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On the sustainable productivity of planted forests

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Key words: history of plantations, site potential, nutrition, soil properties, plantation yield

Abstract. Planted forests have more than a millennium of history and represent the world's best hope for meeting global wood requirements in the twenty-first century. Advances in genetic improvement, nursery practices, stand establishment, and tending, harvesting, and manufacturing have boosted plantation yields to a higher level than at any point in history. Despite this, forest managers face a mounting challenge to demonstrate that plantation productivity is sustainable. Tackling this challenge requires a sound understanding of the principles of forest productivity, how they apply to a developing plantation, and how they are influenced by management. In this paper criticisms of plantation forestry are discussed from the basis of world experience, and examples of productivity decline are described. Obvious declines are rare, and can be attributed to poor soil management. However, ambiguities exist and controversy will continue until sustainable productivity can be demonstrated conclusively. Proposed programs aim to provide the technical base needed for sound soil management and sustainable plantation productivity.

A history of the planted forest

> Planting cuttings of the fir along the roads.
> Enjoying the cool air in the moonlight of the future.
> (Zhu Xi, Song Dynasty, A.D. 1130–1200)

Forests exploited

Artificial forest regeneration has been practiced for more than a millennium. The need for planting is rooted in the clearing of forests – a vital step in the advancement of social order that began 10,000 years ago. As early as 3000 B.C., forests of Cyprus were felled to provide wood for the smelting of copper and silver (Hermann 1976). Solomon, nearly 3,000 years ago, supplied 80,000 fallers and another 70,000 skidders to move cypress and

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cedar timbers from the forests of Lebanon for the construction of the temple in Jerusalem (Winters 1974). In China, extensive clearing commenced about 2700 B.C., and continued unabated for 1,500 years until the Chou Dynasty (1127–255 B.C.) created in essence the world's first "Forest Service." With the demise of the Dynasty, however, deforestation resumed (Hermann 1976).

Europe remained forested through Roman occupation, but the first wave of clearing began with the break-up of the Empire in the fourth century and continued to the reign of Charlemagne about 800 A.D. Much of England remained forested beyond the Norman Conquest in 1066 A.D. Vast areas were set aside by Anglo-Saxon kings as royal game reserves to be guarded zealously against poachers and trespassers. The royal forest reached its zenith – about a third of the country – during the reign of Henry II in 1154–1189 A.D. (Hoskins 1955). Despite severe fines for doing so, peasants continued to clear the best lands for fields and homesteads.

The second great wave of European forest clearing surged in the eleventh and twelfth centuries, as wilderness was converted to arable land and as Germanic populations spread eastward. The single greatest cause of clearing was the demand for charcoal by the iron industry – an assortment of nomadic producers that advanced progressively into the forest (Nef 1952). However, the Salzburg forest ordinance of 1237 prohibited clearing forests for salt mine timbers so that forests would have time to repair themselves (Fernow 1911). By the fifteenth century, forest exploitation nearly brought some regions to economic collapse. Fuelwood shortages caused a decline in European iron production by the sixteenth century (Cramer 1984), thus triggering a timber famine in England in the 1600s. By the eighteenth century, much of Europe faced a wood crisis. France, where forests once flourished on four-fifths of the land, was only 14 percent forested by 1789 (Postel and Heise 1988). Of the 6.2 billion ha of forest and woodland believed to exist on earth at the start of the Holocene epoch, a third has been lost to crop production, fuelwood gathering, livestock grazing, and desertification (Postel and Heise 1988).

Forests restored

Western literature traces forest renewal efforts back, at least two millennia, to the time of the Caesars when Mediterranean gardens were planted to commemorate temples to the gods and to provide respite from the midday sun in the open Roman landscape (Sereni 1974). Later, temples were sacked, and sacred and functional plantings were degraded by the barbaric tribes that followed the collapse of the Roman Empire. But the Middle Ages brought some social stability, and with it an awareness that forests were not infinite. Deliberate forest renewal was practiced in Central Europe about seven centuries ago when feudal lords and communal forest owners sought by edict

to reverse the loss of wood supply and game habitat (Barrett 1949). The first records of artificial reforestation in Europe date to 1368, when the City of Nuremberg seeded several hundred hectares of burned lands to pine, spruce, and fir (Toumey and Korstian 1942). John Evelyn, a Surrey landowner in England, published a plea for reforestation in his 1664 *Sylva* (Hoskins 1955). However, progress was slow because forest rules were based largely on observations and folklore of huntsmen. But the wood shortage crisis and the advent of systematic study in the eighteenth century caused dramatic change in the practice of forest renewal. Sound, reliable forest planting methods developed quickly. Germany, Austria, France, and Switzerland became leaders in reforestation. By 1789, shelterbelt plantings were introduced in the Russian steppes to control wind erosion and protect farmlands.

Planting has a shorter history in North America (Toumey and Korstian 1942; U.S.D.A. 1949). The first successful effort was an experiment in Massachusetts in the 1740s to grow oak for ship timbers. In 1819, *Pinus rigida* Mill. was transplanted from natural forests in Massachusetts to sandy soils too poor for agriculture. For the most part, tree planting (mostly oaks) continued sporadically into the mid-nineteenth century. The Homestead Act of 1862 brought a wave of settlers to the prairie states, and with them came strong appreciation of trees as the substance for shelter and fuel on an otherwise bleak landscape. By 1869, Kansas, Nebraska, and the Dakota Territory had tax exemption laws encouraging tree planting to boost the agricultural economy of the region. The modern sense of forest care and renewal as a general goal traces to Michigan and the formation of the first state forestry commission in 1867. Other state commissions soon followed. By 1872, Arbor Day had been established as a national encouragement to plant trees.

Throughout history, tree planting progress has been slow without governmental help (Stoeckeler and Williams 1949). The Timber Culture Act of 1873 (later repealed) offered individuals title to 65 ha of public land provided that at least one-quarter of it were planted with trees. By 1881 Congress had established a Division of Forestry (later, the U.S.D.A. Forest Service), but little attention was paid to seeding or planting until the national forests were transferred from the Department of Interior to the Department of Agriculture in 1905. In the West – and partly in response to timber losses to wildfire – reforestation began in earnest through the establishment of federal tree nurseries. Planting was expanded to all ownerships through the Clarke-McNary Law of 1924, which provided for cooperation between the federal government and states in the production and distribution of tree nursery stock. By 1920, no more than 200 ha of successful plantations existed in the southern United States, but organized reforestation was accelerating by 1926. Today, the forest bases of the United States and Europe are fairly stable.

World attention has been drawn to the harvesting of the natural forests of the tropics, but less attention is paid to the fact that plantation forestry is on the rise globally. Even in the United States, where even-age silviculture is being de-emphasized on public land (only about 15 percent of all plantings in recent years), the area of all ownerships in new plantings has averaged 1.1 million ha annually for the last decade, and has ranged from a low of 979,000 ha in 1993 to a peak of 1.37 million ha in 1988 (Moulton et al. 1996). One-quarter of this is in the West. Domestic demand for wood products will continue to rise in the twenty-first century. Therefore, timber management deemphasis on public forests and the reclassification of much natural forest to protected status places an unprecedented burden (and opportunity) on planted forests – particularly industrial plantations of the South and Pacific Northwest – to meet the needs of a wood-demanding public.

Modern challenges

A hallmark of a maturing industrial nation is an awareness that natural resources are finite and have values beyond that of economic exploitation. Attaining a comfortable standard of living marks a transition to a growing sense of stewardship and responsibility to future generations. This comes, not from a blinding flash of mass cognition, but through the work of individuals who, by their persuasive power, form groups committed to a central ideal. Assuming that arguments are well intended and reasonable, these groups may generate political force that culminates in laws meant to sustain or to restore the condition of the natural environment for the benefit of the nation. At worst, it leads to obfuscation, turmoil, tension, and heated confrontation.

The path to creating and maintaining productive plantations is not as direct as it might seem. In the United States there is a core of opposition to the prospect of plantation forestry that is rooted partly in personal belief and partly in science. The former concerns a sense of desecration when forests of nature are harvested, groomed, and regenerated artificially. The scarcity of natural forests in much of the developed world imparts in them an element of mystery and spirituality. In the minds of many, converting natural forests to plantations is more than merely a loss of “wilderness.” It is a loss of innocence, too.

Personal beliefs and values are not in the purview of science and technology. However, plantation forestry also has been criticized on technical grounds. Natural forests are seen by some as centers of biotic diversity that, through scientific discovery, may promote the well-being of future generations – a diversity that is narrowed by conversion to simplified plantations. Others view natural forests almost as an organism comprised of interconnected and interdependent parts that promote long-term stability and high

productivity. Proponents reason that simplifying or severing these connections threatens forest health and future productivity. Thus, managers are faced with technical challenges concerning planted forests. Do plantations differ from natural forests in susceptibility to natural disturbances? Do practices that increase short-term productivity sacrifice long-term values? Can productivity be sustained indefinitely? Objective answers will affect public attitudes. And public attitudes will influence policies on how forests will be managed in the future, irrespective of ownership. The technical question of sustainable plantation productivity with principles of forest growth, experience with managed forests, and findings of recent research is considered in this paper. The thrust is on planted forests of the Pacific Northwest, where controversy seems to be centered. However, the principles presented have broad application.

The conceptual basis for sustainable productivity in plantations

Discussing the question of sustainable plantation productivity demands both a clear definition of terms and a basic understanding of how plantations develop and how biomass is partitioned over time. This conceptual foundation gives us sound footing in evaluating sustainable productivity from the perspective of world experience.

Defining productivity

In its most fundamental sense, productivity is the primary synthesis of organic matter from carbon dioxide, water, and nutrients through the absorption of light energy. Generally, this "gross primary production" (GPP) is expressed as units of carbon fixed/unit area/unit time. Largely, the amount depends on the amount of leaf area (and chlorophyll) available to capture sunlight. Plants vary greatly in their photosynthetic capacity to assimilate carbon dioxide into organic compounds. Corn and tropical grasses are the most efficient, and are capable of increasing their photosynthetic rates to very high levels of light intensity (Devlin and Barker 1971). Forest trees are less efficient, and reach a photosynthetic saturation at relatively low light intensities.

Not all of the carbon fixed in GPP appears as the protoplasm, cellulose, and lignin we recognize as plant biomass. Instead, roughly 50–70 percent of fixed carbon is lost to respiration of foliage, woody tissues, and roots, and to allocation to such symbionts as mycorrhizal fungi (Ryan 1991). That which remains accumulates as biomass or is consumed by animals or disease. This is called "net primary productivity" (NPP), a rate expressed as biomass production/unit area/unit time. For land plants, production is affected strongly

by the availability of water – not so much because of the role of water in the synthesis process itself, but more to maintain plant turgor by replacing water lost through transpiration when stomata are open for carbon dioxide uptake. Productivity also is limited by temperature controls of biological processes and by the availability of soil nutrients needed as electron carriers, in enzymatic reactions, and in the diverse compounds of plant cells.

