Nutrient Management of Subalpine *Abies* Forests

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ABSTRACT. Subalpine conifer forests dominated by the genus *Abies* are an increasingly important commercial resource in western North America. Compared with other forest types, subalpine forests rank relatively low in apparent productivity because much of their growth is below ground. Aboveground productivity is limited by shorter growing seasons at higher elevations, weak soil development, and low rates of organic matter decomposition and nutrient release. Under these conditions, most photosynthate is used to support roots and mycorrhizae. Surveys and field experiments suggest that subalpine *Abies* forests tend to be nitrogen limited, with a possible secondary limitation of phosphorus. Management practices that remove sizable amounts of surface organic matter are likely to induce or exacerbate nitrogen and phosphorus deficiencies. Practices such as fertilization that improve nutrient availability should improve forest growth.

Subalpine *Abies* forests are important landscape components of western North America. Managing their nutrition is challenging because our experience is limited and recent, and because many of our concepts were shaped by experiences in lower, more accessible forests with milder climates and different soils. Subalpine forests are remote, and there is an impression that growth rates there are slow. Consequently, attention has centered on other forest types where investment returns are thought to be greater. However, the subalpine *Abies* forest is far more productive than is generally realized, and has an immense potential to react to sound or poor management. This chapter is meant to broaden understanding of this unique forest type and to develop a basis for more effective nutrient management to maintain or enhance productivity.

Subalpine Forest Environment

Setting

We define the subalpine *Abies* forest by the commercial range of the genus *Abies*, or "true fir," growing on soils of frigid and cryic temperature regimes (Soil Survey Staff 1975). Although this formation extends as far north as central Yukon Territory, our discussion applies principally to the montane region between latitude 36° N in the Kern Plateau of California's Sierra Nevada to latitude 55° N south of the Peace River in British Columbia (Figure 1). Included are portions of the Coast Ranges, Klamaths, Cascades, Olympics, and Northern Rocky Mountains. From south to north, the dominant species are white fir (*A. concolor*), California red fir (*A. magnifica*), noble fir (*A. procera*), Pacific silver fir (*A. amabilis*), and subalpine fir (*A. lasiocarpa*). Associated timber species mainly are lodgepole pine (*Pinus contorta*), western white pine (*P. monticola*), and, in Canada and Alaska, white spruce (*Picea glauca*). Engelmann spruce (*P. engelmannii*) and mountain hemlock (*Tsuga mertensiana*) are found at upper elevational limits. Ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*A. grandis*), and western hemlock (*T. heterophylla*) are common at lower elevations.

Climate

Throughout its range, cool to cold humid to superhumid conditions typify the subalpine *Abies* forest. Summer air temperature extremes rarely exceed 32°C in white fir stands (Laacke and Fiske 1983), and average only 13° to 14°C during July and August in subalpine fir (Henderson 1982). Total precipitation generally increases with elevation and latitude, and averages between 90 and 260 cm (Burns and Honkala 1990), but factors other than total precipitation control the distribution of *Abies* forests. Most precipitation forms a

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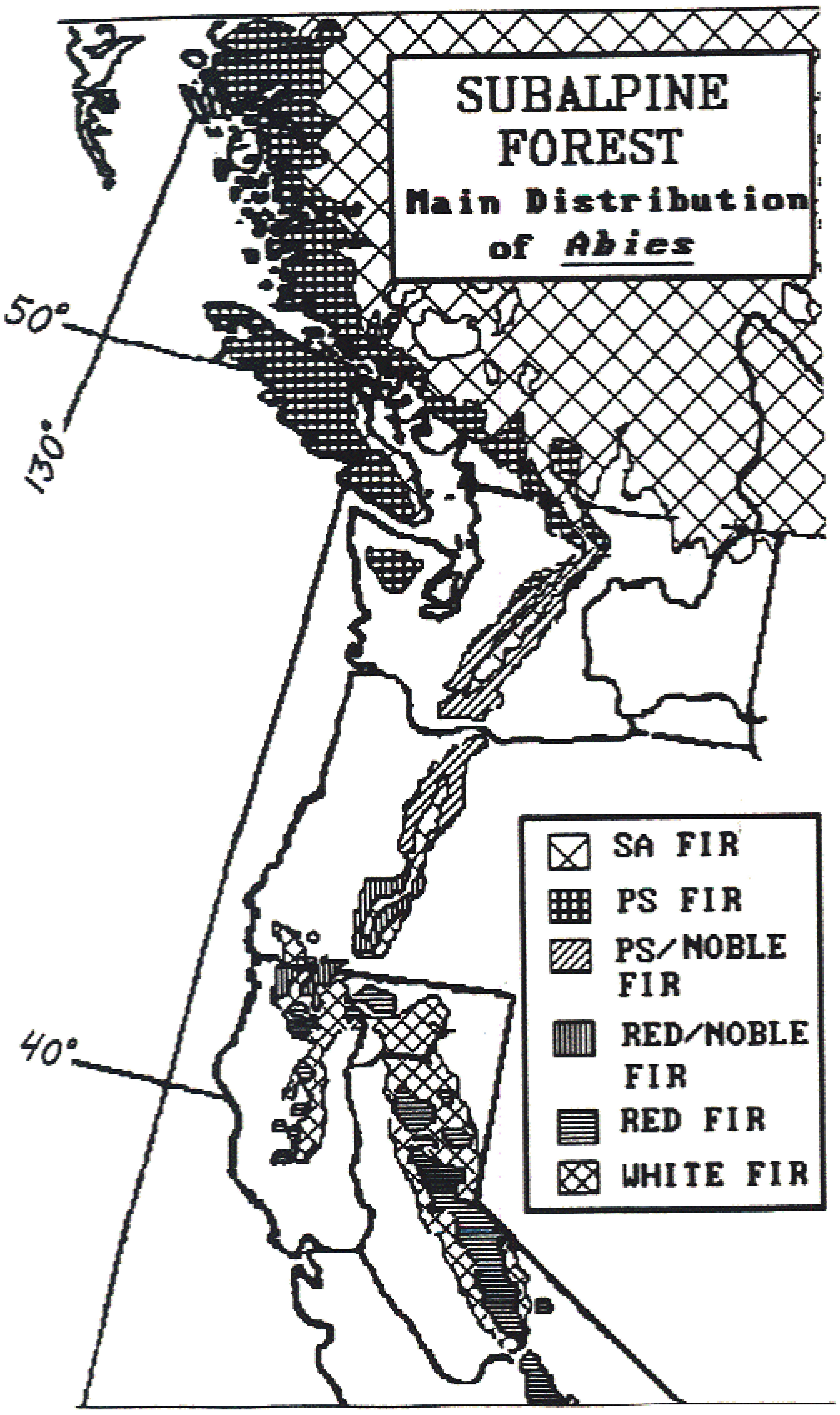

Figure 1. The commercial range of the subalpine *Abies* forest in the Pacific Northwest as delineated by species of subalpine (SA), Pacific silver (PS), noble, red, and white fir.

