NUTRIENT CYCLING IN THE DOUGLAS-FIR TYPE - SILVICULTURAL IMPLICATIONS

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INTRODUCTION

During the development of a forest community, substantial amounts of nutrient elements are taken up, accumulated, and lost by the stand. Without disturbance or unfavorable environment, elements cycle in a relatively orderly fashion with nutrients returned to the soil from vegetation--and then recycled--supplying a large portion of the stand's continuing nutrient requirements. Within the nutrient cycle, however, a number of critical processes are affected by forest management practices.

Our objectives in this paper about coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) forests are: (1) describe nutrient cycling, (2) focus special attention on critical processes in this nutrient cycle, and (3) show how various silvicultural treatments can affect stand nutrition by altering nutrient cycling. We shall deal primarily with nitrogen cycling since nitrogen is normally the critical nutrient limiting growth in the Douglas-fir region. We shall also mention cycling of potassium because of its distinctly different pattern of behavior in nutrient cycling.

NUTRIENT CYCLING

Figure 1 represents nutrient cycling in a forest community. Major processes include: nutrient uptake by root systems; nutrient accumulation in various stand components; return of organic matter and nutrients to the forest floor and soil by litterfall, foliar leaching, and stem flow, as well as root sloughing and mortality; release of nutrients from organic matter by decomposition.

With few exceptions, plants require nutrient elements be in an inorganic form for uptake by their root systems. Yet, only a small fraction of the total nutrient capital of a forest soil is in this ionic or available form. Thus, the amounts of nutrients in ionic form--and not the total amount--control tree nutrition.

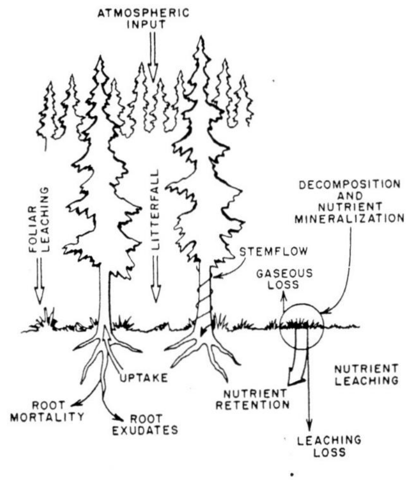

Figure 1. Nutrient cycling in a forest

Most nutrient elements taken up by plants are quickly incorporated into organic compounds which accumulate in various parts of trees and subordinate vegetation. In contrast, most potassium remains in ionic form within vegetation. When leaves, branches, or stems of trees fall, their nutrients are returned to the forest floor as litterfall. In the forest floor and the soil, organic compounds decay and their nutrients are released in ionic form. These nutrients are then leached into--and largely retained by--the soil as available nutrients for micro-organisms and vegetation.

Decomposition of organic matter must occur before nutrients in forest residues can be recycled between soil and vegetation; most potassium is recycled from organic matter by leaching. In addition to releasing inorganic nutrients, decomposition also helps convert plant residues to soil humus, an important factor of soil fertility and moisture relations.

A rapid rate of decomposition of forest residues is a desirable objective of forest soil management. Conversely, natural or man-created situations where forest litter steadily accumulates on the surface of the mineral soil are undesirable, because both nutrients and organic matter cycles develop progressively slower rates of turnover. Organic matter decomposition and mineralization of nutrients are largely biological processes. Like rates of tree growth, rates of these microbial processes are determined by

environmental conditions and available food supply. To the extent that our silvicultural practices change the soil environment or the quantity and quality of organic matter returned to the soil, we can shift conditions to or from optimum levels of microbial activity in the soil (Table 1).

Table 1. Environmental factors and their approximate values for general microbial activity in soil (from Bollen 1974)

Factor	Rate of microbial activity		
	Minimum	Optimum	Maximum
Moisture - percent	5[1/]	50[1/]	80[1/]
Temperature	2° C (35° F)	28° C (82° F)	40° C (104° F)
Aeration	Varies	At 50[1/]	Varies
pH	4	7	10
Food supply	Varies	Balanced; C:N = 25:1	Varies

[1/] Percent of moisture capacity or approximate field capacity.

In the Pacific Northwest, moisture-temperature relations are critical for microbial activity (Fig. 2). During winter and spring, moisture content of forest residues is favorable for microbial activity, but temperatures are below optimum. During summer and autumn, temperatures may be optimum for many microbes, but moisture becomes limiting. The characteristic, rain-free periods during the summer growing season of Douglas-fir forests probably limit moisture supplies for both trees and soil micro-flora that mineralize organic nitrogen. Thus, narrow tree growth rings associated with a year of unusually small amounts of precipitation can reflect both reduced available nitrogen and moisture.[1/]

Physical and chemical characteristics of forest residues also affect rates of decomposition. In general, the higher the nitrogen content and the lower the lignin content of organic matter, the greater the potential for microbial activity and reproduction. Thus, wood with its lower N content and higher content of resistant lignin-cellulose complexes decomposes less rapidly than leaves. For optimum rates of decomposition, the ratio of readily available carbon to nitrogen (C:N ratio) in residues should be about

[1/] W. Laatsch. The nitrogen economy of coniferous forest soils in Bavaria. (Speech) [Presented at Agricultural Institute, Dublin, Ireland, October 1961.]

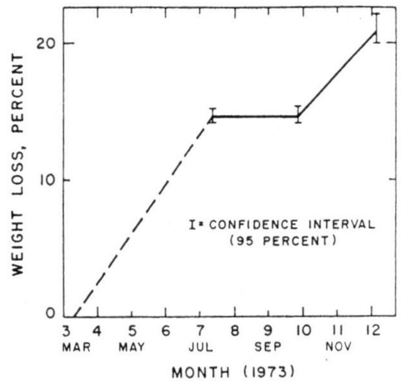

Figure 2. Weight loss of green Douglas-fir needles on the forest floor (from Fogel and Cromack 1974, used with permission)

25:1 (Bollen 1969). In most tree residues, the C:N ratio is much greater than this (Table 2); consequently, decomposition rates are low unless nitrogen-rich organic matter or fertilizer is added to satisfy the needs of the microbes. Through practices such as planting or retaining N-fixing species and fertilizing, silviculturists can improve the quality of organic matter reaching the soil and thus stimulate a more rapid nutrient cycling.

Much current research in nutrient cycling measures nutrients accumulating in forest communities or moving between various stand components (Overton et al. 1973). As an example, Figures 3A and 3B show amounts of certain nutrients accumulated in different parts of young- and old-growth Douglas-fir stands growing on low and average site quality land, respectively. Despite its younger age, lower site index, and a live biomass of less than 40 percent of that of the older stand, the 37-year-old stand has already accumulated nearly as much nitrogen in the live overstory as the old-growth stand (468 vs. 596 kg N/ha2/). The nitrogen accumulated in the live overstory is about 8 percent of the total N capital of both sites (3 458 and 4 899 kg N/ha) in the young- and old-growth stands, respectively. However, understory vegetation is denser in the open, old-growth stand and contains 7-fold more N than understory vegetation in the young plantation. A large part of the N in both stands is in foliage; the much larger wood biomass in the older stand accounts for most of the differences in the two stands.