Therefore, a good working definition of productivity with very broad application is the net production of biomass/unit area/unit time. Forests produce the greatest rates of NPP of any vegetation unit. Closed canopy forests of the tropics average between 6 and 35 mg/ha/yr, forests of temperate regions average 2–25 mg/ha/yr, and grasslands, 2–20 mg/ha/yr (Lieth 1975). Tropical forests have shown the highest rates of NPP, and suggest a ceiling of about 40 mg/ha/yr when climate is nearly optimal (Lieth 1975; Waring and Schlesinger 1985; Lugo et al. 1988). However, recent measurements of periodic increment in young, mixed plantings of *Paraserianthes* (*Albizia*) and *Eucalyptus* in Hawaii (Binkley et al. 1992) suggest that the limit may exceed 50 mg/ha/yr. In their survey of many tropical plantations, Lugo et al. (1988) found that mean annual increments of NPP averaged between 12 and 25 mg/ha/yr for the first 10–20 years of stand development, depending on soil water availability (Lugo et al. 1988). Although plantation data are scarce in the Pacific Northwest, rates for young-growth natural forests often fall between 10 and 38 mg/ha/yr (Grier et al. 1989), which suggests that the potential may even be higher under intensive management.

Traditionally, forest site productivity has been synonymous with stand growth rates. In fact, most of our historical knowledge of forest production rates is based upon simple measurements of tree boles – the part of greatest commercial value. Such cultural treatments as spacing and weeding can enhance stand productivity by allocating fixed site resources set by climate, soil, and relief to a target vegetation – trees, and to a target component – tree boles. However, they have nothing to do with site potential itself. A more useful view is to consider the production of each component of the entire tree – or, even more fundamentally, all of the vegetation on a site, regardless of physiognomy. This has the advantage of providing a more complete view of total carbon capture and how it might be managed to produce products useful to society.

Forest development and the partitioning of biomass

The uninterrupted trend for biomass production in a plantation or any even-aged stand follows a general pattern of increase from stand establishment to maximal production near crown closure when leaf area peaks and trees are

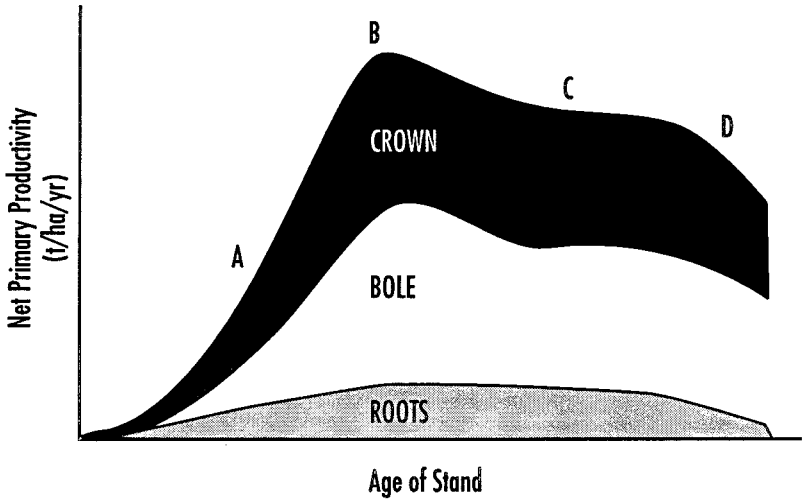

Figure 1. Typical pattern of even-aged stand development showing annual partitioning of productivity into roots, bole, and crown. Major phases are (A) rapid increases in productivity and nutrient demand as trees occupy site resources; (B) peak productivity and nutrient uptake at crown closure; (C) relatively stable productivity to maturity with increasing maintenance respiration (crown mass is fixed and much of the stand's nutrient demand is met through internal recycling); (D) rapid decline as stand senesces from natural causes (Waring and Schlesinger 1985).

fully exploiting the site (Figure 1). Throughout all phases of stand growth there is a close linkage between the mass of the crown and total production. Gross wood production is a linear physiological function of canopy light interception (Cannell 1989), as measured by the leaf area of a tree or stand. In general, the more leaf area, the more wood growth. Although it is modified by respiration (Gholz et al. 1990), the relationship between wood production and leaf area for a given species seems to be unaffected by water or nutrient stress. Although the relationship may be unaffected, however, a site's carrying capacity for leaf area or mass depends upon climate, soil moisture, and nutrient availability (Nambiar and Sands 1993). This carrying capacity is a fundamental property distinguishing one site from another. It is a precise measure of what foresters long have recognized as "site quality." Depending on the extent of limiting factors, it can be increased superficially by weed control or more profoundly by fertilization or drainage (Della-Tea and Jokela 1991), but not by thinning. Thus, climate, soil water supply, and nutrient availability determine site quality.

Crown closure also corresponds to the peak rate of nutrient uptake. Leaf area carrying capacity is reached, growth rates are high, and stands are fully taxing the site's ability to supply water and nutrients. After crown closure,

water demand remains high because leaf area and the transpiring surface remains essentially constant. Despite a continuing high demand, the forest relies less on the soil for its nutrient supply. Once crown mass is fixed, between one-half and two-thirds of a plantation's annual needs for many nutrients, including nitrogen (N) and phosphorus (P), but not calcium (Ca), is met through internal recycling from older foliage to newer before leaf abscission (Miller 1984). Research in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) plantations on a variety of sites in California (Figure 2) shows that roughly 60 percent of foliar N apparently has been retranslocated as amides and amino acids from needle fascicles when crown cover has reached 90 percent or beyond, thus leaving a residue at leaf fall of microbially resistant protein-polyphenol complexes. Compared to other nutrients in foliage, P is especially mobile, with about 80 percent apparently retranslocated as ionic phosphate and various organic compounds at crown closures of 50 percent and greater. That remaining at abscission consists mainly of phospholipids and insoluble calcium phosphate. In contrast with N and P, Ca accumulates in fascicles as insoluble pectates and oxalates even at very high crown closures. But, even for Ca, the proportion retained in senescent needles declines with increasing tree crown cover.

Internal recycling of nutrients is one of the main means by which forest trees cope with low availability of soil nutrients, and is a major nutritional distinction between perennial forest vegetation and annual agricultural crops. The fact that litterfall has higher nutritional quality at lower crown cover (Figure 2) suggests a more favorable dietary substrate for soil fauna during early stages of plantation development or in the period following a thinning. Total production of leaf litter and nutrient return would increase through crown closure, but the nutritional quality would lessen.

Typically, production rates are low when trees are young and crown leaf area is low. Much of the carbon assimilated annually is directed to production of leaves and the twig and branch system supporting them. As crown mass increases per unit area, production rates rise rapidly into an exponential phase that becomes sigmoid as the stand approaches the site's leaf area carrying capacity (Switzer and Nelson 1972; Waring and Schlesinger 1985). At crown closure, leaf area stabilizes and production rate peaks. Beyond crown closure, net production may decline slightly through maturity as an increasing proportion of photosynthate is used to maintain the respiring living matter accumulating in branches, bole wood, roots, and mycorrhizal networks. The pattern varies only by alterations in stocking from thinning or natural mortality, vigor reductions from fire, wind, insects, or disease, or from climatic vagaries. After maturity, productivity declines. This decline generally is ascribed to a lessened ability of a fixed crown mass to meet

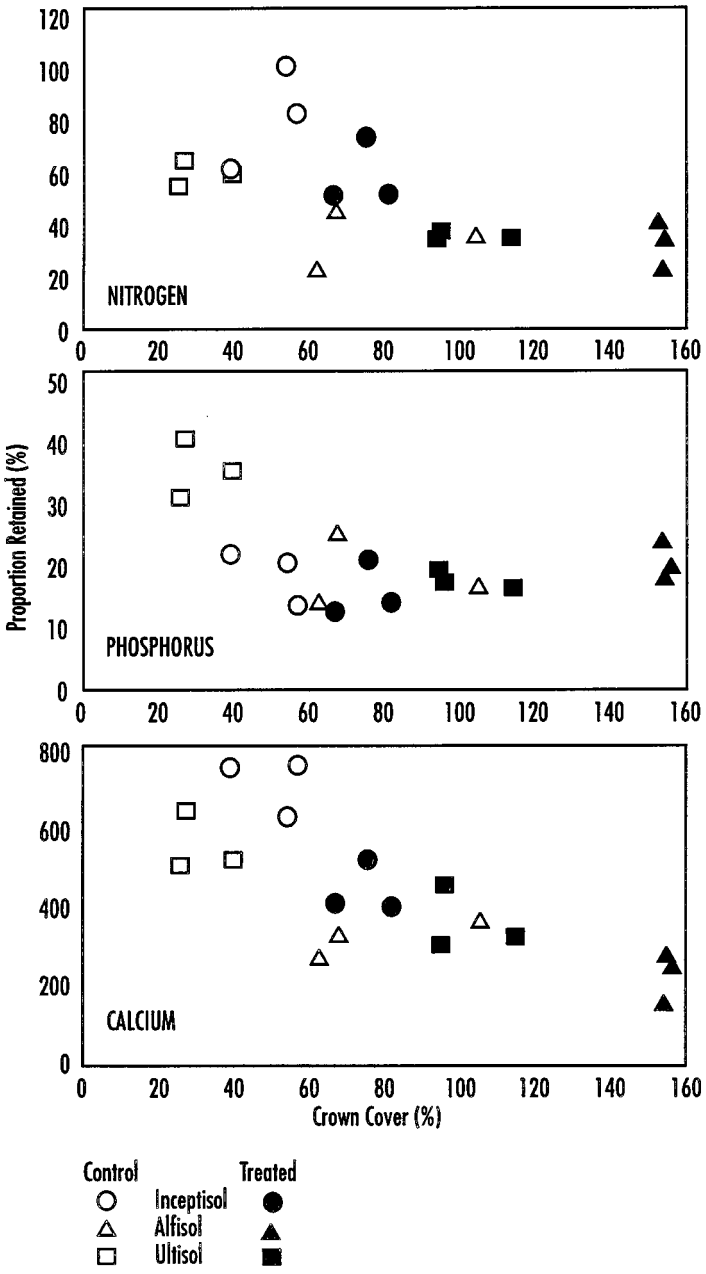

Figure 2. Percentage of initial foliar nutrient content remaining at leaf fall relative to percent crown cover of planted ponderosa pine. Results are from six treatment plots in each of three plantations on volcanic Inceptisols, Alfisols, and Ultisols in California. Open symbols are for control treatments. Filled symbols indicate repeated applications of herbicides and fertilizers.

the carbohydrate needs of respiring tissues in accumulating biomass (Waring and Schlesinger 1985). Thus, growth declines when maintenance respiration approaches assimilation. Because mycorrhizal fungi require steady supplies of carbohydrates from the host plant, mycorrhizal roots may decline because less carbohydrate is available for their maintenance. Reduced root surface leads to reduced water and nutrient uptake and to increasing stress, thereby reducing leaf area of individual trees. Ultimately, stand vigor declines, and insect and disease attacks become more severe. Canopy gaps then appear, leaf area decreases further, and production rate declines for the entire stand.

