SUSTAINING THE PRODUCTIVITY OF PLANTED FORESTS

R.F. Powers and AE. Tiarks, USDA Forest Service, J.A Burger,
Virginia Tech University, M.C. Carter, Louisiana State University

Introduction

Conversion of natural forests to plantations, particularly in the tropics, has drawn global attention and concern. Moreover, plantation forestry is on the rise, especially in tropical and sub-tropical regions where growth rates are rapid. Even in the United States where even-age silviculture is being de-emphasized on public land (only about 15% of all plantings in recent years), the area in new plantings **on** all ownership has averaged 1 .11 million ha annually for the last decade, ranging from a low of 979 thousand ha in 1993 to the all-time high of 1.37 million ha in 1988 (Moulton, et al. 1996). Most of this is in the southern pine region. Since global and domestic demands for wood products will continue to rise in the 21st century, de-emphasis of timber management on public forests and the reclassification of much natural forest to protected status places an unprecedented burden on planted forests on private lands to meet the needs of a wooddemanding public. Pressures will bear particularly on industrial plantations of the South and Pacific Northwest to be more productive than ever. But there is much skepticism that high rates of plantation productivity can be maintained for long periods with repeated cropping. Addressing this criticism requires a definition and understanding of productivity that cuts across all intended uses of plantations.

The Conceptual Basis for Productivity

what is meant by site productivity? Perhaps the most comprehensive measure, one with very broad application, is dry matter production over time (Powers, et al. 1990). Its utility is that **a** site's **capacity** to produce dry matter reflects its capacity for all potential uses and values. However, conventional forest management generally is focused upon tree boles, the forest components of greatest commercial value. Thus, most of what we know about forest productivity is based upon simple measures of tree boles. The more fundamental process, total dry matter production of all vegetation on the site, frequently is ignored (Powers, **et al. 1990). Allen, et al.** (1991) reported that planted loblolly pine ***(Pinus taeda L.)*** biomass was increased nearly fourfold by heavy site preparation and 5 **years of** chemical weed control. **However,** total biomass of all vegetation was slightly higher on plots receiving minimal site preparation and no chemical weed control. Thus, pine productivity was enhanced by treatment but total productivity was unaffected.

Half or more of a forest's production may occur below ground in roots and mycorrhizae (**Bowen** 1984). Generally, the poorer the site, the greater the proportional allocation of photosynthate below ground. However, for our purposes, we will define "productivity' as the dry matter produced above ground.

Recent research has given us a comprehensive picture of how stands develop. In Figure **1,** the unintenupted productive trend for 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 fully exploiting the site. Throughout, there is **a** close linkage between the mass of the crown and total production. Put physiologically, gross wood production is a linear function of canopy light interception **(Cannell** 1989) as measured by the leaf area of a tree or stand. And, 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 unaffected by water **or nutrient stress.** But while the relationship may be unaffected, a site's carrying capacity for leaf area or mass is not. This capacity depends upon climate, soil moisture and nutrient availability (Nambiar and Sands 1993) and is a fundamental property distinguishing one site from another. Depending on the extent of limiting factors, it can be increased temporarily by weed control or for longer periods by fertilization (Della-Tea and Jokela 1991) but not by thinning. Thus, climate, water and nutrient supply determine site quality. Since management practices do not influence climate to any significant degree, water relations and nutrient supplies are key factors in sustaining site productivity.

Crown closure marks a point when nutrient uptake rates are peaking. Leaf area carrying capacity is reached, growth rates are high, and stands are fully taxing the Site's ability to supply water and nutrients. Beyond crown closure, water demand remains high because leaf area and the transpiring surface remains essentially constant. But despite a continuing high demand, the forest relies less on the soil for its nutrient supply. Once crown mass is **fixed,** between half and two-thirds of a plantation's annual needs **for many nutrients including N,** P **and** K are met through internal recycling from older foliage to newer before leaf abscission (Miller 1984).

Typically, productivity rates are low **when trees** are young and crown leaf area is small. 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 ground 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). 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.

Beyond maturity, maintenance respiration approaches assimilation. Because mycorrhizal fungi require steady supplies of carbohydrates from the host plant, mycorrhizal roots probably decline because less carbohydrate is available for their maintenance. Reduced fine root surface leads to reduced water and nutrient uptake and to increasing stress_ Ultimately, stand vigor declines and insect and disease attacks become more severe. Canopy gaps then appear, leaf area decreases and production rate drops. Thus, Figure 1 illustrates the important principle that stand productivity is dynamic. Measurements made at substantially different times during stand development give decidedly different values.

Conceptually, productivity has two major elements. One is "current productivity," or the actual dry matter 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) 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 made at point A in Figure 1 will be vastly different from assessments made later.

The second important conceptual element'is 'potential productivity.' Like current productivity, potential productivity also relates to leaf area. However, it represents the site's potential for dry matter production when the site is at full carrying capacity for leaf area. This occurs between crown closure and stand maturity (Fig. 1, points 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. Depending on management objectives and natural disturbances, a site's productive potential may or may not be achieved. By the same token, we should understand that potential productivity is not immutable. While it is a natural ceiling set by site resources, it can be raised or lowered through substantive changes in soil, climate or-to a certain degree-genetics.

Genetics constrain productivity in several ways. Some genotypes adapt better to given site conditions than others and faster-growing genotypes achieve the site ceiling sooner than others. Also, there can be genotypic variation in the way that photosynthate is partitioned into crown, bole or roots. But popular impressions notwithstanding, genetic improvement is not a panacea. It cannot compensate in any substantive way for poor climate or soil.

Figure 2 illustrates both current and potential productivity and how each can be modified by management. Climate, soil and genetic potential determine natural limits on site productivity, while stocking determines the degree to which this limit is achieved. Figure 2A depicts potential and current productivity for an understocked plantation. The site potential is set by the physical, chemical and biotic components of the soil. However, low tree stocking or a high weed component prevents the plantation from achieving its potential. In Figure **2B,** improved stocking captures the site's leaf area carrying capacity so that current and potential productivity coincide. Although genetics may have been improved as well, the limit remains set by the soil. Unless it can substantially change leaf area at full stocking, genetic improvement merely gets the plantation to the site limit sooner. Conversely, diseases merely prevent a plantation from achieving its genetic potential.

Improving soil properties along with genetics and stocking (Fig. 2C) boosts potential site productivity to a higher plane constrained by climate. Alternatively, soil erosion, compaction or nutrient drain may alter the site's potential to a point were productivity is degraded (Fig. 2D). Superior conditions of climate, genetics or stocking will not compensate for this, and operations are analogous to mining a nonrenewable resource. Viewing the concept another way, management often works within the fixed limits of natural potential productivity (Fig. 3A). The degree of stocking or weed control determines the proportion of potential productivity that is captured by trees. Depending on a site's resistance and resilience, however, this potential can be altered through soil modification, either upward through such treatments as fertilization (Chappell, et al. 1992) or downward through soil degradation **(Powers,** et al. 1999).

