Chapter 18

Fertilizers and Other Means to Maintain Long-Term Productivity of Western Forests

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ABSTRACT. Actions that could increase or decrease long-term forest productivity for both timber and nontimber objectives are discussed. The quantity of sustainable timber harvest is determined by the quantity, or level, of sustainable growth. On some sites in western United States and Canada, improving soil nutrient status by fertilization is one of several ways to increase forest growth. On all sites, however, harvesting stands at or beyond the culmination of mean annual increment and protecting soil productivity by careful road construction, harvesting, and site preparation are recommended. Discrepancies between concepts or generalizations about tree growth and the empirical evidence are discussed. Although the main subject addressed is sustaining timber yields, some connections with other forest resources and values are considered. Clearly, additional research is needed to provide quantitative information to guide decision making.

Most will agree that it is desirable to maintain or improve the capability of some forested land to produce both timber and certain noncommodity resources valued by society. This multiple-use capability depends on a combination of native site potential and the cumulative effects of timber harvesting and subsequent management practices. Given a constant land base, the sustainable level of timber harvest is set by the amount of forest growth and standards of utilization at harvest. In this chapter we assemble information about forest practices that can increase or decrease the sustainable level of both timber harvest and nontimber values. Our purpose is to encourage land managers to modify or augment some current practices to ensure a high level of sustainable harvest.

Maintaining productivity of commercial and multiple-use forests west of the Continental Divide in the United States and Canada is the principal topic of this chapter. We define "maintaining" as the process of continuing a certain condition, and "productivity" as the power to produce or yield benefits, results, profits, or a net return of wealth. For commercial and multiple-use forests, benefits include water (both in terms of its quality and quantity), forage, fish, wildlife, recreation, and natural beauty in addition to timber. Society seeks an adequate and continuing yield or return of these benefits from forests. Hence assessing or monitoring the sustainable level of forest productivity must be based on accurate "long-term" measurements and observations over the course of several generations of stands at numerous locations. We will review some of the aspects and uncertainties of sustainable forestry and then suggest ways to keep western forests yielding products and values that society needs or desires.

Concerns of various groups have led to conflicting demands for change, including major changes in our current systems for managing western forests. Some people support, for example, the New Forestry or New Perspectives methodology; others believe that fine-tuning the "old," or traditional, forestry is sufficient. State and federal legislative and judicial branches of government have been responding increasingly to demands for multiple-use forestry that deemphasizes timber production. These political considerations, as well as economic constraints and the productive capacity of the land, will determine future yields of timber and nontimber values.

A fundamental question is what *sustainable* level of growth and harvest is attainable. Figure 1 illustrates

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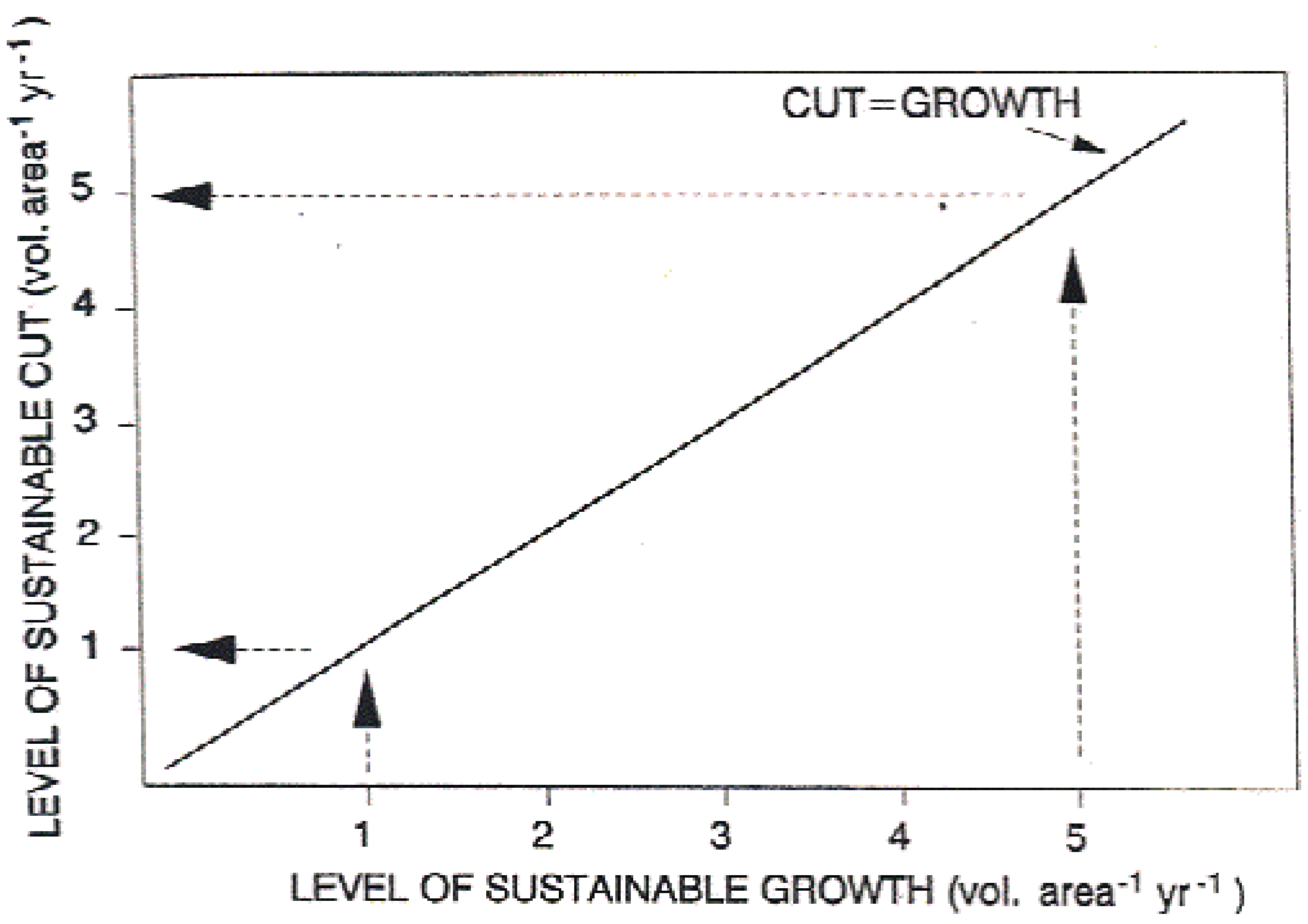

Figure 1. The level of sustainable growth sets the level of sustainable timber harvest.

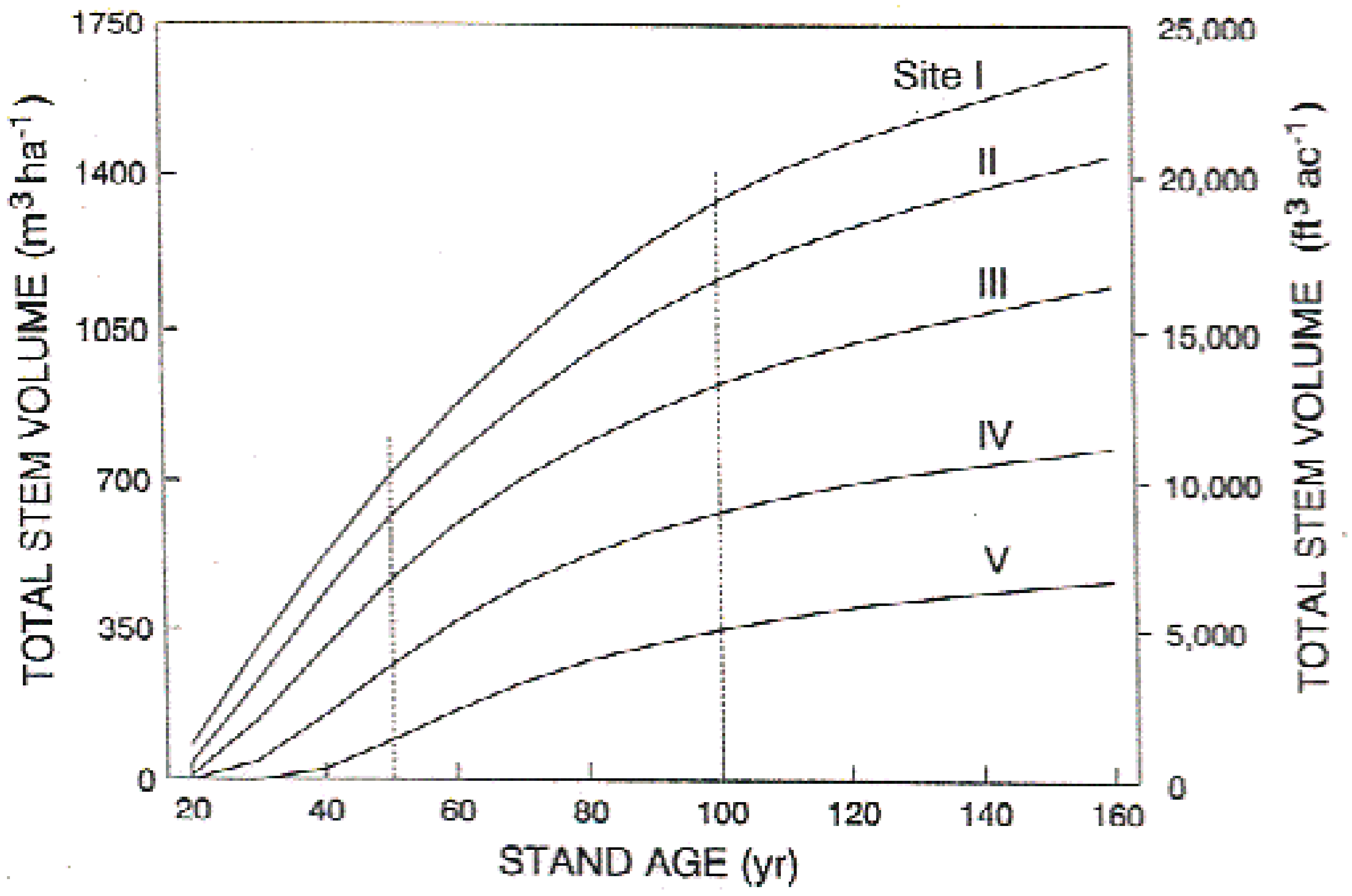

Figure 2. Trends of net cubic volume yields of unmanaged coast Douglas-fir trees 18 cm dbh (7 in.) and larger on sites I to V. Adapted from McArdle et al. (1961). The vertical dotted lines show yields at 50 and 100-year rotation lengths.

that the level of sustainable growth determines the level of sustainable timber harvest. The diagonal line shows that forest productivity could be sustained within a wide range, because sustainability requires only that the quantity harvested not exceed sustainable growth.