2/ Kilograms per hectare X 0.892 = pounds per acre.

Table 2. Nitrogen proportion of various residues1/

Residue species and type	N	C:N
Douglas-fir:		
Needles	0.96	58:1
Bark	.11	491:
Heartwood	.12	429:
Sapwood	.09	548:
Red alder:		
Leaves	2.35	18:
Bark	.72	71:
Sawdust	.37	140:
Alfalfa hay	2.34	18:

1/ Sources: Bollen (1969) except for data for alder leaves (Tarrant et al. 1951).

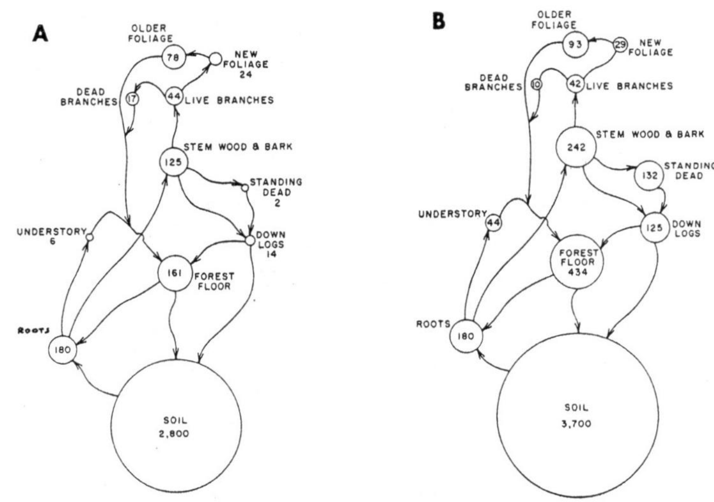

Figure 3. Nitrogen distribution and pathways of net nitrogen movement in a 37-year-old (A) and a 450-year-old (B) Douglas-fir stand, kg per hectare.

Table 3 compares amounts and routes of various nutrients returned to the forest floor in these two stands. Foliar leaching is the predominant means for returning K to the soil. In contrast, little N is recycled in this manner. The larger return of N by litterfall in the old-growth compared to the younger stand is largely due to its greater amount of woody material in litterfall (Abee and Lavender 1972). A third and less investigated pathway of nutrient recycling is root sloughing, exudates, and mortality. Although quantitative estimates are currently not available for Douglas-fir forests, investigation in loblolly pine (Pinus taeda L.) stands shows that returns of N from annual root mortality exceed those of litterfall (Wells and Jorgensen 1975, Henderson and Harris 1975).

Table 3. Annual return of nitrogen and potassium to the soil in young- and old-growth Douglas-fir forests

Source	N	K
	-kg/ha-	
	37 YEARS OLD	
Litterfall:		
Overstory	18.2	0.4
Understory	2.8	.1
Throughfall	1.5	10.7
Stemflow	0.2	1.6
Total	22.7	12.8
	450 YEARS OLD	
Litterfall:		
Overstory	22.1	5.5
Understory	5.2	2.5
Throughfall	2.0	22.0
Stemflow	.1	.6
Total	29.4	30.6

Although rates and amounts of nutrient movement in Douglas-fir forests are related to stand age and site, general cycling patterns remain the same. Thus, the following sequence is repeated time after time in almost all forests: Nutrients are taken up by root systems and incorporated into

living tissues in trees and understory vegetation. Nutrients are leached from plants by rainfall. Decomposition of forest litter changes nutrients from the organic to the ionic or available form. These nutrients are then leached into the soil where they are again eventually available for plant uptake.

Excluding plant uptake, amounts of available nutrients in the soil are largely determined by rates of decomposition of organic matter and weathering of soil parent material. Small contributions to the available nutrient pool also come from nutrients dissolved in precipitation and nitrogen fixation. Weathering of soil parent materials is the major source of most new nutrients in a forest. However, main sources of new nitrogen are nitrogen fixation and nitrogen dissolved in rain. Natural additions of new nutrients to Northwest forests are normally small. Rainfall in the Pacific Northwest adds about 1 kg N/ha per year; this amount normally exceeds leaching losses to streams (Fredriksen 1972, Gessel et al. 1972). According to current estimates, nitrogen fixation, by free-living organisms, can add between 0.1 and 0.2 kg N/ha per year to the existing nutrient capital of a forest. Depending on the species and biomass of N-fixing organisms hosted by plants, annual fixation rates are much higher. For example, stands of red alder (Alnus rubra Bong.) have been estimated to contribute 55 to 202 kg N/ha per year (Tarrant 1968) and as much as 320 kg N/ha per year during the first 15 years after logging and soil disturbance (Newton et al. 1968).

N cycling and growth of Douglas-fir.--In the majority of Douglas-fir stands in the Pacific Northwest, growth is limited by insufficient available nitrogen. Productive Douglas-fir stands apparently require 40 to 100 kg N/ha per year. Nitrogen in the soil of commercial forests ranges from 2 000 to more than 20 000 kg N/ha, but practically all of this nitrogen is in living organic matter or organic residues and is not readily available. Each year, a small fraction of this is mineralized to inorganic nitrogen which is available to plants--as well as competing micro-organisms. In agricultural soils, this annual rate of mineralization is estimated at less than 5 percent. Assuming average soil nitrogen at 5 000 kg N/ha, then a 1-percent rate of mineralization would provide 50 kg of inorganic nitrogen. Largely depending on the nitrogen needs of micro-organisms to decompose forest residues and increase their populations, a net portion of this mineralized nitrogen is available for vegetation, including the forest crop. In low site quality Douglas-fir stands, Heilman and Gessel (1963) estimated this net mineralization, i.e., the annual quantity of N supplied to forest vegetation from soil and forest floor, is slightly less than 0.8 to 1.0 percent of the total present. Presumably, a gross annual organic nitrogen turnover of 2 to 5 percent should satisfy the needs of both micro-organisms and forest crops. Such turnover rates are apparently not achieved as evidenced by response of Douglas-fir that usually follows forest fertilization with 170 kg/ha or more of nitrogen.

OBJECTIVES OF NUTRIENT MANAGEMENT

In the preceding sections, we have reviewed the quantities and distribution of nutrient elements within Douglas-fir forests. The status of nitrogen was emphasized, because low levels of available N frequently limit tree growth in the Pacific Northwest.

As forestry practices in the Pacific Northwest progress from exploitation of wild lands to well-managed forests, maintaining or improving soil productivity becomes a management objective. Silvicultural practices can either help or hinder achievement of these objectives. Harvesting Douglas-fir timber and establishing new crops inherently cause nutrient losses which may reduce soil productivity. Thus, the prudent land manager seeks to reduce this loss by choosing methods to minimize the percentage of area adversely affected and the degree of disturbance to the vegetation, forest floor, and the mineral soil. Additionally, he reduces negative impacts on soil productivity by using stand treatments which improve the soil. In the Pacific Northwest, two achievable objectives are: (1) increasing the quantity and rate of nitrogen available for tree growth and (2) maintaining and improving soil moisture and organic matter relations.

