sulfur, phosphorus, and potassium are lost during combustion and the higher the relative concentrations of calcium and magnesium in the ash (Grier 1975; Raison et al. 1985). In the interior of British Columbia, 0.4 to 2.3 unit increases in forest floor pH have been observed up to 21 months following broadcast burning (Macadam 1987; Taylor and Feller 1987; Blackwell 1989). Blackwell (1989) reported greater losses of volatilized nutrients such as nitrogen and sulfur and greater increases in available phosphorus, calcium, and magnesium beneath windrows than in broadcast burns, likely due to the higher concentration of fuels in windrows. Macadam (1987) observed increases of over 100% in forest floor exchangeable calcium following moderate-impact broadcast burns, and elevated levels persisted five years after burning (Macadam, unpublished data). Effects on magnesium were similar but of lesser magnitude. While decreases were found in forest floor exchangeable potassium, there were significant increases in the 0-15 cm mineral layer.

Increased levels of available phosphorus associated with burning have frequently been reported (Ahlgren and Ahlgren 1960). In interior British Columbia, Mac-

Table 4—Nitrogen losses (kg/ha) within one year after burning in north-central interior British Columbia.

Nitrogen Loss	Substrate	Reference
376	Forest floor to 30 cm mineral	Macadam (1987)
470-650	Slash and forest floor	Taylor and Feller (1987)
232-894	Forest floor only	Blackwell (1989)

adam (1987) found increased concentrations of available phosphorus averaging well over 100% in the forest floor and close to 40% in the upper mineral soil, persisting up to 21 months after moderate-intensity broadcast burns. However, while Taylor and Feller (1987) observed increased phosphorus availability in the forest floor immediately following burning, concentrations had dropped below preburn levels nine months later.

Burning frequently favors seedling survival and early growth (Ballard 1986; Macadam and Trowbridge 1988), especially when an important growth-limiting factor is alleviated as a result of burning. However, short-term benefits such as improved planter access, vegetation control, increased nutrient availability, and improvements in soil temperature regimes may frequently be achieved at the cost of nutritional problems later in the rotation. For example, in a study of some white spruce plantations in north-central British Columbia, Ballard (1986) found better height growth but more frequent nitrogen, copper, and iron deficiencies on burned than unburned sites.

In summary, the effects of prescribed fire on site nutrition depend entirely on the character of the individual site and on the nature of the burning treatment that is achieved. Some forest ecosystems are far more vulnerable than others to nutrient depletion associated with burning, and wide variations in fire impact are possible. Broadcast burns of moderate severity appear to have largely positive effects on productivity on medium and better quality sites, at least over the short term. Long-term effects are not well understood. Nutrient deficiencies, particularly of nitrogen, may result later in the rotation after burning on sites with medium and poorer nutrient regimes, but this has yet to be demonstrated experimentally. Severe burning treatments, or burning on very sensitive sites, can deplete nutrient capital. Particular caution should be exercised on poor, dry sites with coarse or shallow soils and thin forest floors.

Nutrient Amendments

Given the generally poor nutritional status of Interior Northwest forest types and the drain of site nutrients caused by harvesting and site preparation, there can be little doubt that the productivity of many Interior forest sites may decline over the long term without additional nutrient inputs. Inorganic fertilizers and nitrogen-fixing systems are successfully used in many parts of the world to increase forest productivity and at least partly compensate for some of the adverse effects of forest management activities on soil physical, chemical, and biological properties. Municipal and industrial sludges and effluent have also been successfully applied to forest land. Although currently not extensively used, nutrient amendments may become an important component of future nutrient management strategies for Interior forest types.

Fertilization. Numerous research studies in northern temperate and boreal forests have clearly demonstrated that nutrient deficiencies can be alleviated, and growth stimulated, by the application of inorganic fertilizers. For example, the responsiveness of Douglas-fir in the Pacific Northwest (Miller et al. 1986), and Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) in Sweden (Hagner 1991) has been significant enough that large-scale nitrogen fertilization is often considered to be an attractive silvicultural investment. In the Interior Northwest, many fertilizer research trials have documented the potential responsiveness of lodgepole pine (see Weetman et al. 1985; Weetman 1988; Brockley 1989, 1991), white spruce (Van Cleve and Zasada 1976), ponderosa pine (see Powers et al. 1988), Douglas-fir (Scanlin and Loewenstein 1981; Moore 1988; Shafii et al. 1989), grand fir (Shafii et al. 1989), and mixed conifers (Graham and Tonn 1985) to fertilization. However, the vast array of forest types and soils that have formed as a result of climatic and geologic diversity make it difficult to successfully predict fertilizer response. In the Interior Northwest, stand nutrition and fertilization response potential are the result of complex interactions between site factors (e.g., temperature, moisture, nutrient supply), stand factors (e.g., species, age, stocking), and management factors (e.g., stand density control, site degradation). As a result, the high degree of response variability is a characteristic common to most Interior tree species (Graham and Tonn 1985; Moore 1988; Powers et al. 1988; Brockley 1989). For a given species, some sites respond well and others respond poorly. The uncertainty and lack of site specificity regarding growth response potential are undoubtedly major factors in the reluctance of Interior forest landowners to invest in large-scale forest fertilization programs. In the interior of British Columbia, fewer than 30,000 hectares of forest land have been fertilized—virtually all of it done between 1986 and 1989 as part of a federal-provincial forestry agreement. In eastern Oregon, approximately 40,000 hectares of forest land were fertilized by Weyerhaeuser Company in the 1970s (McMahon 1991). However, fertilizer operations were suspended in 1980 due to uncertain profitability.

On many Interior forest sites, nonnutritional factors such as climate, inadequate soil moisture, compacted soil horizons, lack of room for crown expansion, and excessive vegetation competition may exert the primary limitation on tree growth. Fertilization of such sites without ameliorating these other limiting factors may result in little or no growth response. However, substantial responses to fertilization may often be obtained if these nonnutritional limitations are alleviated by combining fertilization with silvicultural treatments such as site preparation, thinning, or weeding. For example, fertilization of lodgepole pine should generally be confined to thinned stands due to the excessive density that is characteristic of unmanaged, fire-origin stands. In unthinned stands, fertilization may accelerate the rate of competition-induced mortality, thereby reducing net treatment response (Yang 1985*a*). On dry sites, response of ponderosa pine to fertilization has been shown to be much greater where competing vegetation is controlled (Powers and Jackson 1978; Powers 1983). However, where amelioration of nonnutritional factors such as inadequate soil moisture and severe climate is not possible, fertilization is probably a poor silvicultural investment. Even where relative growth responses are favorable, the absolute wood production gains on these low productivity sites may be too small to make fertilization profitable.

Powers (1983) reported that fertilization response of ponderosa pine was much higher on sites where topsoil had been scalped into windrows than on sites with little or no topsoil displacement. These results, combined with negative effects of windrowing and prescribed fire on white spruce foliar nutrition, reported by Ballard and Hawkes (1989), strongly indicate that scalping and burning may markedly decrease soil fertility and site productivity, and that fertilization may at least partly compensate for these losses.