Factors of Forest Productivity

Yields of timber and nontimber values from western forests can be estimated by multiplying the area of forested land by the production per unit of land. Political, economic, and biological interactions influence the area and quality of land allocated for timber production.

What Land Base?

In response to political and economic influences, the amount and quality of land allocated to timber and nontimber uses will continue to change. The inherent quality of forest land varies greatly in regard to timber production, as illustrated by net yield trends of unmanaged coast Douglas-fir (*Pseudotsuga menziesii*) on sites I to V (McArdle et al. 1961). Figure 2 shows at least a fourfold difference in yield between native sites I and V. These differences reflect native or inherent potential of the soil, macroclimate, and natural regeneration without silviculture. These are base-level yields before first harvests. Three implications are significant: (1) Future growth and harvest levels of a region may be reduced, simply because foresters may be allocated land that is poorer in quality, either inherently or because of past activities. (2) Harvesting or silvicultural activities that affect inherent soil fertility—positively or negatively—can have substantial effects on forest growth, and thus on timber yield. Hence quality of the land base is not static, although this is usually incorrectly assumed in conventional economic analyses of soil expectation values (Beuter and Johnson 1989; Routledge 1987). (3) Yields of Douglas-fir stands harvested at 50 years are substantially less than those from stands harvested at 100 years.

Yields Per Land Area

Factors determining long-term yields of timber are numerous and interactive. Soil and climate largely determine native or potential productivity of a site. Other influences, such as damaging agents, tree species, silvicultural methods, rotation length, utilization standards, and the net results of all interactions determine how much of this site potential is captured as merchantable yields. Major factors affecting forest productivity are outlined below.

1. *Soil physical, chemical, and biological properties.* These components of the soil system must be protected and improved whenever possible. See recent reviews by Amaranthus et al. (1989), Childs et al. (1989), Edmonds et al. (1989), Froehlich and McNabb (1984), and Lousier (1990).

2. *Macroclimate and microclimate.* Regional macroclimate and local microclimate affect forest productivity directly through solar radiation, temperature, and moisture. Both macro- and microclimate also influence the quantity and activity of organisms important to soil processes such as organic matter decomposition and nutrient cycling. In planning for sustainable forestry into future centuries, however, we must also consider how to hedge our practices to accommodate predicted regional climate changes resulting from industrialization and land use patterns. Although forest managers

Table 1—Characteristics of New Forestry versus traditional methods.

Item	New Forestry	Traditional Forestry
Primary objective	Multiple-use	Timber production
Maintenance of long-term productivity	Assumes natural systems are fragile and complex ("keep all the pieces")	Assumes most systems are robust or resilient to disturbance
Stands	Multi-age, multi-species	Even- or two-age, one or few species
Snags	Keep, create	Salvage, harvest
Coarse woody debris	Retain	Salvage, burn, leave
Harvest pattern	Concentrated	Dispersed
Mature stands	Connected	Fragmented
Diversity:		
Plant	Retain	Control, reduce
Animal	Retain, expand	Passive tolerance

have little control over macroclimate change, they can avoid or minimize further stress on their stands by protecting physical, chemical, and biological properties of soils and by modifying local microclimate. Further, they can plant crop species more tolerant of predicted conditions and encourage a wide range of plant species for natural selection.

3. *Silviculture.* Much of the current shift toward New Forestry (Franklin et al. 1989) and New Perspectives (Salwasser 1990) is in response to concerns about "sustainable" forestry (Maser 1988). Implementation of these new concepts undoubtedly will deemphasize timber production per unit area, at least in the short term (Table 1). Proponents of New Forestry believe this is necessary both to increase nontimber values and to sustain long-term timber production. In fact, no direct evidence is available to support—or reject—speculation that New Forestry practices will ensure these objectives (Heilman 1990; Aune et al. 1990). A compelling reason for change, however, is public-incited political pressure that has generated judicial, legislative, and executive direction.

4. *Harvest cycle and utilization standards.* Rotation length affects timber yields (Figure 2), timber value, and nontimber values that prize large trees and undisturbed landscapes. Long rotations are often financially unattractive, however, when the concomitant greater yields are discounted to present net worth (Routledge 1987). We discuss rotation length and utilization standards in a later section.

5. *Interactions and cumulative effects.* Forest ecosystems are complicated because of the multiple interactions and linkages of the innumerable components. Inadequacies or declines in one factor of productivity, however, can be offset by increases in others. Silvicultural practices or management inputs can sometimes compensate for inherent or induced shortages. Fertilization with nitrogen is a clear example. On the other hand, some interactions may net no effects. For example, in a 40-year study of slash burning, Miller and Bigley (1990) found that burning slash after clearcutting in the Douglas-fir region had no consistent effect on growth of naturally regenerated stands. Growth of the Douglas-fir component was increased by slash burning, but growth of western hemlock (*Tsuga heterophylla*) and *Abies* species was decreased.

6. *Workmanship.* Critical to sustainable forestry is quality workmanship, as manifested in the knowledge, control, attitude, and judgment that humans apply to forest planning and operations. Workmanship can be improved by training, by monitoring to provide feedback and adjustment, and by research to expand knowledge.

Role of Forest Fertilization

The objective of forest fertilization is to improve the nutrient status of soils (hence productivity) over the short or long term. Fertilizers can improve amounts, flux, balance, and availability of nutrients to plants. Practically all fertilization of western forests has a short-term objective: to increase growth of the current crop. Most fertilization in western forests is with nitrogen (N) and most publications report a response period of ten years or less after a single application. This may, however, underestimate response duration on poor quality, extremely nitrogen-responsive sites (Miller and Tarrant 1983). Experimental applications of elements other than nitrogen in western forests have been limited. A few locations show extra growth when other elements are applied, usually in combination with nitrogen (Table 2).

Elsewhere in this volume, authors report substantial gains in volume growth for numerous forest types and site conditions after nitrogen fertilizers were applied. These responses are direct evidence that the native amounts of plant-available nitrogen were limiting tree growth in these locations. Thus, nitrogen fertilizers are a means for maintaining or increasing at least short-term forest productivity and yield.

Site-Improving (Nature-Improving) Fertilization

Fertilizers can reduce or correct inherent shortages of soil nutrients. There are several possible reasons for nutrient shortages: (1) Nutrient limitations or imbalances in the original parent material can extend to the soil developing from this material. (2) Time for sufficient soil development may be too brief for adequate

Table 2—Some locations where western forests have responded to nutrient elements other than nitrogen in field experiments.[1]

Location	Soil Parent Material	Comparison = Control vs. Element alone	Comparison = Control vs. Element(s) and N	Reference
NW Vancouver Island	Glacial till	B	—	Carter et al. (1986)
Interior B.C.	Acid igneous	B	B	Brockley (1990)
NW Washington	Glacio-lacustrine	—	PKS	Gessel et al. (1981)
W. Washington	Unspecified	K	PKS	Gessel et al. (1981)
W. Washington	Unspecified	K	K	Gessel et al. (1981)
W. Washington	Silt stone	P	P	Porada (1987)
W. Washington	Basalt, glacial	P	PN	Radwan et al. (1991)
E. Oregon	Pumice	—	PS	Will and Youngberg (1978)
W. Alberta	—	—	P	Yang (1985)
W. Vancouver Island	—	—	P	Weetman et al. (1989)
N. California, E. Oregon	Several	—	PS	Powers et al. (1988)
N. California	Volcanic	—	PCa	Powers (1981)

[1] Does not include potted seedlings in greenhouse/lathhouse trials, which frequently show greater response to nutrient additions.

weathering of primary minerals to release nutrients, for adequate nitrogen additions from the atmosphere, and for N_2-fixation. (3) Time for soil development may be excessive, resulting in losses or imbalances from nutrient leaching. (4) Cold temperatures or drought can limit rates of nutrient cycling and availability. (5) Soil instability (erosion, mass flows, or slumpage), especially on steep slopes, can regress soil development. (6) Wildfires of high intensity or frequency can produce both atmospheric losses of nutrients and accelerated erosion.

Remedial Fertilization

Fertilization can correct or mitigate human-induced shortages of soil nutrients resulting from harvesting activities and site preparation. For example, intensive, frequent harvests accelerate nutrient export and can accelerate leaching and soil loss; site preparation can cause nutrient losses via removal, displacement, or topsoil erosion; and prescribed burning causes additional losses of nutrients through volatilization or ash being blown away.

Multiple Applications, Induced Deficiencies, and Carryover

Because of earlier research or operational applications, some coast Douglas-fir stands have received two or more applications of nitrogen fertilizers. Thus questions arise about their utility and fate, and whether repeated applications of nitrogen and resulting growth increases might induce deficiencies of other nutrients. This question was investigated at nine trial locations on Weyerhaeuser Company land. Nutrient concentrations in Douglas-fir foliage at only one of the nine trials indicated that potassium (K) and boron (B) concentrations had fallen near or below assumed critical concentrations after repeated annual applications of nitrogen fertilizer (Peterson et al. 1986). Yet no reductions in subsequent growth or response to repeated nitrogen applications were observed in this investigation.

In contrast, Mika and Moore (1991) report that response of Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) to nitrogen fertilizer declines at some locations after fertilization with 225 kg N/ha, and especially with 450 kg N/ha. Nitrogen fertilizer at these locations decreased the K:N ratio in foliage, resulting in nutrient imbalance and reduced response to nitrogen.

As to the fate of fertilizer nitrogen in the ecosystem, that supplied as urea or ammonium is strongly held and little is lost by leaching (Cole and Gessel 1965; Moore 1974; Powers 1981; Heilman et al. 1982; Miller 1988). In most studies, half or more of the retained nitrogen was found in the soil and the remaining amount was in trees and subordinate vegetation (Miller 1988).