EFFECTS OF SILVICULTURAL PRACTICES

Climate, vegetation, soil properties, time, and man's activities influence the amount, distribution, and rate of nutrient cycling in the forest ecosystem. Any significant change in these factors can cause a change in the original balance. Silvicultural treatments affect the nutrient cycle in several basic ways. First, a portion of the total nutrient capital of a stand can be removed through harvesting. Second, nutrients can be added to a forest by fertilization. Third, silvicultural treatments may neither add nor subtract nutrients from the site but may substantially alter stand nutrition by changing the rate of a critical process, such as decomposition. In the following sections, a number of silvicultural practices commonly used in the Douglas-fir region will be discussed regarding their effects on nutrient cycling. Our detailed review of forest fertilization relative to that of other practices reflects our currently greater amount of information about this practice.

Timber Harvest

About 40 000 hectares of old-growth Douglas-fir are harvested annually. Although acreages harvested in mature, young growth are steadily increasing, cutting of old growth is expected to continue for several decades. Comparable acreages are commercially thinned each year. Clearcutting is the most common final harvest system, but shelterwood harvesting is increasing for esthetic reasons or to improve regeneration in the Cascade Range of Oregon (Williamson 1973).

Effect of timber harvest on nutrient cycling depends on several factors, including:

1. Intensity of cut and removal--which are determined by percentage of stand felled, standards of utilization, and yarding method--for example, logs *versus* whole tree logging.

2. Frequency of cutting cycles and rotation lengths. Under future intensive management systems, cutting cycles and rotations will be shorter, utilization more intensive, and nutrient drains greater.

3. Changes in the environment, such as microclimate and physical properties of the soil. These changes may affect rate of organic matter decomposition and subsequent vegetation succession.

4. Initial site conditions--such as nutrient amounts and distribution which interact with the preceding factors.

Intermediate and final harvest cuts have similar effects on components of the nutrient cycle but differ in the degree of their effects. Timber harvest shifts storage of organic matter and nutrients to the soil from the stand. There are obvious losses of nutrients when products are removed; moreover, there are additional relocation and off-site losses--depending on method of yarding and slash disposal. Supplementing an accelerated return of litter to the forest floor, organic matter and nutrients contained in severed root systems also return to the mineral soil. Since root systems of established conifers usually constitute 20-30 percent of the total tree biomass (Santantonio et al. 1974), quantities of nutrients returned from roots are substantial.

Nutrient drain.--If the 450-year-old Douglas-fir stand previously described were clearcut, approximately 242 kg N/ha, or 4.9 percent of the total in the ecosystem, would be removed in boles and bark (Table 4); salvage of standing dead trees would increase nutrient drain to 474 kg N/ha (Fig. 3B). Harvesting the live stand would also remove 157 kg K/ha, or 10.6 percent. Crown removal could nearly double these losses. Because of a high initial rate of nutrient accumulation in Douglas-fir stands, amounts removed by harvesting the 37-year-old Douglas-fir stand would be more than half as much, despite the lower inherent productivity of the site. Thus, 125 kg N/ha and 96 kg K/ha would be removed in boles and bark. The potassium removed in the stems from the younger stand represents 18.9 percent of the total as opposed to 10.6 percent of the total in the old-growth stand; thus, repeated cropping of this less fertile soil would likely induce deficiencies of K.

Compared with clearcutting, shelterwood cutting or commercial thinning removes lesser volumes per cut and these at roughly 5- to 20-year intervals. Over a full rotation, however, off-site nutrient drain will largely depend on the proportion of total wood actually removed and, especially, on the fate of tree foliage and branches. Despite greater bole wood volume in old-growth Douglas-fir, which commonly exceeds 1 200 cubic meters per hectare[3/] in average site quality stands, there is a likelihood of larger drain of nutrients in harvesting mature young-growth stands, because of closer utilization and increased opportunities for whole-tree logging.

Environmental changes.--Effects of final and intermediate harvests on rates of decomposition and release of nitrogen depend largely on the quality and amount of organic matter available for decomposition as well as changes in temperature and moisture relations within the forest floor and surface soil. Although clearcutting temporarily reduces circulation of nutrients between vegetation and the soil system, increases in soil temperature and available moisture (Hallin 1968) and increased amounts of residues in the forest floor generally increase the rate of organic matter decomposition and amounts of nutrients released to the soil and plants. These increases have been measured by collecting and analyzing the nutrient content of leachates from the forest floor (Cole and Gessel 1965). A re-establishment of nutrient cycling accompanies the luxuriant development of brush and herbaceous species which survive logging or rapidly invade clearcuts. This vegetation provides organic matter and helps reduce leaching losses. Fortunately, forest sites in the Pacific Northwest generally have a high capacity to

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[3/] Cubic meters per hectare X 14.3 = cubic feet per acre.

Table 4. Nutrient quantities in major components of a 37-year-old[1] and a 450-year-old[2] stand of Douglas-fir

Component	Element			
	N		K	
	-kg/ha-	-Percent-[3]	-kg/ha-	-Percent-[3]
	37 YEARS OLD			
Boles and bark	125	3.6	96	18.9
Foliage and branches	163	4.7	100	19.7
Understory	6	0.1	7	1.4
Forest floor	175	5.1	32	6.3
Soil	2 809	81.2	234[4]	46.2
Roots	180	5.2	38	7.5
Total	3 458	99.9	507	100.0
	450 YEARS OLD			
Boles and bark	242	4.9	157	10.6
Foliage and branches	174	3.6	154	10.5
Understory	44	.9	23	1.6
Forest floor	559	11.4	73	5.0
Soil	3 700	75.5	1 000[4]	68.1
Roots	180	3.7	61	4.2
Total	4 899	100.0	1 468	100.0

[1] Source: Cole et al. 1967; N and K contained in fine roots were provided by Dale W. Cole, University of Washington, in September 1975, and were added to originally published table.

[2] Source: Charles C. Grier. Unpublished data on file at Forest Research Laboratory, Oregon State University, Corvallis.

[3] Percent of total in ecosystem.

[4] Ammonium acetate extracted.

retain nutrients against the loss to ground water (Cole and Gessel 1965) or surface streams (Fredriksen 1972).

Intermediate cutting also increases soil temperatures (Fig. 4); however, logging slash under a protective canopy does not dry out as rapidly as that in a clearcut (Fahnestock 1960) and thus decay proceeds more rapidly (Aho 1974). After thinning, the amount of litter (Reukema 1964) and recycled N from the stand are reduced (Gessel et al. 1965), but increased litter weight and N from subordinate vegetation can compensate for this (Table 5).