Although results from fertilization research studies indicate that nitrogen is the element most limiting growth of Interior tree species, on many sites nitrogen fertilization alone may cause nutrient imbalances that preclude response or, in certain instances, cause severe growth disturbances resulting in losses to the economic potential of the stand. Sulfur and boron deficiencies, either induced or aggravated by nitrogen fertilization, appear to be the most widespread. Applications of sulfur or boron in conjunction with nitrogen may result in a greater growth response than with nitrogen alone (Cochran 1978; Cochran et al. 1981; Yang 1985*b*; Powers et al. 1988; Brockley 1990; Brockley and Swift 1990; Mika et al., this volume). Sulfur is added to nitrogenous fertilizer for large-scale aerial fertilization projects in the interior of British Columbia. Because boron deficiency symptoms can develop rapidly following an interruption in boron uptake, and because top dieback can have such an adverse effect on stem quality and value, boron is also added to operational mixes when fertilizing forests with low boron status.

Major factors limiting large-scale use of fertilizers in Interior Northwest forestry operations undoubtedly include the absence of reliable prediction systems to identify sites and stands that will respond favorably to fertilization, uncertain profitability, and the general lack of wood supply shortages. However, because of the need to maximize wood production from an ever-shrinking forest land base and to replace nutrient losses from forest management activities, fertilization may play a larger role in the future management of Interior forest types. Recent Scandinavian research shows that forest productivity can be dramatically increased by intensive fertilization (Ingestad 1987). But the potential for significantly increasing the productivity of Interior forest types by intensive fertilization has not been fully evaluated. Nonnutritional factors such as soil moisture and climate may indeed be less limiting to potential site productivity than previously thought.

Unfortunately, large, single applications of fertilizers are sometimes an inefficient way to add nutrients to a forest ecosystem. Investigations with ^{15}N-fertilizer indicate that a relatively small portion of the applied fertilizer N is initially taken up by the trees (Preston et al. 1990). A large amount of the applied N can be rapidly immobilized by microbial or chemical processes (Foster et al. 1985). Although this immobilized N is not permanently lost to the soil/plant system, its long-term fate is uncertain. It is probably released too slowly to have a significant impact on nitrogen availability. As such, long-term site improvement cannot be expected unless inputs are large relative to total site nitrogen (Miller 1981). In addition, the future cost and availability of synthetic nitrogen fertilizers are uncertain. Production requires high energy inputs, the cost of which is closely linked to the availability of energy supplies and political events. On some sites, alternatives to conventional fertilization may be available.

Biological Nitrogen Fixation. In soils low in nitrogen, such as forest soils following severe fire, or severely disturbed and exposed mineral soils, recolonization by nitrogen-fixing organisms is the primary means of restoring nitrogen fertility over time (Burns and Hardy 1975). However, actual N-fixation rates are difficult to measure. Nonsymbiotic N fixation was reported by Fortin et al. (1984) to be 2-5 kg/ha annually; this generally agrees with rates reported by Binkley (1986) of 0-4 kg/ha annually. Actinorhizal plants have been reported to provide 0-150 kg/ha of fixed nitrogen annually (Binkley 1986). Estimates for legumes have been reported from data obtained from experimental treatments. For example, Gadgil (1979) reported that lupines provided 60 kg/ha of fixed N annually under *Pinus radiata* until canopy closure. Jorgensen (1980) suggested that legumes in forest management should provide 50-100 kg/ha annually for three to five years to provide an economic return. Whatever the actual fixation rate is on any given site under the prevailing environmental conditions, biological N fixation has the potential to enhance site nitrogen status, and to ameliorate losses of nitrogen resulting from forestry practices.

While nitrogen-fixing organisms may be free-living or symbiotic, the latter—specifically root nodule symbiosis—can be managed in silvicultural systems. Root nodule symbioses with the bacteria *Rhizobium* and *Frankia* occur with vascular plants of the family Fabaceae (formerly Leguminoseae) and actinorhizal species (e.g., *Alnus*, *Shepherdia*, and *Ceanothus* spp.), respectively. Management of these species in forestry has been considered for many years throughout the world (Assmann 1970; Beuter 1979; Haines and DeBell 1979; Rehfuess 1979; Jorgensen 1980; Granhall 1981; Binkley 1983; Binkley and Husted 1983; Davey and Wollum 1984; Fortin et al. 1984; Binkley 1986), and more recently in British Columbia (Hermansen 1976; Eichel 1979; Kibbey et al. 1981; Carr and Ballard 1980; Beese and Kumi 1985; Trowbridge and Holl 1991).

The primary goal in attempts to manage N-fixing systems in forestry has been to ameliorate soil nitrogen due to its low status in many forest ecosystems, or due to losses caused by some forest management practices (Haines and DeBell 1979; Fortin et al. 1984). Before that amelioration can be achieved, the N-fixing system and tree seedling crop must be established in a regime compatible with forest management objectives. This may be achieved by alternating rotations of N-fixing species and crop trees, but probably more practically as a mixture of both in a plantation. Other benefits of using some N-fixing species in forestry may include: an economic return in forage where integrated multiple use is practiced; reduction of vegetation that competes with crop trees; and the establishment of a more suitable microclimate for tree seedling regeneration and growth. The actual results and benefits, however, may vary widely. This variability is primarily a consequence of the plant-endophyte combinations used and their interaction with site, climate, and soil conditions.

To the best of our knowledge, there have been no reported experiments describing the effects of *Alnus* species on Interior forest soils. Work in coastal British Columbia has shown increased soil nitrogen under *Alnus rubra* and *Alnus sinuata* (Binkley 1981). The effects of *Alnus* species on Interior forests soils are currently being addressed by the B.C. Ministry of Forests (Thomson and Trowbridge 1988; Sachs 1990), however there are no N-fixation data yet reported. Other Interior plants that associate with *Frankia*, and that may be of interest to soil nitrogen management, include such species as *Shepherdia canadensis* and *Ceanothus* species. Hendrickson and Burgess (1989) reported very low rates of N fixation by *Shepherdia* (0.78 kg/ha annually) in southern British Columbia. Binkley et al. (1982) found substantial mean annual accretion of soil nitrogen under *Ceanothus* in the Cascade Mountains of Oregon (42-48 kg/ha). For the time being, these actinorhizal species are probably best managed by leaving them as naturally occurring N-fixing systems in regenerating conifer stands, where they are not negatively competing with the crop trees. Negative effects of these actinorhizal shrub species are generally associated with shading until the crop trees overtop the shrubs. For the interior *Alnus* species, which grow approximately three to five meters tall (the tallest of the interior actinorhizal species), this period is generally 10 to 12 years. After that, crop trees may take advantage of the nitrogen accretion in full sunlight, while the N-fixing symbioses continue to exist as a subcanopy component of the ecosystem. Early adverse effects of these species on crop trees may be outweighed by the long-term benefits of nitrogen accretion.

Legume species are of particular interest in forest management because many of the species' seeds and host-specific inoculants (*Rhizobium* spp.) are commercially available, thus allowing for controlled introduction directly into the reforestation prescription. In addition, because there are a number of species to choose from, specific species (or mixes) can be chosen based on propagation and growth characteristics that match a site's environmental conditions and the silvics of the crop tree(s). Estimates of nitrogen fixed by legumes in forest plantations vary widely; Binkley (1986) reported some results ranging from 35 to 200 kg/ha annually. Trowbridge (unpublished data) found significant increases of forest floor nitrogen accretion in *Trifolium hybridum* (alsike clover) seeded plots compared with controls. After four years, there were approximately 50 kg/ha more total N and 12 kg/ha more mineralizable N in plots with the clover-*Rhizobium* symbiosis.