Miller (1981:103), in speculating about a carryover effect of nitrogen fertilization to the succeeding stand, concluded that only when the amount of retained fertilizer nitrogen is large in relation to the original capital of the site will any measurable long-term benefit accrue: "Thus, for a site with a nitrogen capital of only 2,000 kg N/ha, and making the assumption that both 40% of any added nitrogen is still in the soil organic matter after five years and that the mineralization rate is 3%, then if urea is applied at a rate of 150 kg N/ha, availability at the end of the five-year response period has only increased from 60 kg N/ha per year to 61.8 kg N, a hardly measurable improvement." Miller knew of no substantial case of a long-term response to nitrogen (aside from examples of confused mensuration) or of a detectable carryover response in the second rotation (as distinct from phosphorus treatment, of which he found a few examples). He concluded that a continuing response might be possible, but the rates of application would have to be very high. For example, if 2,500 kg of N/ha were applied as sewage sludge to the site in the above example, and making the reasonable assumption that 80% of this would remain in the soil, availability would be increased to 108 kg N/ha per year. Thus such an application could be regarded as inducing a permanent improvement in the site.

The preceding hypotheses of limited long-term or carryover effect of nitrogen fertilizers in one crop to the succeeding one should be tested. Robert Harrison (pers. comm., University of Washington, November 1989) suggested how this could be accomplished after harvesting stands with fertilizer trials. Most trials consist of plots fertilized with single or multiple applications of urea nitrogen and of unfertilized plots. If these plots were uniformly harvested, planted, and tended, the comparative performance (survival and growth) on fertilized and control areas could indicate the occurrence and magnitude of a carryover effect of earlier fertilization. Concurrent with these comparisons of tree performance should be comparisons of vegetative succession on both fertilized and control plots (pers. comm., John Zasada, USDA Forest Service, February 1991). Variations in vegetation succession could affect tree performance and show effects of nitrogen fertilizers on nontimber values.

Direct and Indirect Effects of Forest Fertilization on Production of Timber and Nontimber Resources

Other authors in this volume describe short-term effects of fertilization on tree and stand growth, and on nontimber values such as water quality, fish, and wildlife. Less is known about the effect fertilization has on insect and disease severity, which can have an impact on management risk, costs, and timber yields. West of the Cascade crest, little evidence for increased or decreased mortality from insects or diseases after fertilizer application has been reported. Although Weetman et al. (1989) report greater incidence of spruce weevil (*Pissodes strobi*) damage after NP fertilization of Sitka spruce (*Picea sitchensis*), the gains in height growth more than compensated for growth reductions from weevil damage.

East of the Cascade crest, however, greater mortality from root disease has been observed on fertilized plots of Douglas-fir and grand fir (*Abies grandis*) (pers. comm., Jim Moore, University of Idaho, Moscow, February 1, 1991). Entry et al. (1991) report greater susceptibility of Rocky Mountain Douglas-fir to inoculation of *Armillaria* root rot in fertilized than in unfertilized plots. This suggests that nitrogen fertilizer may not consistently improve timber yields in interior forests. We speculate that the greatest potential for positive gains from fertilizing inland forests is likely (1) on best sites where environmental buffering is at a maximum and (2) with tree species broadly adapted to a range of environments; these are species with wide seed zones (Rehfeldt 1984). Likely candidate species for fertilization are rust-resistant western white pine (*Pinus monticola*), perhaps western larch (*Larix occidentalis*), and ponderosa pine (*Pinus ponderosa*) on best sites. In contrast, Rocky Mountain Douglas-fir and grand fir seem risky species to fertilize because of their narrow adaptation to specific sites within their broad geographic distribution (narrow seed zones) and their high susceptibility to endemic root diseases. A biological basis for this concern is that fertilization is likely to shift carbon allocation to promote top growth more than root growth (Hermann 1977). An increased top/root ratio could result in greater susceptibility to drought with resulting stress and increased susceptibility to several root pathogens. *Armillaria* species, for example, are widely distributed and damaging, especially where environmental stress reduces tree vigor (McDonald et al. 1987*a*, 1987*b*).

Yet fertilization may improve timber yields by offsetting growth reductions due to other diseases or insects. Filip and Schmitt (1990) suggest that by increasing host vigor and growth, fertilization could counteract effects of dwarf mistletoes (*Arceuthobium* spp.) in true firs (*Abies* spp.). Growth losses from western spruce budworm (*Choristoneura occidentalis*) were offset after urea fertilizer (350 kg N/ha) increased growth and vigor of grand fir (*Abies grandis*) in an eastern Oregon stand near Baker (Wickman et al. this volume, poster abstract).

Role of Fertilizers in Maintaining Long-term Productivity

Improved stand growth after fertilizer application proves that fertilizers can help increase or maintain productivity. Since no direct evidence about carryover effects and cumulative effects of repeated fertilizer applications on long-term productivity is unavailable, speculation is necessary. If a single or repeated application of nitrogen fertilizer were considered analogous to nitrogen fixed and released in soils by N_2-fixing plants during natural forest succession, then one might assume a long-term enhancement of site productivity.

DeBell et al. (1989) provide a framework for further speculation. They consider stand productivity to depend on tree growth rate and the number of trees per unit area. Although fertilizers have increased tree growth in numerous stand and species types, the extent to which fertilizers increase stockability (the number of trees per unit area that can be grown to a given size) is unknown. DeBell et al. (1989:709) define stockability conceptually as the tolerance of a forest system to the presence of or competition from increasing numbers of trees. Does this tolerance increase after fertilization? For several reasons, a positive answer is significant to the role and importance of fertilizers in maintaining long-term productivity. If fertilizers were to increase stand productivity, in part by increasing stockability in the current stand, then more of the increased growth of individual trees in one-time or repeatedly fertilized stands would be retained in eventual crop trees instead of being lost as suppression mortality. To the extent that improvement in soil fertility in a fertilized stand improves stockability and tree growth in the subsequent stand, a cumulative, long-term benefit of fertilizers could be anticipated. We simply do not know if single or multiple applications of nitrogen fertilizer increase (or decrease) stockability. We do know that phosphorus fertilization before planting of pine in imperfectly drained soils of the Atlantic Coastal Plain is critical to plantation establishment; this fertilization clearly increases stockability (Jacobson, this volume).

We believe that fertilizers do have a role in maintaining long-term productivity. This role could be as simple as stimulating short-term increases in tree growth after fertilization in each rotation. If enhanced growth rate were the only consequence of fertilization, then fertilization of young stands (younger than age when mean annual increment culminates) would result in earlier culmination and greater yields per area (pers. comm., David Hyink, Weyerhaeuser Company, March 13, 1991). If, however, fertilization also increased stockability, then mean annual increment (MAI) would culminate later and with even greater yields.

Recommendations

Many of the recommendations that follow were gleaned from recent publications and symposia papers that provide further details and justification. No direct evidence—forest response—is available to support recommendations for maintaining or enhancing long-term productivity of western forests over several rotations. We simply have not harvested and managed these forests long enough. Moreover, here, as elsewhere in the world, adequate measurements are not available to accurately compare trends in stand growth over successive rotations. Thus we—like other authors—are forced to speculate or predict from short-term response or from indirect or circumstantial evidence the effects on soil physical, chemical, or biological properties that are or may be correlated with tree growth.

Recommendations for All Locations

In this section, we suggest actions to maintain high levels of sustainable growth in western forests. These actions can also affect nontimber values, as we will discuss in a later section. First priority is to protect the potential productivity of soils. Recommendations applicable to all western forests are listed in Table 3 and discussed in this section. Recommendations for certain other sites are outlined in Table 4 but not discussed further.

Reevaluate Rotation Length. It is a mathematical fact that the trend of cumulative stand volume has a point of diminishing returns. This optimum efficiency (of time

Table 3—Recommendations for attaining high levels of sustainable yields or values on all locations.

	Evidence[1]		Resource Benefited	
Recommendation	Direct	Speculated	Timber	Nontimber
Reevaluate rotation length (≥ culmination of mean annual increment)	Math. certainty	—	+	+
Construct roads carefully	+	—	+	+
Minimize soil displacement	+	—	+	+
Manage organic residues	+	—	+	+
Consider cumulative effects[2]	+	—	+	+
Simulate natural fire cycles	—	+	+	+
Monitor and evaluate operations	+	—	+	+

[1] Direct evidence is that based on short-term measured response of the timber or nontimber resource to forestry activities.

[2] Cumulative effects at a site result from successive impacts on the site or, on a watershed scale, from off-site activities.

Table 4—Recommendations for attaining high levels of sustainable productivity on specific sites (such as steep slopes, low quality sites, sites with unstable soils).

Recommendation	Evidence[1]		Resource Benefited	
	Direct	Speculated	Timber	Nontimber
Conserve nutrients	+	—	+	+
Conserve organic matter	+	—	+	+
Minimize soil disturbance	+	—	+	+
Fertilize	+	—	+	+
Conserve snags	+	—	—	+
Conserve coarse woody debris	—	+	+	+
Retain biological diversity	—	+	+	+

[1] Direct evidence is that based on short-term measured response of the timber or nontimber resource to forestry activities.

invested in the stand since its origin) is maximum when stands are harvested at the peak or culmination of mean annual volume growth (CMAI) (Figure 3). This mathematical certainty applies to both managed and unmanaged stands, to all site qualities, and to all forest types. For any management regime, rotations shorter than the age of CMAI for that regime will produce less timber volume per hectare per year. We illustrate this loss in production schematically in Figure 1 by shifting the sustainability level from level 3 to level 2, simply because rotation length was less than that set by CMAI. Silvicultural inputs that increase growth rates or improve stockability can offset lower average rates of timber production inherent to rotations shorter than age of CMAI. These silvicultural inputs can gain time, an economic advantage.

Setting rotation length at CMAI meets the objective of maximizing average rate of volume growth over a rotation or a series of rotations. If maximizing average rate of value—instead of volume—growth per area were the objective, rotations would be further extended because larger trees have greater value per unit of volume than smaller ones do. If compound interest is considered, however, then shorter rotations are preferable because stand management costs are compounded and future values are discounted. Details follow.