Ryan et al. (1997) discount the premise that increasing respiration is the principal cause of natural growth decline. Other explanations include decreasing nutrient availability, reduced assimilation because of increasing hydraulic resistance in tall trees, loss of leaf mass from wind abrasion in crowns, physiological aging of tissues, and increased reproductive output. Of these, increasing hydraulic resistance seems to be the most significant single factor (Ryan et al., 1997). All of these mechanisms may be important, and some can be influenced silviculturally. But, regardless of the actual causes, stand productivity clearly is dynamic (Figure 1). An important fact is that measurements made at different times during stand development may yield decidedly different values. Furthermore, measurements taken at a given time in stands of dissimilar stocking also will yield differing values – neither of which may equal the site's natural potential.

"Sustainable productivity," then, is the ability of managers to maintain NPP without a decline in rate. But the dynamic nature of plantation development demands a clear point of reference somewhere in the region B-C in Figure 1. A further need is to summarize NPP in all major forest components – not merely in tree boles. In principle, treatments which enhance short-term NPP in tree boles also may degrade the long-term productive potential of the site. This is important because a site's potential for NPP (its productive capacity) also reflects its potential for myriad uses and values. This productive capacity is a product of climate, soil, and topographic features acting upon vegetation that gives a site a unique potential. And as we shall see, it can be influenced by management.

Actual and potential productivity

What determines a site's natural potential? And, is it always achieved? Conceptually, productivity has two major elements. One is "current productivity," or the actual biomass produced by a forest over a recent period. Assuming that climate, soil, and genetic potential are not limiting, current productivity depends on stage of stand development (mature stands produce more than very young stands, Figure 1) and degree of stocking (fully

stocked stands produce more than lightly stocked stands). Basically, this reflects differences in leaf area (Cannell 1989). Because dry matter production depends on photosynthesis, current productivity depends largely on leaf area of the vegetation. Current productivity can be measured at any time, but assessments at different stages of stand growth will lead to different conclusions.

The second important conceptual element is "potential productivity." Similar to current productivity, potential productivity relates to leaf area. However, it represents the site's potential for biomass production when the site is at full carrying capacity for leaf area. This occurs between crown closure and stand maturity (Figure 1, sectors B and C). A site's potential productivity is independent of stocking. It represents what could be produced if growth were constrained only by the factors of climate, soil, and genetic potential. Under the best of conditions, this may approach 50 mg/ha/yr in young, planted forests (Binkley et al. 1992).

Depending on management objectives and natural disturbances, a site's productive potential may or may not be achieved. Equally important is the fact that potential productivity is not immutable. Although it is a natural ceiling set by existing site resources, it can be raised or lowered through substantive changes in soil, climate, or genetics. Of these, climate and soil are the major factors. And, of these two, soil is most readily affected by management. Genetics has a lesser role in that some genotypes are adapted better to given site conditions than others. However, one should not assume that faster-growing genotypes increase the site potential. Instead, they merely may reach the site ceiling sooner than others (meaning that some genotypes are more adept at reflecting true site potential). Further, there can be genotypic variation in the way that photosynthate is partitioned into crown, bole, or roots (meaning that site potential is reflected differently among genotypes). But, popular impressions to the contrary, genetic improvement is not a panacea. It cannot compensate in any substantive way for poor climate or soil. What, then, are the consequences of management on plantation productivity?

Altering productivity

Both actual and potential productivity can be modified. Climate, soil, and genetic potential determine natural limits on site productivity, whereas stocking determines the degree to which this limit is achieved. For instance, the site potential for an understocked plantation is set by soil physical, chemical, and biotic components. However, low tree stocking or a high weed component keeps leaf area low and prevents the plantation from achieving its potential (Figure 3A). Improved stocking captures the site's leaf area carrying capacity so that current and potential productivity coincide (Figure 3B). Although

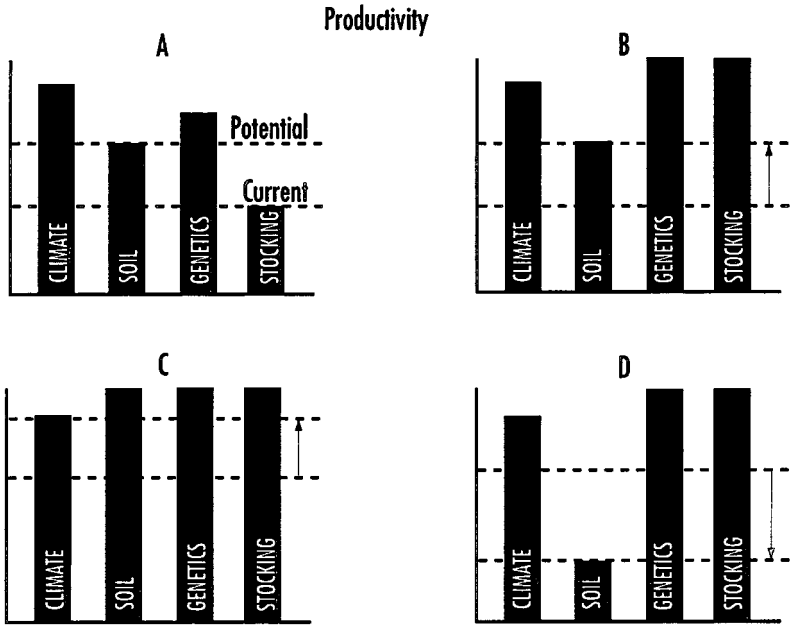

Figure 3. Relationship between current and potential productivity of a plantation as constrained by climate, soil, genetics, and stocking. (A) An understocked stand is performing at less than potential as limited by the natural properties of the soil. (B) Improvements in genetics and stocking increase productivity to the level constrained by the soil. (C) Soil amelioration (fertilization, drainage) raises productivity to a new potential set by local climate. (D) Both current and potential productivity are reduced through soil degradation.

genetics may have been improved as well, the limit remains set by the soil. Unless it can substantially change leaf area at full stocking or can improve photosynthetic efficiency in some fundamental manner, genetic improvement merely gets the plantation to the site limit faster. Conversely, diseases prevent a plantation from expressing its genetic potential. Improving soil properties, genetics, and stocking (Figure 3C) boosts potential site productivity to a higher plane constrained by climate. Alternatively, soil erosion, compaction, or nutrient drain may alter the site's potential so that productivity is degraded (Figure 3D). Superior conditions of climate, genetics, or stocking will not compensate for this, and operations are analogous to mining a nonrenewable resource.

Management often works within the fixed limits of natural potential productivity (Figure 4A). The degree of stocking or weed control determines the proportion of potential productivity that is captured by trees. But, depending on a site's resistance and resilience, this potential can be altered through soil modification – either enhanced through such treatments as fertilization

(Ballard 1984; Chappell et al. 1992), or degraded through soil compaction or erosion (Childs et al. 1989; Powers et al. 1990). Many forest managers – particularly industrial foresters – are philosophically aligned with agronomists who are not satisfied with the natural productivity of the land. They take an aggressive policy of capturing the whole of inherent site productivity or enhancing it further (the right portion of Figure 4B) by correcting soil fertility, drainage, or tilth limitations (Fisher 1984). In contrast, public land managers usually take a more conservative tack by working within the limits of natural productivity. Because the National Forest Management Act of 1976 requires such forests to be managed in a way that protects their long-term productivity (U.S.D.A. Forest Service 1983), national forest managers are concerned particularly with the left portion of Figure 4B. Forest management takes a more defensive posture. Management shall not degrade site productivity. Assuming that productive forests will always be valued by society and that productivity can be enhanced by understanding the controlling factors, why is there controversy over the value of planted forests?

The debate

Despite more than a century of world success in tree planting, the productive stability of planted forests still is questioned on a variety of technical fronts. Concern stems partly from agricultural experiences where repetitive cropping of corn or cotton without replacing nutrients has led to yield declines (Mitchell et al. 1991). Concern also traces to historical misconceptions about the influence of plantations of conifers (usually monocultures, sometimes exotics) on soil and site processes (Maser 1988). The recurrent themes are complexity versus simplicity and sustainable productivity in plantations.

Complexity versus simplicity

The stability of monocultures

Many ecologists believe that diversity is the foundation of stability in natural forests. It follows, they reason, that planted forests are inherently less stable because they are structurally and biologically simpler and less resistant to natural agents of disturbance. Therefore, plantation productivity also must be unstable and – most likely – unsustainable (Maser 1988). Although less dramatic, this concept is illustrated somewhat by entomological research. In one study, Berisford and Kulman (1967) surveyed infestations of Nantucket pine tip moth (*Rhyacionia frustrana*) incidence in loblolly pine (*Pinus taeda*

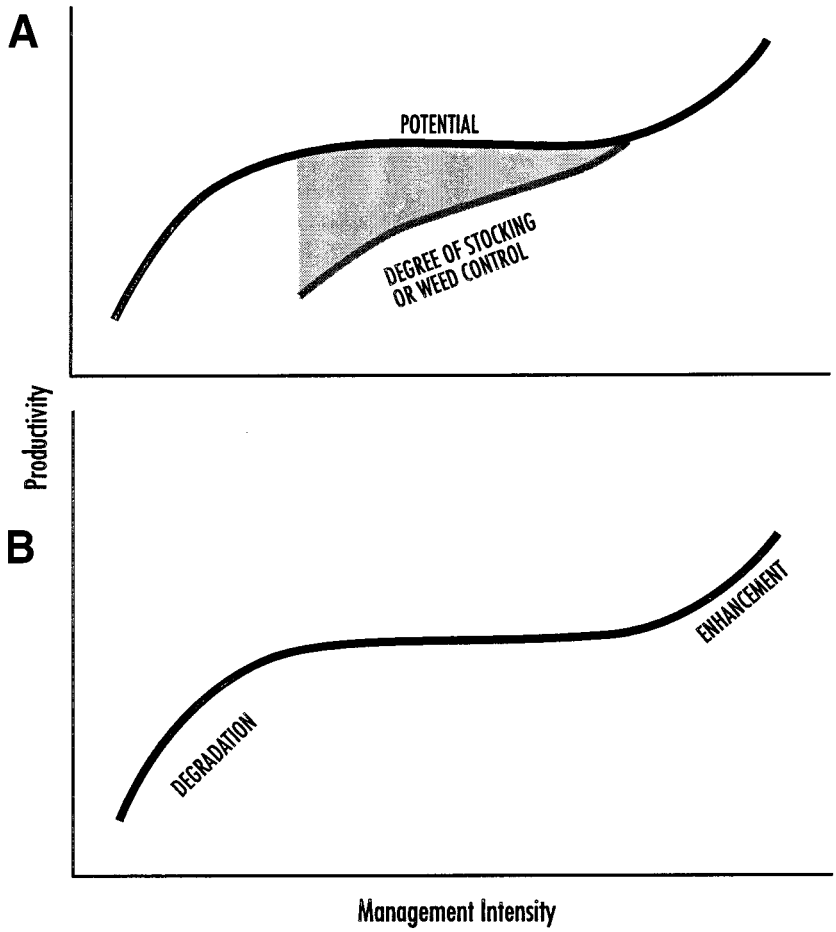

Figure 4. Relationship of management intensity to site productivity. (A) The degree to which the natural potential of a site is captured depends on stocking and weed control. (B) A site's potential productivity isn't static, but may be degraded by careless management (erosion, compaction), or enhanced by favorable soil treatment (fertilization, drainage, irrigation, subsoiling).