Fortin et al. (1984) found little data reporting the results of designed experiments on the effects of N-fixing species on tree growth. Most reports found were based on experiments not designed for that specific purpose. However, the studies that are available generally report positive effects on tree growth (e.g., see Finn 1953; Haines et al. 1978; Gadgil 1979; and Rehfuess 1979). Early results on the effects of increasing seeding rates of alsike clover on the early growth of lodgepole pine in north-central British Columbia showed no treatment effects on seedling height or survival in the first four years (Trowbridge and Holl 1991). During the first three years, negative effects were observed on diameter growth, but by the fourth year diameter increments in controls and clover-seeded areas were no longer significantly different. In the same study, needle mass and foliar nitrogen concentrations were measured in the second and fourth years. In the second year, needle mass was lower in the clover plots compared with controls, but nitrogen concentrations were the same. By year four, both needle mass and nitrogen

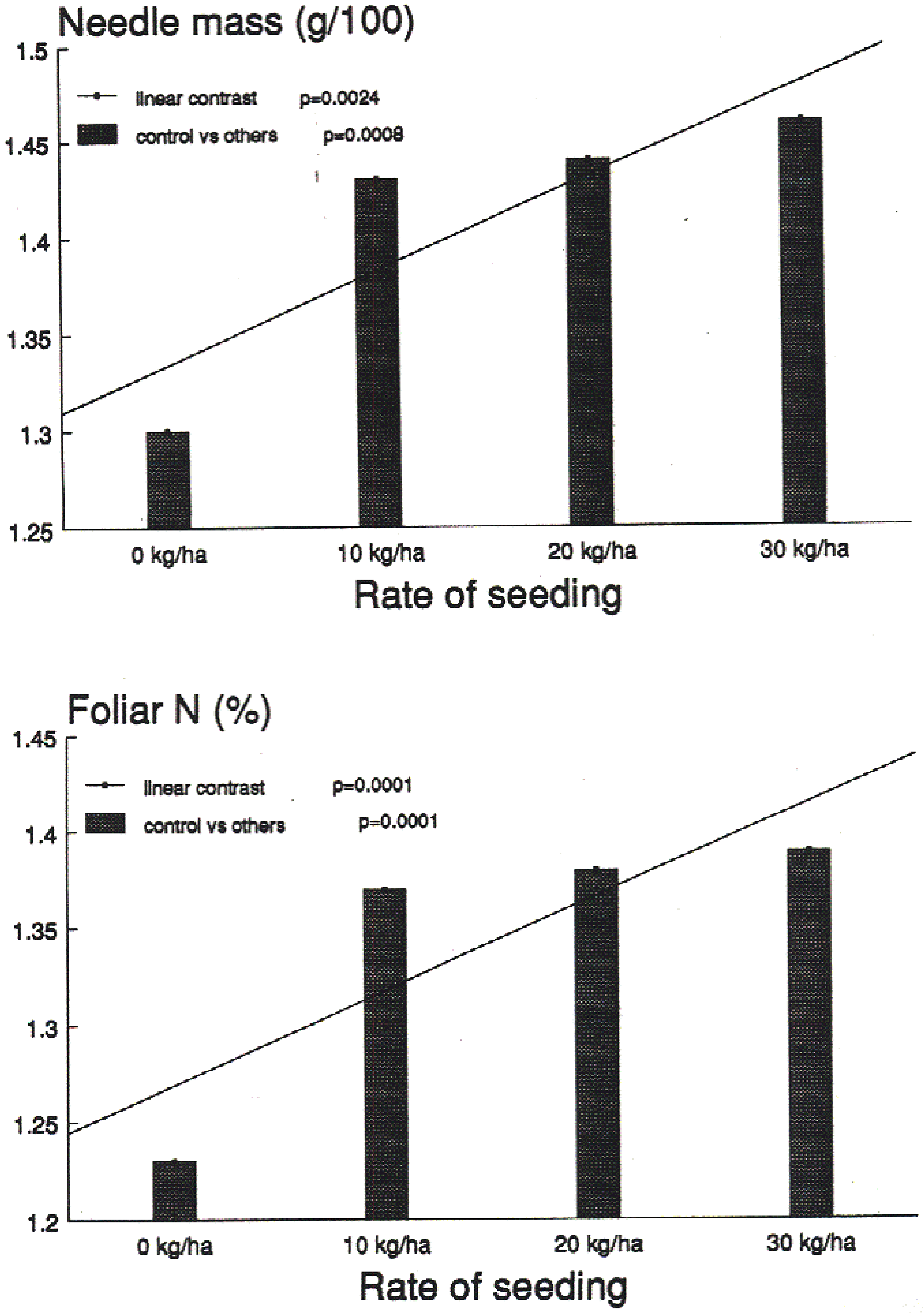

Figure 3. Mass and nitrogen concentration of lodgepole pine foliage in the fourth growing season. From Trowbridge and Holl (1991).

concentrations were significantly greater in the clover-seeded plots compared with controls (Figure 3). These results support the contention of Jorgensen (1980) that trees initially respond to nitrogen fixed by legumes by increasing foliar nitrogen.

Binkley (1986) summarized some possible reasons why foresters have not used nitrogen fixation in their management practices. He suggested one of the main reasons is that the risks of competition between the crop trees and some nitrogen fixers can be real, and that forest managers sometimes perceive all vegetation other than crop trees as a weed problem. Although there remain many research opportunities in the area of managing biological nitrogen fixation in forestry, we nevertheless can apply what knowledge we have to incorporate the operational use of some N-fixing systems in silvicultural systems. In British Columbia, we are encouraging the establishment of standardized field screening trials (Trowbridge and Holl 1989) consisting of N-fixing species-endophyte combinations with crop tree species in silviculturally important biogeoclimatic zones, as well as operationally seeding demonstration areas. This will allow for meaningful predictions of biological N-fixation effects on crop trees and site properties.

In review, we can see that in unmanaged ecosystems, biologically fixed nitrogen accounts for most of the replacement of nitrogen lost by natural processes and other disruptions. Many studies have demonstrated positive effects of root-nodule symbioses on forest soils, and on crop trees. Competition from some N-fixing systems with crop species on some sites is real. However, species and site-specific prescriptions can be made with the current level of knowledge that will benefit both soil nutrition and forest productivity. Further research and field demonstrations are needed to help managers understand the role and opportunities of managing biological nitrogen fixation in forestry.

Sludge and Wastewater. Research and operations conducted outside the Interior Northwest have clearly demonstrated that municipal and industrial sludge and wastewater can substantially increase wood production from forest land and stabilize disturbed sites (see Cole et al. 1986). Forested sites generally have soil infiltration and nutrient uptake rates and nutrient retention capabilities that are well suited to receive sludge and wastewater applications. There may also be fewer public health concerns with the uptake of contaminants by trees than with agricultural crops.

Despite the limited use to date, applications of sludge and wastewater would appear to be particularly well suited to Interior forest land. Research studies have shown that the benefits from sludge applications tend to be greatest on naturally low productivity sites or on disturbed land (Bastian 1986), of which there is no shortage in the Interior Northwest. Since many of the added nutrients are in organic forms, sludge acts as an excellent slow-release fertilizer, thereby providing nutrients at rates more in keeping with crop demands. In addition to the benefits of the added nutrients, the water content of wastewater may provide considerable benefits to dry forest sites.

