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REVIEW OF SITE PREPARATION IMPACTS ON LONG-TERM SITE PRODUCTIVITY IN NEW ZEALAND

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EXECUTIVE SUMMARY

1. A ten-day visit to both the North and South Islands of New Zealand in the first two weeks of February 1990 provided a review of current site preparation practices in both Timberlands and private company radiata pine forests. The tour also reviewed various research installations, and discussions were held with various Forest Research Institute scientists who have been involved in research on the topic. Some of the FRI research literature on the subject was examined.

2. On the basis of the tour, the discussions, and the review of research results, it is clear that forestry in New Zealand has not been, and will not in the future be, immune from the second- and/or third-rotation yield declines that have been reported elsewhere in the world. The greatest risk of such declines has traditionally been thought to occur as a result of short-rotation, plantation forestry with intensive management and harvesting. Much of New Zealand radiata pine plantation forestry satisfies this criterion, especially where intensive site preparation techniques are applied. The traditional view has also held that the problem is mainly one of nutrient-poor sites. However, it is anticipated that careful investigation will reveal losses in site quality (the potential productivity of the site) as a result of some current harvesting and site preparation practices on medium and good sites as well, and that in absolute terms these losses may be greater than the absolute losses on the poor sites.

3. It is thought that the manifestation of site quality decline has been masked to some extent by variation in weed problems and by genetic improvement from one rotation to the next, and also by the intensification of silviculture. Achieved site productivity that is the result of management inputs has been confused with inherent site quality (potential site productivity in the absence of technological inputs). However, it is clear that when these effects are accounted for, there are very serious losses of forest growth on some sites, and that these are persisting throughout the rotation.

4. The greatest threat to long-term site productivity has undoubtedly been the loss of soil organic matter and nutrients caused by slash and soil displacement by windrowing. There would appear to be few cases where a continuance of this practice is warranted or acceptable.

5. Many cases of root-raking, and even some cases of line-raking, appear to have similar effects to windrowing. A major re-evaluation of root-raking is called for, and its use should be restricted to soil types and slopes on which it is clear that its impacts on long-term site quality are acceptable.

6. V-blading would initially appear to pose far fewer threats to long-term site quality than windrowing or root-raking. Soil organic matter is not removed far from the trees, or may be concentrated in the piles beneath the trees. On frosty sites the elevation of seedlings above the frost layer may be a prerequisite for plantation establishment. However,

examples of excessively deep soil gouging were seen, seedling instability in the low bulk density piles was observed, and there are concerns that accelerated leaching of nutrients from the buried organic matter in the piles may result in significant nutrient losses. Considering the extent of V-blading in New Zealand and the lack of knowledge of the dynamics of organic matter and nutrients in the piles, this topic is clearly an urgent research need.

7. Herbicides appear in many cases both to be necessary and to pose the least threat to the environment of any of the alternative weed control methods other than manual weeding. Where manual weeding is not possible for economic, social, or technical reasons, careful use of herbicides appears to be the weed control method of choice. The need for herbicides is greatest in very low-density plantation systems, and if herbicides are restricted by economics or environmental considerations, or by public opinion, higher density plantation strategies may have to be considered. Because of public attitudes, herbicides should probably be replaced with biological methods of weed control, or used as part of an integrated strategy, wherever possible.

8. The sometimes "heroic" site preparation methods are apparently justified in some cases by the needs of the "clearwood regime" silvicultural strategy. In those cases where long-term site quality or other considerations suggest restrictions on these site preparation methods, alternative silvicultural strategies might well have to be reconsidered. Many of the weed problems would apparently be reduced in denser plantations, as would the need for access to prune.

9. Prudence, and the shortcomings of retrospective research, suggest the need for the establishment of well-designed and monitored long-term field trials by which to characterize the long-term effects of various site preparation techniques on site quality. However, foresters cannot await the long-term results of these trials. Alternative prediction strategies are required in the interim. This requires both that process research be conducted in conjunction with the long-term field trials, and that existing and newly acquired understanding of ecosystem processes, and the effects of management thereon, be built into predictive, knowledge-based, or combined experience-based/knowledge-based models. Other management decision-support tools, such as "expert" systems, may also be appropriate. The monitoring data from the long-term installations will provide the opportunity to validate these models or expert systems. Because of the complexity of this research undertaking, an overall research strategy is called for that combines chronosequence research, retrospective research, long-term field trials, and modelling. The first and most critical design criterion for this strategy is the identification of the type of predictive decision support tool that is to be the ultimate product of the research program.

10. There has clearly been a conspicuous failure in many sectors of New Zealand forestry to pay adequate attention to the basic resource (the soil), and to attempt to understand the determinants of production ecology and their economic implications. This is not a unique failing. In fact it is the unfortunate hallmark of forestry around the world. It is clearly time

to integrate site nutrient, organic matter, and overall soil management considerations into all aspects of forest management decision-making.

11. Timber production is first and foremost an economic activity, secondly a social activity, and thirdly an environmental management activity. Around the world, professional foresters and their management of a large proportion of the terrestrial land surface are under attack. Soil degradation, loss of species diversity, water and air pollution, and the greenhouse effect and "ozone hole" are no longer "left wing lunatic-fringe" issues; they have become major political platforms, and rightly or wrongly, foresters are being blamed for many of the problems. Unless foresters are able to demonstrate to the public that they are practising sustainable silviculture, forest management options in the future will be controlled more by an often poorly informed public and politicians than by logic, science, and the principles of sustainable resource management. It is time for foresters to become more sensitive to public concerns, to communicate more effectively with the public about forestry, and to practise sustainable forest management. Only then will they be able to show that they are practising what they have always preached: "sustained yield". A new partnership is needed between professional forest resource managers, forest scientists, and educators in order to achieve high quality, sustainable resource management and a public that understands and respects it. A good place to start in New Zealand would appear to be the question of the impact of site preparation practices on the long-term sustainability of the resource.

ACKNOWLEDGEMENTS

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The authors would like to express their sincere appreciation for the hospitality and information provided on all these tours. Apologies to those individuals whose names have been omitted in error.

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IMPACTS OF SITE PREPARATION ON LONG-TERM SITE PRODUCTIVITY IN NEW ZEALAND

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INTRODUCTION

The profession of forestry has traditionally been dedicated to the concept of sustained yield. Although foresters have long believed in this concept and attempted to achieve it, sustained yield has taken on new meaning in the light of the report of the World Commission on Environment and Development (1987). "Our Common Future" asserts that world population growth and Third World poverty are the two greatest long-term threats to the environment and the health of the human species, and that overcoming these problems requires the continued management and development of the world's renewable resources. However, this important report notes that this development must be demonstrably sustainable and must leave the global environment undamaged if life as we know it on this planet is to continue. This requires that foresters actually achieve sustained yield and not just aspire to do so.

Concerns about global climate change are adding to the forester's responsibility to sustain forest growth and yield. Global re-forestation in conjunction with productive, sustainable forestry would help to ameliorate the "greenhouse effect" by providing an increased sink for atmospheric carbon dioxide. In contrast, exploitive forestry, deforestation, and silviculture that ignores the soil and is insensitive to questions of long-term site quality and productivity contribute to the greenhouse problem by reducing the storage of carbon in forest soil and tree biomass. Clearly, there is a responsibility to sustain or improve the site quality, productivity, and yield of the world's forests that transcends albeit important shorter-term management and economic considerations.

Sustained yield in forestry can be considered at several spatial scales:

1. Global sustained yield of forest products over the next two or three decades will be largely a function of world climate change, air pollution, world population growth and the accompanying deforestation, the global economy, and conflicts between alternative uses of forest lands; issues that are, for the most part, beyond the influence of the local forester. However, over longer time scales, local site productivity will play a major role in determining the total global timber supply.

2. Regional sustained yield in the short run is a function of the area, the age and size class structure, and the species composition of the forest in the region. These variables are more strongly related to the quality of forest management and land-use decisions in the past than to the quality of current forest management. However, in the long run, regional sustained yield will reflect the impact of stand management on local site productivity.

3. Local (i.e., stand-level) sustained yield is a function of the potential site productivity (i.e., site quality) and the various ecological, economic, and management factors that determine the degree to which this potential is achieved. Because of the long-term significance of site quality for both local and regional sustainability of the forest resource, and ultimately for global sustainability, it is critically important that foresters consider the consequences of their local site management decisions for the productive capacity of the site.

The sustainability of forestry can also be considered at several temporal scales. Foresters often evaluate the short-term success of individual silvicultural practices (e.g., site preparation, thinning, fertilization) at increasing or sustaining tree production over five- to ten-year time scales. At the other extreme, we can consider the sustainability of productivity and yield over several successive rotations. In terms of short-term economics, the short-term outcomes of management practices are certainly important. However, in terms of the overall, rotation-length objectives of management, the effects of individual practices are less important than the combined effect of the rotation-length silvicultural system. In general, foresters should consider the consequences of their management decisions and silvicultural investments over at least one complete crop rotation cycle, and how management in one rotation will affect growth and yield in the subsequent rotation. Unfortunately, this has not always been the *modus operandi* in forestry.

This report is primarily concerned with the sustainability of site quality (i.e., potential productivity at the local or site level) over time scales of several rotations (i.e., long-term site quality)[1]. Industrial forest managers must obviously place great emphasis on achieved regional productivity (i.e., regional timber supply) over much shorter time scales than this if they are to remain in the business of forestry. However, for many forest companies or government agencies, the sustainable annual allowable cut (AAC) is largely determined by the current increment of managed stands, and if management causes increment to decline, future AAC's and timber supply can be expected to decrease. Where AAC's still depend largely on old-growth forests (e.g., in some parts of British Columbia, Canada), declines in site quality following forest harvesting and site preparation may not have much effect on the AAC for many years. But even in old-growth-dominated regions, a loss of site quality will eventually be paid for in terms of reduced harvest rates or increased silvicultural costs to sustain productivity. Clearly, it is in the long-term interests of companies who are committed to sustained-yield forest management, and it is their social responsibility as stewards of a substantial proportion of the landscape, to maintain site quality.