L.) stands in North Carolina. They concluded that infestations were greater in plantations than in old field stands, in widely spaced trees than at denser spacings, and in trees under lower competition from hardwoods. Although this seems to be an indictment against intensively managed pine plantations, subsequent studies show that weed control treatments also increased height growth, thus allowing infested trees to recover quickly (Ross et al. 1990). Infestations may be lower on water and nutrient stressed sites, but weakened trees also are less tolerant of damage (Meeker and Kulhavy 1992).

Thus, although intensively managed plantations may have higher rates of infestation, they also are more resilient.

Schowalter (1995) conducted a chronosequence survey of canopy arthropods in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in Oregon. He found that young plantations lacked many of the predator and detritivore taxa present in older stands, and concluded that herbivorous insects would not be regulated by their natural predators. The implication is that planted, intensively managed forests are more prone to pest damage than are natural forests. If this were true to any significant degree, insect problems would be common in intensively managed plantations. This is not the case.

The argument that plantations are inherently unstable is flawed for several reasons. First, it assumes that planted forests are biologically simple and that all are cast from the same "corn-row" mold of genetic, spatial, and structural uniformity. Actually, the principal distinction between planted and natural stands is in their intended use, for this governs the ways in which they are managed. Watershed protection plantations might be managed under extended rotations for continual ground cover and minimal disturbance beyond that of sanitation harvests to maintain plantation vigor. As outlined by Allen et al. (1996), plantations can be managed to enhance wildlife values through irregular stocking with canopy gap recruitment to ensure understory and overstory diversity in species and structure. Such plantations might be maintained longer than those meant for wood production. Finally, plantations meant for wood production are managed for profit. Rotations are shortened to capture a good return on the costs of investment. Hallmarks of such plantations are regular stocking and periodic entry to optimize merchantable wood production relative to cost of operation. But even these descriptions are too confining, because each general aim of plantation management contains a continuum of possibilities that lead to alternative futures. Flexibility in species mix and spatial arrangement makes plantations our best means for achieving a myriad of management options.

Under what conditions might monoculture simplification trigger disaster in planted forests? Perhaps the epitome of simplification exists in the extensive industrial plantings of radiata pine (*Pinus radiata* D. Don) introduced as an exotic monoculture to the geographic region of Australia known as the "Green Triangle." In 1961 the wood wasp *Sirex noctilio* was discovered in one large plantation in the state of Victoria. By 1972, *Sirex* had destroyed about 12 percent of the marketable volume despite the presence of both parasitoids and nematodes, and had killed two-thirds of the trees in severely infested stands (Madden 1988). Of this, about half of the mortality occurred in a single year. Damage was greatest in unthinned stands, and was most pronounced after a period of progressively lower summer rainfalls. Infestations declined after

1978. Earlier outbreaks reported in Tasmanian and New Zealand plantations of radiata pine reflected similar conditions of overstocking and a drought period interrupted by moderate summer rainfall or by thinning operations during the flight period of *Sirex*.

Short periods of tree stress, followed by respite, followed again by stress favor *Sirex* attack. Summer drought characterizes the radiata pine region of Victoria, and drought stress is accompanied by a shrinkage of phloem. Moderate summer rain rehydrates tissues, but if rehydration is followed by a second drying period, phloem shrinkage may release a pulse of water vapor and monoterpenes which attract *Sirex* during flight season (Madden 1988). Similar chemical pulses are emitted when thinning slash or pruning wounds are created during the flight season. The female wood wasp then bores into the xylem, breaks the capillary columns of high-tension water, and introduces mucus and fungi into xylem vessels. This intensifies water and nutrient stress, and leads to death. Although *Sirex* populations can be controlled by chemically attracting the wood wasp to trees inoculated with nematodes, careful timing of weeding and thinning should help maintain tree vigor and reduce risk – even in pure monocultures.

Powers and Ferrell (1996), in a designed stress experiment with pine plantations across an extreme range of sites in California, found no evidence of insect or disease problems, even at extreme intensities of weed control and fertilization. Outbreaks of forest pests generally trace to trees under stress from lack of management or poor timing of silvicultural operations, rather than intensive management per se. Collectively, trees stressed from overstocking because of a *lack* of management create the “forest health problem” that has captured the attention of politicians and the general public. Berryman (1988) presents an excellent review of forest insect outbreaks and management implications.

In the West, plantations managed for wood production often begin as monocultures, but they seldom remain so. California ponderosa pine planted as pure stands for timber production often contain varied understories of conifers and shrubs through crown closure and beyond. Although understory growth is reduced at high stocking densities, diversity persists (Oliver and Dolph 1992). Recently, Miller and Anderson (1995) compared six matched plantations and natural stands originating from wildfire in the coastal Douglas-fir region of Washington state. Although planted purely with Douglas-fir, many tree species had invaded the plantations. By 65 years, more than half of all living trees were other species. Nor are plantations necessarily less diverse than older, natural forests. Halpern and Spies (1995), studying forest chronosequences in the Oregon Cascades and Coast Range, found that changes in understory diversity were fairly short lived after harvest-

ing and relatively few taxa were eliminated by soil disturbance or light burning. By crown closure, species richness on logged sites can recover to preharvest levels. At the stand or watershed scale, flora typical of old-growth understories were maintained.

Component linkages

A companion notion is that ecosystem components and linkages vital to forest health and stability are altered severely or eliminated entirely in planted forests, thus rendering these forests vulnerable to calamity because they are buffered poorly against natural disturbances. From this it follows that plantation productivity probably is unsustainable. Studies have not shown any clear linkages among species diversity, varied structure, and forest health or susceptibility to forest pests. For example, popular claims that large woody debris provides essential repositories of mycorrhizal fungal spores (Maser 1988) are not supported by any objective research. Furthermore, Moldenke (1992) found that young plantations entirely free of surface residues contained the same functional guilds of soil arthropods as occurred in adjacent mature, natural stands except for those of the forest floor (which had not yet developed in the plantations). In fact, arthropod density, diversity, and biomass all were higher on fertilized than on unfertilized plots in the plantations.

Studies on nutrient cycling have not found a scientific basis for the notion that cycles become more complex or efficient with succession (Vitousek and Reiners 1975). Certainly, linkages among components are more varied and structures are more complex in older natural forests than in plantations (Franklin 1993), but this pattern does not emerge until the second century after disturbance (Franklin and Spies 1991). Except for specialized niches, such as those for epiphytes characterizing old-growth forests and the animal communities dependent upon them, the multiple linkages regarded by some as vital to forest health and sustainability are seen merely as fortuitous redundancies by others. Despite heated proclamations on both sides, neither hypothesis has been tested broadly or with rigor.

Resistance and resilience

Ecosystem stability consists of two traits: resistance and resiliency (Webster et al. 1975). Resistance to change is an inertial force associated with large storage of organic matter and nutrients, long turnover times, redundancy, and a complex pathway in the cycling of matter favoring closed nutrient cycles. These are traits of fully stocked forests in more advanced stages of succession, and of soils with a high capacity to absorb stress and immobilize

added chemicals either biotically or physically. Resiliency is a dissipative force that returns a forest back to near its original state following disturbance. Earmarks are rapid turnover and recycling of matter (the normal characteristic of planted forests). Although both traits contribute to stability, they are related somewhat inversely to each other (Webster et al. 1975). Those factors which increase resistance tend to decrease resilience, and vice versa. Compared to older natural stands, intensively managed plantations may have low accumulations of organic matter and less complexity (less resistance); however, they also have higher rates of nutrient turnover and the capacity to expand their crowns and increase their leaf areas when canopy gaps appear (more resilience). Therefore, planted forests are not necessarily less stable than natural forests.

Natural forests sometimes are said to be more resistant and resilient to severe natural disturbances. Wildfire illustrates a severe natural disturbance, but its effect for a given size of tree is no greater in plantations than in natural stands. In fact, given the historical policy of fire suppression in natural forests of the United States, damage from wildfire may be substantially less in well-tended plantations. Weatherspoon and Skinner (1995) studied effects of wildfire on 246 plantations and 874 other stands covering 14,000 ha in northern California. Damage was minimal in uncut natural stands, but was severe in partially cut stands lacking fuel treatment. Where slash had previously been burned in plantations, fire damage often decreased with distance from the edge of the burned natural forest. Plantation damage was spotty and varied where slash had been piled by tractor. Plantations lacking any fuel treatment burned uniformly and severely. Uneven-age management and residue retention in natural stands – a concept with its advocates (Franklin 1993) – may be a recipe for disaster in summer-dry climates without adequate fuel treatment.

That planted forests tend to have low resistance and high resilience is abundantly useful to management. In fact, treatments meant to boost plantation productivity are aimed deliberately at overriding resistance. For example, fertilizers are applied in doses great enough to override the buffering effect of weeds, microbes, and the nutrient-fixing capacity of soil. The aim is to achieve strong, positive, and predictable responses to treatment investments. Such silvicultural tools are not for the exclusive use of timber growers. The variety of intensive silvicultural practices available for regulating forest growth can be used to accentuate other values for those same plantations (Lippke and Oliver 1993). For example, treatments that create escape and hiding cover, improve both quality and quantity of forage for wildlife, and adjust the spatial arrangement of habitats can lend multiple values to plantations (Allen et al. 1996). Resiliency of planted forests also

means that they respond in consistent and predictable ways to treatment. This allows managers to predict the magnitude and duration of treatment response, and thereby determine how treatments should be scheduled in an effective management regime.

Sustainable productivity in plantations

Although many arguments against forest simplification are not supported well by field experience, critics of plantation forestry may present more tangible arguments based on cases that suggest productivity decline. Can such cases stand the test of scientific objectivity? If real declines have occurred, can we infer the causes?