One of the major problems facing Interior communities is how to dispose of municipal and industrial wastes. Population increases and industrial growth result in an ever-increasing waste management problem. Public concern and legislation related to incineration and dumping in lakes and rivers have resulted in considerable interest in land disposal alternatives. Since many Interior communities are surrounded by forest land, forest applications of municipal and industrial wastes may often be as cheap as other land disposal alternatives, or even cheaper. The wood fiber produced from treated lands may also be of economic benefit to the community. The technology and equipment necessary to apply sludge and effluent are readily available. Many young natural stands and plantations are accessible and would benefit from nutrient and water inputs. In addition, the combination of sludge application and ripping may facilitate the rehabilitation of landings and skid roads following harvesting. On these degraded soils, sludge applications would provide essential nutrients as well as the organic matter necessary to improve soil physical and biological properties.

Conclusions

In this chapter we have stressed the importance of soil organic matter in forest nutrient management. We have also discussed the negative impacts that certain forest management activities in the Interior Northwest may have on soil nutrient capital and site productivity. The challenge facing Interior forest managers, therefore, is to extract useful products from the forest and successfully establish and tend new crops without sacrificing the future productivity of the site by excessively depleting soil nutrient reserves or degrading soil physical and biological properties.

Interior forest soils that are characterized by large organic reserves, rapid turnover of residues, and incorporation of organic matter and nutrients in the underlying mineral soil are generally not highly sensitive to displacement or removal of surface organic layers by harvesting and site preparation practices that are undertaken with reasonable caution. Unfortunately, there are many examples of relatively resilient sites that have been severely degraded by careless practices. Despite this evidence, inappropriate prescriptions continue to be made on many of these Interior forest sites. On other sites, the loss of soil nutrient capital may be offset by improvements in soil microclimate in ecosystems where low soil temperatures limit tree growth, by decreased competition by noncrop vegetation, and by reduced risk of severe fires where large amounts of surface organic debris have accumulated. However, as we have mentioned, short-term improvements may be outweighed by long-term impairment of growth if soil nutrient capital is severely depleted.

For many Interior sites, the potential for site degradation is very high. Dry ecosystems, and sites where surface organic layers have been depleted by repeated wildfires, are especially vulnerable to degradation caused by intensive harvesting or site preparation practices. On many Interior sites, these practices may exacerbate existing nutritional problems. Disturbance should be kept to a minimum, and practices such as whole-tree harvesting should be discouraged.

The primary approach of forest nutrient management should be to improve forest management practices to conserve soil nutrient capital rather than to rehabilitate sites after damage has been done. Therefore, although nutrient amendments such as inorganic fertilizers and nitrogen-fixing systems have great potential for improving forest growth, they may be less important than native organic matter in the maintenance of soil physical, chemical, and biological properties.

In this chapter we have discussed certain practices that may result in losses of soil nutrient capital, and have indicated the types of sites that may be most susceptible to damage. An increased recognition of the sensitivity of many Interior soils, and the important role that surface organic layers play in site productivity, will undoubtedly help avoid future degradation. However, we have not quantified the effects that soil nutrient losses may have on long-term site productivity. Unfortunately, direct evidence of productivity decline is lacking for Interior forests. For the moment, we must be satisfied with less-direct evidence from short-term experiments and retrospective studies. However, a network of long-term field research experiments, similar to those proposed by Powers et al. (1990), is currently being established on benchmark sites in the Interior Northwest. These standardized experiments are designed to manipulate fundamental soil and site properties (as opposed to specific operational treatments), examine system processes, and measure vegetation response (Powers et al. 1990). Assessments of soil and productivity changes caused by these manipulations will enable site specific evaluations to be made.

Literature Cited

Ahlgren, I.F. and C.E. Ahlgren. 1960. Ecological effects of forest fires. Bot. Rev. 26:483-533.

Assmann, E. 1970. The principles of forest yield study: studies in the organic production, structure, increment and field of forest stands. Pergamon Press, Toronto. Translated from German.

Ball, W.J. 1990. Site preparation affects white spruce seedling performance after 20 years. Forestry Canada, North. For. Centre, Edmonton, Alberta, For. Manage. Note 47.

Ballard, T.M. 1985. Nutritional demands of planted spruce. *In* Proc. Interior Spruce Seedling Performance—State of the Art, 1985. Prince George, B.C. Northern Silviculture Committee.

______. 1986. Slashburning effects on growth and nutrition of planted white spruce in interior British Columbia. *In* Fire Management Papers submitted to the Fire Management Symposium, 1986. Prince George, B.C. Central Interior Fire Protection Committee, Smithers, B.C.

Ballard, T.M. and R.E. Carter. 1986. Evaluating forest stand nutrient status. B.C. Min. For., Victoria, Land Manage. Rep. 20. 60 p.

Ballard, T.M. and B.C. Hawkes. 1989. Effects of burning and mechanical site preparation on growth and nutrition of planted white spruce. Forestry Canada, Pac. For. Centre, Victoria, B.C. BC-X-309.

Ballard, T.M. and N. Majid. 1985. Use of pretreatment increment data in evaluating tree growth response to fertilization. Can. J. For. Res. 15:18-22.

Bassman, J.H. 1989. Influence of two site preparation treatments on ecophysiology of planted *Picea engelmannii* x *glauca* seedlings. Can. J. For. Res. 19:1359-1370.

Bastian, R.K. 1986. Overview on sludge utilization. p. 7-25 *In* Cole, D.W., C.L. Henry, and W.L. Nutter, eds. The forest alternative for treatment and utilization of municipal and industrial wastes. Univ. of Washington Press, Seattle.

Beaton, J.D. and R.J. Soper. 1986. Plant response to sulfur in western Canada. p. 375-403 *In* Tabatabai, M.A., ed. Sulfur in agriculture. Agronomy Monogr. 27.

Beese, W.J. and J. Kumi. 1985. Forest management strategy task force fertilization working group. Final rep. MacMillan Bloedel Ltd., Nanaimo, B.C.

Beuter, J.H. 1979. Forest fertilization and the economics of perpetual motion machines. p. 4-13 *In* Gordon, J.C., C.T. Wheeler, and D.A. Perry, eds. Symbiotic nitrogen fixation in the management of temperate forests. Proc. of a Workshop. Oregon State Univ., Corvallis.

Binkley, D. 1981. Nodule biomass and acetylene reduction rates of red alder and Sitka alder on Vancouver Island, B.C. Can. J. For. Res. 11:281-286.

______. 1983. Ecosystem production in Douglas-fir plantations: interaction of red alder and site fertility. For. Ecol. Manage. 5:215-227.

______. 1986. Forest nutrition management. Wiley and Sons, New York.

Binkley, D., K. Cromack, Jr., and R.L. Fredriksen. 1982. Nitrogen accretion and availability in some snowbrush ecosystems. For. Sci. 28:720-724.

Binkley, D. and L. Husted. 1983. Nitrogen accretion, soil fertility, and Douglas-fir nutrition in association with redstem ceanothus. Can. J. For. Res. 13:122-125.

Blackwell, B.A. 1989. Some ecological effects of operations used to convert densely stocked lodgepole pine stands into young pine plantations in west central British Columbia. M.S. thesis, Univ. of British Columbia, Vancouver.

Breadon, R.E. 1987. Site preparation equipment in British Columbia: current availability and future needs. Forestry Canada, Pac. For. Centre, Victoria, B.C., FRDA Rep. 016.

British Columbia Ministry of Forests. 1990. Annual report, 1988-89. B.C. Min. For., Victoria.