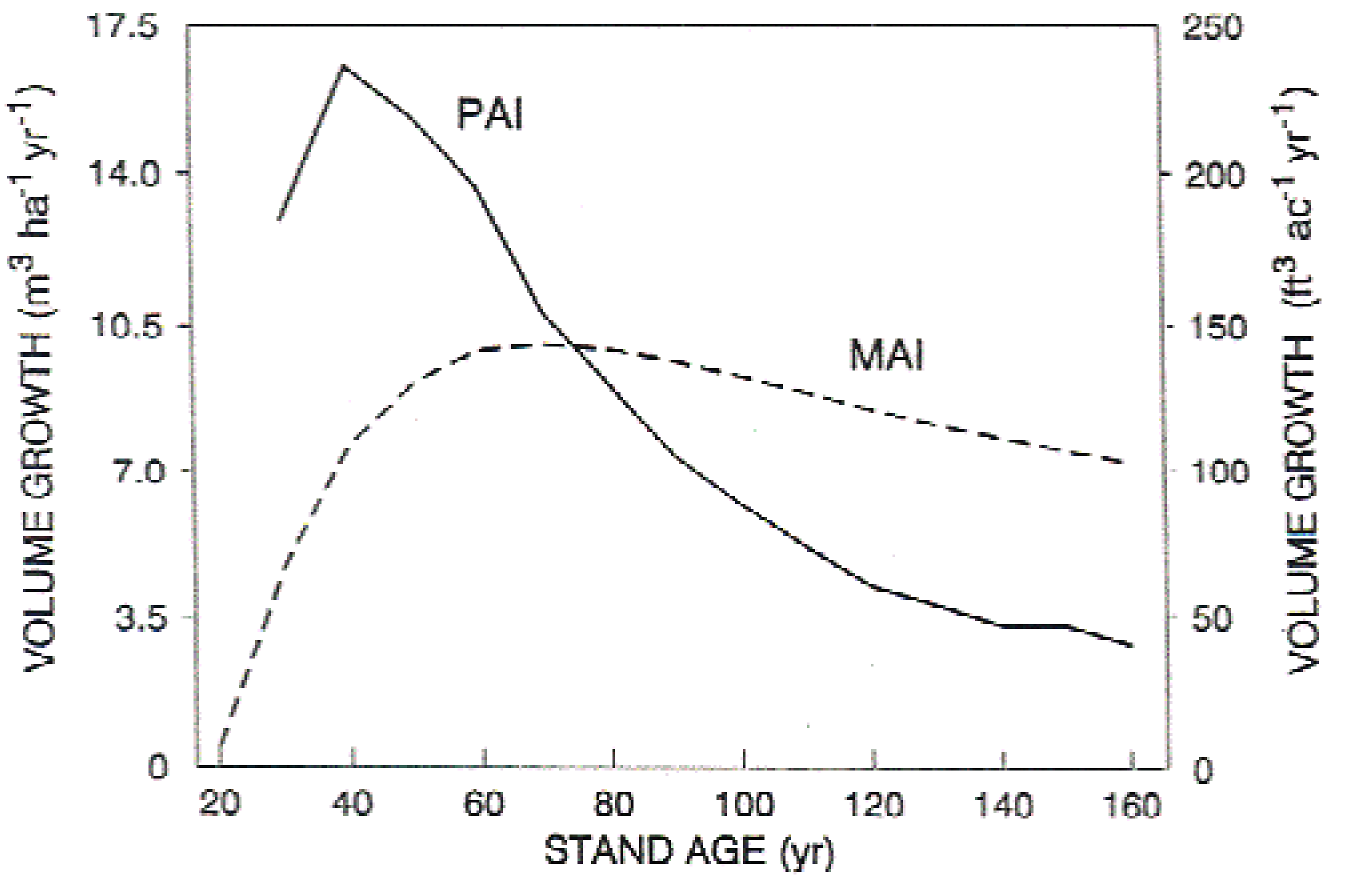

Figure 3. Trends of net periodic annual increment (PAI) and mean annual increment (MAI) of unmanaged site III coast Douglas-fir trees 18 cm dbh (7 in.) and larger. Adapted from McArdle et al. (1961).

The stand age when MAI culminates depends on factors including tree species, site quality, and minimum size of salable trees. Moreover, using board-foot instead of cubic measurements tends to increase age at culmination. In unmanaged coast Douglas-fir stands, MAI in cubic volume of live stems culminates between 60 and 160 years, depending on site quality and dbh (diameter at breast height) of the smallest merchantable tree (Figure 4). If trees as small as 4 cm dbh can be used, then CMAI is about 60 years for sites I through V. If, however, trees must be 30 cm dbh and larger to be utilized, then culmination of MAI occurs later, because more time is required to produce larger trees. For example, a rotation of 160 years for site V and 90 years for site III would be appropriate to attain CMAI (Figure 4).

Silviculture affects stand growth, hence it affects quantity and shape of the MAI trend. To define the shape of the MAI trend and its culmination age, however, one must first define or predict trends of growth. Even for a relatively well-researched species like coast Douglas-fir, researchers cannot yet adequately define the level and age of MAI culmination (CMAI) in managed stands (pers. comm., R.O. Curtis, USDA Forest Service, February 3, 1991). Although the appropriate rotation length to maximize sustainable yield from variously managed stands is uncertain, age to CMAI can be estimated by growth models. Stand simulations by DFSIM (Curtis et al. 1982) for coast Douglas-fir suggest that fertilization of young stands shortens the time to CMAI, but that thinning extends time to CMAI. If set by CMAI (trees 19.3 cm dbh or larger and stem volume to 10.2 cm top diameter), rotations exceeding 100 years are

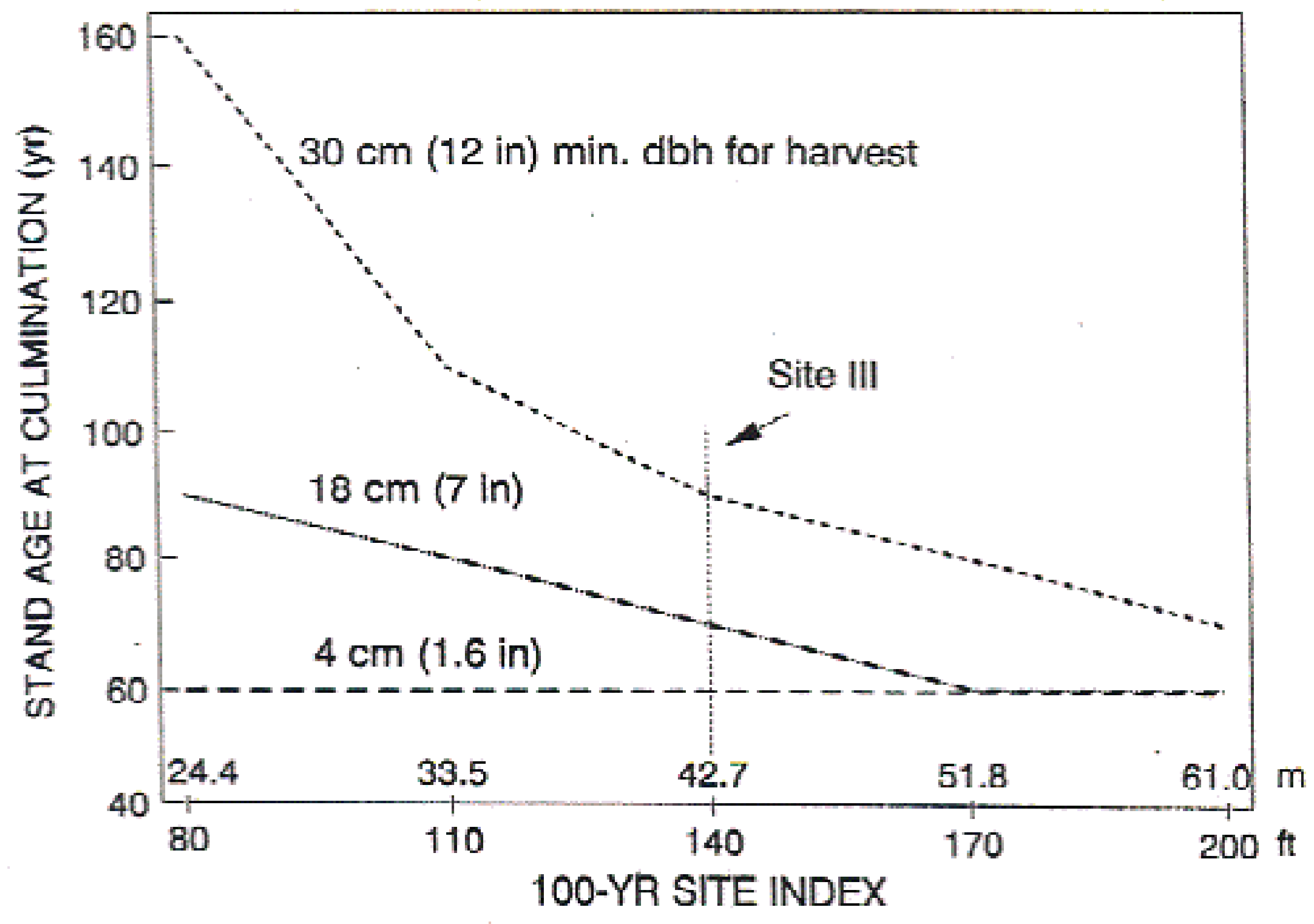

Figure 4. Stand age when net mean annual increment (MAI) culminates in unmanaged coast Douglas-fir, by minimum tree size and site index. Adapted from McArdle et al. (1961).