Spruce sickness

In the early nineteenth century, many of Central Europe's depleted areas and forests of hardwoods were converted to plantations of more profitable Norway spruce (*Picea abies* [L.] Karst.). By the second rotation of spruce, however, yields on some sites were lower than those in the first rotation. From this spread a belief that conifer monocultures degraded the soil (Wiedemann 1923; Ovington 1953; Grigor 1868), dogma that persists today (Sheppard 1986). More modern investigations show that "spruce sickness" was relegated to poorly drained lowland sites with heavy clay soils. There, old root channels from the original hardwood forest gradually plugged, and led to poor internal drainage. Waterlogging in the wet season confined spruce roots to shallow depths, thus leaving them perched and dry during drought (Krauss et al. 1939; Holmsgaard et al. 1961). On better-drained sites, spruce sickness either did not occur, or was relegated to lands already degraded by past practices. Clearly, the cause for spruce decline was quite explainable. Today, this would be known as "off-site planting." In his review of European research on growth changes attributed to plantings of spruce and pine, Stone (1975) concludes that declines often were more mythical than real. Where detailed records were kept, they indicated that growth generally was greater in second generations. Where declines did occur, they could be attributed to pre-existing differences in soils caused by preforestry land uses, to intermediate agricultural use, and to litter gathering which was practiced commonly for decades.

Radiata decline

These concerns resurfaced following a separate event in the southern hemisphere. Beginning about 1920, plantations of exotic conifers, principally

radiata pine, were established in Australia on previously nonproductive scrublands of native species. By 1927, softwood plantings had been established in all states except Tasmania. Of these plantings, nearly 6,500 ha (41 percent of the total) were in South Australia which was considered the most climatically favorable region, and rotations were set roughly at 35 years (Gray 1935). Early success led to further planting with the aim of meeting all domestic wood needs and perhaps a surplus for export. By 1930 the planting area had doubled, and in the next 3 years it grew another 40 percent. By the 1950s the oldest plantations were being harvested and replanted. In some cases, thorough records were kept of first rotation performance, and that of the second rotation as well.

In 1966, Andrew Keeves published a landmark paper in which he compared changes in yield capability classes in first- and second-rotation stands of radiata pine on sandy soils of South Australia's Penola and Mount Burr Forest Reserves (Figure 5). Mapping units of the highest yield class in the first rotation had nearly disappeared in the second, and most mapped units had dropped by a yield class or more (mean annual increment declines of 30–60 percent). Concern spread quickly that pine monocultures somehow were poisoning the soil, negating a huge national investment in plantations. The yield decline between the first and second rotations was indeed real, and speculation abounded about the possible cause (Florence 1967). Similar concerns and possible causes of growth declines in second-rotation pine stands were expressed in New Zealand (Stone and Will 1965) and South Africa (Robinson 1973).

Using innovative methods of matched plots and stem analysis, Squire et al. (1985) showed that second-rotation decline probably could be eliminated merely by retaining logging slash and forest floor after harvest. In fact, slash retention produced greater early growth rates in second rotations than in first. Smethurst and Nambiar (1990) achieved similar results by weed control and N fertilization. Both studies show that the common practice of slash burning following logging led to weed development, soil drought, and reduced N availability on sandy soils. Organic matter retention produced soil moisture and temperature regimes favoring N mineralization. However, higher rates of N mineralization without weed control led to accelerated weed growth. This growth, coupled with declining rates of N mineralization as nutrient demand by trees increases (Figure 1, sector A), exacerbates nutrient deficiency and reduces growth in young stands – at least, on sandy soils (Smethurst and Nambiar 1990).

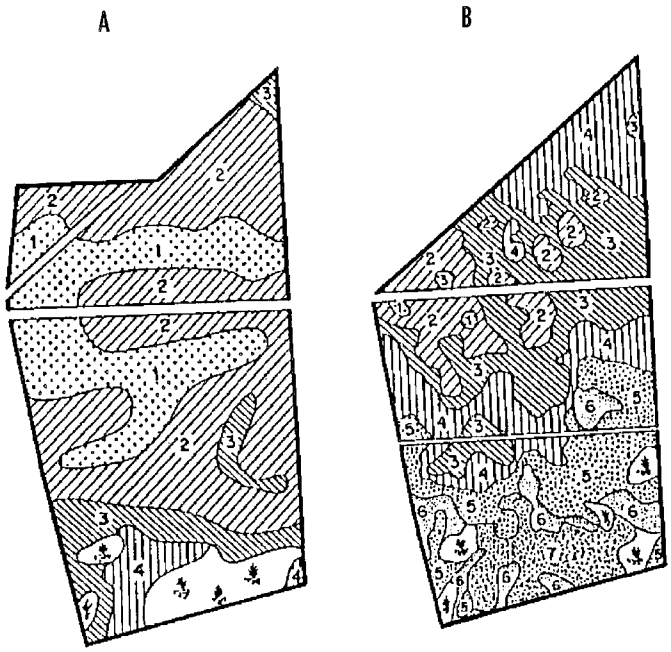

Figure 5. Site class mappings for first (A) and second (B) rotations of radiata pine within the Penola Forest Reserve, South Australia. Numbers 1–7 indicate site-quality classes between 1,500 (1) and 400 (7) m^3/ha over 50 years (Keeves 1966).

The southern pines

Opinions in the United States largely are based on chronosequence studies or retrospective analyses of current stands. For example, findings from repeated forest inventories in Georgia show a progressive decline in diameter growth of pine between 1956 and 1982 (Sheffield et al. 1985). However, declines seem to be restricted to nonindustrial private forest land where shrub and hardwood competition had increased from the absence of regular underburning. On more intensively managed industrial plantations, growth rates were stable or had increased (Sheffield and Cost 1986). Whether the latter is the result of improved genetic selection, better stocking, or weed control, or of maintenance or improvement in potential site productivity is unknown. In fact, one might question why plantation productivity is not greater in the southern United States, given decades of research in tree improvement, stocking control, and fertilization.

Repeated forest inventory may reveal trends, but it cannot establish cause and effect. A study in Louisiana suggests that declines in productivity of the next rotation can occur and may be caused by treatments meant to increase productivity in the present rotation. Tiarks and Haywood (1996) compared

burning only, burning plus disking, and burning combined with disking and bedding before planting loblolly and slash (*Pinus elliottii* Engelm.) pines. The plantation was harvested after 22 years and replanted with the same species. Slash was burned, but mechanical site preparation was not repeated. After 10 years, standing volumes in the second rotation were 56 percent and 38 percent less than in the first rotation for loblolly and slash pine, respectively. Mechanical site preparation before the first rotation increased yields during that rotation, but apparently suppressed yields in the second.

Soil strength was measured in the second rotation, about 34 years after the original site preparation treatments. With few exceptions, strengths remained below 2 MPa throughout the upper 50 cm in the burned-only treatment. In the burned and disked plots, soil strengths exceeded 2 MPa in a continuous band at the 20–25 cm depth, and again at depths beyond 50 cm. Soil strength also was elevated in the burned and bedded plots, but the pattern was discontinuous. High soil strength is an element of compaction and reflects the force required by a small object (such as a root tip) to overcome particle-to-particle resistance as it moves through the soil. For many agricultural crops (Whalley et al. 1995) and forest trees (Sands et al. 1979), root activity declines dramatically as soil strength increases from 1 MPa to 3 MPa, a value at which root growth essentially ceases. In Tiarks and Haywood's (1996) study, increases in soil strength as a result of tillage may have exacerbated an incipient P deficiency, especially on the disked plots where the compacted pan was continuous.

How general is the second-rotation phenomenon noted in South Australia and Louisiana? Evans (1978), comparing first- and second-rotation growth rates on more than 100 matched plots of planted *Pinus patula* Schiede & Deppe in Swaziland, found few instances of statistically significant declines. Interestingly, earlier observations of the same plots suggested that a general decline had occurred (Evans 1975), which underscores the risk of hasty conclusions. In their recent review of the world experience, Morris and Miller (1994) conclude that evidence supporting the notion that long-term productivity generally declines in planted forests is scant.

The case for improvement

Agronomic studies have shown conclusively that yields of cereal and grain crops can be maintained or improved through fertilization, genetic improvement, and crop rotation (Mitchell et al. 1991). The same can be demonstrated in forestry. Plantation productivity – both current and potential – can be increased substantially through soil treatment. Classical examples include drainage and bedding that revolutionized pine planting on wet coastal sites of the southern United States (Pritchett 1979), fertilization (Ballard 1984),

N-fixation (Davey and Wollum 1984), and irrigation when combined with fertilization on dry, infertile sites (Snowdon and Benson 1992). If the change is permanent, it enhances site potential (the right of the curve in Figure 3B). The duration of such effects depends on treatment. On overly wet sites, improved soil aeration through drainage leads to greater growth and the effect remains permanent. However, growth gains resulting from irrigation last only as long as the treatment is sustained.

Productivity gains through fertilization are complex. Because of the general immobility of phosphate in the soil and its high rate of internal retranslocation, P fertilization effects may last for decades and extend perhaps from one rotation to the next. Fertilization rates are high (50–100 kg P/ha), relative to the quantities of P present in stand biomass (5–70 kg/ha; Ballard 1984). Because of its immobility in most soils, massive doses of fertilizer P favor extended uptake. Once absorbed, P shows high rates of internal retranslocation from needles at all stages of maturity (Nambiar and Fife 1991). After senescence, organic P, remaining in litterfall and root sloughage, concentrates in surface horizons in the vicinity of feeder roots where decomposition sustains P availability in a tight nutrient cycle.

In contrast, response to N fertilization seldom extends beyond a decade. As with P, a high proportion of N is retranslocated internally before leaf fall (Nambiar and Fife 1991). Unlike P, amounts typically applied (100–300 kg N/ha) are but a fraction of the mass stored in living vegetation and the forest floor (Ballard 1984). Some N may be volatilized within the first few days following fertilization with urea, particularly if temperatures are warm and granules have lodged in vegetation. Losses of 18–78 percent are common (Wollum and Davey 1975). Regardless of source, ammonia losses are exacerbated in neutral-alkaline soil. Also, surplus ammonium from fertilizer can be oxidized microbially to nitrate – an anion that can be leached through the soil profile beyond the influence of roots. Elevated nitrate concentrations in soil solutions extracted at 1 m depth can extend for up to 2 years following a single N fertilization (Miles and Powers 1988), and losses are greater on coarse-textured soils and on weakly developed soil profiles (Powers 1983). Biological denitrification to oxide gases also is possible if nitrate is abundant. However, competition for N by microbes and higher plants in aggrading plantations, relatively high C:N ratios, and the generally aerobic nature of the soil of conifer plantations suggest that denitrification rates will be acceptable (Davidson et al. 1990). Denitrification has not been studied extensively in plantations. It could be a significant factor if nitrate-forming fertilizers are applied during early stages of stand development when soil moisture is relatively high.

A high proportion of many nutrients absorbed following fertilization and translocated to tree foliage are retranslocated back into the phloem prior to leaf fall. The proportion retained is more a function of crown cover than fertilization per se (Figure 2). At senescence, foliar N concentrations may be somewhat higher in fertilized trees. California pine plantations fertilized repeatedly with N to a total of 1,074 kg N/ha had 11–35 percent higher N concentrations in needles at litterfall than did unfertilized plots in the same plantations. However, high rates of P, K, Ca, Mg, S, Zn, Cu, and B fertilization did not produce a similar effect. Thus, fertilization can result in N-enriched litterfall. Ultimately, some of this forms recalcitrant soil humus, essentially uncoupling a fraction of fertilizer N from the biological cycle. So, in contrast to the tight, closed cycle of fertilizer P, the fertilizer N cycle is comparatively leaky. Like a mechanical gear that wears a little as it turns, portions of N gradually abrade with each cycle.