Brockley, R.P. 1989. Response of thinned, immature lodgepole pine to nitrogen fertilization: three-year growth response. B.C. Min. For., Victoria, FRDA Rep. 036.

______. 1990. Response of thinned, immature lodgepole pine to nitrogen and boron fertilization. Can. J. For. Res. 20:579-585.

______. 1991. Forest fertilization research in the interior of British Columbia. p. 236-251 *In* Lousier, J.D., H. Brix, R. Brockley, R. Carter, and V.G. Marshall, eds. Improving forest fertilization decision-making in British Columbia. Proc. Forest Fertilization Workshop, 1988. B.C. Min. For., Victoria.

Brockley, R.P. and K. Swift. 1990. Interior spruce, Douglas-fir, and western larch fertilizer screening trials in the British Columbia Interior. B.C. Min. For., Victoria, FRDA Memo 129.

Burns R.C. and R.W.F. Hardy. 1975. Nitrogen fixation in bacteria and higher plants. Springer- Verlag, New York.

Carr, W.W. and T.M. Ballard. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. J. Soil Water Cons. 35:33-35.

Carr, W.W., W.R. Mitchell, and W.J. Watt. 1991. Basic soil interpretations for forest development planning: surface soil erosion and soil compaction. B.C. Min. For., Victoria, Land Manage. Rep. 63.

Clayton, J.L., G. Kellogg, and N. Forrester. 1987. Soil disturbance-tree growth relations in central Idaho clearcuts. USDA For. Serv. Res. Note INT-372.

Clayton, J.L. and D.A. Kennedy. 1985. Nutrient losses from timber harvest in the Idaho batholith. Soil Sci. Soc. Am. J. 49:1041-1049.

Coates, D. and S. Haeussler. 1987. A guide to the use of mechanical site preparation equipment in north central British Columbia. 2nd ed. B.C. Min. For., Victoria, FRDA Handbook 002.

Cochran, P.H. 1978. Response of a pole-size ponderosa pine stand to nitrogen, phosphorus, and sulphur. USDA For. Serv. Res. Note PNW-319. 8 p.

Cochran, P.H. and T. Brock. 1985. Soil compaction and initial height growth of planted ponderosa pine. USDA For. Serv. Res. Note PNW-434.

Cochran, P.H., C.T. Youngberg, E.C. Steinbrenner, and S.R. Webster. 1981. Response of ponderosa pine and lodgepole pine to fertilization. p. 89-94 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf., 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

Cole, D.M. and W.C. Schmidt. 1986. Site treatments influence development of a young mixed-species western larch stand. USDA For. Serv. Res. Paper INT-364.

Cole, D.W., C.L. Henry, and W.L. Nutter, eds. 1986. The forest alternative for treatment and utilization of municipal and industrial wastes. Univ. of Washington Press, Seattle.

Cooper, S.V., K.E. Neiman, R. Steele, and W. David. 1987. Forest habitat types of northern Idaho: a second approximation. USDA For. Serv. Gen. Tech. Rep. INT-236.

Cromack, K., Jr., F.J. Swanson, and C.C. Grier. 1979. A comparison of harvesting methods and their impact on soils and environment in the Pacific Northwest. p. 445-476 *In* Youngberg, C.T., ed. Forest soils and land use. Proc. 5th North American Forest Soils Conf., 1978. Colorado State Univ. Press, Fort Collins.

Davey, C.B. and G. Woolum II. 1984. Nitrogen fixation systems in forest plantations. p. 361-377 *In* Bowen, G.D. and E.K.S. Nambiar, eds. Nutrition of plantation forests. Academic Press, London.

DeBell, D.S. 1981. Increasing forest productivity through nutrient management. p. 51-55 *In* Increasing forest productivity. Proc. Society of American Foresters National Convention, 1981.

Dobbs, R.C. and R.G. McMinn. 1977. Effects of scalping on soil temperature and growth of white-spruce seedlings. p. 66-73 *In* Proc. 6th B.C. Soil Science Workshop. B.C. Min. Agric., Victoria.

Draper, D., W. Binder, and D. Spittlehouse. 1985. *In* Proc. Interior Spruce Seedling Performance—State of the Art, 1985. Prince George, B.C. Northern Silviculture Committee.

Dyck, W.J. and M.F. Skinner. 1990. Potential for productivity decline in New Zealand radiata pine forests. p. 318-332 *In* Gessel, S.P., D.S. Lacate, G.F. Weetman, and R.F. Powers, eds. Sustained productivity of forest soils. Proc. 7th North American Forest Soils Conf., 1988. Faculty of Forestry, Univ. of British Columbia, Vancouver.

Eichel, F.H. 1979. Opportunities for the use of nitrogen-fixing plants in British Columbia forestry. B.S.F. thesis, Univ. of British Columbia, Vancouver.

Feller, M.C. 1982. The ecological effects of slashburning with particular reference to British Columbia: a literature review. B.C. Min. For. Land Manage. Rep. 13.

Finn, R.F. 1953. Foliar nitrogen and growth of certain mixed and pure forest plantings. J. For. Jan.:31-33.

Fortin, J.A., L. Chatarpaul, and A. Carlisie. 1984. The role of nitrogen fixation in intensive forestry in Canada. Part 1. Environment Canada, Can. For. Serv. Inf. Rep. PI-X-28.

Foster, N.W., E.G. Beauchamp, and C.T. Corke. 1985. Immobilization of nitrogen-15-labelled urea in a jack pine forest floor. Soil Sci. Soc. Am. J. 49:448-452.

Foster, N.W. and I.K. Morrison. 1989. Effects of site preparation and full tree logging on nutrient cycling. p. 28-46 *In* Corbett, P.M., comp. Proc. Aspects of Site Preparation

Biology and Practice, 1988. Ont. Min. Natural Resources, Northwestern Ont. For. Tech. Devel. Unit, Thunder Bay.

Franklin, J.F. and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA For. Serv. Gen. Tech. Rep. PNW-8.

Froehlich, H.A. 1976. The influence of different thinning systems on damage to soil and trees. Proc. 16th IUFRO Congress 4:33-44.

______. 1979. The influence of clearcutting and road building activities on landscape stability in western United States. p. 165-174 *In* Youngberg, C.T., ed. Forest soils and land use. Proc. 5th North American Forest Soils Conf., 1978. Colorado State Univ. Press, Fort Collins.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1986. Growth of young *Pinus ponderosa* and *Pinus contorta* on compacted soil in central Washington. For. Ecol. Manage. 15:285-294.

Gadgil, R. 1979. The nutritional role of *Lupinus arboreus* in coastal sand dune forestry. IV. Nitrogen distribution in the ecosystem for the first 5 years after tree planting. N.Z. J. For. Sci. 9:324-336.

Garrison, G.A. and R.S. Rummel. 1951. First year effects of logging on ponderosa pine forest range lands of Oregon and Washington. J. For. 49:707-713.

Goulding, K.W.T. and P.A. Stevens. 1988. Potassium reserves in a forested, acid upland soil and the effect on them of clear-felling versus whole-tree harvesting. Soil Use and Management 4:44-51.

Graham, R.T., A.E. Harvey, and M.F. Jurgensen. 1989. Effect of site preparation on survival and growth of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings. New Forests 3:89-98.

Graham, R.T. and J.R. Tonn. 1985. Ten-year results of fertilizing grand fir, western hemlock, western larch, and Douglas-fir with nitrogen in northern Idaho. USDA For. Serv. Res. Paper INT-346.