The objective of the report is to review the impacts of current harvesting and site preparation practices on the long-term site quality and potential productivity of radiata pine stands in New Zealand. The review is based on field inspections of site preparation practices and research thereon, discussions with industrial foresters and with scientists from the Forest Research Institute in Rotorua and Christchurch, and a perusal of some of the relevant literature. On the basis of this review, some critical knowledge gaps are identified, some potential lines of research are suggested, and recommendations are made concerning the manner in which site quality is managed.

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[1] The paper focuses on sustaining the timber resource, and does not discuss various other important renewable forest values that should also be sustained (wildlife habitat, clean water, fish habitat, recreation potential, etc.).

SOME BACKGROUND THEORY

The Determinants of Site Productivity and Yield

Before we can understand and predict both the potential and the achieved productivity of a forest site, we must understand the determinants of production ecology (Figure 1).

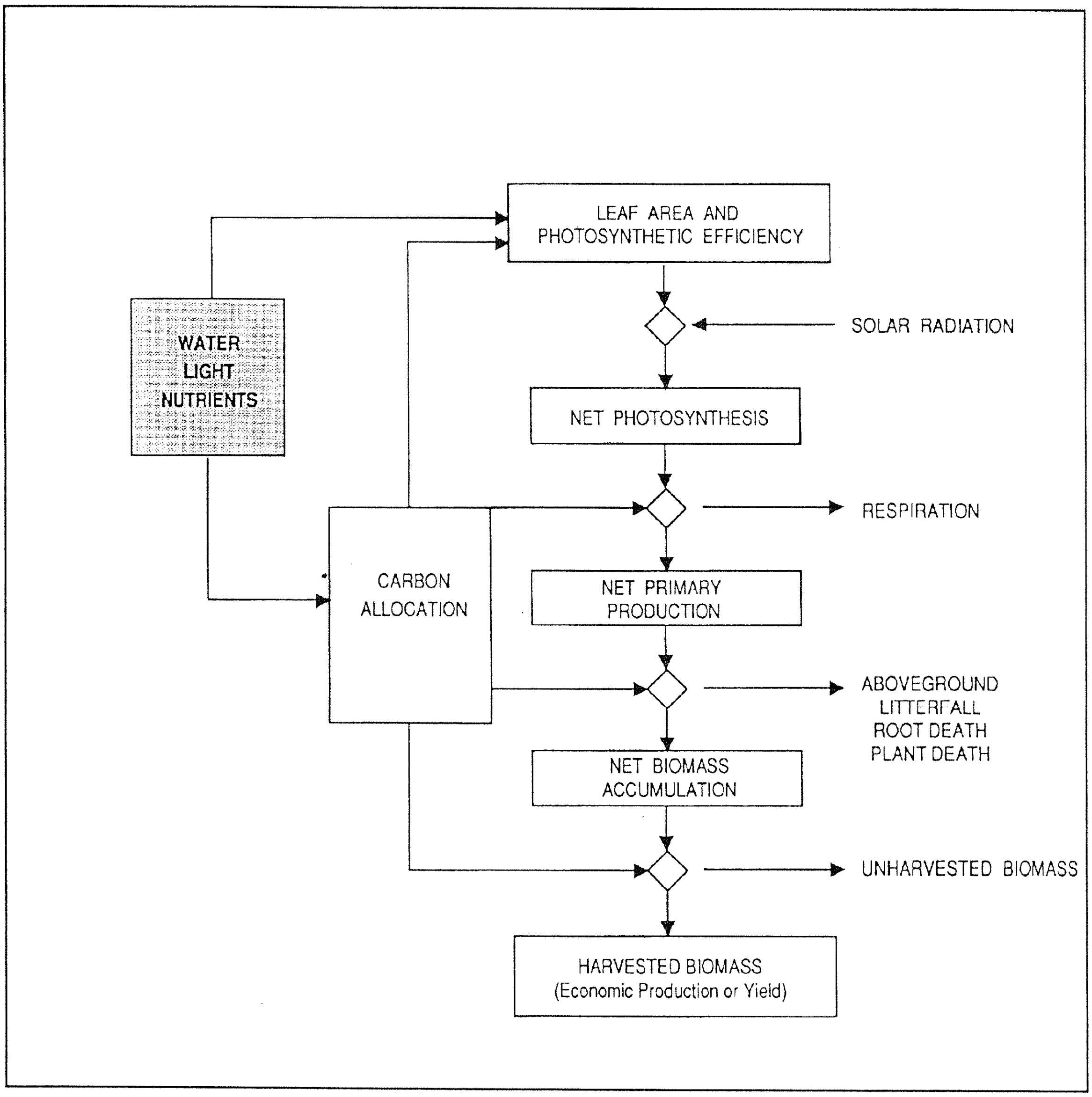

Figure 1: *Major determinants of forest production and yield within a particular climatic region. The diagram emphasizes the importance of the availability of soil moisture and nutrients at almost every stage of the progression from solar radiation to logs ready for transport to the mill. These soil resources may operate directly by determining leaf area and its photosynthetic efficiency, or indirectly through alterations in resource allocation between harvestable and non-harvestable tree biomass components.*

Forest biomass is created by the process of photosynthesis. The magnitude of photosynthetic production (net primary production, or NPP) is determined by the leaf area (or biomass)[2] and the photosynthetic efficiency of this foliage, both of which are determined largely by the soil resources of moisture and nutrients. The number, size, and weight of leaves carried by a single tree or other type of plant may depend more on the size of that individual tree or plant and its ability to compete with other trees/plants for both light and soil resources than on the total inventory of soil resources. However, foliage biomass per hectare, and thus potential site productivity, is largely a function of the magnitude of available soil resources.

Of the quantity of photosynthate produced by trees and other plants, some is lost by respiration, and some by annual litterfall. Loss by respiration will vary according to the weather (mainly temperature), but it also depends on the relative biomass of different tissues which vary in their respiration rate. The relative magnitude of these different tissues depends on plant age, stand density, and the availability of light and soil resources. Loss to litterfall depends upon the proportional allocation of photosynthate to permanent and non-permanent tissue, which is greatly influenced by the supply of soil nutrients and moisture. Of the new production that remains as permanent biomass, only a proportion of it will be economically harvestable, this proportion also being affected by the allocation of growth between different biomass components, which again depends on resource availability.

Both the potential capture of solar energy (i.e., potential leaf area) and the storage of captured energy in the form of economically-harvestable forest biomass are thus largely a function of the soil resources of nutrients and water (i.e., site quality). However, the actual storage of solar energy as economic biomass (i.e., the yield) depends on how much of the potential leaf area is achieved by the crop trees. That depends on the relative proportions of the leaf biomass on the site carried by crop and non-crop species, and on the rapid achievement and maintenance of "optimum" levels of leaf biomass by the crop trees. A high proportion of leaf area in non-crop species early in the rotation (i.e., serious weed competition for soil moisture and nutrients, and for light) will delay achievement of full crop tree leaf area, reducing rotation-length crop yields. Maintenance of sub-optimal leaf area per hectare by heavy thinning or low stocking may optimize the growth, value, and leaf area of individual trees, but will reduce total rotation-length biomass yield per hectare.

The Relative Roles of Soil and Atmospheric Determinants of Yield, and of Moisture and Nutrients as Determinants of Site Quality

Climate is the ultimate determinant of site productivity because it controls the length of growing and frost-free seasons, and the site water balance. The latter is the ultimate determinant of a site's leaf area carrying capacity (Grier and Running 1977; Gholz 1982). However, within a climatic area, variations in topography and soils combine to create closely coupled gradients of soil nutrient and moisture availability that are associated with large ranges in tree stem growth. Kurz (1989) reported that within a climatically-homogeneous area of eastern Vancouver Island, British Columbia, the leaf biomass of Douglas-fir stands changed less than site index ("height index") and much less than above-ground production across a range of sites varying in moisture and nutrient status. As was reported by Keyes and Grier (1981), the explanation was found to be in the variation in allocation of net biomass production to ephemeral below-ground tissues (i.e., fine roots).

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[2] The two terms leaf biomass and leaf area are used interchangeably in the report. The relationship between leaf area and leaf biomass is not constant within a species because of variation in leaf thickness and anatomy, so the use of these terms in this report should be considered to be qualitative rather than strictly quantitative.

Except in some cases of massive deforestation, forest managers cannot affect regional precipitation inputs and evaporative losses because these are determined by the regional climate. They can affect the competition for soil moisture on a site between crop trees and non-crop species ("weeds"), and may in some cases affect soil moisture storage deliberately (e.g., by draining) or by mistake (e.g., loss of soil organic matter). However, a forester generally has much less ability to control the rotation-length moisture conditions experienced by a tree crop than the nutrient status of a site. This variation in the forester's ability to manage moisture and nutrients requires a brief examination of the relative contributions of these two soil resources to site productivity and yield as depicted in Figure 1.