Planting conifers with N-fixing species may enhance plantation growth under certain site conditions. On an N-deficient site at the Wind River Experimental Forest in Washington state, dominant Douglas-fir interplanted with (but a few years in advance of) red alder (*Alnus rubra* Bong.) was 20 percent taller after five decades than Douglas-fir planted in pure stands, and stand volumes were over 90 percent greater in the mixed planting when all species were considered (Miller and Murray 1978). Better sites show a lesser effect. On Hawaii's Big Island, stands of *Eucalyptus* (*Eucalyptus saligna*) interplanted with the N-fixing *Paraserianthes falcataria* near Hilo were equal to or larger than pure stands of *Eucalyptus* that had been fertilized repeatedly (DeBell et al. 1989), but mixed plantings led to no improvement on a drier site. Yet, strategies can be developed for drier sites. Nambiar and Nethercott (1987) demonstrate that annual lupine (*Lupinus*) seeded between rows of radiata pine on droughty, infertile sands serve the double purpose of excluding more persistent weeds while adding N and organic matter to the soil in South Australia. By the fourth year, pines so treated had twice the mass of pure pine controls. Thus, creative use of symbiotic N-fixation may be a way to improve site potential while avoiding chemical treatment.

Conclusions to date

Recent reviews (Powers et al. 1990; Morris and Miller 1994) conclude that direct evidence of productivity decline in managed forests is rare, whereas the converse seems common. Most records indicate sizable gains in actual productivity when planted forests replace natural forests, and suggest that potential productivity may be sustained as well. But most findings are short term and narrowly focused, and many are confounded by factors that add

ambiguity. The rare instances in which true declines seem to have occurred can offer clues to help us adjust forest practices and guide our research programs. True declines point to changes in either of two site characteristics: biologically significant losses in soil porosity and in site organic matter (Powers et al. 1990). These two properties can be visualized as "gatevalves" that regulate more fundamental processes controlling site productivity.

Changes in soil porosity

There is no doubt that soil porosity has been reduced from compaction occurring during mechanized harvesting and site preparation (Greacen and Sands 1980; Froehlich and McNabb 1984). However, the consequences of this on potential productivity are largely unknown. The mechanism by which compaction can degrade productivity is the loss of soil macroporosity and the build-up of strength between soil particles to a level that restricts root growth. Natural soil porosity is a continuum of void sizes that varies with the mineral nature of the parent material and its degree of weathering, the tunneling activity of soil fauna and plant roots, and cycles of freezing and thawing. Reduced porosity lowers the exchange of water and gases between the atmosphere and the earth, the ease with which moisture and nutrients flow to plant roots and plant roots extend through the soil, and the biological activity of aerobic soil organisms. Lowered rainfall infiltration leads to surface runoff and soil erosion.

Few reports of soil compaction are based on controlled field experiments. Most are retrospective studies of operational trials where plot sizes are small (skid trails), true controls (noncompacted areas) are lacking, starting conditions are not clearly known, confounding factors such as weeds are present, and observational periods are short. On the basis largely of retrospective studies, Froehlich and McNabb (1984) conclude that every 10 percent increase in soil density spelled a 6 percent decrease in tree height growth. In contrast, Miller et al. (1996) describe a designed experiment involving planted Douglas-fir in coastal Washington state. Observations over 18 years led them to conclude that neither heights nor stem volumes differ among trees planted on tilled and nontilled compacted skid trails and in the bordering trafficked stands. Trees in all treatment classes were the same height (between 16 and 17 m at 18 years). Mean tree heights were more than four times the width of the skid trails (a small plot problem). Neither report demonstrates that trees in compacted and uncompacted plots were under similar degrees of weed competition, or that the "control plots" of logged-only areas had not been compacted to some degree during logging. Thus, reports from operation-level studies should be reviewed with some skepticism. Without demonstrable proof that compaction leads ultimately to lower yields, forest managers and

equipment operators are skeptical about the worth of avoidance or mitigation (Miller et al. 1996).

The fundamental questions facing field compaction studies are these: (1) Did management activities affect soil porosity? (2) Did soil porosity changes affect actual and potential productivity? (3) Is the experiment rigorous enough to detect this? (4) Are these findings universal? (5) If not, why not?

Recent findings from California installations of the North American network of Long-Term Soil Productivity (LTSP) installations (Powers and Avers 1995) provide strong inferences into how soil compaction affects tree growth, and whether or not effects are universal. Two sites were examined: Challenge – a mesic site averaging 1,650 mm of precipitation annually, and Vista – a xeric site where precipitation is less than half that at Challenge. The Challenge soil is a deep, fine-textured clay-loam, weathered from metamorphosed volcanic rocks. That at Vista is shallower, sandy, and weathered from granodiorite. Following LTSP protocol, the mature natural forests were clearcut at each site and factorial combinations of organic residue removal and soil compaction treatments were applied to 0.4-ha plots. The LTSP treatments included complete removal of all organic surface residues and varying degrees of soil compaction applied as uniformly as possible across the entire treatment plot. Severe compaction increased soil bulk density by 28 percent at Challenge (Table 1), but only 8 percent at Vista (which had a higher bulk density initially). Planting holes then were augered to about 0.5 m, and several conifer species were planted, including ponderosa pine and white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.) – two species that contrast strongly in their response to drought stress (Lopushinsky 1969). Competing vegetation was controlled on one-half of each treatment plot and allowed to develop on the other.

Measurements taken a few years after planting at Challenge indicated that, when weed competition was eliminated, the volumes of planted conifers averaged 42 percent less in the compacted treatment (Table 1), an outcome supporting the Froehlich and McNabb (1984) model. Pore size analysis and water retention studies showed that compaction had reduced surface soil macroporosity by 36 percent, and that the available water holding capacity (A.W.C.) had been reduced by 24 percent. This was substantiated by lower predawn plant water potentials for both pine and fir. Vista, with its coarser textured soil, responded differently. There, compaction reduced macroporosity by only 18 percent. Forcing sand-sized particles closer together reduced large voids and increased A.W.C. by 65 percent. The net result was a two-thirds improvement in seedling growth and a substantial improvement in predawn plant water potential in white fir – an effect contrary to the Froehlich and McNabb (1984) model.

Table 1. Ecological interactions of soil compaction and weed competition on soils of contrasting texture on two LTSP sites in California. Data are means of several measurements in August 1994 at the end of the fourth (Challenge) and second (Vista) growing seasons. Soil depth is 10–20 cm.

Characteristic species	Challenge (clayey texture)				Vista (sandy texture)			
	Not compacted		Compacted		Not compacted		Compacted	
	Weeds	No weeds	Weeds	No weeds	Weeds	No weeds	Weeds	No weeds
Seedling volume growth (1,000 cm)								
Pinus ponderosa	105	321	152	194	15	16	20	27
Abies concolor	4	18	6	10	2	3	3	5
Vegetative cover (%)	91	Trace	56	Trace	55	Trace	68	Trace
Soil bulk density (mg/m^3)	0.88	0.88	1.13	1.13	1.06	1.06	1.14	1.14
Total soil porosity (%)	67	67	57	57	60	60	57	57
Change in aeration (%)	0	0	−38	−34	0	0	−18	−18
Change in A.W.C. (%)[a]	0	0	−24	−24	0	0	+65	+65
Soil moisture 50 cm (%)	29	32[b]	30	33[b]	–[c]	–[c]	–[c]	–[c]
Predawn plant water potential (MPa)								
Pinus ponderosa	−0.88	−0.60	−0.87	−0.66	−1.61	−1.05	−2.05	−1.41
Abies concolor	−1.74	−0.54	−1.15	−0.63	−2.37	−1.13	−3.47	−0.93

[a] Available water holding capacity.
[b] Soil water potential exceeds −1.5 MPa.
[c] Not measured.

The LTSP experiment illustrates that, whereas soil compaction can reduce forest productivity, the effect is not universal – at least, in the short run. On droughty sites, any treatment improving the retention of available soil water without impairing aeration should improve forest productivity. As suggested by Miller et al. (1996), the biological significance of soil compaction must be tempered with regard to climate and soil textural differences.

Changes in site organic matter

Organic matter influences the interception and retention of solar heat by the soil. It dissipates the energy of falling water. It is the ultimate source of substances that bind soil particles together into stable aggregates that resist erosion. Through its carbon compounds, organic matter constitutes the energy source for soil fauna and microbes. Organic matter constitutes a concentrated reservoir of plant nutrients supplied to the soil through pulses in litterfall and root sloughage.

Without question, a sustained flow of organic matter from primary producers to the forest floor and into the soil is vital to sustained site productivity through its influence on the aggregation and physical stability of soil particles, soil water holding capacity, the activity of beneficial soil organisms, and nutrient supply (Jurgensen et al. 1990; Powers et al. 1990; Henderson 1995; Van Cleve and Powers 1995). However, virtually all findings from field experiments show that plantation survival and early growth are favored by removing surface materials during site preparation (Morris and Miller 1994). Therein lies the paradox. Why does practical experience often contradict theory? Is theory too simplistic, or are experiences too short sighted? The question should be examined from a first-principles position.

Temperature, moisture, and biotic activity in the surface soil are affected quickly by organic removal. Particularly, this is noticeable at high latitudes and elevations where surface organic residues insulate the soil. The resultant lowering of soil temperature means that water viscosity rises, soil faunal and microbial activity falls, and nutrients are less mobile.

Studies in boreal, interior British Columbia *Picea* forests (T. A. Black, unpublished; Fleming et al. 1994) showed that soil beneath scalped surfaces was as much as 4 °C warmer during the growing season (Table 2) and had fewer weeds than unscalped controls. In another study in interior British Columbia, both scalping the forest floor and mounding surface materials into raised planting beds improved the initial growth of planted *Picea engelmannii* Parry ex. Engelm. × *P. glauca* (Moench) Voss, but only the mounding treatment (which retained and incorporated surface organic matter) produced appreciably larger seedlings after 27 months (Bassman 1989). Soils remained warmer and better drained within mounds. Similar results were shown for

Table 2. Effect of presence (present) or absence (absent) of forest floor litter on the temperature and moisture in the surface 15–20 cm of soil in boreal and temperate second-year plantations (*Source*: T. A. Black, Department of Soil Science, University of British Columbia, Vancouver, unpublished; Fleming et al. 1994; and R.F. Powers, unpublished).