Granhall, U. 1981. Biological nitrogen fixation in relation to environmental factors and functioning of natural ecosystems. Ecol. Bull. 33:131-144.

Grier, C.C. 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. Can. J. For. Res. 5:599-607.

Hagner, S. 1991. The role of fertilization in forest management. p. 15-20 *In* Lousier, J.D., H. Brix, R. Brockley, R. Carter, and V.G. Marshall, eds. Improving forest fertilization decision-making in British Columbia. Proc. Forest Fertilization Workshop, 1988. B.C. Min. For., Victoria.

Haines, S.G. and D.S. DeBell. 1979. Use of nitrogen-fixing plants to improve and maintain productivity of forest soils. p. 279-303 *In* Leaf, A.L., ed. Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling, 1979. College of Environmental Science and Forestry, State Univ. of New York, Syracuse.

Haines, S.G., L.W. Haines, and G. White. 1978. Leguminous plants increase sycamore growth in northern Alabama. Soil Sci. Soc. Am. J. 42:130-132.

Harvey, A.E., M.F. Jurgensen, and R.T. Graham. 1988. The role of woody residues in soils of ponderosa pine forests. p. 141-147 *In* Baumgartner, D.M. and J.E. Loten, eds. Proc. Ponderosa Pine, the Species and Its Management, 1987. Washington State Univ. Cooperative Extension, Pullman.

Harvey, A.E., M.F. Jurgensen, and M.J. Larsen. 1978. Seasonal distribution of ectomycorrhizae in a mature Douglas-fir/larch forest soil in western Montana. For. Sci. 24:203-208.

______. 1980. Biological implications of increasing harvest intensity on the maintenance and productivity of forest soils. p. 211-220 *In* Proc. Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests, 1979. USDA For. Serv. Gen. Tech. Rep. INT-90.

Harvey, A.E., M.F. Jurgensen, M.J. Larsen, and R.T. Graham. 1987. Decaying organic materials and soil quality in the Inland Northwest: a management opportunity. USDA For. Serv. Gen. Tech. Rep. INT-225.

Harvey, A.E., M.F. Jurgensen, M.J. Larsen, and J.A. Schlieter. 1986. Distribution of active ectomycorrhizae short roots in forest soils of the Inland Northwest: effects of site and disturbance. USDA For. Serv. Res. Paper INT-374.

Hendrickson, O.Q. and D.M. Burgess. 1989. Nitrogen-fixing plants in a cut-over lodgepole pine stand of southern British Columbia. Can. J. For. Res. 19:936-939.

Hendrickson, O.Q., D.M. Burgess, and L. Chatarpaul. 1987. Biomass and nutrients in Great Lakes - St. Lawrence forest species: implications for whole-tree and conventional harvest. Can. J. For. Res. 17:210-218.

Hermansen, C. 1976. Clover plugs: a "slow release" nitrogen source established with seedlings at time of planting. Tree Planters' Notes 27(3):3-4.

Herring, L.J., and R.G. McMinn. 1980. Natural and advance regeneration of Engelmann spruce and subalpine fir compared 21 years after site treatment. For. Chron. 56:55-57.

Ingestad, T. 1987. New concepts on soil fertility and plant nutrition as illustrated by research on forest trees and stands. Geoderma 40:237-252.

Jorgensen, J.R. 1980. Use of legumes in southeastern forestry research. p. 205-211 *In* Proc. Southern Silvicultural Research Conf., Atlanta, Georgia.

Jurgensen, M.F., A.E. Harvey, R.T. Graham, M.J. Larsen, J.R. Tonn, and D.S. Page-Dumroese. 1990. Soil organic matter, timber harvesting, and forest productivity in the Inland Northwest. p. 392-415 *In* Gessel, S.P., D.S. Lacate, G.F. Weetman, and R.F. Powers, eds. Sustained productivity of forest soils. Proc. 7th North American Forest Soils Conf., 1988. Faculty of Forestry, University of British Columbia, Vancouver.

Kibbey, H.J., F.B. Holl, J.D. Lousier, and E.C. Packee. 1981. *Lupinus* spp. in coastal British Columbia forest management. p. 316-331 *In* Clark, K.W. and H.H.G. Stephens, eds. Proc. 8th North American Rhizobium Conf., Winnipeg, Manitoba.

Kimmins, J.P. 1974. Sustained yield, timber mining, and the concept of ecological rotation: a British Columbian view. For. Chron. 50:27-31.

______. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Manage. 1:169-183.

Kimmins, J.P., D. Binkley, L. Chatarpaul, and J. de Catanzaro. 1985. Biogeochemistry of temperate forest ecosystems: literature on inventories and dynamics of biomass and nutrients. Can. For. Serv., Petawawa National Forestry Institute, Chalk River, Ontario, Inf. Rep. PI-X-47E/F. 227 p.

Kimmins, J.P. and B.C. Hawkes. 1978. Distribution and chemistry of fine roots in a white spruce-subalpine fir stand in British Columbia: implications for management. Can. J. For. Res. 8:265-279.

Kimmins, J.P. and G. J. Krumlik. 1976. On the question of nutrient losses accompanying whole tree logging. p. 43-53 *In* IUFRO Oslo Biomass Studies. Univ. of Maine Press, Orono.

Klinka, K., R.N. Green, R.L. Trowbridge, and L. Lowe. 1981. Taxonomic classification of humus forms in ecosystems of British Columbia: first approximation. B.C. Min. For., Victoria, Land Manage. Rep. 8. 54 p.

Klock, G.O., J.M. Geist, and A.R. Tiedemann. 1975. Response of orchard grass to sulphur in sulphur-coated urea. Sulphur Inst. J. 11:4-8.

Krag, R., K. Higgenbotham, and R. Rothwell. 1986. Logging and soil disturbance in southeast British Columbia. Can. J. For. Res. 16:1345-1354.

Krajina, V.J. 1970. Ecology of forest trees in British Columbia. p. 1-146 *In* Krajina, V.J. and R.C. Brooke, eds. Ecology of North America, vol. 2. Department of Botany, Univ. of British Columbia, Vancouver.

Larsen, M.J., A.E. Harvey, and M.F. Jurgensen. 1980. Residue decay processes and associated environmental functions in northern Rocky Mountain forests. p. 157-174 *In* Proc. Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests, 1979. USDA For. Serv. Gen. Tech. Rep. INT-90.

Lewis, T. 1991. Developing timber harvesting prescriptions to minimize site degradation: interior sites. B.C. Min. For., Victoria, Land Manage. Rep. 62.

Lord, T.M. 1982. Soils of the Quesnel area, British Columbia. Agric. Can., Rep. 31 of the B.C. Soil Survey. Land Resource Res. Inst. Contrib. 92.

Macadam, A.M. 1987. Effects of broadcast slash burning on fuels and soil chemical properties in the Sub-boreal Spruce Zone of central British Columbia. Can. J. For. Res. 17:1577-1584.

______. 1989. Effects of prescribed fire on forest soils. B.C. Min. For., Smithers, Res. Rep. RR89001-PR.

______. 1990. Effects of microsite alteration on soil climate and interior spruce establishment in the Sub-boreal Spruce Zone. B.C. Min. For., Victoria, FRDA Memo 157.

Macadam, A. and R. Trowbridge. 1988. Effects of prescribed fire on soil moisture and temperature in two site series of the SBS Zone. B.C. Min. For., Victoria, FRDA Memo 056.