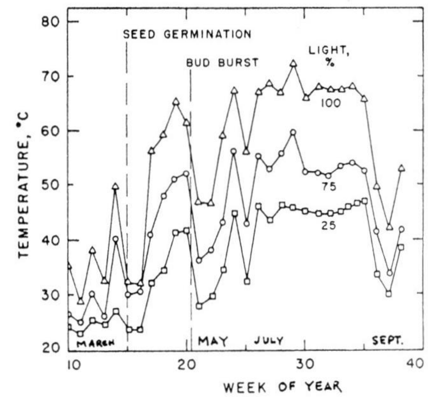

Figure 4. Weekly maximum temperatures in forest floors exposed to three light regimes. Data from Hermann (1960)

For a given site, the amount of subordinate vegetation is roughly proportional to the amount of light passing through the residual tree canopy. Thus, on the average site quality land in the central Coast Ranges of Oregon, repeated thinning of 60-year-old Douglas-fir to maintain basal area levels which averaged 70, 60, and 40 percent of control stands increased percent cover and understory biomass in relation to thinning intensity. Seventeen years after thinning, herbaceous biomass was 70 kg/ha on control plots and 80, 248, and 300 kg/ha with increasing thinning intensities (Witler and Berg 1975). Thinning increased biomass of bracken fern (*Pteridium aquilinum* (L.) Kuhn. var. *pubescens* Underw.) and occurrence of nitrogen-fixing plants (*Lotus crassifolius* (Benth.) Greene and *Lupinus latifolius* Ag.). The latter two N-fixing plants occurred naturally, although thinning may have improved conditions for their growth. Their biomass was only 1 percent of the total understory, yet their litter contributed one-third of the N annually cycled by the understory. If understory stands of such N-fixing plants had been purposefully established, their significant contributions to the N capital of the site would have increased tremendously.

Table 5. Average annual weight and N content of litterfall by thinning treatment at Black Rock Forest, 1965-73

Item	Thinning treatment		
	Control	Light	Heavy
		-Percent-	
Residual basal area	100	82	55
N concentration[1/]			
Needles	0.55	0.52	0.63
Twigs	.36	.36	.38
Branches	.22	.32	.21
		-kg/ha-	
Litterfall - dry weight[2/]			
Needles	2 571	2 459	2 209
Twigs	660	523	415
Branches	778	259	199
Total	4 009	3 241	2 823
Average N content			
Needles	14.1	12.8	13.9
Twigs	2.4	1.9	1.6
Branches	1.7	.8	.4
Total tree litterfall	18.2	15.5	15.9
Subordinate vegetation[3/]	.5	1.5	5.6
Total litterfall	18.7	17.0	21.5

[1/] Mean of collections between September 1956 and August 1962.

[2/] Personal communication with A. B. Berg, Professor, School of Forestry, Oregon State University, Corvallis, August 15, 1975.

[3/] Estimated from 1973 biomass and N content.

Site Preparation

Some form of slash disposal or site preparation to reduce fire hazard and remove physical impediments to planting and subsequent management practices generally follows final and intermediate harvests. On clearcut areas with slopes of less than 40 percent, slash is commonly piled by

machine and burned; on steeper ground, it is generally broadcast burned. Since 1970, however, better utilization standards have been encouraged by the U.S. Forest Service; sale contracts require that all logging residues exceeding specified minimum sizes be yarded to a landing. Cleaner logging has reduced need for both slash disposal and site preparation. In shelterwood areas, slash is generally piled by machine and burned to reduce fire hazard and create mineral soil seed beds.

There are continuing programs to reclaim some of the approximately 4.5 million acres of commercial forest land in western Washington and Oregon now occupied by brush fields and undesirable hardwoods (Gratkowski 1974). Brush field and forest type conversion require site preparation. Methods vary depending on terrain, species, and density of vegetation, as well as management objectives (Gratkowski 1974). Among the various methods for releasing young conifers or preparing sites for reforestation, chemical control probably has the least impact on nutrient cycling; dead plants are allowed to fall and decay in place. Moreover, surviving plants frequently remain to capture released nutrients. In contrast, prescribed burning of chemically dessicated brush or mechanical eradication of brush species has more negative effects on nutrient cycling.

Mechanical eradication of brush species is the most widely used method of preparing brush fields for reforestation. Large tractors with toothed brush blades are used for piling and windrowing brush. Although much of the forest floor and some topsoil are relocated within a mechanically treated area, nutrient losses from the site occur only if piles or windrows are burned.

The impacts of various methods of site preparation on nutrient cycling may be compared by the proportion of the total area that each affects and the degree to which each (1) removes or redistributes organic matter from the forest floor and the soil; (2) physically disturbs the mineral soil--loosens, compacts, or mixes with organic matter; and (3) affects existing vegetation or conditions for invading vegetation.

Broadcast burning.--Broadcast burning after clearcutting creates a mosaic of burning intensities and effects on slash, forest floor, and mineral soil. Results from numerous investigations show that broadcast burning increases the amount of exposed mineral soil by an additional 8 to 43 percent over that exposed by logging (Miller et al. 1974). Burning causes rapid oxidation of organic matter and mineralization of nutrients. When organic matter is consumed by fire, more than half its nitrogen (DeBell and Ralston 1970), most sulphur (Allen 1964), and much phosphorous (Grier 1972) are lost as gasses to the atmosphere. Most of the ash from unconsumed organic matter remains on site. Precipitation leaches this ash into the soil, temporarily increasing pH which can favor nitrate production (Moore and Norris 1974). Where vegetation is present, only insignificant amounts of nutrients are leached from the rooting zone (Grier and Cole 1972, Fredriksen 1971).

Finally, slash burning can change vegetational succession in species composition and abundance. Burning eliminates some species from the original forest and delays expansion of others capable of resprouting. However, at some sites in the southern Cascade Range, heat from slash burning stimulates germination of long-dormant seeds from several brush species not present in the stand at harvest; these include several species of ceanothus which host nitrogen-fixing organisms. Seed beds created by burning are quickly populated by herbaceous species with windblown seed, so that soil and nutrient losses are reduced. Thus, 3 to 5 years after burning, total herbaceous growth was not significantly different between burned and unburned areas (Morris 1970).

Tractor piling and burning.--Use of tractors in site preparation increases disturbance to the mineral soil. For example, tractor logging with slash piling on 11 small clearcuts on 0- to 15-percent slopes left an average of 5-percent undisturbed soil compared with 44 percent after high-lead yarding on a 35-percent slope.4/ Piling of slash implies additional soil disturbance and loss of organic matter in affected portions of the site. Large material is likely to be piled, yet soil and much fine logging slash will also be included unless brush blades are used carefully to avoid soil disturbance.

Burning piled slash creates hotter fires with less air pollution than broadcast burning (Fritschen et al. 1970); however, the high soil temperatures under the piles will affect soil even more adversely than under severely burned spots after broadcast burning. Finally, burning can lead to water repellency in surface soils. At low fire temperatures, vapors and gasses flow from organic matter; some of these gasses contain substances which condense on cooler surfaces within the soil and cause an undesirable water repellency lasting 5 to 10 years; coarse-textured soils become more water repellent than soils of finer texture (DeBano and Rice 1973). This fire-induced water repellency reduces infiltration of soil moisture and probably rates of nutrient and organic matter cycling.

Site interactions.--Nitrogen losses are small in the undisturbed, old-growth forest. These losses chiefly occur as dissolved organic matter or suspended soil in streamflow (Table 6). After clearcutting and slash burning, however, concentrations of nitrogen and phosphorous in streams increase for several reasons: (1) temporary reduction in uptake by vegetation, (2) increased rates of decomposition (Cole and Gessel 1965), and (3) increased erosion (Fredriksen et al. 1975).