In general, the industrial forest approach is to work toward the right of the curve in Figure **3B.** In this sense, many forest managers are philosophically aligned with agronomists who are not satisfied with the natural productivity of the land. Rather, they strive to make it greater by **amending soil fertility, drainage** and **tilth (Fisher** 1984). On the other hand, public land managers may take a more conservative approach by **working** within the limits of natural productivity. Particularly, National Forest managers **are** concerned with avoiding the left portion of Figure **3B** because the National Forest Management Act of 1976 requires such forests to be managed in a way that protects their long-term productivity (USDA Forest Service 1963).

Is Productivity Stable in Planted Forests?

Despite more than **a** century **of world** success in artificially regenerated forests, the question **nags and uncertainty reigns in many circles. This uncertainty** stems partly from agricultural **experiences where repetitive cropping of corn or cotton without** replacing nutrients **led to yield declines (Mitchell, et al.** 1991). Uncertainty also stems from historical **misconceptions about the influence** of conifer plantations (usually monocultures, sometimes **exotics) on soil** and site processes, misconceptions that persist to the present (Maser 1988).

The Case For Decline

In the early 19th century, many of central Europe's abused and depleted forests of hardwoods **were converted to plantations of** more profitable Norway **spruce *(Picea abies*).** But by the **second** rotation of spruce, yields on some sites were lower than those in the first rotation. From this spread a belief that conifer monocultures degraded the soil (Grigor 1868; Wiedemann 1923; Ovington 1953), dogma that still persists (Sheppard 1986). More modem 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, leading to poor internal drainage. Water logging in the wet season confined spruce roots to shallow depths, leaving them parched 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.*

These concerns resurfaced following **a** separate event in the Southern Hemisphere. Beginning about 1920, plantations of exotic conifers, principally radiata pine (***Pinus radiata***) were established in Australia on what had been nonproductive scrub lands of native species. By 1927, softwood plantings had been established in all states except Tasmania. Of these plantings, nearly 6,500 ha (41% 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 ail domestic needs and perhaps a surplus for export. By 1930, the planting area had doubled, and in the next 3 years it grew another **40%.** By the **1950s,** the oldest plantations were being harvested and replanted. Thorough records often 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 mapped yield capability classes in first- and second-rotation stands of radiata pine on sandy soils of South Australia's Penoia and Mount Burr Forest Reserves. 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%).** Concern spread quickly that pine monocultures **somehow were poisoning the soil, negating a** huge national investment in plantations. The yield decline **between first** and second rotations was indeed real, and speculation abounded as 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 following 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 accelerated weed growth. Rapid weed growth, coupled with declining rates of N mineralization at a time when nutrient demand by trees is increasing exponentially (phase 'A' in Fig. 1) leads to nutrient deficiency and arrested growth in young stands, at least on sandy soils (Smethurst and Nambiar 1990).

A study in Louis&a suggests that declines in the productivity of the next rotation may be caused by treatments meant to increase productivity in the present rotation. Haywood and Tiarks (1995) compared burning only; burning and disking; burning, disking and bedding before planting loblolly and slash pine (*Pinus elliotii*). The plantation was harvested after 22 years and replanted with the same species. The site was re-burned but the mechanical site preparation treatments were not repeated. After 10 years, standing volume in the second rotation was 56% and 38 % below the first rotation for loblolly and slash pine, respectively. Also, there was a significant treatment x rotation interaction in loblolly. Mechanical site preparation before the first rotation increased yields during that rotation but apparently suppressed it in the second.

Soil strength was measured in the second rotation, about 34 years after the site was disked or bedded. The soil strengths in the disked plots exceeded 2000 kPa in a continuous band at the 20-25 cm depths and at depths greater than 50 cm (Fig. 4). The increase in soil strength, especially at the 20-25 cm depth, probably reflects a tillage pan formed by the heavy disk An increase in soil strength was also measured in the bedded plots at the same depths but in a discontinuous pattern. For many crops, . root growth declines linearly as strength increases from 1000 to 3000 kPa, where root growth ceases (Whalley, et al. 1995). A similar relation seems true for forest trees (Sands, et al. 1979). In the Louisiana study, even after 34 years, the negative effects of tillage may have exacerbated an incipient P deficiency enough to depress tree growth, especially in the disked plots where the pan was continuous (Fig. 4).

Detrimental effects of management on soil physical properties and productivity have been reported for the Atlantic Coastal Plains (Hatchell, et al. 1970), Washington (Froehlich, et al. 1986), California (Helms, et al. 1986) and elsewhere, but the Louisiana study comes closest to establishing causal mechanisms.

How broadly the second-rotation decline phenomenon occurs is speculative. Evans (1978), comparing first- and second-rotation growth rates on more than one hundred matched plots of planted *Pinus patula* 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), underscoring the risk of hasty conclusions. In their recent review of the world experience, Morris and Miller (1994) concluded 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 said for 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, coastalsites of the southern U.S. (**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 represents the increase in site potential shown to the right of the curve in Figure **3B** caused by soil improvement (Fig. 2C). The duration of such effects depends on treatment. On overly wet sites, improved soil aeration through drainage improves growth as long as the drainage system remains effective. As the canopy closes and trees grow larger, transpiration increases, further drying the soil. Thus, the effect of drainage on early growth is not necessarily indicative of growth later in the life of the stand.

Productivity gains through fertilization are more complex The nutrients most commonly applied are P and N, but managers should understand some fundamental properties of these two nutrients and how they behave in forest ecosystems. For example, P cycling generally is ‘tight,’ meaning that the nutrient is relatively immobile in the soil but quite mobile within trees once it is absorbed by roots. Therefore, it tends to cycle and recycle in vegetation but is not lost readily from the soil **other** than through erosion. Very little P exists as the absorbable phosphate ion in the soil. Rather, it exists as relatively insoluble mineral precipitates and hydrous oxides or as organic P in plant or animal residues. Natural deficiencies may occur under two conditions. One is **where the solubility of** soil P is low because of complexes formed between the phosphate ion and **polyvalent** cations such as **Al^{+3}, Mn^{+3}** and Fe+? This is particularly prevalent in red, acid, clayey soils. Another is where P is scarce in the soil minerals themselves, such **as in sandy soils** derived from quartz rocks. Because sandy soils often are low in nutrients such as P, natural deficiencies may be aggravated by **severe wildfire,** erosion or **removal during forest harvesting. The low availability of** P in many soils means that many forests **experience** P deficiency and will respond well to fertilization.