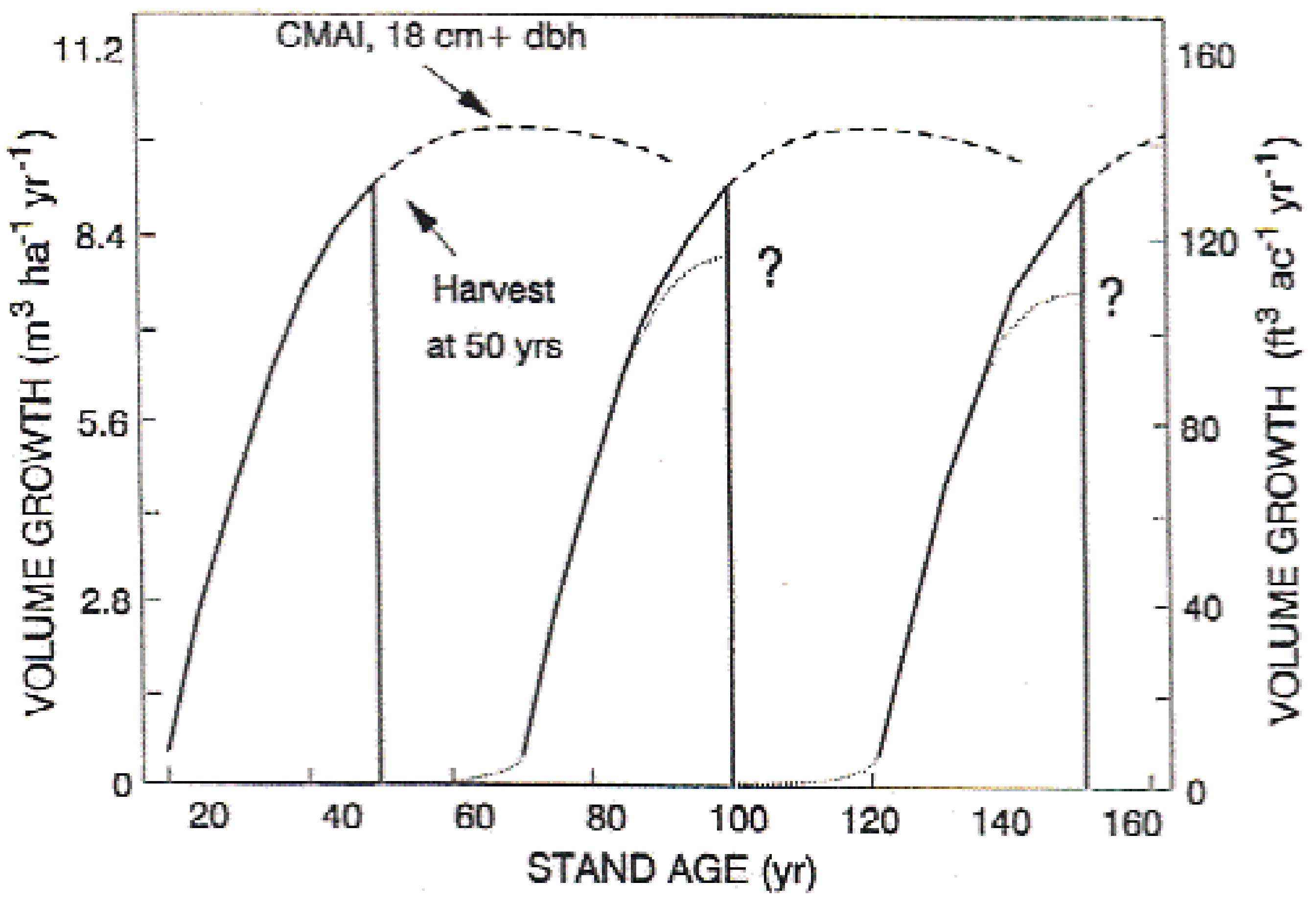

Figure 5. Rotations shorter than those set by culmination of MAI (CMAI) average lower rates of volume growth of unmanaged site III coast Douglas-fir. Adapted from McArdle et al. (1961).

not unlikely for coast Douglas-fir on below-average site qualities (Curtis et al. 1982:34-47).

Mean annual increment during the long term is reduced when successive stands are harvested before culmination of MAI (CMAI). This is shown by the projected trend of MAI for average site-quality, unmanaged coast Douglas-fir (Figure 5). For average site quality and minimum tree size of 18 cm dbh, a series of 50 year rotations without silviculture might produce about 8% less volume per year than would a series of 70 year rotations. As stated earlier, silviculture that increases stand growth or usable yields over that of unmanaged stands can compensate for losses concurrent with rotations shorter than age of CMAI.

Short rotations also allow less time for recovery from (1) the greater rates of nutrient exports inherent to short rotations (Johnson 1983) and (2) the more frequent impacts of potentially soil-damaging harvesting and site preparation equipment. Schematically expressed in Figure 1, sustainability level on some sites could shift from level 2 toward level 1 if the soil resource were degraded. The extent of reduction in soil potential and sustainable growth, however, depends largely on where and how carefully harvesting and site preparation are carried out (Table 5) and what mitigating or compensating practices are accomplished. Choice of logging equipment is critical for minimizing disturbance and physical impacts on the soil (Nakamura 1990). Generally, low-impact logging methods are recommended, but these are often more costly (unless one considers the cost of mitigating or compensating practices).

Setting the rotation length to maximize present net worth (of the flow of revenues generated by harvest) in perpetuity invariably shortens the rotation period below that which would produce maximum sustainable growth. A dilemma clearly exists for managers who must set rotation lengths based on conventional economic analyses, because value of future harvests is discounted (as is the forgone value of decreased yields resulting from soil degradation), management costs are compounded, and taxes must be paid. Routledge (1988:225) summarized the dilemma of the private owner of forest land who would get a higher financial return by investing his money elsewhere:

> Even a moderate discount rate of only 2% can encourage management practices that leave the soil severely degraded after only one or two rotations. Foresters concerned with maximizing the sustainable yield will reach substantially different conclusions about the use of efficient, but potentially damaging logging practices.
>
> The essence of the conflict between these two perspectives is the value of the discount rate. Managing for maximum sustained yield makes sense only if the rate at which distant harvests are discounted is zero. This conflict is not evident in traditional evaluations of the soil expectation value because the potential for soil degradation is ignored.
>
> Management for maximum sustained yield is a substantially different task from management for discounted present net worth. The latter can be achieved by essentially ignoring distant rotations. To achieve the former, we need to examine the possible long-term consequences of proposed logging practices. Predictions of consequences for distant rotations are obviously highly speculative. In Routledge [1987], a method is proposed for putting reasonable limits on the soil expectation value in the presence of uncertain predictions for future rotations.

Table 5—Maximum potential effects of management practices on site productivity.[1] Adapted from Nakamura (1990).

Management Practice	Soil Loss	Soil Compaction	Organic Loss	Productivity Loss
Roads and landings:				
Permanent - out of production	VH	VH	VH	VH
Temporary - return to production	VH	VH	VH	VH
Reconstruction	M	L	L	L
Clearcut harvest:				
Feller-buncher yarding	H	H	M	H
Tractor yarding[2]	H	H	M	H
Cable yarding	M	L	M	M
Helicopter yarding	L	L	M	L
Group selection:				
Feller-buncher yarding	M	H	M	M
Tractor yarding[2]	M	H	M	M
Cable yarding	L	L	M	L
Helicopter yarding	L	L	M	L
Site preparation:				
Machine piling	VH	VH	VH	VH
Terracing	VH	VH	VH	VH
Ripping or disking	M	L	L	M
Herbicide application	L	L	L	L
Broadcast burning	H	M	H	H

[1] "Maximum potential effects" refers to the greatest impact possible, at any single entry, should that practice be applied under the worst possible conditions without mitigating measures.

[2] Tractor yarding includes both tractors and rubber-tired skidders.

Note: L = Low; M = Moderate; H = High; VH = Very high.

Design and Construct Roads Carefully. Roads are necessary to harvest and manage forests, but careful design, construction, and maintenance are recommended. Megahan (1988:63) notes that construction of roads for timber harvest initially removes from about 1 to 30% of the total forest area from tree production, depending on road design and type of harvesting system. He also points out that forest regrowth compensates for some of these losses, so that the ultimate loss of productivity tends to be considerably less than is suggested by the percentage of area devoted to roads. The amount of forest regrowth depends on whether the road is closed to traffic and on site conditions in the immediate area. The most adverse conditions are on road cuts and on the cut portions of the road surface: tree height growth is reduced at these locations. But increases in rooting depth, ease of root penetration, and total moisture-holding capacity in fill portions of the road tend to compensate for unfavorable site conditions, so that tree height growth in fills is usually not reduced—and may be increased—compared to that of trees on slopes next to the road.

Roads also affect site productivity on adjacent slopes. This is possibly because of changes in microclimate, such as increased light, the disposition of runoff excess from the road itself (plus any subsurface flow intercepted by the road), and changes in the unsaturated soil moisture regime. The nature of the road drainage design is important in regulating moisture responses. According to Megahan:

> In some situations, severe damage to site productivity adjacent to roads does occur when road construction raises water tables to critical levels on the uphill side of the road, and when landslides originate in the road and are manifested on the slope below. Site productivity remains permanently impaired in cases where water tables are raised, unless remedial road drainage practices are used. The duration of reduced productivity on slide scars ranges from about 10 to 80 years, depending on location.

Nontimber values, such as water quality and fisheries, are also degraded by accelerated erosion and landslides associated with road construction. Miller (1988:72) suggests that many of the mitigating measures for reducing visual impacts are also sound procedures from the standpoint of soil management and land stewardship. He notes that forest landscape management in British Columbia is still looked upon by many as a frill or an extra hurdle that foresters must clear in order to accomplish their real mission, but it should be considered a part of good forestry, just as a concern for the forest soil is a part of good forestry.

Minimize Soil Displacement. Soil displacement refers to lateral movement of soil by mechanical forces. Tractors and logs can exert such force. Mechanically displaced soil is exposed to erosion, slides, slumps, and dry ravel. The potential for erosion is greatest on steep slopes, following heavy rainfall and with certain rock-soil types. Both soil displacement and erosion can expose subsoil, which is less fertile and has slower infiltration rates. Swanson et al. (1989:78) conclude that in the Pacific Northwest erosion alone seldom results in greatly reduced site productivity, except on slide scars and sites of persistent ravel, which are generally local in extent:

> On severely disturbed sites, however, erosion acts in combination with other factors to reduce productivity on the scale of decades to centuries. Extreme disturbance by intense wildfire or tractor yarding, for example, may cause loss of nutrients, mycorrhizae, and organic matter. These losses not only reduce long-term site productivity, but may also lead to sustained periods of accelerated erosion because the soil-stabilizing effects of live and dead organic matter are reduced or even eliminated. The two major influences of erosion processes in such cases are to remove soil and chronically disturb sites, thus delaying establishment....
>
> The best recommendation for managing the soil resource is to be judicious with the disturbance regime, especially with fire and physical disruption of the soil. Poor forestry practices can trigger long-term degradation of site productivity. We believe that in most areas where sound, modern forestry is practiced, accelerated erosion alone is unlikely to cause widespread, major loss of long-term productivity.

Manage Organic Residues. For a wide variety of sites (Atzet et al. 1989; Harvey et al. 1987*a*, 1987*b*; Miller et al. 1989), minimizing major disturbance or loss of forest floor (0 horizons) is a good precaution to avoid degrading productivity. For some sites in Alaska, however, disturbance can increase decomposition rates and enhance nutrient availability (Bormann and Sidle 1990; Heilman 1968). A reasonable generalization is that knowledge of the role of the forest floor in regard to nutrient storage and availability is important for productivity management. We believe that direct evidence is available for some locations that justifies management of certain other types of organic residues (Table 4). Large snags, for example, are important habitat for cavity-nesting birds and for mammals that are prey for some species designated threatened, endangered, or sensitive (Ruggiero et al. 1991). Coarse woody debris, down logs, or trees may provide important sites for N_2-fixation and plant-available water, especially in dry areas (Harvey et al. 1987*b*).