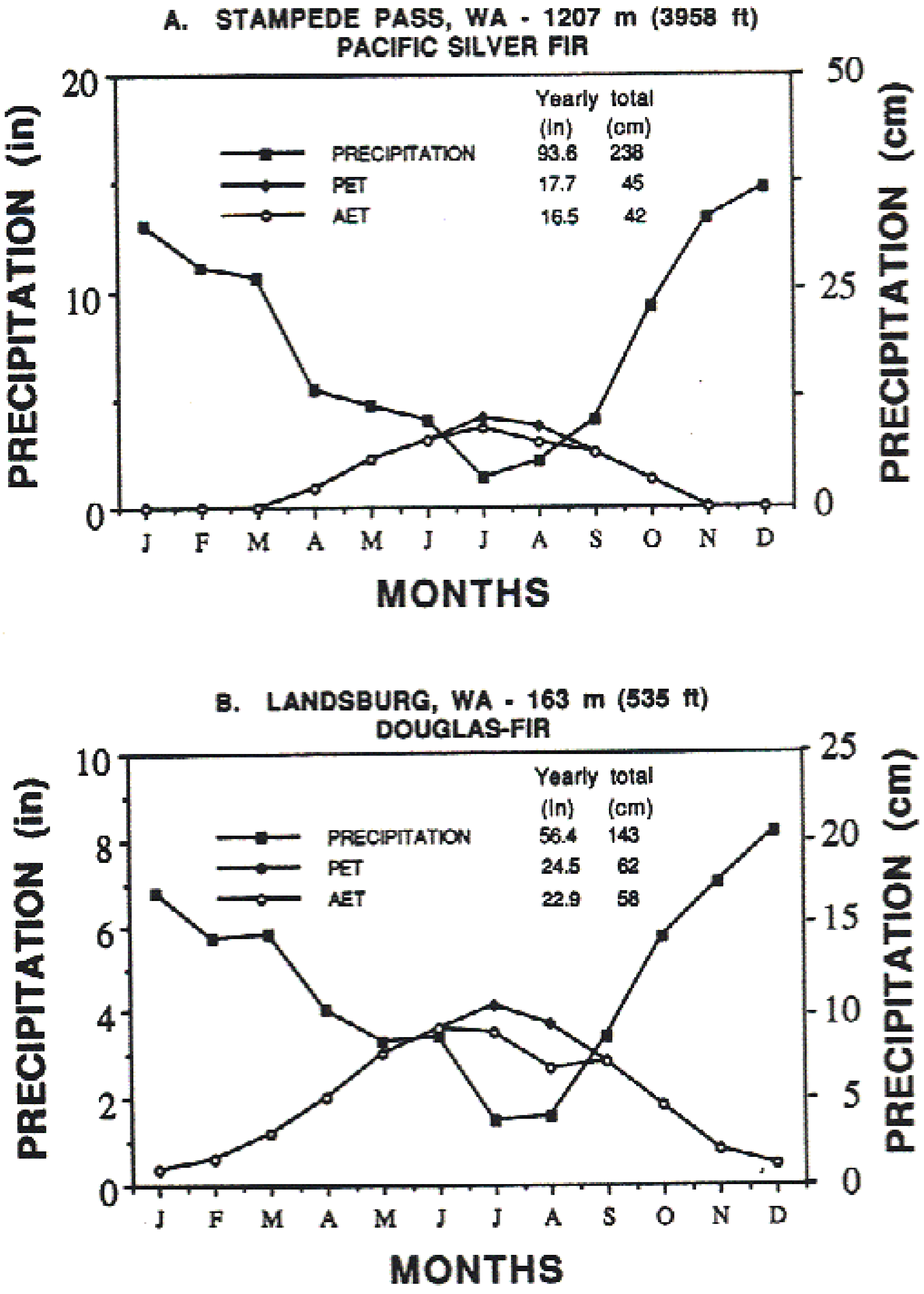

Figure 2. Average monthly precipitation, potential evapotranspiration (PET), and actual evapotranspiration (AET) at (A) a high elevation (Stampede Pass) and (B) a low elevation (Landsburg) in Washington. Yearly totals are also shown. From Cooperative Extension Service (1968).

snowpack that persists through the winter and for much of the spring. Thunderstorms can occur during the summer. Low air temperatures, persistent snow, and summer thunderstorms make for a summer dry period that is brief and late. Subalpine *Abies* forests in western Washington have higher precipitation and lower summer moisture deficits (e.g., Stampede Pass at 1,207 m, Figure 2A) than lowland Douglas-fir forests at the same latitude (e.g., Landsburg at 163 m, Figure 2B). Actual evapotranspiration also is much lower at Stampede Pass than at Landsburg. Thus, subalpine *Abies* forest growing seasons are more likely to be limited by cold temperatures than by moisture.

Topography, Geology, and Soils

Subalpine topography is sloping. Conditions vary from rugged ridge crests to gentle convexities and glacial cirque basins. Pure or nearly pure fir stands are found at elevations of 1,400 to 2,200 m in California, 300 to 2,000 m in Oregon and Washington, and 180 to 2,100 m in British Columbia. Subalpine *Abies* forests grow on parent materials that include granitics, volcanic flow rocks and ejecta, sediments, and all metamorphosed equivalents. Colluvium and glacial materials are common substrates that produce soils high in coarse fragments. Because of cold temperatures, pedogenesis is slow. Entisols and Psamments are common on granitics, while Entisols and Inceptisols dominate the volcanics. Alfisols occur at lower elevational fringes, and Spodosols are found where disturbance is rare and soils have not eroded (Ugolini 1982). Soils tend to be well drained with udic to ustic moisture regimes throughout most of the range. California, with its Mediterranean climate, is the exception. There, particularly on coarse-textured soils, moisture regimes are xeric unless an impervious subsurface layer impedes percolation. Wetter or drier soils produce stunted forests. Invariably, soil temperature regimes are frigid to cryic.

Silvics and Stand Development

Regeneration

Except for noble fir, *Abies* species are moderately to extremely shade tolerant (Baker 1949). Because of this, *Abies* can regenerate under a variety of light conditions, including the deep shade cast by its own canopy. Regeneration is best on bare ground, though seedlings will establish in light litter under protective cover. In many instances, natural regeneration will establish in small openings beneath an otherwise closed forest. Where this occurs, seedlings and saplings often have good vigor and high live crown length to total height ratios, and overstory removal can accelerate their growth (Oliver 1986). However, advance regeneration is infected readily by dwarf mistletoe (*Arceuthobium* spp.) from overstory trees. Growth losses due to dwarf mistletoe render small trees vulnerable to insects and cytospora canker (*Cytospora chrysosperma*).

Until recently, uncertainty over appropriate nursery practices, losses in seedling vigor from high respiration rates during cold storage, and accessibility problems in reaching planting sites in the spring made artificial regeneration risky. However, failures in natural regeneration from seed and seedling predators have spurred progress in nursery practices and outplant success. Increasingly, clearcut and even shelterwood sites are being regenerated artificially.

Compared with pines and Douglas-fir, *Abies* species have poor stomatal control of transpiration (Hinckley et al. 1982). Their inability to compete under droughty conditions restricts them to cool, humid sites and to higher elevations where evapotranspiration is low. For Pacific silver fir—and other subalpine species, presumably—peak root growth occurs in late winter and early spring when snow is still present and soil moisture is abundant (Grier et al. 1981).