Because P recycles readily within trees and because it is not easily lost from the soil, fertilization effects **may last decades** and extend perhaps from one rotation to the next. Fertilization rates are high **(50** to **100** kg P **ha^{-1}),** relative to the quantities of P present in **stand biomass (5 to 70 kg ha^{-1})** (Ballard 1984). The immobility of P in most soils means that massive doses of fertilizer P can extend uptake. Once absorbed, P re-translocates readily from needles at all stages of maturity (Nambiar and Fife 1991). Following **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.**

Soil N comes almost entirely from atmospheric inputs in precipitation and biological fixation. **Once in the soil, mineral N is in high demand** by **a** variety of organisms and is converted rapidly to. organic form in the biomass of microbes, higher plants, and the animals that consume them. While mineral forms of N (ammonium and nitrate) are released through the decomposition of organic matter, ions do not form insoluble precipitates, Thus, mineral N remains soluble in the soil solution. Nitrate, an anion, can be leached readily in the soil solution beyond the influence of roots. Ammonia can be volatilized under very wet conditions.

Response to N fertilization seldom extends beyond a decade. As with P, a high proportion of N is translocated internally before leaf fall (Nambiar and Fife 1991). But unlike P, amounts typically applied (100 to 300 kg N ha") are but a fraction of the mass stored in living vegetation, the forest floor and the soil (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 to 78% are not uncommon (Wollum and Davey 1975). But regardless of source, ammonia losses are exacerbated in any soil of neutral to alkaline pH. Also, surplus ammonium N in fertilizer can be oxidized microbially to nitrate, which can be leached through the soil profile. Biological denitrification to oxide gases also is possible under reducing conditions, but denitrification is not thought to be a very important process in organic, well drained forest soils. Ultimately, some Of the organic N in litterfall forms recalcitrant soil humus,. essentially uncoupling a fraction of 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 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, dominant Douglas-fir interplanted with (but a few years in advance of) red alder (*Alnus rubra*) were 20% taller after 5 decades than Douglas-fir *(Pseudofsuga menziesii)* planted in pure stands, and stand volumes were over 90% 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, *Eucalyptus saligna* interplanted with the N-fixing *Paraserianthes (Albizia) 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 the drier side Of the island. Yet, strategies can be developed for drier sites. In South Australia, Nambiar and Nethercott (1987) demonstrated that annual lupine (*Lupinus* sp.) seeded between rows Of radiata pine on droughty, infertile sands served the double purpose of excluding more persistent weeds while adding N and organic matter to the soil. By year 4, pines so treated had twice the mass of pure pine controls. Thus, creative us8 of symbiotic N fixation can be another way of improving site potential.

Knoepp and Swank (1994) found that the soil profile was depleted of basic cations, especially Ca, by the developing stands of mixed hardwoods or planted whit8 pine (*Pinus strobus*). Richter, et al. (1994) reported similar results in loblolly pine plantations. Both attribute the depletion to leaching and sequestering in the biomass. Olsson (1995) found that levels of K^+ in the groundwater rose sharply following harvesting of spruce or pine in Sweden. The degree of increase was short-lived and appeared to be more related to the amount of soil disturbance than to organic matter removal. Stevens, et al. (1995) reported that most of the K (around 100 kg ha^{-1}) and one-third of the P (10 out of 30 kg ha”) leached from logging slash, through the soil and into streams the first year after harvesting *Picea sitchensis* (Bong.) plantations in the UK They concluded “.. losses (of nutrients) in harvested material are likely to result in long-term depletion of these elements’. Johnson (1994) also concluded that nutrient losses resulting from harvesting may exceed the rate of replacement by natural processes under some conditions.

The Verdict

As noted, recent reviews (Powers, et al. 1990; Morris and **Miller** 1994) conclude that direct evidence of productivity decline in managed forests is rare. But taken collectively, the most convincing examples point to biologically significant losses in soil porosity and in site organic matter. These two properties can be visualized as ‘gate valves” that regulate more fundamental processes controlling site productivity. Porosity influences the exchange of water and gases between the atmosphere and the earth, the ease by which moisture and nutrients flow to plant roots and plant roots extend through the soil and the very existence of beneficial and detrimental soil organisms. Natural soil porosity is **a** continuum of void sizes that depend on 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. 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. It is **a** concentrated reservoir of plant nutrients supplied to the soil through litterfall and root sloughage pulses. Powers, et al. (1990) created a conceptual model that indicates how these two factors regulate net primary productivity within the constraints of genetics and local climate (Fig. 5).

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?

While evidence of **declining** productivity in planted forests is rare, evidence of superior performance, at least in the short run, is abundant. But forestry studies seldom are designed specifically to answer long-term questions, and short-term findings can be misleading (Evans **1975, 1978).** Conclusions drawn from chronosequence studies **or** retrospective analyses of current stands generally are marred by uncertainty over past conditions and by confounding factors that may have influenced stand development **(Powers 1989, Powers, et al. 1994). For** example, findings **from** repeated forest inventory in **Georgia show a progressive decline** in diameter growth of pine between **1956** and 1982 (Sheffield, et al. 1985). However, declines seem restricted to nonindustrial private forest land where shrub and hardwood competition have increased from the absence of regular underburning. On more intensively managed industrial plantations, growth rates were stable or had increased (Sheffield and Cost 1966). Whether the latter is due to improved genetic selection, better stocking or weed-control or to maintenance or improvement in potential site productivity is unknown.

Two examples using the retrospective approach have recently surfaced for the Douglas-fir region. In careful comparisons of paired planted and naturally regenerated stands with similar histories of disturbance and management, Miller and coworkers concluded that planted stands were at least as productive as those regenerating naturally. Stand volumes at mid-rotation in the Cascades of western Washington and Oregon were 41% 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* in the natural stands. While 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. But such careful parings are not common. **Overall,** the rarity of precise, long-term records such as those for South Australia's Penola Forest (Fig. 4) have hampered our ability to address the question squarely. The lack of a conclusive verdict merely may mean that the hypothesis has not been tested rigorously.

Obtaining Reputable Evidence

Successive **Stand Performance**

The usual way of detecting productivity change is to compare growth patterns in an existing plantation with those of previous stands growing on the same site. Growth patterns that were superior, inferior or equal to those for previous stands would suggest improved, degraded or stable site productivity (Fig. **6),** and causes might be inferred. However, this is not appropriate if stands differ greatly in structure, stocking or genotype, or if climate differs appreciably between rotations. In western North America, plantations are first-generation stands that replaced natural stands or brushfields. Natural stands vary immensely in age distribution, stand structure and management history, and valid measures of potential productivity are difficult or impossible to obtain. 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).