Figure 2 describes how moisture and nutrients separately influence the determinants of production and yield shown in Figure 1. As noted earlier, the amount of leaf biomass is ultimately determined by the moisture status of the site: the "drier" the site, the lower the mass of foliage the site can support (Grier and Running 1977). However, on most forest sites, nutrient availability prevents plants from achieving this moisture-regulated foliage carrying capacity. And many forest sites that are dry in the middle of the growing season may not be dry throughout the period when air temperatures, day length, and sunlight intensities are high enough to support substantial photosynthesis. Dry summer weather affects soil processes as well as plant physiology and canopy function. As a consequence, thin, rocky, and/or coarse-textured soils which experience periods of summer drought are generally nutrient-poor and have low productivity. It is suspected, but not yet proven, that it is the effects of summer soil moisture deficits on soil animals and microbes, and therefore on soil organic matter and nutrient dynamics, that determines the low productivity of many summer-dry sites, as much as the direct effects of moisture deficits on canopy function (i.e., photosynthesis). Fertilizer and sewage sludge experiments (e.g., Cole *et al.* 1985; Barclay and Brix 1985) have demonstrated that if nutritional limitations are overcome, summer-dry sites can carry a much higher leaf biomass and have much higher levels of productivity than is characteristic for the unmodified site.

Figure 3 presents a hypothesis concerning the relative roles of the different determinants of site productivity on four hypothetical sites that vary in their soil moisture and nutrient status. The extent to which a "dry" site can have increased leaf area and productivity as a result of nutrient enrichment will depend upon what is meant by "dry". As noted above, where a site has moist soils and suitable temperatures for photosynthesis in the spring and fall, but a marked period of midsummer soil moisture deficit, it may be possible to increase leaf area and site productivity substantially through site nutrient management. Where air temperature is unsuitable for photosynthesis outside of the summer period of soil moisture deficits, the potential for site productivity increase through nutrient management may be limited.

The Role of Soil Organic Matter in Determining Site Quality and Long-term Productivity

The discussion above has presented the case for the importance of nutrients in forest production and yield. Most of the nitrogen and much of the other essential nutrients in the forest ecosystem exist in an organic form, whether this be in the complex organic molecules of living plant tissues, the dead organic matter of the forest floor, or the living and dead organic matter of the mineral soil. There is an important inorganic component to the site's nutrient capital, and much of the initial period of nutrient uptake by a developing forest crop is from this inorganic pool. However, even for nutrients like phosphorus, much of the annual dynamics of nutrients in a closed forest stand takes place in an organic form.

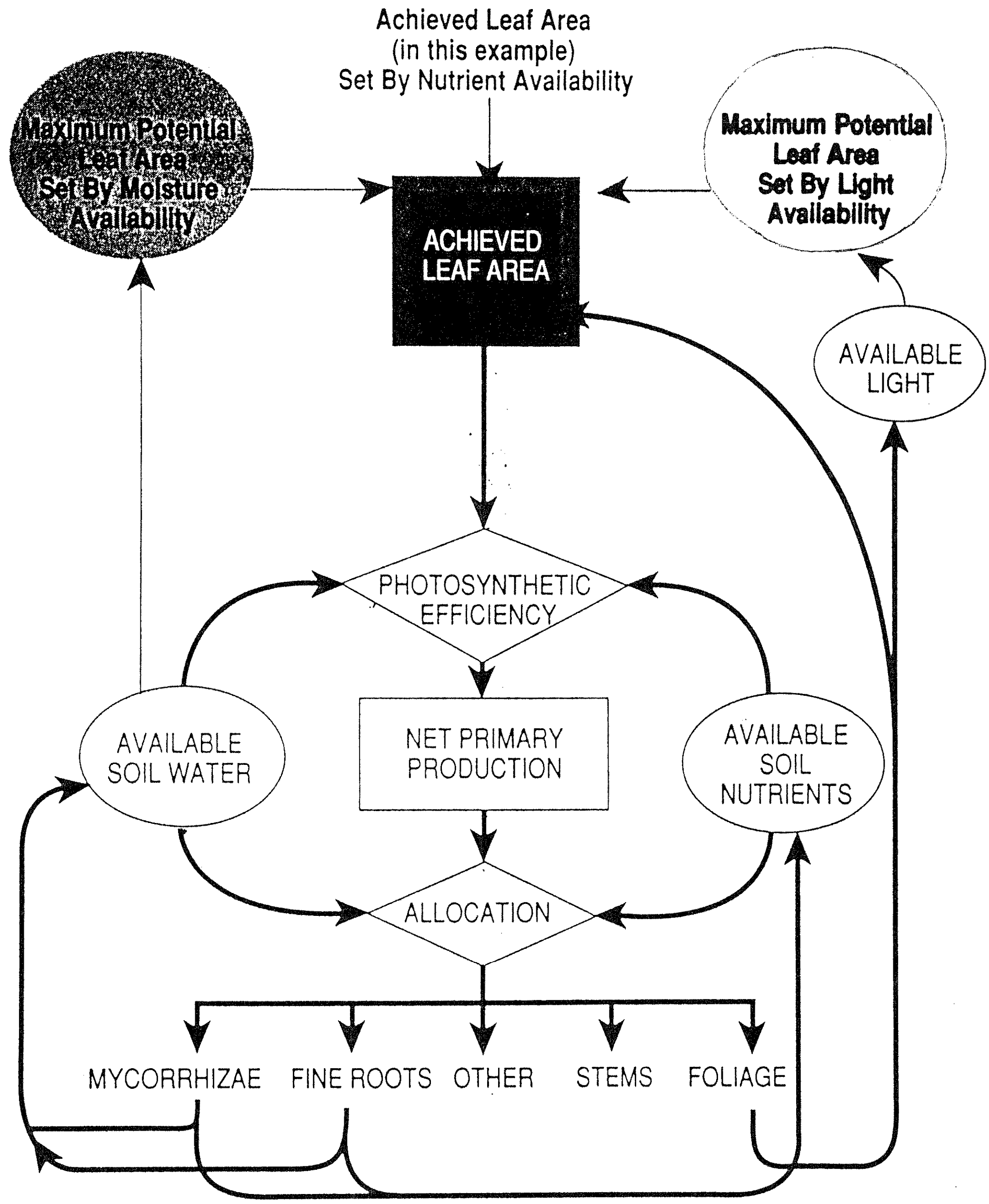

Figure 2: *Diagrammatic representation of the relative roles of moisture and nutrients in the determination of net primary production and resource allocation. The example shown represents an ecosystem in which nutrients are the site resource that is most limiting leaf area. In a very moist and fertile site, maximum leaf area would be set by the light factor, according to the foliar light adaptations of the plant species involved. In a nutrient-rich, dry site, leaf area would be set by moisture limitations. To the extent that management or environmental change alter the availability of site resources, the factor that is limiting productivity through leaf area will change.*

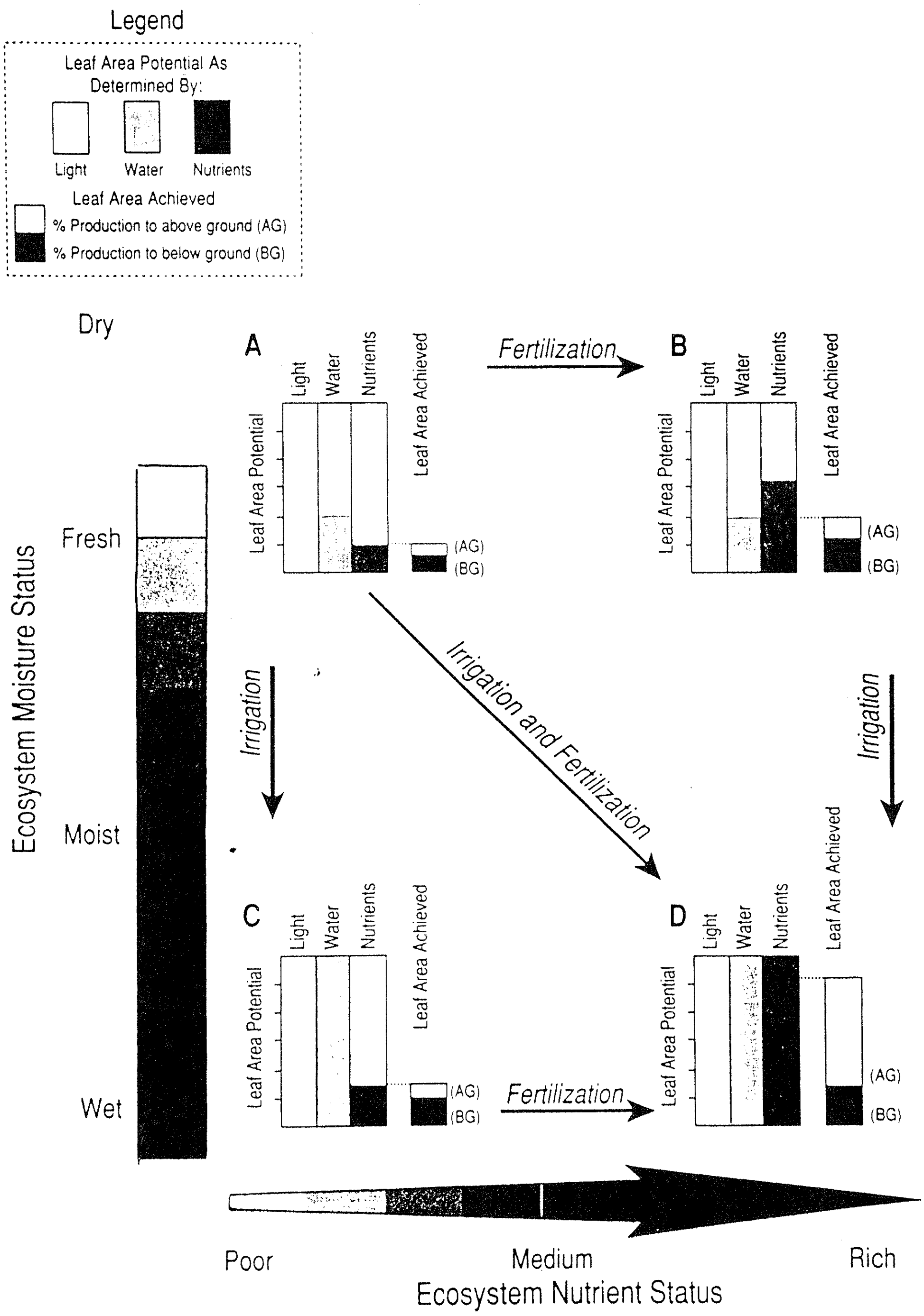

Figure 3: *Relative roles of different determinants of site productivity on four hypothetical sites that vary in their soil moisture and nutrient status. See text for further details.*

The dominantly organic form of nutrients in the forest ecosystem over the life of the stand is the result of the dynamics of nutrients in three types of cycles: geochemical, biogeochemical, and biochemical (or internal).