Stand Development

Shade tolerance allows fir to survive in dense shrub communities that develop after rare but intense wildfires. Depending on shrub competition and site quality, noble fir may take 5 to 12 years to reach breast height, and subalpine fir may take 20 to 40 years (Harrington and Murray 1982). Trees overtop shrubs after 30 to 50 years and begin to dominate the site. Early growth rates also are slow because of deep snowpacks (Williams 1966) and a short growing season. Typically, snow remains for as long as nine months, and time is needed for trees to grow above the winter snowpack and resist snow bending. This period can be shortened through timely thinning (Oliver 1986) and fertilization (Powers 1981 and this volume). From sapling stage to maturity, height growth is essentially linear and extends longer in true fir than for associated conifers, allowing them to overtop trees with faster early growth rates (Herman 1967).

Height growth generally culminates later for true fir than for more mesic species (Hoyer and Herman 1989; King 1966). The crown of Pacific silver fir builds slowly, but needles are retained for as much as 21 years (Vogt et al. 1989), producing high foliage biomass and large live crown ratios. By breast-height age 50 years, dominant and codominant white fir were 24 m tall on average sites and 40 m tall on the best sites (Dolph 1987). By breast-height age 50, noble fir is 20 m tall on average sites and 28 m tall on the best sites (Herman et al. 1978). Height growth is sustained to advanced ages. The best California red fir sites produced trees averaging 15 m tall at total age 50, 44 m at 100, and 65 m at 175 (Schumacher 1928). More recently, Dolph (1991) reported mean dominant tree heights of 18 m at breast-height age 50 years on average sites, and 34 m on the best. On favorable sites, height growth may continue for 400 years (Harrington and Murray 1982). Depending on age and the nature of its establishment, *Abies* stands may consist of single or multiple age classes and structures. Because of the shade tolerance of most species of *Abies*, mature stands represent climax to near-climax stages of succession.

Growth and Yield

Stands in larger openings achieve high stocking densities. The high live crowns maintained by shade-tolerant *Abies* forests permit them to respond quickly to thinning, unlike less shade-tolerant species that sometimes show thinning shock when thinned from very high densities. Removing up to half the basal area in a 100-year-old stand of California red and white fir had little effect on 10-year volume production (Oliver 1988).

To date, the only yield tables for subalpine conifers of the Pacific Coast are those for California red fir (Schumacher 1928) and white fir (Schumacher 1926). Shade tolerance, sustained growth rates, and low levels of physiological drought allow extremely high levels of

Table 1—Percentage of net primary production (NPP) above and below ground in two Pacific silver fir stands at Findley Lake, Washington. From Vogt et al. (1982).

Forest Component	Stand Age 23 yr	Stand Age 180 yr
Below ground		
Fine roots	43.5	53.6
Mycorrhizae	13.9	15.0
Coarse roots	15.2	13.1
Total below ground	72.6	81.7
Total above ground	27.4	8.3
Forest total	100.0	100.0

basal area and volumes in natural stands. By 100 years, white fir attains basal areas of 91 m²/ha and standing volumes of 805 m³/ha on average sites (Schumacher 1926). For California red fir at 100 years, basal areas average 92 m²/ha and volumes average 738 m³/ha (Schumacher 1928). On the best sites, white fir maintains basal areas as high as 108 m²/ha, and red fir as high as 134 m²/ha. Volumes as great as 2,100 m³/ha have been reported for 110-year-old noble fir (Franklin 1990) and 2,300 m³/ha for 160-year-old California red fir (Schumacher 1928). Annosus root disease (*Heterobasidion annosum*) is present in most natural stands and is the principal cause of windthrow and breakage (Laacke and Fiske 1983).

Primary Productivity and Carbon Allocation

Estimates of aboveground net primary production (NPP) for subalpine forests from 23 to 180 years of age range from 4.5 to 16.6 Mg/ha per year, a range only slightly narrower than for similarly aged Douglas-fir stands (5.7 to 17.8 Mg/ha/yr) (Grier and Lee 1982; Grier et al. 1989; Long 1982). Stands dominated by noble fir may be more productive than Pacific silver fir (Grier and Lee 1982). The NPP reported by Fujimori et al. (1976) for a noble fir stand in Oregon (16.6 Mg/ha/yr) is greater than that reported for many lowland stands of Douglas-fir. We conclude that subalpine *Abies* forests have considerable potential for growth.

Aboveground NPP tells only part of the story. In a 23-year-old Pacific silver fir stand near Findley Lake, Washington, 73% of total NPP was below ground, and an even greater proportion—82%—was found for a 180-year-old stand nearby (Vogt et al. 1982) (Table 1). Most belowground NPP was allocated to fine roots (44 to 54%) and their mycorrhizae (14 to 15%) (Table 1). The proportion of carbon sent to fine roots was greater in the older stand. Keyes and Grier (1981) theorized that on less fertile sites, trees invest a greater proportion of NPP below ground. If this theory is correct, perhaps this balance could be shifted in the subalpine *Abies* forest through effective nutrient management.

Nutritional Ecology

Nutrient Distribution

In general, the colder the ecosystem, the greater the proportion of organic matter sequestered below ground (Powers and Van Cleve 1991) (Table 2). An important feature of true fir ecosystems is the high proportion of organic matter in the soil and surface detritus. At Findley Lake, approximately one-third of the ecosystem organic matter is in the aboveground biomass, and the rest is in the detritus, roots, and soil (Vogt et al. 1982) (Table 3). The proportions in coarse woody debris, forest floor, mycorrhizae, and the surface soil are greater than in many lowland forest types (Johnson et al. 1982). Nitrogen concentrates below ground, with 40% of the ecosystem nitrogen in the forest floor and 47% in the soil (Table 4). About four times more nitrogen is in the forest floor than in the aboveground standing forest. Phosphorus shows a similar pattern to nitrogen, but a much

Table 2—Characteristics of organic carbon in some major forest biomes of the earth. From Powers and Van Cleve (1991).

Forest Biome	Above Ground (Mg/ha) Veg.	FF	Tot.	Below Ground (Mg/ha) Veg.	Soil	Tot.	Ecosystem Total (Mg/ha)	% Below Ground	% Below Ground + FF
Taiga	98	46	144	46	157	203	347	58	72
Semiboreal[1]	76	29	105	24	159	183	288	63	74
Cool temperate	148	22	170	32	132	164	334	49	56
Warm temperate	84	10	94	20	96	116	210	55	60
Semiarid temperate	55	12	67	7	86	93	160	58	66
Subtropical	120	6	126	16	101	117	243	48	51
Tropical	157	4	161	15	107	122	283	43	44

[1] Conditions in the subalpine *Abies* forest are equivalent to those in the semiboreal forest biome.

Table 3—Distribution of living organic matter in a 180-year-old Pacific silver fir stand, Findley Lake, Washington. From Vogt et al. (1982).