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 multi-layered, heterogeneous forests. Also, stocking is irregular, and 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 (sectors B-C, Fig. 1). For example, they may be understocked at the time of harvest (Fig. 2A) 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 have nothing to do with the site itself but have everything to do with genotypic adaptation. In essence, comparing natural stands with plantations risks comparing apples to oranges.

The Organic Matter Paradox

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 soil protection, the activity of beneficial soil organisms, soil water holding capacity, soil structure and aggregate stability 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). And therein lies the paradox. Why is practical experience so often at odds with 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. At high latitudes, the resultant lowering of soil temperature by surface residues 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 4^0 C warmer during the growing season while soil moisture was affected negligibly (Table 1). 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 x glauca*, but only the mounding treatment produced appreciably larger seedlings after 27 months (Bassman 1989). Soils remained warmer and better drained within mounds. Similar results were shown for *Pinus monticola* on cool, dry sites in northern Idaho (Jurgensen, et al. 1990). After 3 years, soil N availability was 10-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 beneficial effect in warm, dry regions. On a temperate site in California's Sierra Nevada as part of the. North American network of Long-Term Soil Productivity (LTSP) installations (Powers and Avers 1995), surface soils remained 3 to 4 degrees cooler throughout the growing season where litter was present and the period of plant-available soil moisture was extended for several weeks

(Table 1). Both results favor growth under hot, xeric conditions.

A progressive view of the value of surface organic residues is that value depends very much onclimate. At higher latitudes, anything reducing 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%** greater at **5^0** C than at **10^0)** 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 or wildfire and insect risks will be high. Alternatives include low-intensity bums, 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 (Fig. **1** B). However, special care must be taken to overcome problems of planting through slash and thick forest floors.

while 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.

The Compaction Controversy

Another management effect thought by many to degrade potential site productivity is **soil compaction. The mechanism** for degradation is the loss of soil aeration and moisture availability and increased resistance of soil particles to root growth. Reduced aeration **also** can reduce infiltration rate, thereby accelerating surface runoff and soil erosion (Childs et al. 1989). The problem is exacerbated on fine-textured soils (Powers, et al. **1990),** particularly where it is severe enough to extend into the subsoil beyond the influence of freezing and thawing (Morris and Miller 1994). But **as with organic matter, operational** experiences with soil compaction often seem at odds with theory. Without demonstrable proof that compaction leads ultimately to lowered yields, forest managers and equipment operators are skeptical about the worth of avoidance or mitigation (Miller, et al. 1996).

Effects of compaction are not always obvious, and findings from semi-controlled studies can be influenced by **other** factors. For example, paired measurements of trees planted on compacted skid trails and in adjacent, less compacted logged areas in the

Douglas-fir region showed little difference in heights after several years (Miller, et al. 1989). The authors suggest that soil densities may have been too low and climate too favorable for compaction to show much effect. These may be valid explanations, but other factors accompanying compaction commonly cloud the issue.

Many studies such as those reported by Miller, et al. (1989) reflect operational conditions lacking a true control. That is, other factors co-vary with compaction to such a degree that the main factor of interest, compaction, cannot be isolated. The net effect is statistical confounding. For example, compacted skid trails and landings usually have much lower densities of seed-regenerated weeds than adjacent, less-compacted areas. Thus, tree growth comparisons are clouded by less weed competition where soils are compacted and more weed competition where they are not. Furthermore, skid trails are narrow, meaning that biological research involving them suffers from the bane of small plot studies. Namely, that skid trails are small plots and therefore have a tremendous edge effect (Powers, et al. 1994). Root systems of trees growing on compacted skid trails eventually tap resources in the less compacted soil beyond. Conversely, trees growing near compacted skid trails and landings ultimately are affected to some extent by the compacted soil nearby. The net effect is a tendency toward a leveling of growth over time. A corollary is that 'control plots' established off skid trails generally are not true controls at all because they usually have had some degree of traffic (a true control would not). Finally, height, the measure traditionally used in young tree studies (Froehlich and McNabb 1984, Miller, et al. 1989), may not be a particularly sensitive measure of growth response.

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, causes trace not so much to demons from hell as to the experimenter's lack of foresight and to inadequate experimental control. Weed competition, particularly in summer-dry climates, dominates early stand performance and serves to illustrate demonic intrusion. Often, weeds are ignored or discounted because of erroneous notions about their competitive effect.

The confounding effect of weeds in interpreting soil compaction is seen in an experiment on a strongly developed clay-loam soil at California's Challenge Experimental Forest where a highly productive site was clearcut in 1990; treated, and planted according to LTSP standards (Powers and Avers 1995). AS part of the LTSP design, all surface organic residues were removed on 0.4-ha treatment plots. Next, plots either were compacted severely or left uncompacted. Planting holes were drilled with a soil auger and four species of conifers were planted. One-half of each plot was kept weed-free through repeated herbicide treatment. The other half received no herbicides. Various measurements were taken periodically and are summarized in Table 2.

Compaction increased soil bulk density from 0.88 to 1.13 Mg m^{-3} (28%), which should spell about a 20% loss in height growth according to the model of Froehlich and McNabb (1984). However, when weeds were present, tree heights and volumes were half again greater on compacted plots than on plots which 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 2), 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 clayey soil was revealed.

Does this mean that soil compaction always is detrimental? Possibly not. Findings from Vista, another LTSP site in California, contrast sharply with those from Challenge. The climate at Vista is considerably drier and the weakly developed, sandy soil there is weathered from granodiorite. Severe soil compaction at Vista increased seedling growth, regardless of weed competition (Table 2). And without weed control, weed coverage actually was about one-quarter greater on compacted plots. This distinct contrast in how soil compaction affects plant growth on these two sites can be explained by differences in climate, soil texture and the retention of plant-available water.

Although soils at Challenge and Vista were compacted to similar bulk densities and total porosities (Table 2), aeration porosity was decreased an average of 36% on the clayey soil but only 18% on the sand. Laboratory analyses indicate that resultant changes in pore size distribution caused by compaction translate to a 24% loss in the clayey soil's ability to hold water at tensions low enough for plant uptake. On the compacted sandy soil, reduction in very large pores increased available water holding capacity by an average of 66%. Field measurements of soil moisture and predawn water potential in seedlings confirm that this is true (Table 2). On droughty sites like Vista, anything that reduces water stress favors growth. Clearly, compaction effects hinge strongly on soil texture, climate and the presence or absence of weeds.