Initial and subsequent effects of harvesting on mineral cycling and site productivity vary with site. Reductions in productivity are likely less on higher quality sites which generally have (1) a relatively large capital of nitrogen and organic matter in the mineral soil; (2) deep, well-drained soils with high infiltration rates and moisture-holding capacity--in most cases, such soils are more stable and have minimal potential for surface erosion and mass movement, or are relatively less affected if these occur; (3) favorable climatic conditions which can compensate for degradation of chemical or physical soil properties; and (4) rapid secondary succession by a wide variety of plants which re-establish a nutrient and organic cycle. In contrast to productive sites, areas of low or medium site quality generally have less total nutrient and organic matter capital with a higher proportion of this capital in the forest floor and stand than in the soil. Both these aboveground sources are vulnerable to destruction by slash burning. Moreover, restricted soil depth or large content of gravel or rock outcrops are characteristics which further reduce nutrient and moisture storage capacity of soil on poorer sites.

4/ Personal communication with Dr. C. T. Dyrness, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, October 1972.

Table 6. Yearly losses of nitrogen in dissolved organic matter and suspended sediment in streamflow from clearcut and control watersheds in old-growth Douglas-fir, H. J. Andrews Experimental Forest1/

Year and activity	Clearcut			Control		
	NH_3-N	NO_3-N	Total N	NH_3-N	NO_3-N	Total N
			-kg/ha-			
1966, clearcut	Trace	0.26	0.26	Trace	0.08	0.08
1967, slash burned	1.50	.69	2.19	0.03	.03	.06
1968, revegetation	.01	2.41	2.42	.00	.01	.01
1971, revegetation	Trace	.82	.82	Trace	.005	.005
1972, revegetation	Trace	.49	.49	Trace	.03	.03
Total	1.51+	4.67	6.18	.03+	.155	.185

1/ Data through 1968 from Fredriksen (1971). Remainder from personal communication with Richard L. Fredriksen, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, September 1975.

Thus, some soils have less tolerance for losses of nutrient or organic matter through harvest, fire, or surface erosion. The land manager must choose his logging and site preparation methods carefully for such sites.

In the interest of nutrient management, the land manager should:

1. Minimize the drain on nutrients removed from or relocated within a site by conserving tree foliage and branches. Thus, felling, lopping, and scattering are more desirable than whole tree yarding or piling and burning unmerchantable material.

2. Improve temperature and moisture relations of the forest floor. In the Pacific Northwest, reducing stand densities on north aspects, at higher elevations, or in the more northerly limits of Douglas-fir are likely to shift moisture and temperature to levels more favorable for rapid organic matter decomposition; however, decreasing stand density on south slopes and on more southern portions of the region are likely to shift environmental conditions to those less favorable for mineral cycling.

3. Encourage vegetative succession by species which either add nitrogen to the site or accumulate nutrients in luxury quantities.

Conifer Release or Weeding

Many of the trees and brush species that completely replace coniferous forests after fire or logging activities also exist in varying proportions in conifer stands. On mesic sites of western Washington and Oregon, red alder is an aggressive invader following site disturbance. On drier sites, various ceanothus species and broad-leaved evergreen tree species such as Pacific madrone (Arbutus menziesii Pursh), golden chinkapin (Castanopsis chrysophylla (Dougl.) A. DC.), and tanoak (Lithocarpus densiflorus (Hook. & Arn.) Rehd.), become undesired competitors of Douglas-fir and other conifers. Approximately 60 000 to 80 000 hectares per year are treated, usually by chemical spray applications to release conifers from brush and hardwood competition.5/ In most cases, a single spray treatment is sufficient to check undesired vegetation until Douglas-fir can gain a more competitive position.

Although means are available for totally controlling competing vegetation, selective use of these tools and chemicals is desirable. Some brush species and "weed" trees have or may have beneficial influences on the nutrient cycle and forest ecosystems. In a region where nitrogen fertilizers usually improve tree growth, removal of species hosting symbiotic N fixers seems conflicting. Although some of the potential gains of nitrogen to the site are eliminated when such vegetation is controlled, control is generally partial and temporary; moreover, most of the contribution by N-fixing plants tends to occur in the initial years of occupancy (Youngberg and Wollum 1975). For example, on mesic sites where topsoil had been removed by logging, dense stands of red alder fixed approximately 320 kg N/ha per year during the first 15 years of occupancy. Thereafter, rate of fixation rapidly declined and little nitrogen was added after 20 years (Newton et al. 1968). Although weeding initially accelerates return of organic matter and nutrients to the soil system, residual vegetation probably prevents off-site losses of nutrients. For example, no increase of nitrate in ground water and streamflow was determined after herbicide treatment of mixed alder/conifer stands (Miller 1974) even though high rates of N-mineralization and nitrate accumulation in the soil are characteristic of red alder ecosystems (Bollen and Lu 1968, Miller 1974).

Precommercial Thinning

Precommercial thinning is standard silvicultural practice in 3- to 10-meter-tall Douglas-fir stands. Excess trees are generally killed by felling or chemical injections. Depending on management objectives, between 750 and 1 500 stems per hectare remain as future crop trees. Plantations, as well as natural stands, commonly require stocking control to achieve more uniform stem distribution and to concentrate growth on fewer trees that can more quickly attain merchantable sizes of 15- to 20-cm d.b.h. Ideally, precommercial thinning should occur at or soon after crown closure, when the stand is making maximum nutrient demands on the site but before growth of crop trees is seriously reduced by competition.

At first glance, thinning a stand having 2 500 to 25 000 or more stems per hectare to approximately 1 000 stems seems as drastic a treatment as heavy commercial thinning or shelterwood cutting. Although large quantities of organic matter are returned to the forest floor, this material is small in dimension and generally averages higher in nutrient content than comparable material of older trees. Thus, decomposition should proceed fairly rapidly. Because precommercial thinning generally occurs when crown expansion is rapid, microclimate probably reverts to the original conditions much faster than after thinnings in older stands. Thus, changes in microclimate and understory vegetation are quantitatively less important since individual tree crowns more rapidly occupy space created by precommercial thinning.

Increases in individual tree growth after precommercial thinning can be due to reduced competition for light, moisture, and nutrients. In the Douglas-fir stands of the Pacific Northwest, an increase in available nitrogen resulting from decreased competition and increased decomposition rates should contribute to this response.

Thinning Douglas-fir does not always provide anticipated increases in growth. On low quality sites, recent observations support an early report (Staebler 1956) that precommercial thinning can temporarily reduce height growth of residual trees. A possible explanation is that thinning could cause a temporary nitrogen deficiency if large quantities of residues with high C:N ratio are added to the forest floor. Preliminary calculations suggested that slash from thinning ponderosa pine (Pinus ponderosa Laws.) is unlikely to seriously affect the C:N balance of the soil and rates of mineralization, unless the slash has direct contact with the soil (Cochran 1968). Recent data from Oregon State University's Black Rock Forest in the Oregon Coast Ranges indicate that commercial thinning of Douglas-fir may temporarily reduce N availability. Initially, assuming the forest floor of these medium site quality stands had steady decomposition rates, i.e., no net loss or gain in quantities of N, we computed residence time for N by dividing the N capital in the forest floor by the average amount of N annually added by litterfall (needles and branches) during the 17-year period. These nitrogen residence times were 18-35 percent longer in the thinned than in the unthinned stand (Table 7). However, residence times were likely increased by addition of an estimated 2 400 to 3 600 kg/ha of thinning slash 3 years prior to our sampling of the forest floor. Although this recent thinning weakens our initial assumption of steady-state rates of decomposition, reduced nitrogen turnover and available N would likely result from this thinning because input of N-rich foliage litter was reduced at the same time that the C:N ratio of the forest floor was widened by addition of much woody materials.