Ecosystem Component	Organic Matter (kg/ha)	(%)
Trees		
Foliage	21,650	1.7
Wood	423,880	33.8
Understory	1,870	0.2
Roots		
Coarse	127,820	10.2
Fine	12,110	1.0
Mycorrhizae	4,150	0.3
Detritus		
Forest floor	149,500	11.9
Standing dead	164,900	13.1
Logs	75,000	6.0
Soil organic matter (0-60 cm)	273,000	21.8
Total	1,253,880	100.0

Table 4—Nutrient content in ecosystem components in a 185-year-old Pacific silver fir ecosystem, Findley Lake, Washington. From Vogt et al. (1989).

	Nitrogen		Phosphorus	
Ecosystem Component	(kg/ha)	(%)	(kg/ha)	(%)
Foliage and branches	177	3.6	64	2.0
Stem wood and bark	285	5.7	37	1.2
Understory	TR	TR	TR	TR
Roots	228	4.6	61	1.9
Forest floor	1,971	39.6	83	2.6
Soil (0-30 cm)	2,320	46.6	2,894	92.2
Ecosystem total	4,981	100.0	3,139	100.0

TR = trace.

Table 5—Nitrogen transfers in various Pacific silver fir stands in Oregon, Washington, and British Columbia. From Turner and Singer (1976); Crawford et al. (1982); Krumlik et al. (1982).

Source of Flux	Nitrogen Transfers (kg/ha/yr)
Inputs	
Precipitation and dryfall	1.3
N fixation (no data)	–
Return to forest floor	9.5-35.5
Fine root turnover	60-110
Loss from rooting zone	2.7

higher proportion—92%—is in the soil and only 3% is in the forest floor (Table 4). Only 5% of ecosystem phosphorus is in the living biomass, compared with 15% of ecosystem nitrogen.

Table 5 shows annual nitrogen transfers in Pacific silver fir stands. Precipitation inputs are low (1.3 kg N/ha/yr). Reports of N fixation rates are lacking, but we expect them to be low. Nonsymbiotic N fixation probably is less than symbiotic fixation. Sitka alder (*Alnus sinuata*), the common alder at high elevations, fixes less nitrogen than red alder (*A. rubra*) common to low elevations, although it may comprise an important proportion of total nitrogen input (Bardo 1980).

Fine root turnover rates of nitrogen are very high but nitrogen losses from the rooting zone are small without disturbance. Nitrate leaching losses are expected to be higher following disturbance, although no nitrification was observed in trenched plots in a Pacific silver fir stand in Washington (Vitousek et al. 1982), and net nitrification occurs only sparingly in subalpine *Abies* forests of California (Powers 1990).

Organic Matter Decomposition

The principal source of nitrogen, sulfur, and to some degree phosphorus available for plant uptake is through the decomposition and mineralization of forest organic residues. Edmonds (1984) found that 60% of the original lignin content of Pacific silver fir needles remained after six years of decomposition, compared with only 22% of the original cellulose. Weight losses were greatest in the first six months, about two-thirds had disappeared by six years, and the mean residence time was estimated at about nine years. Other things being equal, rates of decomposition and mineralization follow a Q_{10} pathway of approximately "2," meaning that rates double for every 10°C rise in soil temperature (Powers 1980). Rates of decomposition are not static across the life of a stand, but tend to peak around crown closure, which coincides with optimal conditions of temperature and moisture during the summer (Edmonds 1979).

Compared with other forest types, subalpine *Abies* forests have low decomposition rates. Edmonds (1980) found that 55% of Pacific silver fir needle mass remained after two years of decomposition at 1,150 m elevation, while only 42 to 47% of Douglas-fir, western hemlock, and red alder litter remained at a site over 900 m lower and several degrees warmer. Lower decomposition rates probably are due to the overriding control of temperature, rather than inherent species differences. In a California study, white fir litter was no more resistant to decomposition than that of most other conifers growing nearby (Stohlgren 1988).

Low decomposition and mineralization rates in the subalpine *Abies* forest should translate to low nutrient concentrations in tree foliage if a true stress exists.

Table 6—Nutrient concentrations in current-year needles of dominant true fir.

Fir Species	Nitrogen (%)		Phosphorus (%)		No. Sites	Reference
	Mean	Range	Mean	Range		
Pacific silver	0.93	0.70-1.06	0.12	0.09-0.14	19	Radwan et al. (1989)
Red and white	1.10	0.72-1.39	0.14	0.11-0.18	16	Miles and Powers (1988)

General surveys of foliar chemistry in forests of Pacific silver fir (Radwan et al. 1989) and California red and white fir forests (Miles and Powers 1988) indicate that concentrations of nitrogen and phosphorus are low compared with conifer forests at lower elevations (Table 6). Mean foliar concentrations are less than the critical levels of 1.15% N and 0.15% P suggested as thresholds for deficiency for true fir (Powers 1983). On the average, mineralizable soil N tests lower in the true fir zone than in any other forest type in California (Miles and Powers 1988).

Organic Matter Quality

Organic matter quality also has a bearing on nutrient release, and a useful index of quality is the ratio of elemental carbon to other nutrients in the material. Threshold values for immobilization and release vary by the type of substrate, probably reflecting differences in organic chemistry and in types of decomposing organisms. Edmonds (1987) found that nitrogen is not released until C:N ratios have fallen below 30 for needles, 100 for twigs and cones, and 300 for branches and logs. He suggested critical C:P ratios for silver fir and mountain hemlock cones of about 6,000, and 1,672 for needles. Ratios of C:N and C:P are slightly higher in fresh litter of subalpine compared with lowland species, but slow litter decomposition rates in subalpine *Abies* forests probably reflect the overriding control of temperature on microbial activity rather than substrate chemistry. Low rates of microbial activity mean that high carbon-to-nutrient ratios are maintained and nutrients are immobilized for long periods. In true fir forests, nitrogen may be immobilized for at least four years after litterfall (Edmonds 1984).

Available Moisture

If temperature was the only factor controlling nutrient release in the subalpine *Abies* forest, net mineralization would be mostly a summer event. This is not necessarily so. Powers (1990), studying patterns of nitrogen mineralization and immobilization in three forest types, found that most mineralization in a red fir forest occurred during the wet season (Table 7). He concluded that most net mineralization occurs under snow or as the snowpack recedes in the spring. In both wet and dry seasons, the forest floor was the principal source of mineral nitrogen, with net immobilization in the surface soil during summer. Larsen et al. (1981) found that the psychrophilic ("cold loving") filamentous fungus *Athelia epiphylla* works beneath snow to remove high proportions of potassium, magnesium, and phosphorus from subalpine fir residues by the time of snowmelt. This finding suggests that psychrophilic microorganisms can work efficiently as long as moisture is adequate. Presumably, protein released during the decomposition of fungal mycelia would shorten the time for net mineralization.

Table 7—Nitrogen mineralization characteristics of the forest floor (FF) and top 15 cm of mineral soil (MS) along an altitudinal transect of three forest types in California. From Powers (1990).