Other Effects of Weeds

An on-going study in Louisiana demonstrates that weeds, especially grasses, can have an ameliorative effect on soil compaction. Figure 7 shows the bulk density at planting for plots that ware compacted to three distinct levels. At 5 years and on plots where competing vegetation was controlled and only pines were allowed to grow, the differences in bulk densities are still apparent. On plots where grasses were permitted, the effects of compaction on bulk density have nearly disappeared. At age 6 the average volume per pine on weed control plots is still twice as large as on unweeded plots at a given compaction level. However, as the pines on the unweeded plots shade out the grasses, the beneficial effects of the lower soil bulk densities may outweigh the early gains from grass control.

Weeds affect nutrient availability, too. Messier (1993) showed that removing ericaceous shrubs from young cutover stands on Vancouver Island 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% greater volume growth). As Nambiar and Sands (1993) point out, it's difficult to imagine any treatment affecting water availability that doesn't affect nutrient availability as well.

Many forest soils are fragile in their physical, chemical and biological characteristics. Increasing production by increasing one input may only exacerbate another deficiency, but with delayed effects. Two studies in Louisiana illustrate the potential confounding of weed control on soils that are limited in nutrients. In both studies, no weed control was compared with complete weed control for the first 5 years after planting. Organic matter levels were applied in distinctly different ways. In one study, the organic matter levels were (1) pine boles only removed, (2) complete removal of the above ground portions of the pines and (3) removal of all above ground organic matter, including pines, understory and forest floor. In this experiment, weed control doubled pine volume at age 6 (Table 4). Pine volume on plots where slash was retained was about 60% greater than on plots where all vegetation and the forest floor had been removed. Weed control increased the concentration of K in the foliage of the new rotation, but organic matter removals had no consistent effect on K concentrations. Thus, it appears that weed control increased K uptake in pine and furthered its growth. When weed control was applied, K concentrations in the top 10 cm of soil declined to deficiency levels.

In the other study, rather than removing different amounts of organic matter, abscised pine needles were added as a treatment (Sword, et al. in review). Again, weed control increased pine growth and the concentration of K in the foliage (Table 5). The addition of pine needles reduced the amount of weeds somewhat and increased pine volume but had no effect on K concentration in the foliage. As in the other study, soil K levels were much lower in the weeded plots. The fast-growing pines on the weeded plots may be draining soil K and redistributing it to other parts of the system but preserving the nutrients for future recycling and growth. Alternatively, control of all vegetation except the pine seedlings may result in leaching of the K (and other ions) from the surface soils as observed at Hubbard Brook (Likens, et al. 1970). Since neither the K content of the pine biomass nor that in soil rooting zone was measured, these possibilities are only speculative.

Tracking a Solution - Standardized Experiments

Is there broad and definite proof that plantation productivity is sustainable? No! Nor is there proof that it is not! Ironically, the ancient and noble practice of forestry-- the management of long-lived vegetation-has a dearth of long-term records concerning sustainable productivity. And until there is broad, convincing evidence, questions and controversy will persist. The subject is far from 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.

- Tree growth differences must be attributable to true changes in site conditions and not merely on how site resources are partitioned.
- Enough time must pass so that early, possibly misleading trends can subside and more substantive, long-term effects can be seen.
- There must be adequate experimental control.

Several alternative approaches meeting these criteria are described.

The **Long-Ten Soil Productivity Study (LTSP)**

In 1989, the USDA Forest Service launched **LTSP** to address the questions concerning the maintenance of soil productivity on the National Forest System (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 shown in Figure 5. Authors of the program concluded that porosity and organic matter are the key properties most influenced by management and that research should center on how changes in soil porosity and site organic matter influence the basic processes governing forest health and growth. 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 the management disturbances likely now or in the future. The 3 x 3 factorial design is shown in Figure 9A. This simple but elegant design should allow construction of response surfaces describing productivity as influenced by various 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 and the treatments indicated in Figure 9A are installed on plots measuring at least 0.4 ha. This plot size reduces edge effect problems inherent in growth studies on smaller plots meant to be carried for-many years (Powers, et al. 1994), and enables the study to continue for a full rotation. However, it does require a substantial investment in land, labor and capital.

Initial soil conditions are measured on each plot. The site is then regenerated with the tree species suited to the area. To avoid confounding connected with variable understory competition, one-half of each treatment plot is maintained weed-free. This split-plot design ensures that regional vegetation will develop naturally on the second half. This design has the added benefit of research into the long-term value of a diverse flora. Periodic measurements of trees alone and of total vegetation on all plots allows direct comparisons of productivity as measured by volume, dry matter and leaf area. Plots with "bole-only removal, no compaction" (Fig. 8A) serve as controls for testing the effects of all other treatments. Major soil properties (density, porosity, strength, organic matter and nutrient content, moisture availability) also are measured at regular intervals and continuous meteorological records are kept as well. 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 . c site will be carried for a full rotation to overcome early trends that may change with time. Findings also are compared with "best management practices" operational plantations established nearby. To date, nearly 4-dozen installations exist across North America. Of these, four have been installed 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 (USDA Forest Service 1983). For this reason, LTSP focused on the left half of the curve in Figure 3B. However, attention should focus on the right side of Figure 3B, as well. Can management enhance site productivity above that inherent to the natural site? Or, alternatively, can mitigative treatments overcome the effects of detrimental soil impacts? In recant 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. Another disadvantage of the LTSP design is that the disturbance impact and its spatial distribution cannot be associated directly with operational harvesting practices.

A promising solution to these limitations in the LTSP study is emerging. In partnership with forest industry, long-term productivity studies are being installed on privatelands. Some (but not all) treatments are in common with LTSP and the same or similar measurement protocols are being followed. New treatments involving mitigation and amelioration have been added to address issues of site enhancement and recovery from negative impacts.

Two examples of ongoing research partnerships with industry, wherein impact, mitigation, and enhancement treatments have been applied in the context of operational plantation management, are located in the southern pine region of the United States. On the Gulf Coastal Plain, a cooperative long-term productivity project known as Monitoring Productivity and Environmental Quality in Southern Pine Plantations (MPEQ) was initiated in 1993. On the Atlantic Coastal Plain of South Carolina, a cooperative long-term soil productivity study known as the Virginia Tech/Westvaco Sustainable Forest Management project was initiated in 1991. Both projects are cooperatives involving participation from one or more forest industries, universities, and Forest Service research units. Both of these industry-centered projects are based on the notion that sustaining forest soil productivity and enhancing forest production are fundamentally important objectives of forest-land stewardship initiatives. These studies meet the spirit and letter of the American Forest and Paper Association's "sustainable forestry initiative" which calls for research to ensure sustainable forest management.