Madgwick, H.A.I., D.S. Jackson, and P.J. Knight. 1977. Above-ground dry matter, energy and nutrient contents of trees in an age series of *Pinus radiata* plantations. N.Z. J. For. Sci. 7:445-468.

Majid, N.M. 1984. Some aspects of boron, copper and iron nutrition of lodgepole pine and Douglas-fir. Ph.D. diss., Department of Soil Science, Univ. of British Columbia, Vancouver.

Maliondo, S.M. 1988. Possible effects of intensive harvesting on continuous productivity of forest lands. Forestry Canada, Maritimes Region, Fredericton, New Brunswick, Inf. Rep. M-X-171.

Maliondo, S.M., M.K. Mahendrappa, and G.D. van Raalte. 1990. Distribution of biomass and nutrients in some New Brunswick forest stands: possible implications of whole-tree harvesting. Forestry Canada, Maritimes Region, Fredericton, New Brunswick, Inf. Rep. M-X-170E/F.

Mälkönen, E. 1986. A review of soil preparation in Finland. IUFRO Working Party S1.05-12, Grand Prairie, Alberta, and Dawson Creek, British Columbia.

Mann, L.K., D.W. Johnson, D.C. West, D.W. Cole, J.W. Hornbeck, C.W. Martin, H. Riekerk, C.T. Smith, W.T. Swank, L.M. Tritton, and D.H. Van Lear. 1988. Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital, and regrowth. For. Sci. 34:412-428.

McMahon, J.P. 1991. Assessing the potential for forest fertilization in western forest management. p. 5-14 *In* Lousier, J.D., H. Brix, R. Brockley, R. Carter, and V.G. Marshall, eds. Improving forest fertilization decision-making in British Columbia. Proc. Forest Fertilization Workshop, 1988. B.C. Min. For., Victoria.

McMinn, R.G. 1982. Ecology of site preparation to improve performance of planted white spruce in northern latitudes. p. 25-32 *In* Murray, M., ed. Forest regeneration at high latitudes: experiences from northern British Columbia. Proc. 3rd International Workshop, 1981. School of Agriculture and Land Resources Management, Univ. of Alaska, Fairbanks.

McMinn, R.G. and I.B. Hedin. 1990. Site preparation: mechanical and manual. p. 150-163 *In* Lavender, D.P., R. Parish, C.M. Johnson, G. Montgomery, A. Vyse, R.A. Willis, and D. Winston, eds. Regenerating British Columbia's forests. Univ. of British Columbia Press, Vancouver.

McMorland, B. 1980. Skidding with small crawler-tractors. For. Engin. Res. Inst. Can., Vancouver, B.C., Tech. Rep. TR-37.

Megahan, W.F., N.F. Day, and T.M. Bliss. 1979. Landslide occurrence in the western and central northern Rocky Mountain physiographic province in Idaho. p. 116-139 *In* Youngberg, C.T., ed. Forest soils and land use. Proc. 5th North American Forest Soils Conf., 1978. Colorado State Univ. Press, Fort Collins.

Miller, H.G. 1981. Forest fertilization: some guiding concepts. Forestry 54:157-167.

Miller, R.E., P.R. Barker, C.E. Peterson, and S.R. Webster. 1986. Using nitrogen fertilizers in management of coast Douglas-fir: I. Regional trends of response. p. 290-303 *In* Oliver, C.D., D.P. Hanley, and J.A. Johnson, eds. Douglas-fir: stand management for the future. Institute of Forest Resources, Univ. of Washington, Seattle.

Moore, J.A. 1988. Response of Douglas-fir, grand fir, and western white pine to forest fertilization. p. 226-230 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Morris, L.A., W.L. Pritchett, and B.F. Swindel. 1983. Displacement of nutrients into windrows during site preparation of a flatwood forest. Soil Sci. Soc. Am. J. 47:591-594.

Morrison, I.K. and N.W. Foster. 1979. Biomass and element removal by complete-tree harvesting of medium rotation forest stands. p. 111-129 *In* Leaf, A.L., ed. Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling, 1979. College of Environmental Science and Forestry, State Univ. of New York, Syracuse.

Örlander, G., P. Gemmel, and J. Hunt. 1990. Site preparation: a Swedish overview. B.C. Min. For. and For. Can., Victoria, FRDA Rep. 105.

Page-Dumroese, D.S., M.F. Jurgensen, R.T. Graham, and A.E. Harvey. 1986. Soil physical properties of raised planting beds in a northern Idaho forest. USDA For. Serv. Res. Paper INT-360.

Pfister, R.D., B.L. Kovalichick, S.F. Arno, and R.C. Presby. 1977. Forest habitat types of Montana. USDA For. Serv. Gen. Tech. Rep. INT-34.

Powers, R.F. 1983. Forest fertilization research in California. p. 388-397 *In* Ballard, R. and S.P. Gessel, eds. Proc. IUFRO Symposium on Forest Site and Continuous Productivity. USDA For. Serv. Gen. Tech. Rep. PNW-163.

Powers, R.F., D.H. Alban, R.E. Miller, A.E. Tiarks, C.G. Wells, P.E. Avers, R.G. Cline, R.O. Fitzgerald, and N.S. Loftus, Jr. 1990. Sustaining site productivity in North American forests: problems and prospects. p. 49-79 *In* Gessel, S.P., D.S. Lacate, G.F. Weetman, and R.F. Powers, eds. Sustained productivity of forest soils. Proc. 7th North American Forest Soils Conf., 1988. Faculty of Forestry, Univ. of British Columbia, Vancouver.

Powers, R.F. and G.D. Jackson. 1978. Ponderosa pine response to fertilization: influence of brush removal and soil type. USDA For. Serv. Res. Paper PSW-132. 9 p.

Powers, R.F., S.R. Webster, and P.H. Cochran. 1988. Estimating the response of ponderosa pine forests to fertilization. p. 219-225 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Preston, C.M., V.G. Marshall, K. McCullough, and D.J. Mead. 1990. Fate of ^{15}N-labelled fertilizer applied on snow at two forest sites in British Columbia. Can. J. For. Res. 20:1583-1592.

Raison, R.J., P. K. Khanna, and P.V. Woods. 1985. Mechanisms of element transfer to the atmosphere during vegetation fires. Can. J. For. Res. 15:132-140.

Rehfuess, K.E. 1979. Underplanting of pines with legumes in Germany. p. 374-387 *In* Gordon, J.C., C.T. Wheeler, and D.A. Perry, eds. Symbiotic nitrogen fixation in the management of temperate forests. Proc. of a Workshop. Oregon State Univ., Corvallis.

Rosén, K. and A. Lundmark-Thelin. 1986. Hyggesbruket ooh markvirden. [Clearcutting and soil conservation]. Sver. Lantbruksuniv., Skogsfakta Konferens 9:42-49.

Ross, D.W., W. Scott, R.L. Heninger, and J.D. Walstad. 1986. Effects of site preparation on ponderosa pine (*Pinus ponderosa*), associated vegetation, and soil properties in south central Oregon. Can. J. For. Res. 16:612-618.

Sachs, D. 1990. Determination of nitrogen fixation by Sitka alder in the southern interior of British Columbia. Working Plan, B.C. Min. For., Kamloops. Internal report.

Scanlin, D.C. and H. Loewenstein. 1981. Response of inland Douglas-fir and grand fir to thinning and nitrogen fertilization in northern Idaho. p. 82-88 *In* Gessel, S.P., R.M. Kenady, and W.A. Atkinson, eds. Proc. Forest Fertilization Conf., 1979. Institute of Forest Resources Contrib. 40, Univ. of Washington, Seattle.