1. The geochemical cycle consists of additions of nutrients to, and losses of nutrients from, the ecosystem (Figure 4). The majority of these inputs and outputs are in inorganic form. The balance between them determines the inventory of nutrients in the ecosystem. In ecosystems that initially lack large quantities of organic matter, much of the uptake of nutrients by plants during the early stages of stand development are from inorganic sources via geochemical inputs.

2. The biogeochemical cycle is the circulation of this inventory between the vegetation and the soil, the majority of this circulation occurring in organic form as a result of litterfall, root death, mortality, and organic matter decomposition. Much of the nutrients in circulation pass briefly through an inorganic phase as organic matter decomposes and the organic molecules are "mineralized", but in many forests the mineralized nutrients are rapidly taken up by roots, and there may be a "direct" nutrient cycle by which much of the nutrient content of decomposing organic matter is taken up directly by fine roots or mycorrhizal fungi, virtually by-passing the free inorganic phase. This results in a very "tight" or "closed" biogeochemical cycle. The quantity of nutrients circulating in the biogeochemical cycle is determined both by the total inventory in the ecosystem and by the proportion of this inventory that is available for uptake from the soil as a result of decomposition processes and inorganic soil processes. As noted above, the rate of growth of trees and other vegetation is closely related to this availability because it plays a major role in determining leaf biomass and efficiency.

3. The biochemical or internal cycle is the conservation of nutrients inside plants. Nutrients are removed from tissues as they age, or just before they die (e.g., during the senescence of old foliage, or of sapwood just before it becomes heartwood). The nutrients are moved directly to newly developing tissues, or to storage sites from which they can be withdrawn when needed for the production of new biomass.

The relative magnitudes of these three cycles varies between different nutrients, different tree species, different stand ages, and different ecosystem types. In general, the annual geochemical inputs and outputs are much smaller than the quality of nutrients cycling in biogeochemical pathways. For nutrients such as nitrogen and phosphorus, the internal retranslocation (biochemical cycle) in mature stands may equal or exceed the quantity in the biogeochemical cycle. For some nutrients (e.g., calcium) internal cycling is insignificant. Early in the life of the stand, geochemical inputs are often more important than the biogeochemical cycle, but the latter usually dominates the site's nutrient dynamics in a closed stand. The relative importance of the three cycles thus varies as a function of stand age.

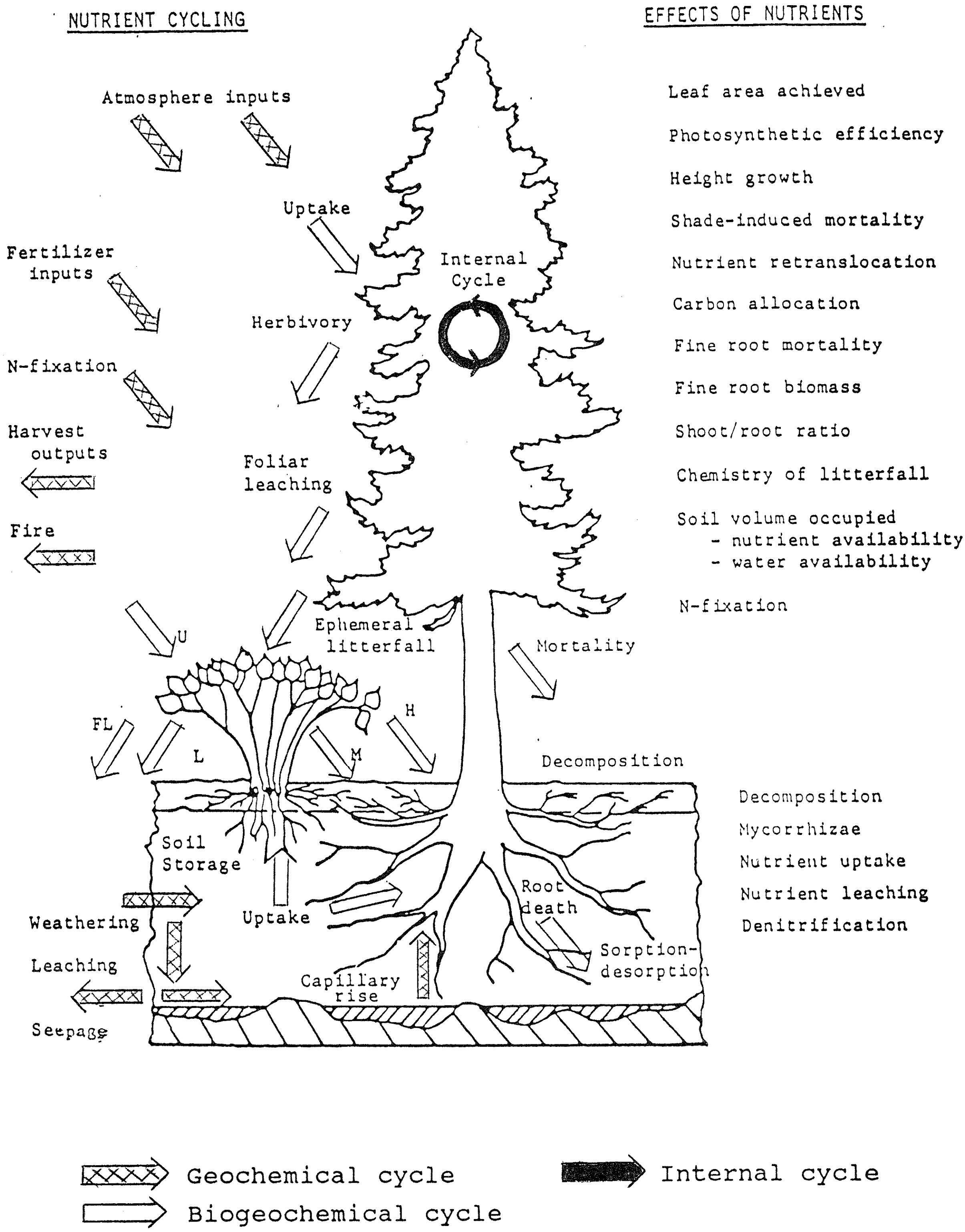

Figure 4: *Diagrammatic representation of the three major types of nutrient cycle: geochemical, biogeochemical, and biochemical (or internal).*

Undisturbed forest ecosystems are extremely efficient at accumulating relatively small annual inputs of inorganic nutrients from the geochemical cycle, combining them into organic matter, and then minimizing nutrient losses back to the geochemical cycle by maintaining a very "tight" biogeochemical cycle. The resulting positive input/output balance leads to the accumulation of an inventory of nutrients, (much of it contained in organic matter) that circulates in the biogeochemical cycle and supports forest growth. In spite of this efficiency, early successional forest ecosystems often have a relatively small inventory of nutrients in the biogeochemical cycle, and plant growth in such ecosystems is often nutrient-limited. In a more mature (later successional) ecosystem, considerable quantities of nutrients are accumulated in the live tree and minor vegetation biomass, and in dead organic matter in the forest floor and mineral soil. Growth in mature forest is thus less likely to be less nutrient-limited, though in over-mature climax forests nutrient availability may decline again. This successional variation in nutrient accumulation and availability in the biogeochemical cycle is not to be confused with variation in the nutrient reserves in unweathered minerals in the soil between young and very old mineral soils. Geologically young soils often have much higher reserves of mineral nutrients than geologically very old and weathered soils.

Where most of the nutrient inventory of a site is accumulated in living vegetation, the soil may have few nutrient reserves, and productivity in such ecosystems will be very sensitive to disturbance, or to harvest-related losses (e.g., some tropical rain forests). Ecosystems with substantial reservoirs of nutrients in organic matter, especially soil organic matter, are much more resilient to such disturbance, unless the soil organic matter reserves are mobilized too rapidly. If organic matter decomposes and releases the nutrients it contains before a new community of trees and/or non-crop vegetation has developed that can utilize these nutrients, they may be subject to loss by leaching or, in the case of nitrogen, by volatilization. Such leaching losses tend to be particularly important for nutrients such as nitrogen and boron which often exist in anionic form.

Dead organic matter in a forest contributes to the functioning of the ecosystem in a variety of ways. It holds substantial quantities of water, which generally improves the moisture status of the site, and it contributes humus, which is so important in the development of soil structure and good aeration. Inputs of litter provide the energy supply for soil animals and microbes; organisms that are responsible for maintaining soil structure, mixing organic matter and mineral soil, and ensuring a supply of mineralized nutrients to plants. Organic matter at the soil surface protects soils from surface erosion and the physical impact of heavy rain, and reduces moisture loss by evaporation. Soil organic matter contributes to the soil's ability to retain available nutrients, preventing them from being leached away.