Month	Soil temperature (°C)				Soil moisture (%)			
	Boreal forest		Temperate forest		Boreal forest		Temperate forest	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent
April	2.1	4.5	12.8	13.3	31	33	34	34
May	6.6	7.7	17.8	21.5	35	34	26	14
June	10.3	12.4	19.0	22.8	26	26	21	13
July	12.6	16.5	20.2	24.6	20	25	25	18
August	10.1	11.4	18.5	23.7	25	27	20	13
September	9.8	11.6	17.5	21.0	25	26	15	12

Pinus monticola Dougl. ex D. Don on cool, dry sites in northern Idaho (Jurgensen et al. 1990). After 3 years, soil N availability was ten times greater for mounded and control treatments than for scalped treatments, and seedlings growing on mounds were twice as large as in any other treatment.

The same insulating properties of surface residues that retard tree growing processes in cold forests produce a contrasting and beneficial effect in warm, dry regions. On a temperate LTSP site in California's Sierra Nevada, surface soils remained 3–4 degrees cooler throughout the growing season where logging slash had been retained, and the period of plant-available soil moisture was extended for several weeks (Table 2).

Temperate forest studies show that substantive or persistent removals of surface organic matter can trigger growth decline under certain conditions. On marginally fertile, pumice soil in New Zealand, Dyck and Skinner (1990) found that overall productivity in a windrowed *Pinus radiata* plantation with minimal displacement of topsoil was only two-thirds that of an adjacent plantation where slash had been left. Although soil compaction may have been a contributing factor to poor growth, foliar N, Mg, and B concentrations in trees between windrows were at marginal levels. Elsewhere in New Zealand, litter raking repeated annually for 26 years and unconfounded by machine compaction led to depressions both in total soil N and C and in extractable soil P and Ca, and increases in soil bulk density (Dyck and Skinner 1990). In Washington state on uncompacted sites of moderate to marginal fertility, planted Douglas-fir were nearly one-third shorter after 10 years where all surface residues had been removed than they were where residues had been retained (Compton and Cole 1991). Accelerated growth

after fertilizing these plots at 5 years suggests that removing organic matter induced N deficiency in this temperate forest.

A progressive view of the value of surface organic residues is that value depends very much on climate. At higher latitudes, anything that reduces soil temperature reduces productivity. Surface residues accumulate and insulate the soil. There, soil temperature is lowered and shows little fluctuation, and biological processes in the rooting zone are slowed. Moist sites remain wet and aeration may be impaired. Such soils also warm slowly in the spring. On better drained sites, water stress may develop if the high viscosity of soil water (16 percent greater at 5 °C than at 10 °C) prevents soil supplies from replacing transpirational water losses. Barring significant disturbance from fire or mechanical operations, productivity will decline as surface residues accumulate. In contrast, surface residues on warm, xeric sites reduce evaporative losses of soil moisture in young, open stands. Residues also keep soil temperatures in a range more favorable for microbial activity and the release of organically bound nutrients. Obviously, slash must be modified if wildfire or insect risks are high. Alternatives include low-intensity burns, mechanical removal of some of the fuel load, and chipping residues either to provide a uniform mulch or to concentrate the chips into piles. On more mesic sites with less fertile soils, loss of surface residues will likely lead to deficiencies of N and P as canopies close and nutrient demand peaks (Figure 1B). However, special care must be taken to overcome problems of planting through slash and thick forest floors.

Although organic matter replenishment undoubtedly is crucial to sustained productivity in all ecosystems, its significance to important soil and site processes hinges on decomposition and on the climatic factors controlling it. Therefore, guidelines for organic matter retention during harvesting and site preparation operations must consider the overriding influence of climate.

Powers et al. (1990) created a conceptual model that indicates how soil porosity and site organic matter regulate net primary productivity within limits set by genetics and local climate (Figure 6). To some degree, all forest management activities affect one or both of these properties. The question, of course, is how much disturbance is too much? And how is this conditioned by climate and soil type? Although direct evidence of declining productivity in planted forests is rare, evidence of superior performance – at least, in the short run – is abundant. Forestry studies seldom are designed specifically to answer long-term questions, and short-term findings can be misleading (Evans 1975, 1978). Overall, the rarity of precise long-term records such as those for South Australia's Penola Forest (Figure 5) has hampered our understanding of the long-term effect of planted forests. The lack of a conclusive verdict merely

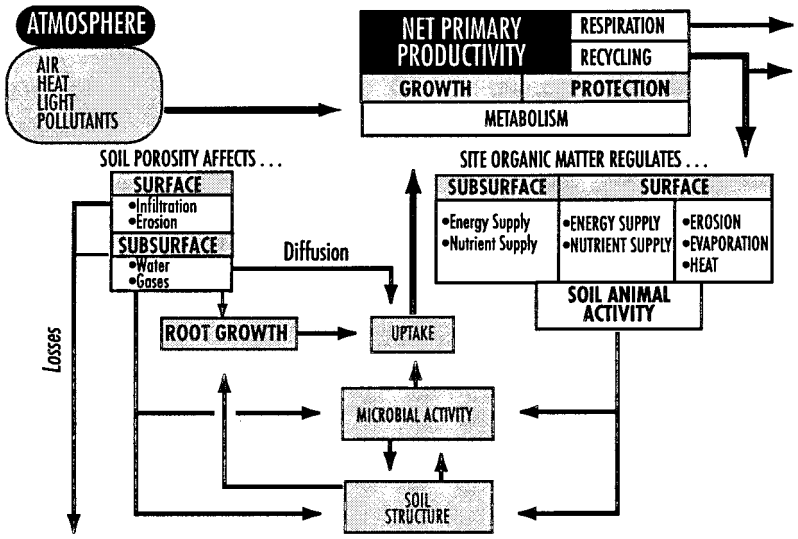

Figure 6. Conceptual model of the roles of soil porosity and site organic matter in regulating the processes controlling site productivity within the limits set by climate and genotype (Powers et al. 1990).

may mean that the hypothesis has not been tested rigorously. Until it is, critics of plantation forestry will continue to oppose modern forest practices.

Obtaining reputable evidence

Basically, there are three approaches to obtaining objective findings on the sustainable productivity of planted forests. The first is to compare cumulative patterns of plantation productivity in consecutive rotations. The second is to do the same with matched stands differing mainly in how they originated. The third is to conduct experiments to test critical hypotheses about planted forest productivity. Growth patterns that were superior, inferior, or equal to those for adjacent or previous stands would suggest improved, degraded, or stable site productivity (Figure 7), and causes might be inferred.

Paired stand comparisons and ambiguity

The direct way to detect productivity change is to compare growth patterns in an existing plantation with those for an adjacent natural stand or for previous stands growing on the same site. In western North America, plantations are first-generation stands that replaced natural stands or brush fields. Previous natural stands often are overmature, riddled by pests, or decadent. Trying

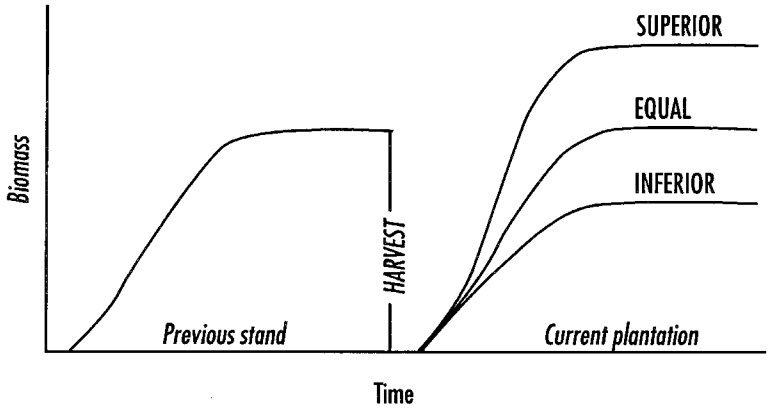

Figure 7. Growth patterns of current plantations can be compared to patterns from previous stands on the same site. Superior growth in the current plantation could indicate site improvement. Inferior growth could indicate site degradation.

to reconstruct past patterns of productivity is an exercise in extreme futility. Sites converted to plantations from grass or shrub communities commonly lack a historical record of tree growth, and site carrying capacity can be estimated only crudely from soil or environmental variables (MacLean and Bolsinger 1973). Therefore, successive rotation comparisons possible in the southern United States, Europe, Australia, and New Zealand are not yet feasible in the West. Furthermore, consecutive stand comparisons are inappropriate if stands differ greatly in structure, stocking, or genotype, or if climate differs appreciably between rotations. In the Pacific Northwest, the second alternative is to turn to productivity comparisons between adjacent stands of natural and planted origin.

This is not easily done. Natural stands vary immensely in age distribution, stand structure, and management history, and valid measures of potential productivity are difficult or impossible to obtain. The standing volume, biomass, or leaf area in irregularly structured natural stands preceding plantations rarely are practicable measures of a site's carrying capacity. Such data are physically difficult to collect in multilayered, heterogeneous forests. Also, stocking is irregular, stands may be senescing, and productivity may be declining. Even-aged natural stands offer mensurational advantages, but may be outside the period of relative stability in current productivity (Figure 1, sectors B-C). For example, they may be understocked at the time of harvest (Figure 3A) for reasons that have no bearing on the site's potential. Reconstructing growth patterns in natural stands via stem analysis has limited value because of uncertainties about stocking and crown conditions in the past. Moreover, genotypic differences between natural and planted

stands may suggest increases or decreases in potential productivity that are unrelated to the site itself (the actual cause may be genotypic adaptation). In essence, comparing natural stands with plantations risks comparing apples with oranges. Only rarely do planted and natural stands of similar ages and management history exist side by side.

Two recent reports from the Douglas-fir region do seem to meet the requirements of sound comparisons. Miller and coworkers conclude that planted stands are at least as productive as those regenerating naturally when their disturbance and management histories are similar. Stand volumes at midrotation in the Cascades of western Washington and Oregon were 41 percent greater in plantations than in stands regenerated naturally (Miller et al. 1993). In older stands bordering Puget Sound, total volumes were essentially identical in planted and natural stands (Miller and Anderson 1995). The principal difference was that growth centered on Douglas-fir in the planted stands and on *Tsuga heterophylla* (Raf.) Sarg. in the natural stands. Although the possibility exists that planted sites have been degraded but that improved cultural treatments have masked the effect, the similarity of paired stand histories reported by Miller and colleagues argues strongly that this is not so. Such careful parings are not common. Too often, such comparisons are marred by uncertainty about past conditions and by confounding factors that may have influenced stand development (Powers 1989; Powers et al. 1994). Generally, findings from paired stands studied retrospectively are ambiguous.

Eliminating ambiguity through controlled experiments

Two interrelated steps are proposed for eliminating ambiguity. The first is to recognize and control extraneous factors that may cloud experimental results. The second is to conduct standardized, powerful experiments designed to get to the root of the most critical questions.

Weeds as "demonic intruders"

The appearance of one or more unplanned, unwanted, and often unrecognized factors that can influence the outcome of a study is known as "demonic intrusion" (Hurlbert 1984). Generally, this traces not so much to demons from hell as to the experimenter's lack of foresight and to inadequate experimental control. A classic example of demonic intrusion is weed competition. Weeds often are ignored in Northwestern studies. However, their influence on early plantation growth can be profound – particularly in summer-dry climates.