Site Characteristic	Forest Type (elevation)					
	Oak woodland (400 m)		Mixed conifer (1,600 m)		Red fir (2,400 m)	
	FF	MS	FF	MS	FF	MS
Mean temperature (°C)						
Wet season	11.4	11.7	5.1	5.2	3.3	2.1
Dry season	18.1	19.0	10.3	10.3	10.4	11.0
Net mineralization (kg/ha)						
Wet season	16.5	9.6	9.5	17.0	11.4	3.6
Dry season	10.0	11.6	8.6	23.4	7.3	-2.4
Component annual	26.5	21.2	18.1	40.4	18.7	1.2
Forest type annual	47.7		58.5		19.9	

Soil Warming

Certain psychrophilic microorganisms important in converting organic N to mineral N may not respond much to warming soil temperatures. Powers (1980) collected surface soil from five forest types covering thermic to cryic soil temperature regimes. Samples from each type were transplanted reciprocally to all types and incubated anaerobically in the field for six months. Specific rates of nitrogen mineralization (the proportion of total organic N mineralized) increased with soil temperature for all soils except those taken originally from frigid and cryic soil temperature regimes. Those from thermic and mesic regimes responded with Q_{10}'s of essentially "2." However, samples taken from cooler sites showed little response to temperature. Probably, psychrophilic microorganisms from frigid and cryic soils are adapted for efficient activity at cold temperatures, but they may be too narrowly adapted to respond much to warming soil conditions (Powers 1980). This suggests that nitrogen mineralization and nitrification rates following timber harvest or climatic warming will be less in subalpine *Abies* forests than in forests at lower elevations.

Acidity

Subalpine *Abies* forest soils are relatively acid and often are low in exchangeable calcium (Stangenberger 1979). Acidity favors the release of iron and aluminum from silicates. Under normal conditions, soluble organic acids formed from the dissolution of organic matter chelate these metal cations and transport them downward beyond the zone of feeder roots. Thus, Al^{3+} uptake remains low enough to preclude plant toxicity. Pacific silver fir avoids high levels of aluminum accumulation that seem common to mountain hemlock, and fine root senescence may prevent high levels of aluminum accumulation in mature stands (Vogt et al. 1987, 1989).

An exception exists where sites have little ground cover and have been subjected to long periods of leaching. Such sites in California are known collectively as "red fir barrens," and one such site is on granodiorite near a contact with serpentine. There, the soil is acid (pH 4.3) and severely leached (base saturation, 1%). Stunted seedlings of California red fir growing on the site have only one-third the concentrations of foliar calcium as healthy seedlings growing in a recent clearcut nearby and over five times the foliar concentrations of iron (Powers 1976). Zinke found that aluminum concentrations were extraordinarily high in stunted seedlings. They varied from a low of 598 ppm in juvenile foliage to 1,668 ppm in five-year-old needles. Such concentrations are more than twice the highest found rangewide for either Douglas-fir or ponderosa pine, and are among the highest ever reported for red fir. (Information on this California study is from personal correspondence with P.J. Zinke; preliminary data on file in the Department of Forestry and Resource Management, University of California, Berkeley.)

Management Effects on Nutrition and Productivity

Subalpine *Abies* forests generally are not limited by moisture because most are in regions of high precipitation and low evapotranspiration. Instead, productivity is limited through short, cool growing seasons and the general scarcity of mineral nutrients. Frost and winter desiccation also may be important. Climatic variability also determines yearly productivity rates in subalpine *Abies* forests. Warmer temperatures extend the growing season and increase growth, and projected changes in global climate have interesting implications for the subalpine forest zone. Although there is little we can do to modify the climatic factors constraining productivity of subalpine forests, we can modify site nutrition through such management activities as harvesting, residue treatment, and fertilization.

Harvesting

Only recently has the remote subalpine *Abies* forest come under management in the United States. While all silvicultural systems are possible, even-aged systems are preferred, and concerns over windthrow and disease in residual trees make clearcutting the prevalent practice. Utilization standards and rotation length affect rates of biomass and nutrient removal. Boles contain most of the biomass, but only 40 to 60% of the nitrogen and 50 to 70% of the standing calcium (Kimmins et al. 1985). This means that whole-tree harvesting only increases organic matter removal incrementally, but doubles the drain of many nutrients. As a general rule of thumb, a 1% increase in biomass removal spells a 3% increase in nutrient removal (Switzer et al. 1981). Shortened rotations deplete nutrients more rapidly than long rotations because forests are harvested during more rapid stages of biomass and nutrient accumulation, and less time is allowed for nutrient replenishment. Switzer et al. (1981), comparing models of three short rotations versus one long rotation for the same period, estimated that the former would remove three-quarters

Table 8—Nitrogen capital remaining after harvest in Douglas-fir and subalpine ecosystems in the Pacific Northwest. From Edmonds et al. (1989); Kimmins et al. (1985).

Tree Species	Age (yr)	Total Ecosystem N (kg/ha)	Percentage of Ecosystem N Left after Removing: Boles only	Whole tree	All veg.	All veg. + CWD/FF[1]
Douglas-fir	22	3,281	95.6	93.1	91.7	85.6
Douglas-fir	73	3,751	95.4	90.7	90.2	74.9
Douglas-fir	130	8,775	97.9	95.6	95.5	n.a.[2]
Douglas-fir	450	5,725	93.9	90.1	89.9	78.2
Lodgepole pine	125	2,625	98.3	94.1	94.1	87.1
Pacific silver fir (PSF)	23	2,868	99.0	94.1	93.1	73.3
Noble fir	130	15,500	97.5	96.0	96.0	n.a.
PSF/mountain hemlock (MH)	130	6,529	97.2	94.0	93.7	n.a.
PSF/MH/western hemlock	170	4,895	96.9	93.1	92.8	67.3

[1] All aboveground vegetation, coarse woody debris (CWD), and forest floor (FF).

[2] Data not available.

more organic matter, over twice as much nitrogen, but only slightly more calcium.

Clearcutting mature North American forests removes 100 to 470 Mg/ha organic matter, 100 to 450 kg N/ha, and 100 to 1,050 kg Ca/ha (Johnson 1983; Kimmins et al. 1985). While nitrogen losses may seem massive, simple balances show that even the most intensive harvests usually remove less than 10% of total ecosystem nitrogen (Edmonds et al. 1989) (Table 8). Subalpine forests seem no different in this respect. We doubt that direct losses of nutrients in harvested products have an appreciable impact on the nutrition of subalpine *Abies* forests over conventional rotation lengths of 100 years or more.

Site Preparation

Logging residues are appreciable, and site preparation involving some type of residue control and surface soil scarification is needed to secure adequate stocking. Methods depend on topography, with tractor piling and burning of residues common on gentler slopes and broadcast burning practiced on steeper slopes (Laacke and Fiske 1983). In the subalpine forest, the proportions of ecosystem nutrients contained in surface residues are much greater than in warmer ecosystems (Powers and Van Cleve 1991) (Table 9). Commonly, the mass of nitrogen in the forest floor is two to four times that in the standing forest, and removing all organic residues in harvesting may deplete as much as one-quarter of ecosystem nitrogen (Table 8).

According to Vogt et al. (1989), practices that destroy the forest floor may decrease long-term productivity because trees would compensate for nitrogen losses by investing a higher proportion of their total photosynthate into fine roots and mycorrhizae. The phosphorus content in the forest floor is about double the amount in the standing forest, but the total of both accounts for a relatively small fraction of ecosystem phosphorus (Table 9), and organic losses generally are thought to be balanced by mineral weathering. Yet the significance of organic P to plant nutrition may be disproportionally great (Kadeba and Boyle 1978)—particularly if forest

Table 9—Typical ranges in total N and P contents (kg/ha) for true fir, pine, and Douglas-fir ecosystems in North America. From Powers and Van Cleve (1991).