The MPEQ Consortium

A companion study to LTSP has been initiated in loblolly pine at several locations along the U. S. Gulf Coast from Georgia to Texas. Known as MPEQ (Monitoring Productivity and Environmental Quality **in Southern** Pine Plantations), the effort involves the USDA Forest Service, three forest industries and two universities.

Objectives for the MPEQ project are:

- Provide creditable documentation of soil productivity in managed southern pine plantations.
- Provide a pooled database for linkage of industrial operations to the USDA LTSP Study.
- Provide **a** laboratory for assessing the impact of plantation management on soil processes and non-timber values.
- Identify and guide the development of new technologies.

MPEQ is focused upon industrial plantations using more intensive management and shorter rotations than normally employed on the National Forests. A core design is used at all locations incorporating the hand harvesting, minimum impact treatment of the LTSP and three other treatments. Additional treatments are chosen by the cooperating industry, including conventional harvesting, site preparation and growth enhancing technologies. The common design is:

Harvesting Methods:

- H_0 Hand felling, boles only removed - LTSP C_0 OM_0
- H_1 Whole-tree harvesting using conventional mechanical equipment

Site Preparation Methods;

- SP, Low-impact aerial application of herbicide
- SP_x SP, plus one or more mitigating and/or growth enhancing treatments.

Plots are smaller than those used in LTSP (0.12-0.15 ha compared with 0.4 ha), but at least three blocks are included at each site. Measurement and documentation of the soil and vegetation prior to harvest equals or exceeds those used in LTSP.

The VPI/Westvaco Sustainable Management Study

The fundamental objectives of this study are:

- To determine if soil and site disturbances associated with logging and forest management practices have a negative effect on soil, site and forest productivity.
- If disturbances have negative impacts, to determine if tillage, bedding and subsoiling mitigates the disturbance effects.
- To determine if intensive forest management sustainably enhances productivity above natural levels.

Like the Forest Service LTSP and the Gulf Coast MPEQ projects, this study is a rotation-length project that will measure **treatment effect on** productivity among treatments and against that of the previous stand. Studies **on** major soil, site and stand processes including net biomass production, site hydrologic response, organic matter decomposition, nitrogen mineralization and the role of subordinate vegetation are under way to define and describe the mechanisms of disturbance effects. Disturbance of site organic matter and soil porosity are also the two key experimental factors in this study design (Figure 8). Gradients in organic matter and soil porosity were created by operationally logging 3 ha units of 20-year-old loblolly pine plantations under both wet (surface soil water content between the plastic and liquid limits) and dry (soil water content less than 50% field capacity) conditions. Bedding and mole-subsoiling were applied to both wet and dry harvested plots to test their mitigative effects on soil disturbances. The study **design** is **a** completely randomized block with three replications. The **actual layout of one** block is shown in Figure 9 along with a blowup of one plot.

Organic matter and soil disturbance were mapped on a 10 by 10 m grid across all 3.2 ha treatment plots by disturbance class (Figure 10). Five organic matter classes ranged from slash piles to bare soil, and five soil disturbance classes ranged from no disturbance to severe soil churning. These disturbance gradients are shown in two dimensions in Figure 11 along with a hypothesized management-induced productivity gradient. Three replications of each cell in the disturbance matrix were randomly identified on the plot maps (Figure 10). Soil, site and stand process studies are under way in each of the 25 cells represented in the disturbance matrix This disturbance matrix and the research being conducted in each call are very similar in approach to that of the Forest Service LTSP study. An important difference is that the spatial extent and location of each disturbance class is mapped for each of the 3.2 ha operational treatment plots. These spatial maps will allow direct extrapolation to the operational level, soil and stand responses to impact, mitigation and enhancement treatments.

The expected benefits of this project are also similar to those of the LTSP and MPEQ projects. Over time they will answer the following questions and perhaps some that have not yet been asked: (1) What are the determinants of soil, site and forest quality? (2) Under what conditions do forest harvesting and management practices enhance, maintain or damage sustainable forest function? (3) What information is needed to avoid negative disturbances? (4) If damaged, can function be restored, and at what rate of recovery? (5) Are plantation forests a net sink or source for atmospheric carbon? (6) Are wetland functions altered? (7) How does biodiversity at the site level change, if at all? (8) Do certain disturbances impede drainage and restrict management access? (9) Are BMP's realistic and effective? (10) Are current practices consistent with sustainable management philosophies?

The CIFOR Study

Recently, a standardized experiment has been developed to study plantation productivity and sustainability on degraded soils in the tropics (Cossalter, C. 1995, personal communication). The plan, developed under the leadership of the Center for International Forestry Research (CIFOR), is focused on short rotations (7-15 years) being grown on sites where the native timber was removed many years ago and soil limitations have prevented utilization of the land for agriculture or other purposes. The study is designed to test management practices that not only prevent further degradation of the soil but also improve the long-term productivity of the site. Properly managed, the fast growing species often supply a good environment for the native species to regenerate, so that returning the site to productive, native forests may be an option after several rotations of plantations.

Similar to LTSP, the CIFOR program is designed to use se&contained studies at multiple sites, but coordinated so that the value of management practices can be demonstrated under different environments and in a multinational context. At each location, the objectives are to (1) evaluate the impact of soil and site management practices on the productivity of successive rotations of plantations, (2) develop management options for maintaining or increasing productivity and (3) strengthen local institutional capacity to respond to new problems and opportunities.

The core treatments consist of four levels of above ground biomass retention. They are:

BL_0 All above ground residue, including the crop trees, understory and litter removed from the plots.

BL_1 Whole tree harvest including removal of all above ground components of commercial sized trees.

BL_2 Stemwood + bark harvest or removal of only the delimbed main bole of commercial-size.

BL_3 Double slash. Branches, leaves and other noncommercial components of the BL, plots are transferred to this treatment. Similar to the heavy slash (OM2) treatment in the VPI/Westvaco study.

Other site-specific treatments that may increase productivity or the understanding of basic processes are encouraged. The plan was finalized in late 1995, so no sites have been installed as of this writing. The first locations will probably be in China, Congo and India. Possibly, the study will also be located on suitable sites in Southeast Asia and South America.

Changing Forest Management Systems

Many forest managers, especially on the public lands, are de-emphasizing even-age forest management suggesting that harvest openings now and in the future will be smaller and more dispersed. Thus, some would argue that the need for research on how soil disturbance affects productivity is minimal. Although they may ‘not occur in a large pulse as in an even-age system, soil impacts from the multiple entries required in an unevenaged management systems may be cumulative. The long-term effects of even mild disturbance and compaction on the root systems of residual forest is not known. Regardless of the silvicultural system employed, sound soil management must be an integral part if the systems is to be sustainable.