It has long been a basic principle in traditional European silviculture that a major goal of stand management should be the maintenance of an "active" forest floor of sufficient magnitude to provide these positive roles. Experience has suggested that where forest floors are repeatedly removed from nutrient-poor sites by litter-raking or burning, there may be a loss of site quality, but that excessive accumulations of organic matter in the forest floor may be equally undesirable. Accumulation of a lot of woody material with a high carbon to nitrogen ratio may cause immobilization of nitrogen and lead to reduced nutrient cycling and tree growth. Excessive depths of forest floor may result in colder soils, reducing decomposition rates and site quality. The depth of forest floor that is optimum for tree growth will vary greatly between different types of forest, but for each type of forest there will be a range of forest floor depth and composition that is optimum.

As the need to sustain the productivity of forests without the excessive use of fossil-fuel based technologies increases, "site nutrient management" must become an essential component of stand management, and site nutrient management requires the conservation and management of soil organic matter. It is to be expected, therefore, that a major concern about forest harvesting and site preparation techniques is over its effects on forest floor and mineral soil organic matter, and the fate of the nutrients it contains. The maintenance of long-term site quality is intimately related to the dynamics and inventories of organic matter in the system.

EXAMPLES OF THE IMPACTS OF HARVESTING AND SITE PREPARATION TECHNIQUES ON SUBSEQUENT SITE QUALITY AND TREE GROWTH

Historical Perspectives

Large-scale changes in vegetation and loss of site quality caused by human activity have occurred at many times in history and in many parts of the world. The history of deforestation of the Mediterranean and the accompanying degradation of the productive capacity of the land are described by Thirgood (1981), and similar consequences of human population growth continue to occur in many developing countries today.

One of the better-documented cases of loss of site quality and tree growth caused by removal of organic matter is that of litter-raking in Scots pine forests in northern and eastern Germany early in the last century (Ebermeyer 1876; Weidemann 1935). Landless peasants and poor farmers annually raked the branches and leaves in community forests for use as organic fertilizer and bedding for cattle. The resultant decline in soil fertility and forest growth led to ordinances that restricted such raking, and stimulated an early interest in the role of forest soil organic matter in the maintenance of site quality (Rennie 1956).

The case of the second-rotation yield decline in radiata pine plantations near Mt. Gambier, South Australia is another example of management-induced yield decline that has been well documented. Piling and burning of slash between first and second, and second and third rotations caused loss of organic matter and nutrients from the infertile, dry sandy soils of the area. This loss, in combination with weed competition for moisture, resulted in a significant loss of both site quality and achieved economic productivity (Keeves 1966; Squire 1983; Squire *et al.* 1979, 1985; Raison 1984).

More recently, studies of whole-tree harvesting and site preparation in Sweden have identified significant declines in tree growth on low productivity sites following whole-tree thinning (Andersson 1984) and slashburning or mechanical site preparation (Lundmark 1977). The reduced growth in these studies was attributed to loss of organic matter and associated nutrients. An important lesson to be learned from Lundmark (1977) is that site treatments (scarification, slashburning) that resulted in a significant reduction in rate of tree growth by mid-rotation (40 years) had produced accelerated height growth for the first 15 to 20 years. Clearly, we need long-term studies on the consequences of organic matter and nutrient removal for tree growth. Short-term evaluations may give us completely the wrong impression.

Concerns About Management-Induced Loss of Site Quality and Tree Growth Potential in New Zealand

With this history of documented site quality loss accompanying the harvest-induced or site preparation-induced loss of soil organic matter and nutrients, it is not surprising that similar losses of site quality (potential productivity) and forest growth (achieved productivity) have been reported for New Zealand. For many years, concerns in New Zealand about forest nutrition focused mainly on differences in the initial nutrient status of different sites. Many soils being afforested were deficient in one or more micronutrients or macronutrients (Will 1985), and excellent work was done on how these inherent deficiencies could be remedied by fertilization and/or the use of nitrogen-fixing lupins. Less attention was paid initially to the possible impacts of management on the sustainability of soil fertility and site productivity. However, studies over the past decade on the effect of windrowing and of soil compaction on the growth of the subsequent radiata pine crop (e.g., Dyck and Skinner 1990; Skinner *et al.* 1989; Dyck *et al.* 1989) have confirmed what many forest ecologists and soil scientists have predicted: that site quality is not sustainable in the face of forest harvesting and site preparation practices that result in substantial losses of soil organic matter and nutrient reserves, loss of top soil, or in reduced access by the roots to the soil due to compaction.

It is reasonable to enquire as to why, with numerous historical precedents and an increasing recognition of the importance of conserving soil organic matter and nutrients, the concerns about sustainability of yield in New Zealand's exotic conifer plantations did not develop at an earlier date. One major reason for this delay is to be found in the difference between site quality (potential site productivity) and yield (achieved economic productivity), and in the commonplace misunderstanding or ignoring by foresters of the critically important role of soil in determining site quality and yield.

Site quality, as noted above, is a measure of the potential of a site to support net primary production. Potential NPP is primarily a function of climate, and of soil moisture, fertility, and aeration. Biotic factors that affect the activity of plants may also contribute to the determination of potential site productivity, but generally the role of biotic factors is more in regulating the distribution of production between different species than actually setting the ecosystem's potential productivity. Site quality also determines the allocation of net primary production to different biomass components, and hence contributes to the determination of yield (Figure 1). Any long-term directional change in climate (e.g., Bolin *et al.* 1986; Shands and Hoffman 1987; Harrington 1987; Schneider 1989), or any change in the resources of soil moisture and nutrients, in soil architecture, or in soil aeration can be expected to result in changes in site quality and potential organic matter production, and in the distribution of this production between harvestable and non-harvestable plant parts.

The actual yield of forest products, on the other hand, is determined by the effects of management on the proportion of the site's resources that are accessible to the tree crop rather than to non-crop vegetation, on the temporal pattern of availability of soil resources, and on the allocation of NPP between marketable and non-marketable crop biomass (i.e., the crop's "harvest index"):

1. The proportion of the site's resources accessible to the crop trees is determined both by the stocking density of the crop species (i.e., degree of soil occupancy by fine roots, and canopy area occupancy by foliage), and by the occupancy of the site by, and the competitiveness of, non-crop species, both of which can be controlled by management.

2. Site preparation, weed control, and fertilization can accelerate the rate at which soil nutrients become available to tree crops, and result in an increase in the rate of tree growth.

3. The allocation of NPP to harvestable biomass can be manipulated by management of the availability of soil resources, and also by genetic tree improvement. High levels of soil moisture and nutrients will reduce the tree's investments in fine roots, releasing photosynthate for stem production. However, this may result in a high allocation to branch biomass to support the large leaf area carried by open-grown trees on moist, fertile sites. Pruning can prevent undesirable accumulation of branch biomass, and genetic improvement has reallocated NPP from heavy branches to stems, with resultant improvements in harvest index and yield of open-grown trees.

Aggressive and successful control of competing vegetation, reduction in allocation of NPP to branches by genetic improvement and pruning, and site preparation techniques that increase the accessibility of soil moisture and nutrients to tree crops in the early years of the plantation have combined to greatly increase early radiata pine performance, and rotation-length growth and yield. This increase in plantation performance has masked any change in site quality: a situation closely analogous to what has happened to site quality and yield of grain crops in the Canadian prairies since the turn of the century. Continued cropping from 1900 to the Second World War resulted in a general decline in yield of grain per hectare that paralleled a similar reduction in "native soil productivity" (i.e., site quality) as measured by the percentage of the original soil organic matter remaining. This innate productive potential of the soil has continued to decline, but grain yields showed a dramatic increase after World War II as a result of increased use of fertilizers, improved tillage, improved weed, disease and insect pest control, and genetic improvement of the crop species. The application of genetic improvements, in conjunction with intensive cultural techniques, has completely masked the continuing erosion of site quality. The complete recovery and actual increase in growth and yield of radiata pine in South Australia as a result of intensive weed control and fertilization is another demonstration of how changes in site quality can be masked by management activities. However, conservation of organic matter and nutrients is considered to be the key factor for the long-term maintenance of productivity on these nutrient-poor sandy soils (Squire 1983).

It can be argued that as long as we have technology we can sustain production and need not be concerned about site quality. This is an incorrect and inappropriate view. Technology may be able to replace lost nutrients and sustain growth and yield on sites whose productive capacity has been reduced, but if economic and environmental considerations deny or restrict the use of the appropriate technologies in the future, yields will decline if site quality has been degraded. Fertilization can replace nutrients, but will not necessarily result in the replacement of soil organic matter which plays such an important role in soil fertility, moisture, structure, aeration, and erosion resistance. In the face of concerns about climate change, acid rain, the "ozone hole", and water pollution, agriculture and forestry must increasingly depend on and respect the natural mechanisms that sustain site quality and productivity, and utilize biological mechanisms for the achievement of management goals (e.g., use of N-fixing plant species, or domestic animals for weed control) wherever possible. Economics will certainly influence the management techniques that are used, but the choice must also be conditioned by considerations of the sustainability, the global environment, and long-term site quality.

SUMMARY OF SOME RECENT RESEARCH IN NEW ZEALAND ON THE IMPACTS OF MANAGEMENT ON LONG-TERM SITE QUALITY

The earliest evidence of decreased growth in second-rotation radiata pine forest in New Zealand was reported by Stone and Will (1965). Nitrogen deficiency and reduced growth was observed in young, second growth on gravelly soils near Nelson. The problem was related to the apparent ability of radiata to access soil organic nitrogen that had been unavailable to the native vegetation that previously occupied the site. This inventory of previously inaccessible organic nitrogen was utilized by the first-rotation crop which therefore grew well, but as a result the level of soil nitrogen available at the beginning of the second rotation was greatly reduced. Subsequent studies suggested that this deficiency may be confined to the first 5 to 8 years of the second rotation (Whyte 1973), and that growth can be restored by the use of NPK fertilizer.