Ecosystem Component	True Fir N	True Fir P	Pine N	Pine P	Douglas-fir N	Douglas-fir P
Trees						
Above ground	80 - 686	12 - 83	180 - 556	12 - 31	84 - 728	18 - 112
Below ground	24 - 72	4 - 12	12 - 117	2 - 21	30 - 90	5 - 18
Understory	2 - 50	TR - 14	1 - 54	TR - 5	5 - 66	1 - 9
Forest floor	666 - 2,300	55 - 217	80 - 1,240	9 - 103	110 - 1,249	19 - 115
Soil to 1 m	5,237 - 14,000	3,212 - 6,317	1,753 - 5,554	146 - 4,457	1,770 - 15,400	3,878 - 3,900

TR = trace.

Table 10—Conditions (mean ± standard error) in and adjacent to a California red fir clearcut at Swain Mountain Experimental Forest ten years after slash burning.

Characteristic	Clearcut		Adjacent Undisturbed Forest
	Burned	Unburned	
Mineralizable N (ppm)	18.1 ± 2.2	26.8 ± 5.4	28.4 ± 3.1
Total foliar N (%)	1.40 ± 0.03	1.80 ± 0.13	-
Soluble foliar N (%)	0.16 ± 0.01	0.22 ± 0.02	-
Annual height growth (cm)	23.0 ± 11.9	38.1 ± 9.4	-

canopies have closed and readily available mineral fractions have been depleted by uptake (Polglase 1989).

Burning. Forest floor consumption from slash burning in subboreal British Columbia clearcuts led to a 14% reduction in nitrogen reserves to a soil depth of 30 cm (Macadam 1987). Burning also triggered substantial increases in pH and extractable P and cations through the first nine months. At least in the short run, nitrogen losses may be outweighed by improved soil microclimate and the availability of other nutrients. In their investigation of long-term slash burning effects in both coastal and interior British Columbia, Curran and Ballard (1990) concluded that burning may improve growth on very cold sites even though nutrients are lost.

At Swain Mountain Experimental Forest in the southern Cascades, a particularly severe burn reduced all logging slash to charred logs and bare mineral soil following clearcutting in a dense stand of old-growth California red fir. Despite subsequent planting of fir and abundant natural seedfall, regeneration was sparse and consisted mainly of lodgepole pine. Ten years after burning, tree growth and foliage from burned and unburned parts of the clearcut were analyzed, as were soil samples from both areas and from the adjacent undisturbed forest. Results (Table 10) show that severely burned portions of the clearcut were marked by lower nitrogen availability and poorer tree growth.

Mechanical Piling. Although mechanical piling may increase tree survival by controlling vegetative competition and raising soil temperature, subsequent growth may be reduced because of surface soil loss and exposure of a less fertile subsoil (Figure 3). However, research findings for subalpine *Abies* forest species are scarce. Nakamura (1985) compared soil and seedling conditions in a young white fir plantation in northern California. Site preparation consisted of tractor piling vegetation and 5 cm or less of ashy topsoil into windrows, then flattening and respreading the windrows laterally to produce a level surface. Four years later, measurements were taken relative to the location of the respread windrows. Table 11 shows poorer soil organic matter, nitrogen availability, and height growth in the scalped area.

The oldest plantations on mechanically piled fir sites are stocked with ponderosa and Jeffrey (*P. jeffreyi*) pine because of historical problems in planting fir species. Thus the oldest records we have of mechanical piling in subalpine sites are for pine. Volume accumulation in ponderosa pine planted on a lithic Xerumbrept in the southern Cascades shows the effect (Figure 4). There, as on many plantations, windrows were separated by scalped areas measuring about 30 m wide. Transects across windrows and scalped areas show that trees bordering the windrows contain twice the volume after 26 years as trees planted outward into the scalped areas. Regardless of forest type, machine piling that displaces sizable amounts of surface soil leads inevitably to site quality decline (Powers et al. 1990).

Fertilization

Although Powers (1981) and Gessel and Klock (1982) concluded that nitrogen availability should be low in subalpine *Abies* forests because cold temperatures retard mineralization of organic matter, such forests seldom are fertilized because of a belief that economic returns will be low. Powers (1981) reported that nitrogen deficiencies are fairly common in fir forests of California, and that growth gains of 50% or more are possible for three to five years after one application of urea. Weetman

Table 11—Soil and tree conditions four years after planting white fir on an Andic Xerumbrept. Originally, the site had been windrowed and soil had been respread into bands before planting. From Nakamura (1985).

Sampling Position	Surface Soil		Current-year Foliage			Seedling Height (cm)
	Org. C (%)	Min. N (%)	N (%)	P (%)	SO_4-S (ppm)	
Between windrows	1.30	11.6	1.4	0.07	137	46
Within windrows	3.93	37.5	1.5	0.09	107	74