Monitor and Evaluate Operations. It is important to measure the impacts of our forest practices. Miller and Hazard (1988:61-62) point out that to know the effects of timber harvesting and forest practices on long-term wood production we must measure volume growth on permanent plots in a sampling of stands. Changes in soil characteristics, or other substitutes, can provide indirect evidence, when such features are shown to be reliable predictors of long-term tree growth. They note:

> Quantitative monitoring involves statistical sampling. Without a formal and valid sampling plan, no assurance can be given that the monitoring effort will generate the required information with specified reliability. Data collected on suitable monitoring or survey plots can be used both to supplement research data used in growth and yield simulations and to validate or calibrate regional simulations for more local situations. The general plan for monitoring long-term site productivity should integrate all levels of sampling and other types of monitoring or surveys as appropriate. An integrated plan should satisfy numerous monitoring objectives at least cost.

Additional research is needed to complement and support operational monitoring and decisions (Powers 1987). Powers et al. (1990*a*, 1990*b*) describe a plan for responding to this need.

Recommendations for Specific Forest Types

Recommendations in the preceding section apply to all forest types. In this section, we discuss concerns and recommendations for specific forest types.

Upper-slope Forests of the Cascade Range. High elevation forest sites are especially vulnerable to forest practices requiring heavy machinery that displaces, compacts, or erodes the soil. High elevation forests are cold and wet much of the year and the trees have a large proportion of fine roots in the surface organic layers which structurally hold the soil (Vogt et al. 1989). According to these authors (p. 156), nitrogen is the nutrient most affected by management practices because large quantities accumulate in surface organic horizons and in vegetative biomass, which are either disturbed or removed by harvesting and site preparation. Most critical is disturbance of the forest floor. If the forest floor is burned, the nitrogen lost cannot be readily replenished:

> If N fertilization were feasible at high elevations, then replenishing N lost because of harvesting or residue management would be possible. Some growth increases have been reported after fertilizing upper slope forests.... Fertilization may also increase the decomposition rate of surface organic layers; yet more rapid decomposition may not be desirable at these elevations if the nutrients immobilized in organic layers form a critical reservoir. How nitrogen fertilization affects such nutrient conservation mechanisms as well as tree growth mechanisms, such as frost hardiness or carbon allocation to roots, needs to be examined at these elevations.

Powers (this volume) reports positive response to nitrogen fertilizers in two-thirds of 21 trials in upper-slope types in northern California. This is about the same proportion of responding stands as in coast Douglas-fir (Miller et al. 1986; Chappell et al., this volume). Moreover, the average five-year volume gains in young stands of *Abies* species are similar and intermediate to regional averages reported for Douglas-fir for a four-year period (15.7 m^3/ha; Turnbull and Peterson 1976) and for a six-year period after fertilization (22.3 m^3/ha; Peterson 1979). Indications are that phosphorus exists as a secondary deficiency. Probably this relates to the reliance of high elevation forests on organic sources of phosphorus (where availability is determined by slow rates of decomposition). In cold-dominated systems, what applies to nitrogen also seems to apply to phosphorus. This is discussed by Powers and by Powers and Edmonds (this volume).

Lodgepole Pine (*Pinus contorta* var. *latifolia*). According to Harvey et al. (1989, 1987*a*), minimizing soil displacement and conserving organic matter are the keys to maintaining long-term productivity of lodgepole pine. Soil compaction is a significant hazard on the fine ash soils (Geist and Strickler 1978). Benson (1982) describes and evaluates initial and ten-year effects of alternative harvesting and residue treatments. There was no single best alternative among pile/burn, broadcast burn, residue removal, and chip/spread to attain all forestry objectives. A treatment that works well for one objective may not for another. The different harvest treatments resulted in complex interactions among the various impacts. Benson provides a method for comparing various trade-offs among forest objectives, including wildlife and aesthetics. Mika et al. (this volume), Yang (1985), and Brockley (1990) quantify response of lodgepole pine to fertilization.

Mixed Conifers of Interior Forests. According to Harvey et al. (1989:174-175), mixed conifer forests occupy a wide range of conditions, and species composition is diverse. Species composition and stand productivity are mainly governed by available soil moisture, nutrient supply, and temperature. One of the most dominant and essentially universal features of such sites is the presence of surface-deposited pumice and volcanic ash varying from about 15 to 76 cm deep, generally underlain by older, buried soils of varied origin with textures from sandy loams to clays. Some buried portions are gravelly and stony. Soils influenced by ash usually have relatively high water-holding capacities. Plant-available water capacities of 25 cm are common. Natural soil bulk densities average about 0.6 g/cc but may vary depending on location and management impacts. These low densities provide for rapid infiltration, high water-storage capacity, and good aeration. Maintenance of long-term productivity requires protection from excessive compaction and displacement of the surface soil (ash and organic matter components). Accordingly, Harvey et al. conclude: "The soils in both the frigid and cryic regimes are among the most fertile of the Inland forests, but management of nutrient reserves and organic matter is critical to maintain productivity levels."

Moreover, interior mixed-conifer forests are particularly prone to insect and disease attack. Thus disturbances that are likely to induce mechanical injury or water or nutrient stress in these stands are likely also to induce subsequent pest problems that can dramatically reduce short-term productivity.

Mika et al. (this volume) provide encouraging results from fertilizer trials in this type.

Ponderosa Pine. See the review by Breuer (1989). According to Harvey et al. (1989:174), ponderosa pine forests generally grow on three broad but distinct groups of soils:

> Probably the most prominent and contiguous of these soils in Oregon are those from air-laid pumice and ash. These cindery and pumiceous soils often overlie older, loamy, buried soils at depths of about 12 to more than 60 in. (30-150 cm). These soils are coarse textured but store relatively high amounts of readily available soil moisture.... Soil OM is concentrated within 6-10 in. (15-25 cm) of the surface, and nutrient content declines rapidly with depth. Although these soils are relatively resilient, assurance of site productivity potential requires that the nutrient regime be maintained by conserving OM and minimizing soil displacement.
>
> The second most prominent group of ponderosa pine soils are those that are moderately deep and dark colored, fine, and fine-loamy, derived from basalts, andesites, and clayey sediments. These soils are easily puddled and compacted when wet but have relatively high strength when dry. On slopes

greater than 30%, surface erosion is especially significant when vegetation is removed....

The third group of ponderosa pine soils are those that are coarse, loamy, and shallow to deep, derived from rhyolite, andesite, granitics, glacial till, and outwash. They usually have low OM content and low plant-available water-holding capacity (less than 3-4 in., or 8-10 cm). Soil displacement and erosion represent potential hazards to long-term productivity, particularly on slopes greater than 30%. Organic matter, surface soil nutrients, and moisture conservation are likely critical on all these soils for maintaining long-term productivity of ponderosa pine.

Powers et al. (1988) found severe nitrogen deficiencies in older plantations scalped of topsoil during site preparation. Invariably, growth was poor and response to nitrogen fertilization was high.

Mika et al. (this volume) and Powers et al. (1988) summarize results from fertilization trials in the ponderosa pine type. On the whole, nitrogen fertilization can improve five-year volume growth by an average of 30%. Where summer drought occurs, fertilization response is improved greatly if young stands are free of weed competition. Once moisture and nitrogen deficiencies are corrected, other nutrient deficiencies limit growth. In California, volume increases of up to 400% are possible in young plantations kept free of weed competition and fertilized regularly with multiple nutrient fertilizers (Mika et al., this volume).

Forests of Interior British Columbia. In western Canada, as elsewhere in western forests, nitrogen is an important nutritional factor commonly limiting tree growth. In the interior of British Columbia, however, climatic and other factors limit response to nitrogen fertilizer, so that forest fertilization is often economically unattractive. Hence, conservation and effective utilization of site nitrogen reserves are particularly important.

Low concentrations of sulfur are common in foliage of interior conifers (Ballard 1986). Also, some trials have shown that N+S application resulted in better growth than nitrogen fertilization alone (pers. comm., R.P. Brockley, B.C. Forest Service, November 1991). Consequently, attention must be paid to such practices as prescribed burning, which volatilizes sulfur and thus may increase the need for sulfur application where nitrogen fertilizer or biological N_2-fixation is used to enhance site nitrogen status.

Soil surveys in interior British Columbia have indicated extensive areas where exchangeable potassium in the root zone is less than twice the amount of potassium in harvestable stands. Because low specific surface area of soil particles limits rate of nutrient release by mineral weathering, concerns are focused particularly on the coarse-textured, low potassium soils (e.g., the Alix, Kaslo, Ptarmigan, Ramsey, and Toneko soils, all of which are of glaciofluvial origin). However, some finer-textured soils (e.g., the Dezaiko soil, derived from loamy till) also contain little exchangeable potassium. Research is in progress to quantify the rate at which the available potassium level in such soils can be replenished by weathering. Because bolewood and bark harvesting in interior stands removes only about half as much potassium as whole-tree harvesting, some constraints on the latter may be needed to ensure sustainability.

Mechanical site preparation or prescribed burning commonly results in faster growth of conifer plantations in the northern and central interior of British Columbia (Ballard and Hawkes 1989). Although several influences may be at work, the enhancement is thought to result mostly from increased root-zone temperature in the growing season, due to forest floor removal or incorporation with mineral soil. Burning or scalping of forest floors, however, often results in poorer nutrient status of conifers. Long-term productivity might be enhanced by selecting site preparation methods which improve microsite temperature regime at the time of planting, yet keep forest floor nutrients within reach of the root systems as trees mature.

Excessively large areas have been subject to soil degradation associated with skid roads and landings in many interior forest areas. The wide range of log sizes and large number of species in many interior stands have induced some operators to construct very large landings for use as dry-sort areas. Moreover, the network of skid roads within logged areas is often excessively dense, and some logged areas are surrounded by deeply bladed, very wide fireguards. Thus, on a significant fraction of harvested land, the more productive soil horizons may be lost by blading and the remaining materials may be compacted. Ground-based skidding, particularly on fine-textured soils under wet conditions, has degraded soil structure. Implications of these activities for long-term productivity have led the provincial Ministry of Forests to establish interior harvesting guidelines to prevent or minimize soil degradation. Soil physical properties and nutrient conservation are major considerations underlying these new guidelines.

Coast Douglas-fir. Miller et al. (1989:125) conclude that timber harvesting, site preparation, and vegetation control can affect short-term, and potentially long-term, site productivity in several ways. Harvesting and site preparation rarely increase inherent long-term site productivity and always result in soil disturbance and some loss of nutrient capital. The location and frequency of occurrence of forest practices contribute to their cumulative effects.