An Alliance for Cooperative Research

In November 1995, a meeting was held in St. Louis, MO to develop a strategy for coordination and cooperation among research monitoring productivity in planted forests. Attending this meeting were leaders from research and management in the U.S. Forest Service; Canadian Forest Service, North American Forestry Schools and Colleges, American Forestry and Paper Association and the National Council for Air and Stream Improvement. All participants shared a belief that sustaining or enhancing the site productivity are central to sound stewardship in plantation management. They saw soil/site research as key to accomplishing this and agreed that a coordinated, cooperative research alliance that crosses traditional boundaries between agencies and ownerships would be in everyone’s interest. Taken individually, soil/site studies usually are anecdotal and of limited depth and scope. Taken collectively, good studies will be complementary. Patterns may emerge that provide deeper insight and contribute substantially to theory.

As a first step, the working group prepared a questionnaire aimed at establishing a directory of soil/site research programs underway by federal, university and forest industry scientists in the U.S. and Canada. The questionnaire, accompanied by an explanatory cover letter signed by all working group members, will be distributed in spring, 1996. Responses will be summarized by geographic region and ownership and distributed in a timely fashion.

Commitment to a Solution

Planted forests represent the best hope for meeting our global wood requirements while maintaining the quality of life throughout the 21 st century. Today, merchantable yields stand at historical highs because of advances in site preparation, genetic selection, planting techniques, stand tending, harvesting methods and manufacturing efficiency. But these high yields cannot be sustained-much less increased-unless the productive capacity of the supporting soil systems are maintained. Understanding the impact of management practices on potential productivity is a responsibility of ail land stewards and a necessity for sustainable forestry. Solutions will only be found through cooperative, integrated programs that 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 the program work Following installation, 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 recent review of forestry research programs around the world, Powers and Van Cleve (1991) concluded that all successful long-term programs are founded on such core commitment. A further earmark of successful long-term programs is that they be founded on issues of continuing social relevance. Certainly, the sustainable productivity of planted forests is an issue of highest merit.

Literature Cited

1. Allen, H. L., L. A Morris and T. R. Wentworth. 1991. Productivity comparison between successive loblolly pine rotations in the North Carolina Piedmont. p. 125-l 36. In: W.J. Dyck and C.A Mees (eds.) IEA/BE T6/A6 Report No. 5, FRI Bulletin No. 159, Forest Research Institute, Rotorua, New Zealand.
2. Ballard, R. 1984. Fertilization of plantations. p. 327-360. In: G.D. Bowen and E.K.S. Nambiar (eds.) Nutrition of Plantation Forests. Academic Press, New York.
3. Bassman, J.H. 1989. Influence of two site preparation treatments on ecophysiology of planted Picea engelmannii x glauca seedlings. Canadian Journal of Forest Research 19: 1359-l 370.
4. Bowen, G.D. 1984. Tree roots and the use of soil nutrients. p. 147-l 79. In: G.D. Bowen and E.KS. Nambiar (eds.) Nutrition of Plantation Forests. Academic Press, New York
5. Cannell, M.G.R 1989. Physiological basis of wood production: a review. Scandinavian Journal of Forest Research 4: 459-490.
6. Chappell, H.N., G.F. Weetman and R.E. Miller (eds.) 1992. Forest Fertilization: Sustaining and Improving Nutrition and Growth of Western Forests. Institute of Forest Resources Contribution no. 73. College of Forest Resources, University of Washington, Seattle. 302p.
7. Childs, S.W., S.P. Shade, D.W.R. Miles, E. Shepard, and H.A. Froehlich. 1989. Soil physical properties: importance to long-term forest productivity. p. 53-66. In: D.A Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, and R.F. Powers. Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. Timber Press, Portland, Oregon.
8. Davey, C.B. and AG. Wollum II. 1984. Nitrogen fixation systems in forest plantations. p. 361377. In: G.D. Bowen and E.K.S. Nambiar (eds.) Nutrition of Plantation Forests. Academic Press, New York
9. DeBell, D. S., C. D. Whitesell and T. H. Schubert. 1989. Using N_2 fixing *Albizia* to increase growth of Eucalyptus plantations in Hawaii. Forest **Science 35: 64-65.**
10. **Della-Tea, F. and E. J. Jokela. 1991. Needlefall,** canopy light interception, and productivity of young intensively managed slash and loblolly pine stands. Forest **Science 37: 12984 313.**
11. **Evans, J. 1975. Two rotations of Pinus patula in the Usutu forest, Swaziland. Commonwealth Forestry Review 54: 64-81.**
12. Evans, J. 1978. A **further report on** second rotation productivity in the Usutu Forest, Swaziland-results of the 1977 reassessment. Commonwealth Forestry Review 57: 253-261.
13. Fisher, R.F. 1984. Predicting tree and stand response to cultural practices. p. 53-65. In: E.L. Stone (ed.) Forest **Soils & Treatment Impacts. Proceedings of the 6th North American Forest Soils Conference,** June 19-23, 1983, Knoxville, TN. Dept. of Forestry, Wildlife and Fisheries, Univ. Tennessee, Knoxville.