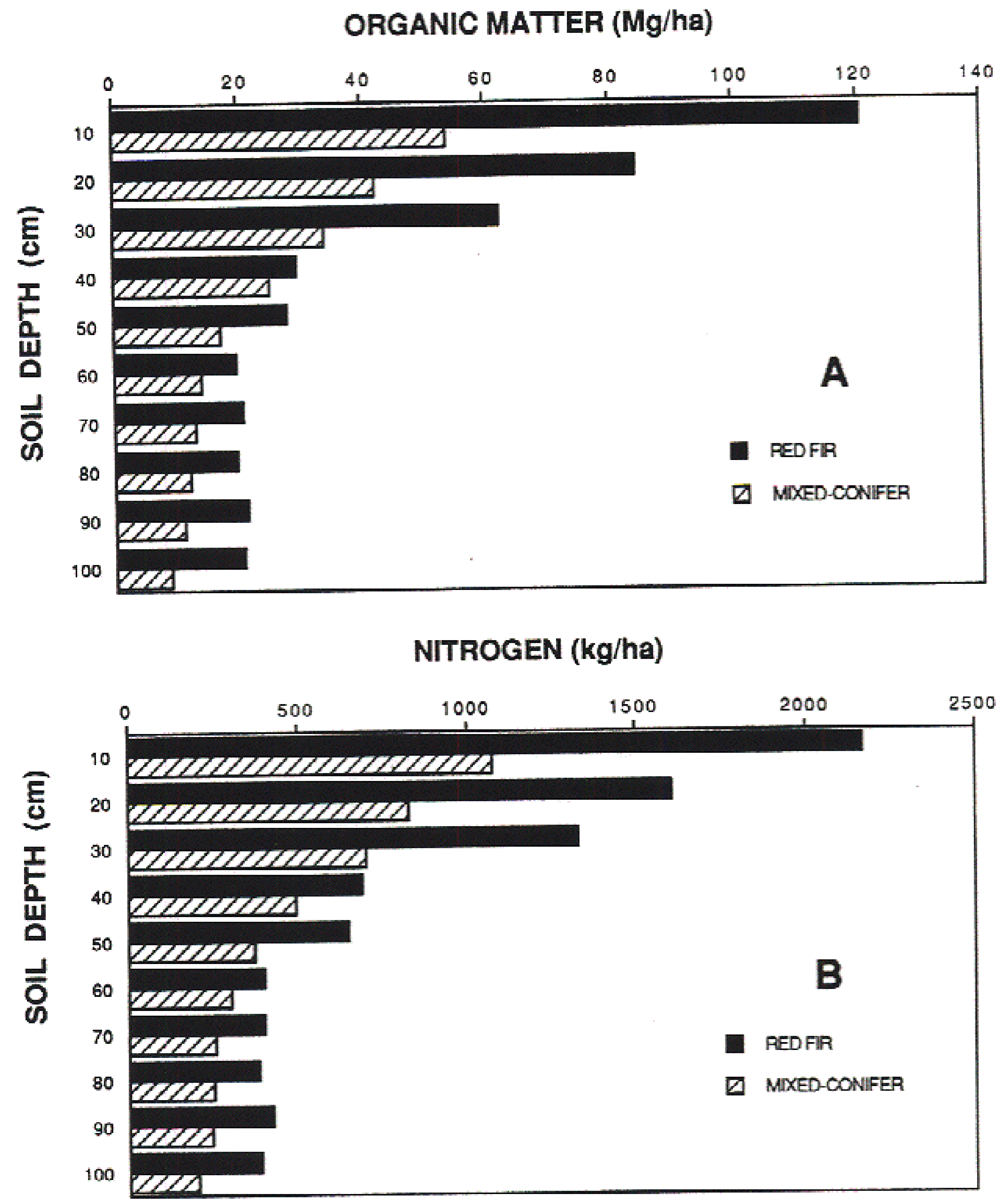

Figure 3. Total organic matter (A) and nitrogen (B) content of mineral soil by 10 cm depth classes for typical soils of the California red fir and mixed-conifer forest types. Each type is the average of several profiles. From unpublished data, P.J. Zinke and A.G. Stangenberger, University of California, Berkeley.

et al. (1988), working with lodgepole pine in interior British Columbia, found that about half the stands responded well to nitrogen fertilization, particularly if phosphorus was included as well. Gessel and Klock (1982) cautioned that fertilization response might be low in subalpine *Abies* stands, compared with Douglas-fir. But Powers (this volume) found average volume response to nitrogen in *Abies* stands of saplings and poles to vary between 8 and 22 m^3/ha for five years—responses equivalent to those of Douglas-fir and ponderosa pine. Chappell and Bennett (1988) also found good response to nitrogen fertilization in true fir stands of Oregon and Washington.

Summary and Conclusions

Subalpine *Abies* forests are unusual. Growth rates seem low, partly because a large fraction of net primary productivity occurs below ground. Trees of the subalpine zone do not suffer prolonged moisture deficits common to lower, warmer sites where evapotranspirative stress is greater. Organic matter accumulates in the subalpine *Abies* forest, and much is sequestered below ground or as detritus on the soil surface, where it comprises a nutrient reservoir. Soils often are stony and shallow, or deeper but highly leached. Rates of nutrient input in precipitation, mineralization, and weathering are low compared with other commercial forest types in warmer regions or near industrial centers.

The principal factor dominating all subalpine site processes is temperature. Cold temperatures produce short growing seasons, slow decomposition rates, and low nutrient mobility. Because of cold temperatures, nutrients accumulate in the forest floor and in coarse woody debris. We conclude that this organic accumulation is significant to the nutrition of the subalpine

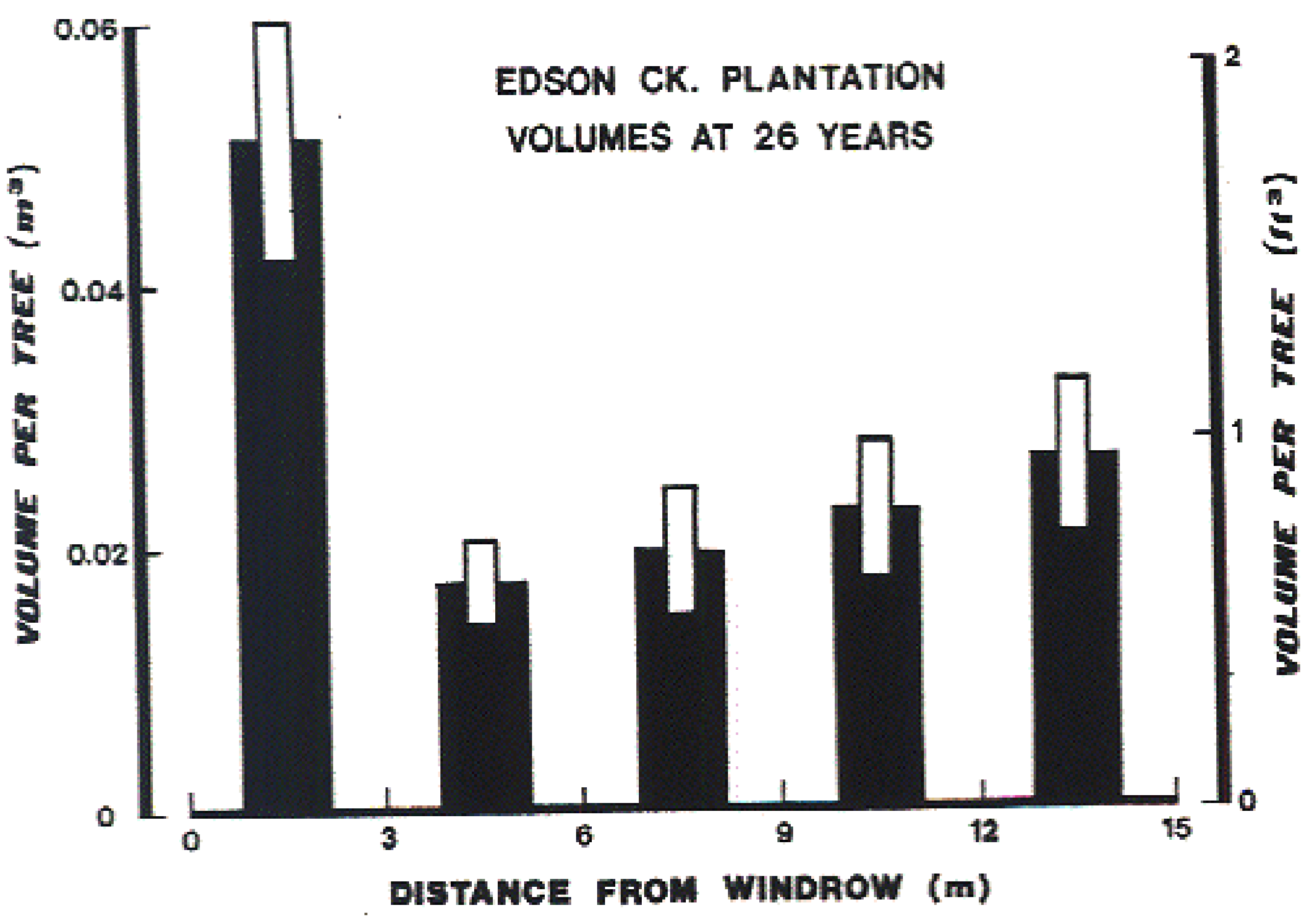

Figure 4. Average tree volume for 26-year-old ponderosa pine planted on a mechanically piled white fir site in the southern Cascades relative to distance from the edge of a windrow. Means and standard error bars are for about 13 trees in each distance class. From unpublished data, R.F. Powers; Pacific Southwest Research Station, Redding, California.