Effects of forest practices in regard to site productivity are likely to vary depending on the site, the practices, and the operators. Negative effects on soil properties, however, do not always reduce growth of trees and stands. Such variation means that predicting consequences is uncertain, techniques or prescriptions must fit the local situation, and more information on tree response is needed to improve predictions.

Maintaining or increasing timber production over one or more rotations may be possible by using intensive silvicultural practices to make up for losses of inherent site productivity. But in the final analysis, the comparative biological and economic costs of soil conservation versus soil substitution or replenishment must be evaluated.

Miller et al. thus suggest two strategies to cope with uncertainty and reduce skepticism about the real effects of forest practices on long-term site productivity: (1) Avoid unnecessary soil disturbance and loss of organic matter. Conservation is a common-sense approach to soil management. Conserve premanagement conditions of the soil. When in doubt, minimize change. (2) Use existing information and keep abreast of new developments. If information is inadequate, decisions should be based on biological principles, common sense, and past experience.

Chappell et al. (this volume) and Miller et al. (1986) summarize results from fertilization trials in Douglas-fir stands. Absolute and percentage responses to nitrogen fertilizer are inversely related to site index; thus response in stem volume growth is greater on below-average sites than on above-average ones. These results indicate that conserving nitrogen on poor quality sites during harvesting and site preparation will especially benefit site productivity.

Coastal Hemlock (*Tsuga heterophylla*) and Spruce (*Picea sitchensis*). This forest type generally occurs within the coastal fog belt in Oregon through southeastern Alaska. General recommendations for soil management apply to this type. Climate and soil fertility generally favor rapid tree growth; however, both of these growth factors progressively decline toward Alaska. Some sites in southeastern Alaska are noteworthy exceptions to the common recommendation to minimize soil disturbance during harvesting and site preparation. The natural trend of large accumulation of forest litter atop the forest soil progressively leads to slower rates of nutrient turnover (Bormann and Sidle 1990). Similar situations were earlier reported for the interior forests of Alaska, where natural succession to closed stands of conifers cools the underlying soil, thereby slowing nutrient cycling and raising the permafrost toward the soil surface (Heilman 1968). Physical disturbances provided by natural windfall, or harvesting and site preparation, are proven ways to stop or reverse this progress of declining soil temperatures and nutrient availability.

Chappell et al. (this volume) and Miller et al. (1986) summarize results from fertilization trials in coastal hemlock.

Mixed Conifers of Southwestern Oregon and Northern California. Atzet et al. (1989:197) concluded that in this area, as in the rest of the Pacific Northwest, management practices can significantly affect long-term productivity:

> Research shows that trends are similar regardless of the climatic regime. Most practices that manipulate the top layer of soil, and particularly those that remove it, degrade productivity as measured by any standard. Nitrogen fertilization, on the other hand, consistently improves productivity. Perhaps these overall results indicate the need to assess the balance of inputs and outputs associated with current management practices.
>
> Although trends are similar among climatic regimes, the details presented show that rates of change differ. The higher temperatures and drier climate of the Mediterranean regime affect rates of soil development. But generalization is difficult because the SWO/NC Area is so variable. The warm, wet climate of coastal sites accelerates decomposition and incorporation of organic matter into the soil system, but the cold, dry climate of high-elevation inland sites allows organic matter to accumulate on the soil surface. Local research is our best source of information. Site-specific dynamics must be considered when planning management strategy....
>
> The fate of organic matter is loosely related to site N and productivity. It plays an important role in the C and N cycles, stores nutrients and energy, and hosts plants and animals that build soil. Organic matter is visible, easily measured, and sensitive to management activities and could be used to indicate trends in long-term productivity.

In California, the mixed-conifer forests of the Sierra Nevada rank very high in soil nitrogen availability compared with other forest types, and growth response to nitrogen fertilization in natural stands is comparatively low (Miles and Powers 1988).

Sustainable Levels of Productivity in Multiple-Use Forests

Productivity of western forests for timber and some nontimber values could be sustained at various levels.

With an objective of maximum rates of wood volume production from each stand or the forest as a whole, we should harvest at the age when mean annual increment culminates (CMAI). This age to culmination of stem volume depends on numerous factors including silvicultural regime, species, site quality, and utilization standards. For reasons explained earlier, rotations set by CMAI are invariably longer than those currently set by optimizing financial returns. Rotation length near CMAI also favors many nontimber values. Water quality and fisheries are favored because long rotations imply fewer major mechanical disturbances of soil during logging and site preparation. Disturbance can increase erosion and mass soil movement. Longer rotations clearly benefit wildlife species designated threatened, endangered, or sensitive (TES) because much of their favored habitat is stands with old-growth characteristics. Food and cover requirements of other wildlife can be provided by stand conditions ranging from recent clearcuts to mature stands. Although people vary in their opinions about aesthetics of forested landscapes, most probably favor landscapes with large trees and little evidence of recent harvesting activity.

Silvicultural inputs affect the level of sustainable timber growth, especially the proportion that is merchantable. Stand conditions resulting from planting, weed control, early thinning, and fertilization also affect attainable levels of nontimber values. The tradeoffs and optimum balance of management decisions, like rotation length and choice and intensity of silviculture, and resulting levels of nontimber values need clarification. In Figure 6, we express opinions about the likely effects of some of the management scenarios we discussed before.

In summary, most will agree that it is necessary to sustain the capability of forest land to produce timber and other values. Uncertain, however, is the quantity of timber yields that can be sustained and the balance among amenities. For some combinations of sites and management intensities, silvicultural inputs are required for sustaining even minimum levels of timber productivity. For most sites, maximum productivity can be sustained only with appropriate, carefully planned and executed silviculture. In addition, the soil fertility must be protected by careful harvesting and site preparation. Until additional data and analyses are available, we advise forest managers to consider existing evidence and speculations, and adopt a conservative rather than a risk-taking attitude. This means balancing harvest levels with realistic estimates of sustainable growth. This recommendation is illustrated by the diagonal zone of Figure 7. We have suggested ways to increase the level of sustainable growth. These potential gains from silviculture can be conservatively or optimistically estimated, with attendant effects on setting harvest levels. We have suggested that future political or regulatory actions, economic constraints, and possible climate changes could affect the levels of sustainable growth. These uncertainties must also be considered as risks in setting harvest levels.

Conclusions

Others have also reviewed existing information and recommended ways to maintain or improve forest productivity. Collectively, our purpose is to encourage western land managers to adopt practices likely to sustain forest productivity at high levels. About the

ACTION			ASSUMED REACTION						
							Wildlife		
G=C level	Rotat. length	Silvic. inputs	Soil product.	Timber MAI	Water quality	Fish quantity	protect TES *	maintain habitat	Aesthet.
1	<CMAI	none	lower	min	min	min	min	min	min
2	<CMAI	↓	normal	↓	↓	↓	↓	↓	↓
3	CMAI	↓	↓	↓	mod	mod	mod	↓	↓
4	CMAI	mod	↓	↓	??	??	??	max	max
5	CMAI	max	greater	max	??	??	??	??	??

Figure 6. Management options for sustainable growth and harvest levels. *TES = threatened, endangered, and sensitive species.

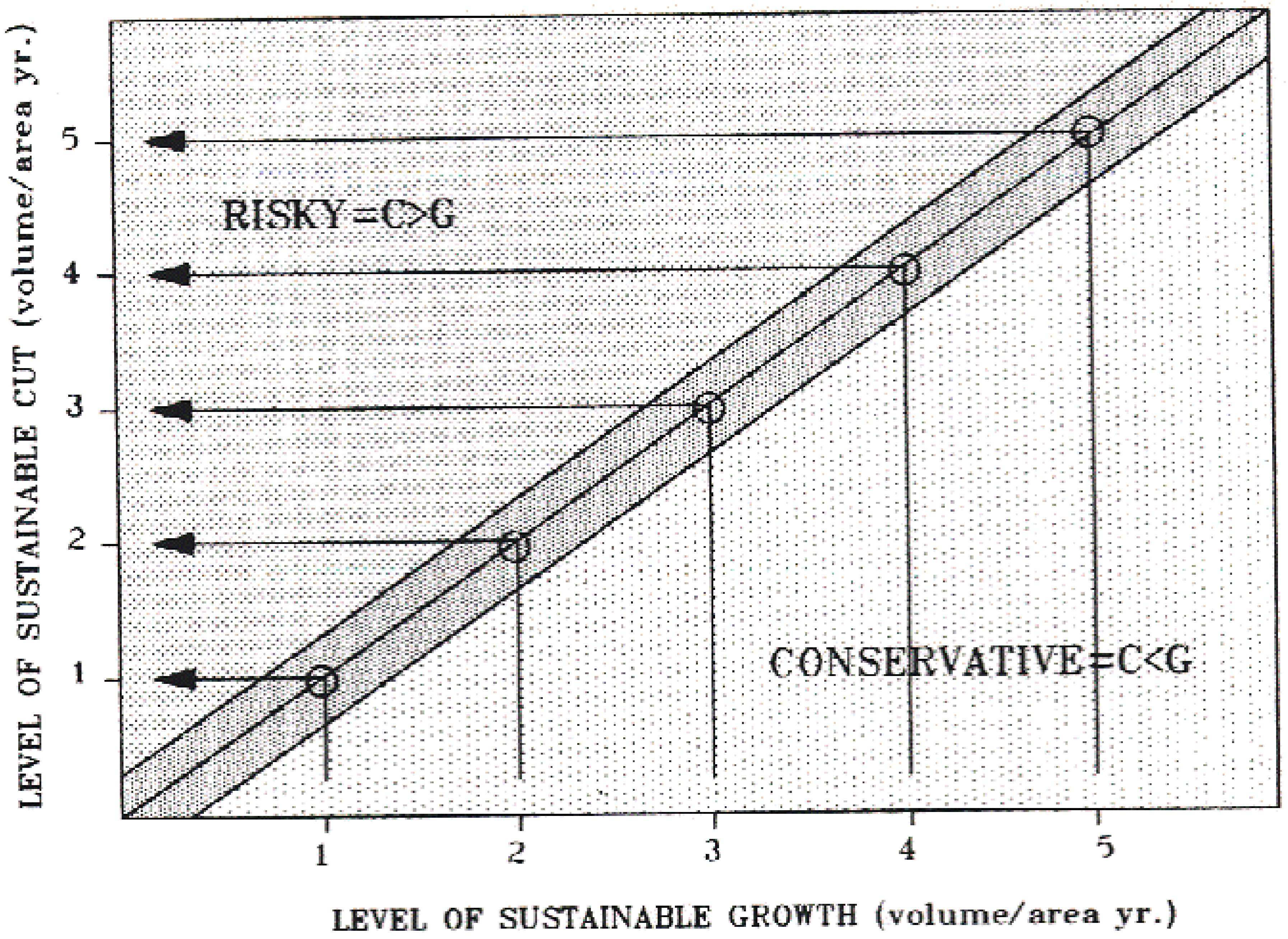

Figure 7. Rotation length, silvicultural inputs, and impacts on soil productivity determine sustainable levels of timber and nontimber yields.

topic of maintaining or improving forest productivity over several rotations, direct evidence for western forests—yields of wood, water, wildlife diversity—is clearly nonexistent. Hence we, like our predecessors, can offer only general principles of biology and soil science and a scattering of short-term data or observations to support our recommendations. The available evidence may convince some practitioners to modify their operations—usually at increased costs. Others, who consider themselves equally prudent, will await more quantitative data, hence economic analysis, before deciding. Because the current rate of forestry operations and the number of attendant questions far exceed the rate at which such quantitative data are produced, this second strategy of waiting for more reliable information is more likely to place long-term forest productivity at risk.