Forest Fertilization

Based on field trials installed during the last two decades, forest fertilization has become a practical tool for rapidly increasing growth of Douglas-fir forests. Between 1966 and 1975, more than 250 000 hectares have been fertilized in western Washington and Oregon. Application rates are typically 168 or 224 kg N/ha. Practically all fertilization of Douglas-fir has been with urea fertilizer (46-percent N). Although some ammonium nitrate has been used, it is less attractive because of its lower content of nitrogen and somewhat higher cost per kilogram of nitrogen. Since the different sources of nitrogen are subject to various transformations and fates within forest ecosystems, their comparative effectiveness may depend on specific ecological conditions (Wollum and Davey 1975). Thus, duration, time of peak, and magnitude of the response depend on the ability of the ecosystem to circulate and supply the limiting element (Curlin 1970).

5/ Personal communication with Michael Newton, Professor, Oregon State University, Corvallis, September 24, 1975.

Table 7. Residence time[1/] of N in the forest floor of thinned or fertilized young-growth Douglas-fir, Black Rock Forest[2/]

Treatment	Nitrogen in		
	Forest floor	Annual litterfall	Residence
	-kg/ha-		-Years-
Thinned plots:			
Control	188.6	18.5	10.2
Light thinning	237.4	17.2	13.8
Heavy thinning	260.2	21.7	12.0
Fertilized plots:			
Control	174.7	12.0	14.5
168 kg N	211.5	15.4	13.7
504 kg N	191.6	17.7	10.8

1/ Residence time (in years) = N capital in forest floor ÷ N in annual litterfall.

2/ A. B. Berg, D. P. Lavender, and C. C. Grier. Unpublished data on file at Forest Research Laboratory, Oregon State University, Corvallis. Litterfall averaged over 17 years for thinned plots and 11 years for fertilized plots.

The land manager applying nitrogen at a current total cost of approximately $0.75 per kg of nitrogen, or $168 per hectare for a 224 kg N/ha dosage, is keenly interested in full utilization of this applied nitrogen by his forest crops--with minimum losses to the atmosphere as gasses or to the ground water and streams by leaching. Temporary tie-up in the almost instantaneous build-up of soil microbial populations or in the subordinate vegetation is tolerable, if these amounts, or additional amounts released by a so-called biological priming action, are eventually available to his tree crop. In short, the fate of applied nitrogen within the nutrient cycle is currently of great practical and scientific interest.

Urea fertilizer.--Effective use of urea is particularly significant to fertilization programs in the Pacific Northwest. Urea **pills** or granules rapidly dissolve in water and since urea attracts water, dew or even relative humidities exceeding about 70 percent provide sufficient water for dissolution. Dissolved urea freely leaches in this non-ionized state; however, it is rapidly hydrolyzed by the enzyme urease so there is little opportunity for leaching (Cole et al. 1975). As a result of this enzymatic reaction, urea forms NH_4HCO_3 which partially dissociates into ammonium and bicarbonate ions. As the ammonium ion, nitrogen can be temporarily immobilized by soil micro-organisms, utilized by plants, held on cation exchange sites, physically fixed within clay lattice-structures, or oxidized by soil bacteria to nitrate which is readily utilized by plants or leached from the soil.

Leaching losses.--Leaching losses occur primarily when N is in the nitrate-ion form. Thus, leaching from the forest floor to and through the mineral soil may occur where ammonium or urea fertilizers are converted to nitrate by soil bacteria. Comparing numerous studies utilizing isotopically tagged N, Knowles (1975) concluded that consistently higher recoveries in the forest floor of nitrogen from urea fertilizer, rather than other N sources, were observed and this greater recovery was apparently related to the greater retention of urea-N in organic layers. Although laboratory studies show that many forest soils of the Pacific Northwest convert urea fertilizer and organic matter to nitrate ions (Heilman 1974), only small quantities of applied urea or ammonium fertilizer have been collected in leachates below the rooting zone (Cole and Gessel 1965) or in stream water (Moore 1974), presumably because NH_4+ or NO_3- (if produced) are readily taken up by soil organisms and vegetation. Thus, Moore (1974), in his investigation of approximately 20 urea-fertilized watersheds in western Washington and Oregon, concluded that less than one-half percent of the applied nitrogen appeared as a temporary increase in nitrogen levels in adjacent streams. Initial increases in N content of streams following fertilization were primarily attributed to inadvertent application of fertilizer into small streams within the fertilized area.

Additions of nitrogen fertilizer to the forest floor cause leaching of organic matter and cations from the forest floor into the mineral soil. In the interest of nutrient cycling, this is a desirable effect. Urea fertilizer at 224 kg N/ha dosage increased dissolved organic matter in leachates from the forest floor 15-fold; in contrast, ammonium nitrate did not dissolve organic matter but did cause greater and deeper cation movement.[6/] Greater dissolution of organic matter and increases in soil pH after application of urea also greatly increased conversion of ammonium to nitrate; in contrast, no increases in nitrification followed ammonium nitrate application.[7/]

Gaseous losses.--In addition to leaching losses, other losses of nitrogen can occur through gaseous exchange with the atmosphere. Denitrification or reduction of nitrate to gaseous forms of N is considered an important process of gaseous loss from the soil (Broadbent and Clark 1965); this process requires existence of nitrate and is prompted by oxygen deficiency, available organic matter for energy, and increasing temperatures.

Currently, there is a major concern with volatilization losses after application of urea in warm, dry weather. Past research provides a wide range of estimated losses after surface application of urea fertilizer. For example, field and laboratory investigations at the University of Washington indicate losses of up to approximately 10 percent of the applied dosage (Cole

6/ B. D. Webber. 1973. Nitrogen movement and urea-induced transformation in forest soils. Study PC-23-094. Project outline prepared for the tour of the IUFRO Mensuration Group, August 28, 1973, Victoria, B.C.

7/ J. A. Dangerfield. 1973. The soil microflora and biotic processes in managed forest stands. Study PC-23-134. Project outline prepared for the tour of the IUFRO Mensuration Group, August 28, 1973, Victoria, B.C.

et al. 1975). Simulated rainfall immediately following urea fertilization reduced gaseous loss of N to minimum values and also caused a deeper leaching of the nitrogen into the profile (Table 8). Watkins et al. (1972), however, reported much higher volatilization losses in laboratory studies using soil and litter from several Northwest forest species. Under simulated field conditions of warm weather, surface pH approaching neutrality, and normal airflow across the soil surface, nitrogen losses as ammonia were as much as 46 percent of a 224 kg N/ha dosage of urea. Similar percentage losses were reported after field application of urea to jack pine (*Pinus banksiana*) in which percentage loss increased as dosages increased from 112, through 224, to 448 kg N/ha (Carrier and Bernier 1971).