Abies forest. First, the nitrogen and phosphorus content of surface organic matter may be several times that of the standing forest—a characteristic that is unusual in the commercial forest. Second, large accumulations of carbon provide a major reserve of energy to fuel belowground microbial processes that affect sustained productivity. Soluble products of surface decomposition may be important in chelating potentially toxic metals and decreasing their availability for absorption by roots. Accumulations of organic matter also insulate the soil, creating cooler temperatures that reduce microbial activity in the mineral soil, slow decomposition and mineralization rates, and confine feeder root and mycorrhizal activity to organic horizons at or near the surface.

We suggest that practices causing large losses of surface organic matter from the subalpine *Abies* forest will trigger declines in long-term productivity. Short-term gains through a general soil warming will not balance long-term declines through nutrient loss. To a certain extent, declines may be countered with appropriate fertilizers, which may increase the proportion of NPP occurring above ground. The best prescription is to prevent such a condition from occurring through sound organic matter management. We recommend that more research be directed toward understanding how changes in physical and chemical properties of the subalpine *Abies* forest affect the more fundamental site processes controlling forest productivity. Particularly relevant topics include how changes in soil temperature, moisture, and organic matter quality affect above- and belowground photosynthate allocation, decomposition and mineralization of organic residues, soil respiration, metal chelation, and microbial response to environmental change.

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Questions and Answers

You mentioned that subalpine* Abies *soils in California contained about 8,000 kg N/ha in their profiles [Figure 3]. This would be about twice the average for mixed-conifer soils found at lower elevations. What is the source of such large amounts of nitrogen?

The primary source, of course, is the same as for any other forest type—atmospheric N added through precipitation and biological fixation. Many subalpine *Abies* forests originated following a wildfire. Nitrogen-fixing species such as *Ceanothus* quickly established dense shrub cover, and gradually added nitrogen to the soil. However, this doesn't really explain the differences because many lower-elevation stands began that way, too. More organic N accumulates in the soil component of subalpine ecosystems because of substantive differences in what controls the cycling process. Undoubtedly, there is as much nitrogen in circulation in forests at lower elevations, but it just doesn't linger as long in the soil as it does in the subalpine zone. At least two reasons account for this. First, more than half of subalpine forest NPP is directed below ground. Senescing roots and mycorrhizae cycle organic N into the soil horizons. Second, cold temperatures dominate the subalpine ecosystem. This slows the decomposition process so that organic N accumulates. Thus a large proportion of a tree's organic

N is added to the soil annually, and there it sits because it doesn't mineralize very quickly. In warmer ecosystems, it turns over more rapidly.

Are you suggesting that upper-slope forests not be burned as a means of site preparation? If not, can you give a guess as to how much organic matter should be retained?

We are not suggesting that slash burning has no place in subalpine silviculture. We are recommending that more care be given to protecting the surface soil and some of the O horizon. The proportion of nitrogen in logging residues is small relative to the nitrogen content of the forest floor and soil (Tables 4 and 9). Consuming much of the logging slash and some—but not all—of the forest floor in broadcast burning may simply be a cost of doing business if fuel risks are too great and if mineral soil must be exposed for natural regeneration. Complete removal of the forest floor will lead to soil drought and to erosion if slopes are steep enough. The experience at Swain Mountain Experimental Forest (Table 10) was an extreme situation that shows what can happen if *all* surface organic materials are consumed. Operational broadcast burns can be very effective and be much less severe.

The amount of organic matter that "needs" to be retained remains speculative. We suspect that on thin, shallow soils, almost any losses are detrimental. However, work is under way—at least in other forest types—to address this very question. In the interim, we would advocate leaving as much coarse woody debris and forest floor material as possible while still achieving adequate regeneration and fire protection. Organic materials need not be contiguous. Breaking them up is okay if they are retained on the site. But we have to get away from the notion that baring the mineral soil is "good forestry."

You have stated that subalpine soils generally are shallow and weakly developed, and that protecting the surface layers is important. Is tractor piling a very realistic option if topsoil is displaced? Can you suggest other mechanized methods that provide a lower risk to the soil surface?

In our view, piling logging slash by tractor is a much riskier practice than broadcast burning because topsoil can be bladed away along with surface organic matter. As Figure 3 shows, at least one-quarter of the nitrogen stored in a soil's surface meter is in the top 10 cm. For red fir forests in California, this amounts to more than 2 Mg N/ha. For shallower soils, the absolute values go down, but the proportional values are balanced even more heavily toward the surface.

One alternative is to use a brush rake, rather than a blade, during piling operations. This has the effect of removing major fuels and most potentially sprouting competitors while leaving a partly disturbed soil in place. It does not remove seeds, but germinating competitors should not threaten conifer survival. And if competition is retarding growth, careful choice and timing of herbicides should take care of that. Low consumption broadcast burns can reduce fire hazard and leave larger materials to retain some shade and shelter for small mammals and soil fauna. This can be accomplished by burning when duff and larger fuels have high moisture contents. "Lop and scatter" hand treatment of slash is also effective (but expensive). Mechanically chipping organic materials and blowing the chips back on the site may be another option for reducing fuels while conserving soil fertility, and there is some evidence that water-soluble phenolics released from chipped heartwood and bark will reduce nitrification and subsequent leaching losses of nitrogen.

What effect would mounding have on planting success? Would this increase soil temperature and improve nutrient availability in the subalpine Abies *zone?*

Mounds created during site preparation should improve soil temperatures and mineralization slightly, in that cold air would drain into lower positions of microrelief. Whether this would be enough to matter remains to be seen in such cold ecosystems. Brockley's chapter in this volume discusses mounding for interior forest types of British Columbia and in Scandinavia. Certainly, mounding would improve temperature, aeration, and mineralization in poorly drained areas, and is a proven silvicultural practice in many forested regions of North America.

If subalpine Abies *forests are nutrient limited, would you advocate fertilization? If so, what have you found out and what elements would you prescribe?*

Empirical fertilization trials support our ecologically based conclusion that subalpine *Abies* forests are nutrient limited. The primary deficiency is nitrogen, and a secondary deficiency seems to be phosphorus. In California, 224 kg N/ha as urea will increase five-year volume growth by one-third on average sites, and growth can be doubled if nitrogen is combined with phosphorus (Powers, this volume). Chappell and Bennett (unpublished) have found that Washington and Oregon stands of noble and Pacific silver fir respond strongly to nitrogen fertilizers. Except for some possibilities involving sulfur and boron in British Columbia, or on the most leached soils elsewhere, there is little reason to believe that nutrients other than nitrogen and phosphorus are limiting growth. Based on findings in California (and preliminary findings in Oregon and Washington) we would recommend fertilization in many stands containing trees up to pole size, because the subalpine *Abies* forest responds very well.