Conclusions that apply generally to western forests include the following:

1. Long-term productivity for timber is sustained when volume harvested equals sustainable volume growth of trees larger than some specified minimum size. It follows, then, that the level or quantity of sustainable growth sets the level of sustainable cut. For values other than timber, careful applications of appropriate silviculture or extended rotation length can usually maintain and often enhance their productivity or value.
2. To maintain or increase long-term sustainable levels of both timber and nontimber objectives, it is necessary to conserve the basic factors of site productivity. These include suitable soil for root proliferation, essential nutrient elements, and organic matter which contributes to soil maintenance and nutrient supplies. Operationally this means minimizing erosion and soil compaction; limiting leaching, removal, or volatilization losses of nutrients; optimizing retention, decomposition, and incorporation of organic residues in soils; and ameliorating accidental soil degradation. Additions of fertilizers or other materials and cultivation of N_2-fixing plants can, in some places, replace or supplement these "natural" processes of site maintenance. However, the basic structural, chemical, and biological properties of soils must be maintained or enhanced in order to best utilize management supplements. Details of maintenance or enhancement of productivity factors and of suitable management inputs must be tailored to fit each forest ecosystem, recognizing limiting factors and those amenable to manipulation. There is no universal panacea, and no substitute for knowledge that is site-specific.
3. To maximize average rate of volume growth in a rotation or series of rotations, managers should set rotation length to equal or exceed culmination of MAI (mean annual increment) for the intended tree size, utilization standards, and management regime. These rotations favor most nontimber values.
4. To reduce uncertainty in forest management, managers need additional quantitative data via research and long-term monitoring.

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Questions and Answers

Authors' note: These questions were written and submitted at the conference. Since the questioners had limited time to compose their questions, our answers may not always fit their real or full concerns.

In dealing with balancing growth, cut, and sustainability, you ignore forest-level effects of fertilization. You cannot do this! It is not realistic to consider only stand-level concerns and growth rates. In fact, the argument for use of fertilization comes via ACE [allowable cut effect] and faster operability, rather than technical rotations. The sustainable basis for forestry comes first via both maintaining soil fertility and balancing age classes. In fact, many companies accept reduced growth rates to accelerate operability.

Thank you for adding another viewpoint: that by increasing growth in immature stands, foresters accelerate cutting of overmature or mature stands to secure a more uniform distribution of age classes. The benefit of balancing age classes of stands within a forest is increased "operability," as you comment. This means a steadier flow of volume available for harvest. We assume that cutting overmature stands (those past the point of diminishing returns) of volume MAI would also provide opportunity to have more stands that could eventually be cut at CMAI. Hence, we agree that fertilization, through the ACE effect, could also increase the level of sustainable growth from the forest.

Your speculative comment about reduced site productivity by shorter (50 year) rotations is not substantiated by any data I've reviewed on Northwest forests. Why not speculate that shorter rotations may increase long-term productivity? Especially if soils are cared for, and new technology (i.e., genetic and other silvicultural tools) can be incorporated into shorter rotations, on a more responsive timely manner than 120 year rotations.

(Miller): You are correct, my comment was speculative, yet was limited to worst-case scenarios—rotations shorter than CMAI and with excessive soil damage or nutrient export. Circumstances leading to these scenarios would probably include (1) poorer quality sites (low supply of nutrients and soil organic matter); fine-textured soils prone to compaction, puddling, and erosion; and intensive utilization of bole wood, (2) on-site concentrating or burning of slash, (3) no or unsuccessful remedial measures to compensate for such activities repeated at short (ca. 50 year) intervals. Currently, the "data" to substantiate this pessimistic view are no less—and probably more—than the data to support an optimistic, "no negative consequences" view. The professional consensus of the authors of this paper is that the harvesting practices and site conditions specified above would result in reduced capacity of the soil to grow desired crops, especially in nonmesic (less favorable) climatic conditions.

Yes, we agree that shorter rotations could increase long-term productivity *if* soils were cared for and silviculture were intensive. Our questions are (1) increased over what base level? and (2) at what cost relative to other options (longer rotations, conservation and prevention vs. less intensive inputs)? In conclusion, we agree that repeated short-rotation, intensive silviculture forestry is appropriate for some commercial forest sites, but not all.

By short rotations we convert to improved stock sooner. Won't productivity be enhanced?

Yes, provided the "improved stock," as a single factor, enhances yield more than "woods-run stock" would. In the talk and the preceding text, we attempted (1) to separate the rotation-length issue from the benefits of intensive management issue, and (2) to specify the base of comparison. For any management regime (improved stock, fertilization), setting rotation length to where MAI culminates equates to maximum average rate of volume production for that regime. Rotations shorter or longer than years to CMAI will not be as productive (of the specified product size) per unit of time and of area.

Can short rotations with intensive silviculture be more productive (greater MAI) than longer rotations without or with less intensive silviculture? Yes. How much more? Let's compare the MAI estimates of the two regimes. If the question is which regime will provide the greater economic return, this measure of productivity requires additional analyses.

Doug Daoust, Mt. Hood National Forest, showed a slide illustrating the gains of tree improvement. If I can increase the productivity in the next crop by 10%, why would I wait until the existing stand peaked MAI before harvesting it? I would grow more wood by getting the faster growth rates.

We agree. Perhaps you would decide this after you compared the two options as to *assumed* benefits and costs. But your estimates of "genetic gains" on a volume per hectare basis will be imprecise and probably decrease your certainty.

Can you move CMAI forward to 50 years by speeding up Douglas-fir dominance of the site through plugged seedlings, vegetation management, and spacing control?

We do not pose as experts in our response to this question, although we have discussed this with some growth and yield specialists (see text and Figure 4). In general, regeneration and early silvicultural practices that increase stocking to full occupancy of the site will decrease age of CMAI. Spacing control has the opposite effect, however, if it is severe enough to reduce stocking and occupancy.

Doesn't fertilization, simply put, move up in time the point that CMAI is reached?

That explanation or assumption is generally correct. See the text section "Role of Fertilizers in Maintaining Long-Term Productivity." Exceptions to that explanation are (1) if the time of first fertilization was after CMAI and (2) if fertilization would increase "stockability" or "carrying capacity"—that is, increase the number of crop trees that were retained and not lost to suppression mortality. Quantifying the relative importance of item 2 is yet to be done. If "stockability" were proved to vary among site quality classes, then this would suggest that fertilizers, by temporarily increasing site quality, could have a similar effect.

Clarify the mitigative role of fertilizer in long-term productivity. Can and should fertilization be used for <u>future</u> mitigation on sites we feel will be damaged and still maintain long-term site productivity?

We know that appropriate fertilizers and dosages can improve nutrient status of some soils before or after forests are first harvested and managed. Vegetative growth and other biological processes are enhanced by fertilization at these locations. It follows that fertilization can and should be used for future mitigation on sites where inherent or management-induced nutrient deficiencies limit the desired level of site productivity. Fertilization, however, is but one mitigative tool. It is potentially appropriate for some sites to mitigate nutrient export or losses. It can help maintain long-term site productivity. Determining where and how is our collective task!

Your graph showing role of growth versus sustainable rate of cut [Figure 1] does not explicitly acknowledge changes in input requirements over successive rotations to maintain a given level of growth. Can you suggest certain soil/climate conditions whose inputs (i.e., fertilizers) may degrade the site rather than improve the site? Mining of soil organic matter?

Your concern has a valid theoretical basis: actions like fertilization create reactions; these reactions, however, depend on specific conditions—what, when, where, how. What will be our measure of "site degradation"? Loss of organic matter or nutrients? If so, then, yes, large dosages of nitrogen as single or cumulative applications could degrade some sites to some extent. This would be most likely (1) where nitrogen severely limited rates of organic matter decomposition and (2) where soil and vegetation were unable to capture (retain) a large pulse of nutrients released by accelerated rates of organic matter decomposition. How much degradation should we accept as a trade-off for possible benefits? Is zero impact (negative) in managed forests possible, even with current best measures to mitigate?

Are you not mixing up productivity and yield? Your yield is changing in the model but not productivity.

I assume this refers to Figure 1, which schematically shows the dependence of yield on sustainable productivity of the site. Both yield and productivity are measured by wood volume per unit area and per year. The intent of this model (figure) is to show the need to balance the rate of volume harvested (yield) with the sustainable rate of volume growth. Volume harvested is the dependent variable; so it is changing (as you stated). Yet productivity or sustainable growth in this figure can also change depending on how the factors contributing to growth are changed. The diagonal line in Figure 1 depicts the consequence of changed growth rate on harvest rate.

Why do you take the very safe approach of cutting less than we grow. This is not a challenge to anyone. Are you considering the reduced area for growth? Maybe we need to make this reduced area more productive and then cut more on this area?

(Miller): I have a conservative bias about level of harvest. First, because current procedures for measuring and estimating current growth rates—let alone sustainable growth rates—are imprecise and of unknown accuracy. Second, there are additional uncertainties that should temper or reduce optimism during this transition from exploitative to managed forestry. Yes, the quantity (and quality) of the commercial forest land base is one uncertainty; other uncertainties include the regulatory environment and the rate at which growth-enhancing techniques will be developed and, especially, implemented. I believe the "challenge" is for pessimists to be more optimistic and, conversely, for optimists—as most foresters and farmers tend to be—to be more objective in their predictions of future forest yields.