Weeds have a surprisingly strong effect on nutrient availability in plantations. The presence of weeds can completely block tree response to fertilization, even when trees are under severe nutrient stress (Powers 1983).

Table 3. Effect of competing vegetation on elemental concentration in ponderosa pine needles and relative volume growth at 5 years (*Source*: Powers and Ferrell, 1996).

Site index (m)	Annual precipitation (mm)	Competing vegetation	Foliar concentration of N (g/kg)	P (g/kg)	K (g/kg)	S (mg/kg)	Al (mg/kg)	Relative volume growth (%)
17	1,015	Present	8.8a[a]	1.0a	6.7a	574a	159a	100a
		Absent	10.2b	1.2b	8.7b	659b	154a	307b
23	1,140	Present	9.5a	0.7a	4.4a	595a	161a	100a
		Absent	12.8b	0.8a	5.6b	748b	163a	240b
30	1,780	Present	11.3a	1.0a	6.3a	767a	176a	100a
		Absent	11.0a	1.0a	6.5a	773a	178a	152a

[a] Column means for a site quality class followed by the same letter do not differ significantly at $p = 0.05$.

Messier (1993) shows that removing ericaceous shrubs from young cutovers on Vancouver Island, British Columbia increased both N and P availability in the soil. In California, elimination of weeds from ponderosa pine plantations not only increased plant water potential during summer months, but also improved nutrient uptake (Powers and Ferrell, 1996). On the poorest and most droughty sites, weed control led to significant increases in foliar concentrations of all nutrients measured. In some cases, concentrations were raised above deficiency levels. On the best sites, foliar nutrient concentrations were unaffected by weeding (Table 3), but this does not mean that nutrient availability was unaffected. Rather, it suggests that availability and uptake kept pace with biomass increase (as indicated by 52 percent greater volume growth). As Nambiar and Sands (1993) point out, any treatment affecting water availability affects nutrient availability as well.

Weeds also can confound the effects of other treatments. This is illustrated by the LTSP experiment cited previously at Challenge and Vista (Table 1). Compaction increased soil bulk density from 0.88 to 1.13 mg/m^3 (28 percent), which predicts about a 20 percent loss in height growth according to the model of Froehlich and McNabb (1984). When weeds were present, tree heights were as great or greater on compacted plots than on plots that had not been compacted. This contradiction to conventional wisdom can be explained by differential weed competition. Compacted plots also had one-third less weed cover (Table 1), meaning that trees there had less weed competition. Less weed competition implies greater moisture availability, which is verified by higher predawn water potentials in tree seedlings on compacted plots. Thus, the presence of weeds can mask the actual impact of soil compaction.

On plots free of weed competition, tree growth was substantially greater where soils were not compacted, predawn potentials were lower, and the true effect of soil compaction on this clay-loam was revealed.

Standardized experiments

Ironically, the ancient and noble practice of forestry has a dearth of long-term records concerning sustainable productivity. Until there is broad, convincing evidence that plantation productivity is sustainable, controversy and confrontation will persist. The subject is not academic. From an economic perspective, North America will rely increasingly on plantation growth to fill the supply and demand gap caused by harvest reductions in older, natural forests. From the political viewpoint, managers will face increasing challenges to prove that their practices are ecologically sound. Therefore, we need an objective means for measuring long-term changes in potential site productivity of managed forests. Morris and Miller (1994) propose three criteria:

1. Tree growth differences must be attributable to true changes in site conditions, and not merely the partitioning of site resources.
2. Substantive, long-term effects must be considered, because short-term trends can be misleading.
3. Adequate experimental control must be established.

In 1989 the U.S.D.A. Forest Service launched the Long-Term Soil Productivity program to tackle directly the question of sustained productivity (Powers and Avers 1995). LTSP is predicated on the principle that the fundamental processes controlling site productivity involve interactions between soil porosity and site organic matter – the conceptual model in Figure 6. The LTSP scientists concluded that these properties are the key variables affected by management. Accordingly, they agreed to a common experimental design that creates gradients in soil porosity and site organic matter after harvest. Realizing that no single answer will fit all situations, the design team developed guidelines that could be adapted to specific conditions of soil type and climatic regime. The experimental design for LTSP creates gradients in soil porosity and site organic matter following harvest. The result is a range of stress extending from minimal to extreme that is meant to encompass management disturbances now or in the future. The 3×3 factorial design is shown in Figure 8A. This simple but elegant design affords a mathematical response surface covering many possible combinations of disturbance. Furthermore, it meets all of the criteria of Morris and Miller (1994).

Major soil types meeting specific criteria are identified on public lands within major commercial forest types and climatic regions. Stands are harvested carefully, biomass and nutrient content are determined by major

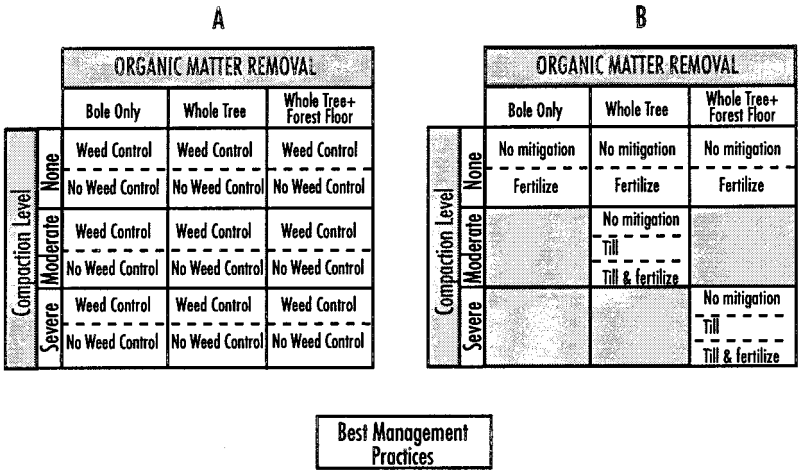

Figure 8. Two field designs for experiments on the long-term impacts of management practices on site productivity and the processes controlling it. (A) the standard LTSP design used by the U.S.D.A. Forest Service. Each plot is 0.4 ha with vegetation control/no control as a split plot. (B) An alternative design for satellite studies of amelioration and mitigation after harvest.

component, and the standard treatments (Figure 8A) are installed on plots measuring at least 0.4 ha. This plot size reduces edge effect problems inherent in growth studies on smaller plots maintained for many years. However, it does require a substantial investment in land, labor, and capital.

Initial soil conditions are measured on each plot. Then the site is regenerated with the tree species suited to the area. To avoid confounding weed competition with compaction effects, one-half of each treatment plot is kept weed-free. This split-plot design ensures that regional vegetation will develop naturally on the second half, thus yielding information on the long-term value of a diverse flora. Periodic measurements of vegetation on all plots provide direct comparisons of productivity as measured by volume, dry matter, and leaf area. Plots with “bole only removal, no compaction” (Figure 8A) serve as controls for testing the effects of all other treatments. Major soil properties (density, porosity, strength, organic matter and nutrient content, and moisture availability) also are measured at regular intervals, and continuous meteorological records are kept. Thus, both relative and absolute measures of productivity can be related to changes in soil properties as influenced by treatment and local climate. Each study site will be followed for a full rotation to overcome early trends that may change with time. Findings also will be compared to “best management practices” in operational plantations established nearby. To date, more than 60 installations exist across North America. In the West, nineteen are in the mixed-conifer forests of California, Oregon,

and Idaho, and twelve others have been regenerated to *Picea glauca, Pinus contorta* Dougl. ex Loud., or *Populus tremuloides* Michx. by the Ministry of Forests in interior British Columbia.

The impetus for the LTSP study is the legal requirement established by the National Forest Management Act of 1976 that national forest lands be managed in ways that do not impair their long-term productivity (U.S.D.A. Forest Service 1983). For this reason, we have focused on defining the site degradation portion of Figure 4B, but site enhancement should be studied as well. In recent years, LTSP scientists have included mitigative and ameliorative treatments (generally tilling and/or fertilization of supplemental plots) at several locations, but prospects are dim for extending this costly design to new sites or "retrofitting" them to old ones.

A promising alternative would be to forge new partnerships with the forest industry by extending related experiments of joint interest to satellite installations on private lands. Some (but not all) treatments should be in common with LTSP to forge a direct link, and measurements should follow a similar protocol. New treatments involving mitigation and amelioration would be added in order to address issues of site enhancement and recovery from negative impacts. Conceptually, this could be done by modifying the LTSP design to somewhat smaller plots, by eliminating some of the factorial cells of a more academic nature, and by incorporating a standard suite of mitigative and ameliorative treatments (Figure 8B).

As proposed, treatments in common with LTSP are the three levels of organic removal without compaction, as well as intermediate and extreme levels of organic matter removal combined with compaction. Amelioration (site enhancement) could be addressed through fertilization of the uncompacted plots. Following compaction, mitigation (recovery from disturbance) could be tested through soil tilling both with and without fertilization. Cooperators likely will be tempted to test particular types of harvesting or site preparation equipment. However, the goal is not to test operational practices per se, because current operational or innovative practices will surely become *passe*. Obsolescence cannot be a part of long-term studies. Rather, we should commit to the goal of understanding the mechanistic pathways that lead to site productivity.

Other standardized experiments are possible and some are underway in the pine region of the southern United States and on degraded soils of the tropics (Powers et al., 1996). However, I believe that the experiments depicted in Figure 8 stand the best chance of meeting all the requirements of Morris and Miller (1994) and addressing the myriad questions facing plantation forestry in the future.

Epilogue

Planted forests are the world's best hope for meeting global wood requirements in the twenty-first century. In the West, intensive management practiced on lands already in plantations, or to be planted following stand-replacing wildfires or type conversions, will help supplant the reductions in annual wood harvest from natural forests. Thanks to advances in genetic selection, nursery practices, site preparation, planting techniques, stand tending, harvesting, utilization, and manufacturing efficiency, merchantable plantation yields stand at historical highs. But high yields may be short term if the soil support system is degraded through carelessness or ignorance. Plantation yields cannot be sustained, much less increased, unless the productivity capacity of the soil is maintained or enhanced. Understanding the impact of management practices on potential productivity is a responsibility of all land stewards and a necessity for sustainable forestry. Solutions will only be found through cooperative, integrated research programs which transcend agency and political boundaries to serve the greater good.

Central to the success of such a program is philosophical commitment by both scientists and administrators to make such programs work. Once treatments have been installed, commitment must be made that sites will receive at least the minimum maintenance needed to protect their integrity. Oversight must be provided by a cadre of scientists and administrators who believe in the worth of the effort and who will strive to ensure its success. In their review of forestry research programs around the world, Powers and Van Cleve (1991) conclude that all successful long-term programs are founded on two key elements. The first is core commitment to achieving the research goal, and the second is that the program address issues of continuing social relevance. Certainly, the issue of sustainable productivity of planted forests meets these criteria.

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