Early studies of nutrient removals in harvested stem biomass revealed that relatively small amounts of nutrients are removed compared to the nutrient reserves on most sites (Webber and Madgwick 1983). In contrast, burning and windrowing can remove substantially more nutrients (Webber 1978). As early as 1978, windrowing was shown to result in 40% reductions in tree growth over 66% of the area in a 7-year-old radiata pine plantation on pumice soils (Ballard 1978a, b). This reduction was believed to be due to declines in soil fertility, but other factors, such as soil compaction, could not be ruled out. By the time the stand was 17-years-old, the growth reduction between the windrows was 43%, and foliar N, Mg, and B levels were marginal for growth (Dyck and Beets 1987; Dyck *et al.* 1989).

Nutrient losses are greater with whole-tree harvesting than with stem harvesting, but they are not as great as with windrowing. In a study of whole-tree-harvesting followed by annual litter-raking on a pumice soil, tree stem volume was reduced by 12% at both 16 and 26 years (Ballard and Will 1981; Dyck and Skinner 1990). By year 26, exchangeable Ca and Mg in the upper 20 cm of soil had been reduced by 69% and 66% respectively, foliar B was reduced to critical levels, foliar Mg and N were marginal, and soil mineralizable N was significantly reduced (Dyck *et al.* 1983; Dyck and Skinner 1990).

Differences in the growth of competing vegetation can have a great effect on initial growth differences between sites that have been mechanically prepared and control sites. On droughty gravel soils of the Canterbury Plains on the east side of the South Island, only 20% difference in tree growth was observed between 9-year-old pines growing between windrows and those growing in untreated plots (compared with 43% difference reported for a moist North Island site by Dyck *et al.* 1989). Weed competition (thought to be largely for moisture) was more severe in the untreated control areas than in the windrowed area; trees with no weed competition were 34% and 67% larger than trees with partial or heavy weed competition, respectively (Dyck *et al.* 1989).

Much of the initial work done on harvesting and site preparation impacts on long-term site quality were done on gravel and pumice soils which are not generally susceptible to severe problems of soil compaction. Recent studies of compaction effects on low fertility fine-textured soils revealed that at age 4 years, tree growth relative to untreated control plots had declined by 25% where the forest floor had been removed by hand, 65% where it was removed by machine, 70% where forest floor and topsoil had been removed but compaction was low, and 80% where forest floor and topsoil were removed and compaction was high (Skinner *et al.* 1989).

There are several other studies of harvesting and site treatment impact studies in New Zealand, but this sampling of the literature should serve to demonstrate the very considerable potential damage to site quality that has been done, and in some places continues to be done by management. A small installation in Baigents Forest near Nelson (unpublished) illustrates the interaction between genetic improvement and the impacts of site preparation treatment on tree growth. Natural regeneration from a second-rotation crop growing on an unprepared plot was compared with two different "improved" genotypes. The only apparent correlation with growth was the degree of site disturbance, with the worst growth on "scalped" spots, and the best growth on undisturbed soil. Clearly, the potential gains offered by genetic tree improvement cannot be achieved if the "improved" trees are not adequately supplied with soil resources, and although genetic improvement and weed competition may confuse the issue and mask declines in site quality, ultimately the growth of the tree crops will reflect the manner in which management has impacted the soil resource.

EVALUATION OF THE IMPACTS OF SOME CURRENT HARVESTING AND SITE PREPARATION PRACTICES ON LONG-TERM SITE QUALITY IN NEW ZEALAND

The maintenance of long-term site quality can be affected by many different management practices. Many of these practices may result in short- or medium-term increases in yield whilst degrading site quality. This may act to create an "addiction" to certain technologies: a situation in which the technology may become indispensable for the maintenance of production rather than a mechanism to increase site productivity. The withdrawal of the technology may result in significant loss of production.

Whole-tree Harvesting

There appears to be a world-wide trend towards whole-tree harvesting in which the entire above-ground biomass is removed from the site. Increasing mechanization of harvesting because of economics and reduced availability of human resources, and smaller tree sizes because of shorter rotations are resulting in the removal of logging slash from an increasing proportion of harvested sites. This trend is supported in some areas of the world by the development of markets for non-traditional biomass (branches, stem tops, foliage, stumps). Sometimes removal of tree tops is simply an unintentional consequence of the prevailing method of harvesting. Easier planting because of the reduced amount of slash and the increased physical damage to weed species caused by the removal of tree crowns, easier access to the plantation later in the rotation, and reduced fire hazard are some other silvicultural benefits.

Tree tops contain a significant percentage of the nutrients in tree biomass (especially nitrogen and phosphorus), and on nutrient poor sites this may be a significant proportion of the total site nutrient capital. Whole-tree harvesting can increase nutrient withdrawals at the time of harvest by as much as 3 to 4 times for some nutrients in some forest types (Weetman and Webber 1972; Kimmins 1977; Freedman 1981).

In contrast to slashburning, whole-tree harvesting does leave the forest floor intact, but by removing the shading effect of slash it may alter site moisture relationships and the rate of decomposition and mineralization of the forest floor. Nitrogen availability may be increased early in the rotation by removing the high C/N ratio stem tops and larger branches (Matson and Vitousek 1981), but this will reduce N availability later in the rotation when these woody substrates would have decomposed and released their N content if they had been left on the site.

Conclusions about the loss of nutrients due to whole-tree harvesting are relatively straight-forward because it is fairly easy to identify the magnitude of most of the pathways of loss. However, the long-term implications of the loss for productivity may be difficult to predict (Kimmins 1977; Johnson 1983), and may require the use of an ecosystem simulation model in conjunction with long-term field trials for validation purposes.

Slashburning

Slashburning is a valuable silvicultural tool that can be used successfully to reduce fire danger, improve access for planting and stand tending, temporarily reduce above-ground weed competition, warm up cold soils, reduce excessively thick forest floors, and increase soil pH. Correctly applied on a site-specific basis, it can result in the retention of larger fuels, minimum loss of forest floor and the nutrients contained therein, and a general site improvement.

However, fire is a very powerful technique, and there are opportunities for misuse, resulting in considerable soil damage: loss of virtually all slash and forest floor, the loss of organic matter from the upper mineral soil, and the loss of soil structure and nutrients. A useful review of slashburning in the US Pacific Northwest can be found in Hanley *et al.* (1989).

In general, slashburning is most appropriate during the conversion from old growth to second growth, or from noncommercial woody vegetation to tree plantations: situations in which there is typically a lot of unused woody biomass and understorey, and where the forest floor condition may not be desirable. The need for slashburning between successive plantation crops declines as utilization standards increase, or if whole-tree harvesting is used. In conjunction with herbicides, slashburning may continue to have a role in weed control, however. "Brown-and-burn" potentially has a lower impact on long-term site quality than stand-conversion slashburning which should be used with caution because of the potential for long-term site damage.

Conclusions about slashburning are difficult because the intensity and duration of the fire, and thus the impacts on long-term productivity, can vary so much. The impacts will also vary greatly according to the soil depth, texture, moisture, organic matter content, and mineralogy. The complexity suggests the need to use ecosystem-level predictive models in the short run, and to establish long-term field trials to validate these models. The general reduction in the use of slashburning in the US and Canada because of public concerns about smoke and air quality, and also because of the increase in whole-tree harvesting, is reducing somewhat the need for long-term trials on slashburning in these areas. However, it expected that some slashburning will be done for the foreseeable future, and therefore there is still interest in having a few long-term trials of this management practice.

Very little slashburning was seen in the forests visited. A severe burn on a steep slope at Whitford Forest (Carter Holt Harvey) was justified in terms of clearing the site to provide access to a mechanical ripper. Local experience is probably a better judge than scientific theory in such a case, but theory would have argued against such a hot burn on such a steep slope.

Mechanical Site Treatment

Windrowing and Root Raking

The removal of all slash and stumps, most of the forest floor, the tops and roots of competing vegetation, and sometimes "topsoil" into piles or continuous windrows has been a common practice in radiata pine silviculture in New Zealand and Australia. There is now a considerable body of evidence concerning the impacts of this practice on long-term site productivity (see references given earlier for research in New Zealand and S. Australia), especially where the majority of the soil fertility is provided by the uppermost layer of soil, and this is physically moved into the windrows.

Conclusions concerning the long-term effects of windrowing on site quality are not difficult to reach given the available field and experimental evidence. It is most surprising, therefore, that this practice is being continued on soils that are without doubt susceptible to degradation by this practice (e.g., some areas in Balmoral Forest, South Island). Considering the accumulated practical and research experience, one would expect that this practice would be discontinued immediately on all sensitive sites. Because of the nutritional importance of organic matter and the uppermost layers of mineral soil (e.g., Will and Knight 1968; Klock 1982), there will be relatively few situations in which this could be considered an acceptable practice. These would include sites with deep, moist, fertile soils that contain significant reserves of organic matter, or situations in which the windrowing removes only the larger woody debris. However, the effects on soil physical properties also need to be considered, and there will be an increased risk of soil compaction on the very sites on which the nutritional concerns would be less pressing.

Root-raking is very similar to windrowing in that all large slash and stumps are removed from the site. In theory, the topsoil and most of the forest floor should remain on the site. In practice, the results of root-raking are often little different from windrowing, especially on steep slopes where the operator may be obliged to lower the blade to act as a brake, removing much or all of the top soil. Examples of severe soil damage caused by this practice were seen near Nelson.