Table 8. Effect of irrigation rates on ammonia volatilization and the translocation of urea-N after application of 200 kg N (adapted from Cole et al. 1975)

Irrigation	Volatilization loss		Recovery of N in the profile at depth of		
			0-4 cm	4-15 cm	15+ cm
-cm-	-kg N/ha-	-Percent-	-kg N/ha-		
60	11.6	5.2	181.2	27.5	3.7
120	9.5	4.2	179.1	35.4	.9
240	1.1	.5	165.4	58.6	4.5

The actual off-site losses of applied urea may be less than those measured immediately above the forest floor. Since ammonia vaporizes as aqua-ammonia ($NH_3.nH_2O$) and is readily absorbed by plants in this form, Edwards8/ doubts that much of the vaporized ammonia would actually get through the minor vegetation and tree canopy. Edwards believes that aqua-ammonia would likely diffuse to the plants and thus be retained. However, DeBell9/ cautions that diffusion is only one means for moving gaseous nitrogen from a fertilized stand; mass flow by major air movement is another.

8/ A. P. Edwards. 1971. The recycling of nutrients from collodial complexes. (Speech) U.S. Department of Agriculture Forest Service, Olympia, Washington. [Presented at Probable urea fertilizer transformations in the forest environment seminar, Corvallis, Oregon, May 3, 1971.]

9/ Personal communication with Dean S. DeBell, former research scientist with Crown Zellerbach Corporation, Camas, Washington, on June 14, 1972. DeBell is now with Pacific Northwest Forest and Range Experiment Station.

Thus, Young10/ found practically no aqua-ammonia absorbed by foliage of a dense stand of sugar cane when aqua-ammonia fertilizer was applied to the soil. Young indicated that dilution of the ammonia is probably so great that no effective gradient in ammonia concentration would exist between the soil (the ammonia source) and the plant for appreciable aqua-ammonia uptake by the plant.

In summary, significant losses from nitrogen application in the Douglas-fir type are not likely if current operational practices which maintain untreated buffer areas along major streams and avoid application during summer months are continued. Gaseous losses of urea fertilizer are likely, but the magnitude of these losses from the forest ecosystem remains in question (Mahendrappa 1975). However, greater losses are likely from previously fertilized stands as indicated by recent laboratory studies using disturbed (Heilman 1974) and undisturbed soil samples under controlled temperature and moisture regimes.11/ If stands are refertilized with urea at 4- to 6-year intervals, higher volatilization losses and increased nitrification with perhaps greater likelihood of leaching could occur.11/

Microbial utilization and immobilization.--When nitrogen fertilizer is added to the forest floor, some N is rapidly immobilized in living and dead organic matter. This tie-up (immobilization) and its counterpart, a release of inorganic nitrogen (mineralization), occur simultaneously. Tie-up is greatest with urea, especially at low (100 kg/ha) dosage rates, moderate with ammonium NH_4-N, and very slight with ammonium nitrate (Overrein 1971). This immobilization is eventually reversible through mineralization of organic matter. Immobilization of fertilizer N is frequently accompanied by simultaneous release or displacement of native inorganic and soluble organic N. The amount of N released by this "priming effect" compared with the amount of fertilizer immobilized by soil organic matter is variable (Knowles 1975). The difference between immobilization and priming effect is "net immobilization" or "net mineralization" and is the amount of nutrient potentially available for vegetation.

Although rate of litter decomposition depends on temperature and moisture conditions, as well as the physical and chemical characteristics of the litter, addition of fertilizer can stimulate this rate if the nutrient supplied is limiting the population growth of soil micro-organisms. For example, Table 7 shows effect of ammonium nitrate application on N residence time in the forest floor of a low-site stand in the Oregon Coast Ranges. Fertilization with 168 and 504 kg N/ha evidently decreased residence time by 5 and 25 percent, respectively. This effect is likely due to input of litter with higher N content in the fertilized stands (Table 9); the narrower C:N ratio of this litter would facilitate more rapid decomposition.

An increased rate of decomposition does not always result in an immediate increase in available N and tree growth. For example, addition of lime to an

10/ Personal communication with Donald C. Young, Research Chemist, Union Oil Research Center, Brea, California, on June 14, 1972.

11/ Personal communication with Dean S. DeBell, former research scientist with Crown Zellerbach Corporation, Camas, Washington, on July 16, 1975.

Table 9. Nitrogen concentration in current needles and litter after fertilization of Douglas-fir with ammonium nitrate, Black Rock Forest[1]

Treatment and sample	Year and month of sample								
	1962			1963	1964	1966	1968	1971	1973
	Feb.	Apr.[2]	Dec.	Dec.	Jan.				
	-kg N/ha-								
0									
Foliage	1.13		1.34	1.33		1.45			
Litter (needles)			.77	.67	0.61	.61	0.53	0.50	0.59
168									
Foliage	1.19		1.54	1.50		1.42			
Litter (needles)			.77	.71	.63	.63	.57	.53	.62
336									
Foliage	1.24		1.94	1.71		1.47			
Litter (needles)			1.03	.97	.75	.70	.56	.55	.67
504									
Foliage	1.13		2.94	2.33		1.72			
Litter (needles)			1.12	1.17	.80	.82	.68	.52	.67

[1] D. P. Lavender. Unpublished data on file at Forest Research Laboratory, Oregon State University, Corvallis.

[2] Month of fertilization.

acid litter under Sitka spruce (Picea sitchensis (Bong.) Carr.) stimulated organic matter decomposition; however, this caused a temporary immobilization of the released nitrogen in micro-organisms and thus a decrease in uptake of nitrogen by the trees (Adams and Cornforth 1973). Similar short-term decreases in available nitrogen may also occur in Douglas-fir forests following low dosages of fertilizer nitrogen.[12] Steinbrenner applied nitrogen dosages of 112, 336, and 560 kg N/ha as urea in numerous stands in western

[12] Personal communication with Eugene C. Steinbrenner, Soil Scientist, Weyerhaeuser Company, Centralia, Washington, on October 10, 1975.

Washington and Oregon. In many stands, the apparent effect of the 112 kg N dosage was to reduce growth during the first 3 years after treatment below that of the unfertilized stand. This suggests that soil micro-organisms are effective competitors for available nitrogen in the soil and that a certain threshold dosage of nitrogen needs to be applied on some sites to satisfy the requirements of soil microbes. The N-residence times at our Black Rock stand (Table 7) suggest that this threshold could be close to 168 kg N/ha.

Competing vegetation.--Understory vegetation also utilizes and, at least temporarily, immobilizes fertilizer nitrogen. For example, a study with N isotopes in Sweden showed that young Scotch pine (Pinus sylvestris L.) and a heather-huckleberry community about equally shared a nitrogen fertilizer (Björkman and Lundeberg 1971). Presumably, older trees with deeper and more extensive root systems would be less susceptible to root competition.

Analysis of biomass and nutrient concentration build-up in subordinate vegetation under fertilized stands suggests that subordinate vegetation is an effective competitor for fertilizer nitrogen. Since manipulating tree canopy and thus the amount of light reaching the forest floor is an effective means for controlling vegetation, the relationship between stand density and forest fertilization regimes seems particularly significant.

Tree uptake.--Increased volume growth after fertilization is the land manager's ultimate proof of fertilizer uptake and treatment effectiveness. In the cooperative regional fertilization trials installed over a wide range of sites in western Washington and Oregon by the University of Washington, 70 percent of the 85 installations in Douglas-fir stands showed at least a 10-percent improvement in volume growth following urea fertilization (Atkinson 1974).