Schreier, H. 1989. Asbestos in the natural environment. Elsevier, Amsterdam.

Schwab, J.W., and W.J. Watt. 1981. Logging and soil disturbance on steep slopes in the Quesnel Highlands, Cariboo Forest Region. B.C. Min. For., Victoria, Res. Note 88.

Shafii, B., J.A. Moore, and J.R. Olson. 1989. Effects on nitrogen fertilization on growth of grand fir and Douglas-fir stands in northern Idaho. West. J. Appl. For. 4:54-57.

Smith, C.T., Jr., M.L. McCormack, Jr., J.W. Hornbeck, and C.W. Martin. 1986. Nutrient and biomass removals from red spruce-balsam fir whole-tree harvest. Can. J. For. Res. 16:381-388.

Smith, R.A. 1988. Environmental impact of ground harvesting systems on steep slopes in the Vernon Forest District. p. 13-43 *In* Lousier, J.D. and G.W. Still, eds. Degradation of forested land. Proc. 10th B.C. Soil Science Workshop, 1986. B.C. Min. For., Victoria, Land Manage. Rep. 56.

Smith, R.B. and E.F. Wass. 1976. Soil disturbance, vegetative cover and regeneration on clearcuts in the Nelson Forest District, British Columbia. Can. For. Serv., Pac. For. Res. Centre, Victoria, B.C., BC-X-151.

______. 1979. Tree growth on and adjacent to contour skid roads in the subalpine zone, southeastern British Columbia. Can. For. Serv., Pac. For. Res. Centre, Victoria, B.C., Inf. Rep. BC-R-2.

______. 1980. Tree growth on skidroads on steep slopes logged after wildfires in central and southeastern British Columbia. Can. For. Serv., Pac. For. Res. Centre, Victoria, B.C., Inf. Rep. BC-R-6.

______. 1985. Some chemical and physical characteristics of skidroads and adjacent undisturbed soils. Can. For. Serv., Pac. For. Res. Centre, Victoria, B.C., Inf. Rep. BC-X-261.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69:1689-1702.

Stark, N.M. 1979. Nutrient losses from timber harvesting in a larch/Douglas-fir forest. USDA For. Serv. Res. Paper INT-231.

Tamm, C.O. and A. Pettersson. 1969. Studies on nitrogen mobilization in forest soils. Stud. For. Suec. 75.

Taylor, S.W. and M.C. Feller. 1987. Initial effects of slashburning on the nutrient status of Sub-boreal Spruce Zone ecosystems. *In* Fire Management Papers submitted to the Fire Management Symposium, 1986. Prince George, B.C. Central Interior Fire Protection Committee, Smithers, B.C.

Thomson, S. and Trowbridge, R. 1988. Establishment and progress report: *Alnus viridus / Pinus contorta* trial. B.C. Min. For., Smithers, B.C., Internal report.

Trowbridge, R. 1986. Current fire research in British Columbia. *In* Fire Management Papers submitted to the Fire Management Symposium, 1986. Prince George, B.C. Central Interior Fire Protection Committee, Smithers, B.C.

Trowbridge, R.L. and F.B. Holl. 1989. Legumes in reforestation: field screening trials. B.C. Min. For. Res. Rep. 88003-PR.

______. 1991. Effects of alsike clover on early growth of lodgepole pine in west central British Columbia. Can. J. For. Res. *Submitted*.

Utzig, G.F. and L. Herring. 1975. Forest harvesting impacts at high elevations: five case studies. B.C. Min. For., Victoria, Res. Note 72.

Utzig, G.F. and M.E. Walmsley. 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia: a problem analysis Phase I. Can. For. Serv., Pac. For. Centre, Victoria, B.C., FRDA Rep. 025.

Van Cleve, K., L. Oliver, R. Schlentner, L.A. Viereck, and C.T. Dyrness. 1983. Productivity and nutrient cycling in taiga forest ecosystems. Can. J. For. Res. 13:747-766.

Van Cleve, K. and J.C. Zasada. 1976. Response of 70-year-old white spruce to thinning and fertilization in interior Alaska. Can. J. For. Res. 6:145-152.

Watt, W.J. and R.K. Krag. 1988. A comparison of soil disturbance caused by cable and small tractor logging. p. 44-53 *In* Lousier, J.D. and G.W. Still, eds. Degradation of forested land. Proc. 10th B.C. Soil Science Workshop, 1986. B.C. Min. For., Victoria, Land Manage. Rep. 56.

Weetman, G.F. 1988. Nutrition and fertilization of lodgepole pine. p. 231-239 *In* Schmidt, W.C., ed. Proc. Future Forests of the Mountain West: A Stand Culture Symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Weetman, G.F. and D. Algar. 1983. Low-site class black spruce and jack pine nutrient removals after full-tree and tree-length logging. Can. J. For. Res. 13:1030-1036.

Weetman, G.F., R.M. Fournier, and E. Schnorbus. 1988. Lodgepole pine fertilization screening trials: four-year growth response following initial predictions. Soil Sci. Soc. Am. J. 52:833-839.

Weetman, G.F. and B. Webber. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can. J. For. Res. 2:351-369.

Weetman, G.F., R.C. Yang, and I.E. Bella. 1985. Nutrition and fertilization of lodgepole pine. p. 225-232 *In* Baumgartner, D.M., R.G. Krebill, J.T. Arnott, and G.F. Weetman, eds. Proc. Lodgepole Pine, the Species and Its Management, 1984. Washington State Univ. Cooperative Extension, Pullman.

Wellburn, G.V. 1975. Alternative methods for logging steep slopes in the Nelson Forest District of British Columbia. Can. For. Serv., For. Manage. Inst., Inf. Rep. FMR-X-76.

Wells, C.G., R.E. Campbell, L.F. Debano, and others. 1979. Effects of fire on soil: a state of knowledge review. USDA For. Serv. Gen. Tech. Rep. WO-7.

Wert, S. and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45:629-632.

White, E.H. and A.E. Harvey. 1979. Modification of intensive management practices to protect forest nutrient cycles. p. 264-278 *In* Leaf, A.L., ed. Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling, 1979. College of Enviornmental Science and Forestry, State Univ. of New York, Syracuse.

Will, G.M. and C.T. Youngberg. 1978. Sulfur status of some central Oregon pumice soils. Soil Sci. Soc. Am. J. 42:132-134.

Yang, R.C. 1985*a*. Ten-year growth response of 70-year-old lodgepole pine to fertilization in Alberta. Can. For. Serv., North. For. Res. Centre, Edmonton, Alberta, Inf. Rep. NOR-X-266.

______. 1985*b*. Effects of fertilization on growth of 30-year-old lodgepole pine in west-central Alberta. Can. For. Serv., North. For. Res. Centre, Edmonton, Alberta, Inf. Rep. NOR-X-268.

Yole, D., R. Carter, and R. Trowbridge. 1991. Evaluation of five single tree fertilizer trials in thinned lodgepole pine stands in the Prince Rupert Forest Region. B.C. Min. For., Smithers, Res. Rep. RR91002-PR.

Young, H.E., P.N. Carpenter, and R.A. Altenburger. 1965. Preliminary tables of some chemical elements in seven tree species in Maine. Maine Agric. Exp. Stn. Tech. Bull. 20.