V-blading

The combined pushing of slash, vegetation, and forest floor away from 2- to 3-m wide swaths, and the subsequent or accompanying burying of this organic material by topsoil or a mixture of topsoil and subsoil appears to have several silvicultural benefits. It removes slash and competing vegetation, especially troublesome species such as gorse, *Rubus* sp. and bracken, from the swaths, thereby facilitating the planting and subsequent location and treatment of seedlings. It removes roots and reduces risk of infestation by root rots. In many cases the mineral soil left exposed in the swath is so infertile that invasion of all vegetation on the swath area is extremely slow. This would reduce moisture competition. By exposing mineral soil for heat exchange, some frost damage problems may be reduced or eliminated. By creating mounds, seedlings are elevated above frost pockets on particularly frost-prone sites. By cultivating the soil in the mounds, root development may be improved on sites with compacted soils, at least initially. If the seedlings are planted adjacent to the mounds, their roots should have access to all of the site's organic matter and topsoil resources. These resources have merely been reorganized and rearranged on the site; they have not been totally removed from the trees as was the case in windrowing. By burying logs, their decomposition and mineralization will in most cases be speeded up. On first analysis, it would therefore seem that V-blading has many desirable attributes. However, the practice requires a more detailed evaluation.

In some of the more extreme examples of V-blading that were seen, the piles into which seedlings were planted consisted primarily of infertile subsoil. In many cases, especially on pumice soils, the bulk density of the piles was extremely low, offering the seedling inadequate anchorage and apparently contributing to problems of toppling. It is noted that Mason (1985, 1989) does not attribute toppling to mechanical site preparation. However, Ainsworth (1989) does list the loosening of soil by mounding as a contributor to toppling. Where insufficient mineral soil is applied to the piles of slash, air pockets will probably result in both stability and growth problems, at least initially. Disturbance and burying of forest floor material and logging slash is believed to accelerate decomposition and mineralization in comparison to undisturbed areas. If young radiata pine trees are not able to take up this "luxury" supply, especially of nitrogen, anionic nutrients such as nitrate-nitrogen and boron may be leached away. Thus, although the site's organic matter and nutrient resources are not far-removed from the crop trees, and may even be concentrated around them, the tree's inability to utilize this "assart flush" (Rommell 1935; Tamm and Pettersson 1969) may result in accelerated nutrient losses. Such losses have been demonstrated below slash piles in Sweden (Rosén 1986), but the magnitude of the losses caused by V-blading in New Zealand are not known: neither the absolute magnitude of the losses, nor their magnitude relative to losses from windrows, from whole-tree harvesting, or from slashburning.

Once a tree crop has closed canopy, nutrients from the piles will be redistributed back to the V-bladed swaths by above-ground litterfall, root growth and death, and slash deposited during thinning and pruning. This will gradually restore the fertility of the degraded area, the speed of recovery depending on the degree of soil compaction, the loss of site fertility, and the growth of the trees on the mounds. If their growth, and hence litterfall, is poor, recovery of the bladed areas will be delayed. Until the fertility and bulk density (in the case of compacted areas) of the bladed areas has recovered, rooting would be expected to be restricted to the more fertile and better aerated and rootable mounds. This may contribute to tree instability problems until a more widely-spread root system has developed (see Ainsworth 1989).

The potential problems alluded to above will be more serious where the V-bladed areas are only separated by a single narrow mound. They will be less serious where every other pass is missed.

V-blading has an even more detrimental impact on site quality on sites that have already been windrowed. Because the windrowing generally removes all the organic debris, the forest floor and some of the upper mineral soil, the V-blading can only cut further down into the subsoil. The extent of the additional site damage will depend upon the depth of the V-blade.

Ripping

Where the layer of soil accessible to tree roots is shallow and is underlain by a compacted layer that can be broken up mechanically, considerable gains in ease of planting and subsequent tree stability, and possible improvements in site moisture status and fertility, can be achieved by ripping. Ripping of naturally compacted gravels, machine-compacted landings, and of unstructured clay soils has considerable silvicultural benefits. However, ripping is difficult unless slash is removed, and the desire to rip may lead to windrowing, root-raking, or high intensity slashburning which can result in the type of site degradation described above. Thus, while ripping offers several silvicultural benefits, the preparatory activities that are necessary to permit effective ripping may negate the site improvement effects of this practice. The balance between the negative and beneficial effects of ripping will depend on the site quality damage done by the pre-ripping site preparation, on the benefits of the ripping, and on the extent of soil compaction done by the ripping operation. Although soil physical properties may be improved in the line that is ripped, if heavy equipment is required, some additional physical damage may be done to the soil on each side of the rip.

Line-Raking

The major objective in line-raking is to move large slash away from the planting line to facilitate access for planting and other silvicultural activities, and to eliminate non-crop weed species from the planting line. Applied following slashburning during the conversion of native forest or scrub to pine plantations, or between pine rotations where pine slash and competing vegetation are heavy and slashburning is not desirable, it can be an effective treatment which poses little additional threat to long-term site quality. Unfortunately, it is sometimes applied much like V-blading; all forest floor and much of the topsoil is also removed. This occurs especially on steep slopes where line-raking is done straight down the slope and the operator is obliged, or feels obliged, to keep the blade much too deep in order to control the downhill speed.

As with so many site treatments, it is difficult to generalize about line-raking. Correctly applied on soils that can withstand the heavy equipment without compaction damage, and with the tines only deep enough to remove large slash and the surface roots and rhizomes of weed species, line-raking appears to pose little threat to long-term site quality. Used, as it apparently often has been, as a land clearance technique, it is probably as bad as windrowing and root-raking.

Herbicidal control of non-crop vegetation

For a variety of reasons, many of the exotic conifer plantations in New Zealand suffer from moderate to extreme weed problems. The history of native forest clearance for agriculture and the introduction of exotic weeds that are strong competitors for moisture and light, and which create stand access problems, have resulted in a widespread need for weed control. Manual weed control is used but may be limited by lack of human resources, economics, efficacy, or simply technical difficulty. Mechanical options are effective, but often result in unacceptable soil chemical and physical alteration (see discussion above). Slashburning can remove above-ground weed biomass, but will stimulate the germination of gorse seeds (for example), and permit resprouting of many species from underground organs; the benefits are very temporary. Biological controls (sheep, cattle) can be very effective on some weed species as a stand maintenance strategy, but are ineffective against the more difficult weed problems and may cause soil compaction on fine-textured soils. Because the use of herbicides generally avoids the use of those mechanical site treatments that pose the most serious threats to long-term site quality, the chemical option appears to be attractive. In many cases, weed control at the establishment phase, especially where access is difficult because of slash, is best achieved chemically, and research has identified effective chemical solutions to most of the weed problems faced in radiata pine silviculture.

In some cases the use of herbicides will reduce the input of N due to symbiotic biological N-fixation. It may also eliminate the "nutrient sponge" effect in which non-crop vegetation takes up nutrients during the "assart" period that are in excess of the uptake capacity of the pine crop and of the soil exchange capacity, and may therefore be leached away. Nutrients taken up by non-crop vegetation are subsequently released to the tree crop if the weed species are shaded out following crop canopy closure. Because the herbicide treatments generally do not completely devegetate a site, and because vegetation reduction is temporary, chemical vegetation control is not considered to be as great a threat to long-term site quality as mechanical site preparation. Spot herbicide treatments are even less damaging than broadcast treatments, but may fail to achieve the silvicultural objective of access for subsequent silvicultural treatments.

Economic considerations often constrain the use of herbicides, and although environmental or emotional concerns have not yet interceded against their use in New Zealand to nearly the extent that has occurred in North America, the use of herbicides in some areas of New Zealand will probably become more restricted in the future.

Mechanical site preparation that moves slash and forest floor material into piles and windrows, or slashburning, are likely to pose a more serious risk to long-term site quality following a pine rotation than in the initial site conversion from native vegetation or afforestation of old pasture sites in New Zealand. In contrast to grasses and many broadleaved forests, pines appear to be particularly efficient at accessing and taking up nutrients from rather stable humus forms in the mineral soil (Stone and Will 1965). These nutrients become distributed in the live pine biomass and in the forest floor, most of which are removed if harvesting is followed by windrowing or slashburning. Thus, lack of evidence that these practices are detrimental in the first rotation provides little basis from which to conclude that they will not be detrimental if they are practised between subsequent radiata pine rotations.

NUTRIENT AND ORGANIC MATTER MANAGEMENT GOALS FOR NEW ZEALAND

It is difficult to generalize about silvicultural techniques in any country that includes a wide range of climates and soils. However, because of the prevailing climatic conditions, organic matter decomposes relatively rapidly in many of the exotic plantation forests of New Zealand. The resulting rapid mineralization of litter nutrients is one of the reasons why radiata pine is able to achieve such high growth rates in New Zealand, and in many cases forest productivity appears to be limited more by the total inventory and balance of nutrients in the system than by their speed of circulation in the biogeochemical cycle. Consequently, site nutrient management in New Zealand should generally focus more on the conservation of organic matter than on its mobilization. In countries in which the rate of organic matter decomposition is slow, and where this is a major limitation on the rate of tree growth, fire and mechanical disturbance that accelerate decomposition can have a beneficial effect on long-term site quality.

Although further research is required to provide empirical evidence in support of the following points, theory would suggest that reforestation practices in New Zealand should generally be designed to promote the retention of organic matter on the site, and, with the exception of compacted, structureless, or indurated soils, should minimize disturbance treatments that accelerate the decomposition of organic matter. The high moisture levels, intense faunal activity, and dense fine rooting seen in decaying logs on some windrowed Kaingaroa Forest sites provides convincing evidence of the potential response of the resource-deficient trees growing on the inter-row areas of the windrowed site to the retention of such organic matter.

It is obvious that mechanical site disturbance offers considerable benefits on some sites in terms of frost damage and weed control. However, these benefits appear to be outweighed in many cases by the negative effects. Reduction of the negative effects whilst retaining many of the beneficial effects could be achieved by spot-treatments. Research is needed to compare the benefits and costs of spot *vs.* strip *vs.* broadcast mechanical site treatment.