Prior to measurable increases in tree growth, however, improved color of needles and increases in nitrogen content are indirect evidence of fertilizer uptake and future growth improvements. Although the annual requirement of Douglas-fir stands is generally less than 100 kg N/ha, additional amounts can be taken up and stored within the plant. This "luxury consumption" is evidenced by abnormally high concentrations of nitrogen in the foliage (Table 9) and is generally desirable because the nitrogen within the tree is conserved by internal translocation from older needles before leaf fall. Despite this translocation, Douglas-fir needles from fertilized stands provided increased amounts of N-enriched litter to the forest floor (Heilman and Gessel 1963) (Table 9); increased rates of litter decomposition are therefore likely. In a direct comparison of urea and ammonium nitrate as fertilizer sources, Webber[13] found greater increases in nitrogen concentration of foliage treated with ammonium nitrate than with urea.

Fertilizing a 45-year-old Douglas-fir stand on a low-quality site with ammonium nitrate increased amounts of nitrogen cycling between the stand and soil (Table 10). Weight and N concentration of the various litter components were increased. More N was annually returned by leaf washings and throughfall, especially in plots treated with 504 kg N/ha (Table 10). Thus, fertili-

[13] B. D. Webber. 1973. Nitrogen movement and urea-induced transformation in forest soils. Study PC-23-094. Project outline prepared for the tour of the IUFRO Mensuration Group, August 28, 1973, Victoria, B.C.

Table 10. Average annual weight of litterfall and N content after fertilization at Black Rock Forest, 1962-73, kg per hectare basis

Item	N dosage			
	0	168	336	504
Dry weight				
Litterfall:				
Needles	1 667	1 990	2 276	1 982
Twigs	526	635	714	543
Branches	125	294	295	192
Total	2 318	2 919	3 285	2 717
Average N content				
Litterfall:				
Needles	9.90	11.92	15.83	14.42
Twigs	1.82	2.39	3.11	2.55
Branches	.47	1.15	1.18	.77
Total	12.19	15.46	20.12	17.74
Annual throughfall[1/]	2.14	2.09	2.91	3.49
Total aboveground N return[2/]	14.33	17.55	23.03	21.23

[1/] Based on 15 months' data.

[2/] Excluding stemflow which ordinarily contributes less than 1 percent to aboveground N return (see Table 3).

zation increased the amount of N immediately available for uptake and increased the rate of N cycling.

As a practical consequence of fertilization, average annual cubic volume growth was increased by 21 to 48 percent during the subsequent 10-year period (Table 11). This provided an additional 28.0 to 64.0 cubic meters per hectare (400 to 915 cubic feet per acre). Despite higher and more sustained levels of foliar nitrogen, there was an apparent lesser volume response with 504 kg N compared with that following the 336 N dosage. This is in part due

Table 11. Periodic annual volume growth and mortality[1/]

Treatment	Average site index	Initial stand	Net growth[2/]		Mortality[2/]	Gross growth[2/]	
-kg N/ha-		-Cu. M-	-Cu. M-	-Percent-	-Cu. M-	-Cu. M-	-Percent-
0	94	276	12.2	100	1.0	13.2	100
168	--	278	15.6	128	1.8	17.4	132
336	102	293	18.5	152	1.1	19.6	148
504	86	293	13.7	112	2.3	16.0	121

[1/] Ten-year period, all trees 1.5-inch d.b.h. and larger, total stem volume. Average of three plots per treatment, per hectare basis.

[2/] Adjusted to a common initial plot volume for all treatments.

to a lower average site quality in the plots receiving the highest N dosage. Differences in growth at the end of this 10-year period suggest that continued response is likely, especially at higher dosage levels.

CONCLUSIONS

As the forest community develops, nutrient elements are taken up, accumulated, and lost. Without disturbance or unfavorable environment, nutrients cycle in a relatively orderly fashion with nutrients returned to the soil from vegetation--and then recycled--supplying a large portion of the stand's requirements.

Decomposition of organic matter must occur before nutrients in forest residues can be recycled. Decomposition also converts residues to soil humus which is important for soil fertility and moisture relations. A rapid rate of organic matter decomposition is a desirable objective of forest soil management in the Douglas-fir forest--if vegetation is present to capture the released nutrients. Conversely, natural or man-caused situations where excessive amounts of forest litter accumulate on the surface of the soil are undesirable because both nutrients and organic matter cycles develop slower rates of turnover.

Decomposition of organic matter and mineralization of nutrients are largely biological processes. Like rates of tree growth, rates of these microbial processes are controlled by environmental conditions and available food supply. To the extent that our silvicultural practices change soil environment or quantity and quality of organic matter returned to the soil, we can shift conditions to or from optimum levels of soil microbial activity.

To improve soil fertility and growth of coastal Douglas-fir forests of the Pacific Northwest, two achievable soil management objectives are: (1) increase quantity and recycling rate of available nitrogen and (2) maintain and improve soil moisture and organic matter relations.

Silvicultural practices affect the nutrient cycle in several basic ways. First, some of the total nutrient capital of the site can be removed by timber harvest or site preparation. Second, nutrients can be added by fertilization. Third, silvicultural practices may neither add nor subtract nutrients from the site but may substantially alter the rate of a critical process such as organic matter decomposition.

Initial and subsequent effects of harvesting and site preparation on nutrient cycling and site productivity will vary with site. Detrimental effects are likely to be minimal on high quality sites characterized by deep soils with large nutrient capitals. Low quality sites have less tolerance for nutrient and organic matter losses; thus, the land manager must choose his logging and residue treatment methods more carefully for such sites.

Extensive acreages of young Douglas-fir are treated each year for stocking or species control. On some sites and stands, the consequences of either adding large quantities of thinning slash or removing competing vegetation which host N-fixing organisms need further consideration by land managers and researchers.

Silvicultural practices in established stands can change the rate of N cycling and the distribution of nutrients among vegetation, forest floor, and soil. The amount of N annually transferring between the vegetation and the soil system (forest floor and mineral soil) is a direct measure of the rate of N turnover. This annual flux consists of N in litterfall from trees and subordinate vegetation, in leaf washings and stem flow, and in root sloughing and mortality. The N flux changes when either quantity of organic matter or throughfall water or their nitrogen concentrations change. Although commercial thinning reduces the amount of tree litter, a higher nitrogen concentration in the tree litter or greater contributions from subordinate vegetation may compensate. Fertilization of forests invariably increases nitrogen content of foliage and amount of litterfall. These increases probably increase rates of organic matter decomposition and amounts of available nitrogen. Thus, through his silvicultural practices, the land manager can improve forest nutrition and growth.

Forest research should seek means to accelerate the natural rate of nutrient turnover in some stands. Through stand density control, soil temperature and moisture relations may be improved. Also, fertilizing with nutrients--which limit growth of micro-organisms and the forest crop--has promise. In the Pacific Northwest, use of nitrogen-fixing plants to replace or complement use of commercial fertilizers needs investigation. Use of red alder, an increasingly valuable tree species with rapid rates of volume growth and an effective host for nitrogen-fixing organisms, provides another way to improve nutrient cycling and forest yields.

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