A RESEARCH STRATEGY WITH RESPECT TO THE EFFECTS OF HARVESTING AND SITE PREPARATION TECHNIQUES ON LONG-TERM SITE PRODUCTIVITY

The best way to evaluate the long-term effects of harvesting and site preparation treatments on site quality and forest productivity is to use long-term experience. Medium-term experience exists concerning some of the silvicultural treatments used in New Zealand. For example, measurements of tree growth on windrow and inter-row microsites twenty or more years after planting gives an accurate picture of the within-rotation consequences of this site treatment. However, between-rotation comparisons are confounded by rotation-to-rotation changes in crop genotype, in the nature and treatment of weed competition, and in the methods of site treatment. As discussed above, site quality (or potential site productivity) may be declining at the same time that crop yields are actually increasing as a result of silvicultural investments. If the silvicultural technology remains economic, environmentally acceptable, and politically available, this situation may not be a matter for concern. The site may simply be regarded as a rooting substrate with an appropriate climate, technology being used to provide the other resources required for plant growth. However, this approach may in essence be "timber mining": treating site fertility as a non-renewable resource to be utilized and replaced by technology. Such a resource strategy has attendant risks of declining yield should the technology become unavailable, or should the changes produced in the site reduce its resilience in the face of other environmental changes (e.g., global climate change).

In those cases where one lacks appropriate empirical experience, predictions about the long-term consequences of silvicultural investments must be made on the basis of an understanding of the ecology of forest growth and yield, or on a combination of available experience and ecological understanding. Foresters around the world have generally relied on experience-based approaches for the prediction of the consequences of their management, and long-term field trials will always be a critically important part of forest science. However, because of the long time scales involved in gathering empirical evidence of rotation-length or multi-rotation treatment responses, research must also be conducted to provide the understanding of ecosystem processes needed to make interim knowledge-based predictions of growth and yield. Research on the long-term impacts of harvesting and site treatment on site quality and yield should therefore be conducted under an overall strategy that integrates long-term field trials, retrospective and chronosequence research, and process-level studies (see papers in Dyck and Mees 1989). The strategy should also identify forest management and silvicultural decision-support tools that should be developed to integrate the results of these different types of research and provide predictions about the economic, site quality, yield, and environmental consequences of alternative stand and forest management strategies.

The following discussion identifies the components of a research strategy with respect to harvesting and site preparation effects on long-term site productivity. Many of the ideas presented are taken from Dyck and Mees (1989).

Chronosequence and Retrospective Research

Some very useful qualitative conclusions can result from descriptive research that quantifies tree growth, ecosystem conditions (e.g., soil nutrient inventories), and ecosystem processes (e.g., nutrient leaching, canopy function) across age sequences of plantations where site, site history, and stand treatment have been very similar. Where time has been the major variable in the age sequence, one or two years of such research can give a picture of the temporal pattern of ecosystem development over many decades. This type of research does not remove the need to establish and monitor long-term field trials, but can give an interim estimate of the probable pattern of events in a fraction of the time required by the long-term trials.

Unfortunately, chronosequence research generally fails to explain why things have happened, the history of site treatment or the earlier site history is generally not well known, and there is often inadequate evidence that the various different sites that make up the chronosequence were in fact initially similar. The ecosystem condition prior to the harvesting and site preparation treatments is generally not well known. Chronosequence research is an excellent way to derive hypotheses about the long-term impacts of harvesting and site preparation treatments, but cannot be relied on by itself to provide the basis for developing management policy.

Retrospective research involves making observations and/or measurements on sites that received known treatments in the past. In essence, a retrospective study can be considered to be a single site from a chronosequence. It gives a result at one point in time but does not define the temporal pattern of ecosystem development and function. Frequently the ecosystem condition prior to the treatment is not well known, the details of the treatment are not well quantified, and little may be known of what has happened to the stand since the harvesting and site preparation treatment. Thus, retrospective research has all the shortcomings of the chronosequence approach, plus the additional problem of providing a single estimate of the response of the ecosystem to the treatment(s).

Chronosequence and retrospective research (see Cole and Van Miegroet 1989, and Powers 1989) thus have an important role to play in a research strategy, but are inadequate on their own. They provide documentation of the available empirical evidence concerning long-term treatment effects and can provide an excellent basis on which to design research by which to explain and predict the short and long-term consequences of alternative harvesting and site treatment strategies.

Long-term Field Trials and Process Research

There can be little doubt that the best basis for prediction in forest management is practical experience. The most believable evidence concerning the long-term effects of a given harvesting or site preparation practice is obtained by imposing the practice on a stand and monitoring the response. "If in doubt, ask a tree" is a tried-and-true approach that foresters have always relied on. As part of a strategy for research on site preparation treatments, it means installing well documented and replicated long-term field trials that can be monitored over periods of time corresponding to the time scales over which you require prediction.

Long-term field trials in combination with research on a variety of soil and plant processes can provide not only an empirical record of the consequences of particular practices: they can also answer the question "why did it happen?". Ultimately, it is as important to know why a particular growth response occurred as it is to know what the response to a particular experimental treatment is. Every ecosystem is slightly different. Most stands are to some extent unique. Extrapolation of the results of long-term field trials from the research site to other areas that are ecologically very similar is easy. However, we can never install trials in every type of forest, so we will always be faced by having to extrapolate results of research to sites that are somewhat different. By understanding why a response happened, such extrapolations can be made with confidence.

In addition to providing explanations for treatment responses, process research is also important for the development of predictive models. The greatest single draw-back of long-term field trials is that they are long-term. One does not get the answers one seeks for many years. Knowledge-based predictive models can provide an interim basis from which to develop management guidelines while one is waiting for the long-term trials to provide an empirical base for such guidelines.

An Overall Research Strategy

An effective overall research strategy by which to guide harvesting and site preparation decisions should thus include:

A. Chronosequence and retrospective research by which to provide an initial estimate of probable treatment responses, and from the results of which to design long-term field trials and process research.

B. Long-term field trials and process research to test the hypotheses derived from the initial, descriptive chronosequence and retrospective research. The early results of the process research can be synthesized into models by which to predict the probable treatment responses.

C. Modelling to develop predictive models on the basis of which management can be guided until the long-term field trials have been in place for long enough to provide an empirical basis for predictions.

Where well-documented chronosequences of stands of known initial condition, site treatment, and stand history are known, and where they cover appropriate time scales (e.g., at least one full rotation, and preferably multi-rotations), it may not be necessary to undertake long-term field trials, process research, or modelling. However, very few cases of adequate chronosequences have been described, and in most cases it appears that we must use long-term field trials, process research, and modelling as our major focus in research designed to give forest managers the predictive tools they need.

CONCLUSIONS

1. There is no reason to believe that the problem of second- or third-rotation yield decline that has been seen in intensively managed forests harvested on short rotations on nutritionally-marginal soils in many parts of the world will not occur also in New Zealand's radiata pine forests. In fact, there is clear evidence from retrospective studies that very significant losses of forest growth have already occurred in some areas. The precise reasons for the loss of growth that has been documented are not always identifiable from such studies, but they appear to be closely related to losses of soil organic matter and nutrients.

2. The major threats to long-term site quality in New Zealand appear to be current site preparation practices, especially windrowing, root-raking, and some applications of line-raking. V-blading appears to be an appropriate technique for some sites, but has been applied to excess in some places with potentially serious implications for long-term site quality.

3. Whole-tree harvesting and slashburning are practices which can reduce the need for the type of mechanical site preparation that appears to pose the greatest long-term threat to site quality, but they also have potentially serious consequences for site quality on some sites. In many cases, their impacts will be less damaging than windrowing and root raking, but this does not imply that they will not cause loss of site quality if applied wrongly.

4. In many cases, loss of site quality has probably been masked by problems of weed competition and the benefits of genetic tree improvement. Also, assessment of site quality using tree height (site index) rather than a measure that reflects the plant growth potential of the site more accurately may have led to an underestimate of site quality declines, especially on the better sites. The most dramatic cases of growth decline are relatively easy to document, but there may have been much more extensive but smaller growth declines that have escaped detection because of the relative insensitivity of currently-used mensurational techniques.

5. Weed problems clearly dominate early-plantation silviculture in many radiata pine forests. Herbicides, possibly in combination with slashburning, appear to pose much less threat to long-term site quality than many of the alternatives, but it is anticipated that their use

may become more restricted, not necessarily on logical or scientific grounds, in some areas as the New Zealand public becomes more "environmentalist" in attitude.

6. There is little doubt that technologies exist to overcome many of the potential problems of management-induced site quality decline. In an increasingly competitive world, and with an apparently steady growth in environmental concern by the public, many of these technologies may be unavailable. It therefore would appear that the best strategy will be to minimize dependence on potentially threatened technologies and to rely increasingly on the inherent productive capacity of the land. This implies the need for site nutrient and organic matter management to become one of the key considerations in forest management.

7. In many cases the justification for some of the more extreme mechanical site preparation practices appears to be the use of a "clearwood" silviculture system. Where site quality is not threatened by this strategy, it seems reasonable. But in many cases it appears that the economic advantages of this silvicultural system will be reduced because of the reduction in site quality. There needs to be a careful re-evaluation as to which sites can tolerate the treatments that are required to make this high-value sawlog strategy workable and sustainable.

8. Because of the inadequacies of chronosequence and retrospective research, and because of the long time required to get meaningful indications from empirical field trials concerning long-term impacts on site quality, it is recommended that a comprehensive research strategy be developed that combines the long-term field trial approach with sufficient process research to permit the development of appropriate predictive models. Such models are needed as the basis for ranking the sustainability and other aspects of alternative silvicultural strategies. Well designed and monitored long-term field trials can provide both the scientific understanding needed to develop and calibrate predictive models, and they will in due course provide data against which the models can be validated.

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