14. Fleming, R.L., T.A. Black and N.R. Eldridge. 1994. Effects of site preparation on root zone soil water regimes in high-elevation forest clearcuts. Forest Ecology and Management 68: 173-l 88.
15. Florence, R.G. 1967. Factors that may have a bearing upon the decline of productivity under forest monoculture. Australian Forestry 31: 50-71.
16. Froehlich, **H . A** and D.H. **McNabb.** 1984. Minimizing soil compaction in Pacific Northwest forests. p. **159-192.** In: **E.L.** Stone (ed.) Forest Soils & Treatment Impacts. Proceedings of the 6th North American Forest Soils Conference, June 19-23, 1983, Knoxville, TN. Dept. of Forestry, Wildlife and Fisheries, Univ. Tennessee, Knoxville.
17. Froehlich, **H.A.,** D.W.R. Miles and R.W. **Robbins.** 1986. Growth of young ***Pinus ponderosa*** and ***Pinus contorta*** **on** compacted soils in central Washington. Forest Ecology and Management 15: **285-294.**
18. **Gholz, H.L.,** KC. Ewel and R. 0. Teskey. 1990. Water and forest productivity. Forest Ecology and Management 30: l-l 8.
19. Gray, H.R. 1935. Coniferous planting in Australia. Commonwealth Forestry Bureau Bull. No. 15, Commonwealth Govt. Printer, Canberra. 13 p.
20. **Grigor,** J. 1868. Arboriculture. Enmonston and Douglas, Edinburgh.
21. Hatchell, F.E., C.W. Ralston and R.R. Foil. 1970. Soil disturbance in logging. Journal **of** Forestry 68: 772-775.
22. **Haywood,** J.D. and AE. Tiarks. 1995. Growth reductions in short-rotation loblolly and slash pines in central- Louisiana **-** 10th year results. p. 268-274. In:. Edwards, M.B. **(comp.)** 1995. Proceedings of the Eighth Biennial Southern Silvicultural Research Conference, November l-3, **1994.** Auburn, AL. General Technical Report SRS-1. USDA, Forest Service, Southern Research Station, Asheville, NC.
23. Helms, **J.A.,** C. **Hipkin** and E.B. Alexander. 1986. Effects of soil compaction on height growth of a California ponderosa pine plantation. Western Journal of Applied Forestry 1: **104-l** 08.
24. Henderson, G.S. 1995. Soil **organic matter: a link** between forest management and productivity. p. **419-435.** In: W.W. **McFee** and J.M. Kelly (eds.) Carbon Forms and Functions in Forest Soils. Proceedings of the 8th North American Forest Soils Conference, May 1993, Gainesville, FL. Soil Science Society of America, Madison, Wisconsin.
25. Holmsgaard, E., H. Holstener-Jorgensen and A Yde-Anderson. 1961. Bodenbildung, **Zuwachs** und Gesundheitszustand von Fichtenbestanden erster und zweiter Generation. 1. **NordSeeland. Forstl.** Forsogv. Danm. 27: **167 p.**
26. Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological experiments. Ecological Monographs 54: **187-211.**
27. Johnson, D.W. 1994. Reasons for concern over impacts of harvesting, p. 1-12. In: W.J. **Dyck,** D.W. Cole, and N.B. Comerford (eds.) Impacts of Forest Harvesting on Long-Term Site Productivity. Chapman & Hall, London.

28. Jurgensen, M.F., A.E. Harvey, R.T. Graham, M.J. Larsen, J.R. Tonn and D.S.Page-Oumroese. 1990. Soil organic matter, timber harvesting, and forest productivity in the Inland Northwest. p. 392-415. In: S.P. Gessel, D.S. Lacate, G.F. Weetman, and R.F. Powers (eds.) Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conference, July 24-28, 1988, Vancouver, B.C. Univ. British Columbia, Faculty of Forestry, Vancouver.

29. Keeves, A 1966. Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. Australian Forestry 30: 51-63.

30. Knoepp, J. D. and W. T. Swank. 1994 Long-term soil chemistry changes in aggrading forest ecosystems. Soil Sci. Soc. Am. J. 58:325-331.

31. Krauss, G., K Muller, G. Gartner, F. Hartel, H. Schanz and H. Blanckrneister. 1939. Standortsgemasse Durchfuhrung der Abkehr von der Fichtenwirtschaft im nordwestsachsischen Niederland. Tharandter Forstliches Jahrbuch 90: 481-715.

32. Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher and R. S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook ecosystem in New Hampshire. Ecological Monographs 40:23-47.

-33. MacLean, C.D. and C.L. Bolsinger. 1973. Estimating Dunning's site index from plant indicators. Research Note PNW-197. USDA Forest Service Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 10 p.

34. Maser, C. 1988. The Redesigned Forest. R. & E. Miles, San Pedro, California.

35. Messier, C. 1993. Factors limiting early growth of western redcedar, western hemlock and Sitka spruce seedlings on ericaceousdominated clearcut sites in coastal British Columbia. Forest Ecology and Management 60: 181-206.

36. Miller, H.G. 1984. Dynamics of nutrient cycling in plantation ecosystems. p. 53-78. In: G.D. Bowen and E.KS. Nambiar (eds.) Nutritionof Plantation Forests. Academic Press, New York_

37. Miller, R.E. and H.W. Anderson. 1995. Stand characteristics of 65-year-old planted and naturally regenerated stands near Sequim, Washington. USDA Forest Service Research Paper PNW-RP482. Pacific Northwest Research Station, Portland, OR. 11 p.

38. Miller, R.E., R.E. Bigley and S. Webster. 1993. Early development of matched planted and naturally regenerated Douglas-fir stands after slash burning in the Cascade Range. Western Journal of Applied Forestry 8: 5-10.

39. Miller, R.E. and M.D. Murray. 1978. The effects of red alder on growth of Douglas-fir. p. 283-306. In: D.G. Briggs, D.S. DeBell, and W.A. Atkinson (comp.) Utilization and Management of Alder. USDA Forest Service General Technical Report PNW-70. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

40. Miller, R.E., W. Scott and J.W. Hazard. 1996. Soil compaction and conifer *growth* after tractor yarding at three coastal Washington locations. Canadian Journal of Forest Research 26: 225-236.

41. Miller, **R.E., W.I.** Stein, R.L. Heninger, W. Scott, S.N. Little and D.J. Goheen. 1989. Maintaining and improving site productivity in the Douglas-fir region. p. 98-136. In: D.A Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry and R.F. Powers. Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. Timber Press, Portland, Oregon.

42. Mitchell, C.C., R.L. Westerman, J.R. Brown and T.R. Peck 1991. Overview of long-term agronomic research. Agronomy Journal 83: 24-29.

43. Morns, **L.A.** and R. E. Miller. 1994. Evidence for long-term productivity change as provided by field trials. p. **41-80.** In: W.J. **Dyck,** D.W. Cole, and N.B. Comerford (eds.) Impacts of Forest Harvesting on Long-Term Site Productivity. Chapman **&** Hall, London.

44. Moulton, R.J., F. Lockhart and J.D. Snellgrove. 1996. Tree planting in the United States-1995. USDA Forest Service State and Private Forestry, Cooperative Forestry, Washington, D.C. 18 p.

45. Nambiar, E.KS. and D.N. Fife. 1991. Nutrient retranslocation in temperate conifers. Tree Physiology 9: **185-207.**

46. Nambiar, E.KS. and KH. **Nethercott.** 1987. Nutrient and water availability to and growth of young radiata pine plantations intercropped with lupins. *New* Forests 1: **117-134.**

47. Nambiar, E.KS. and R Sands. 1993. Competition for water and nutrients in forests. Canadian Journal of Forestry Research 23: 1955-l 968.

48. Olsson, B. 1995. Soil and vegetation changes after clear-felling coniferous forests: effects of varying removal of logging residue. Dissertation. Swedish University of Agricultural Sciences, Dept. of Ecology and Environmental Research. Report 80.

49. Ovington, J.D. 1953. Studies of the development of woodland conditions under different trees. Journal of Ecology 3: **12-34.**

50. Powers, R.F. In press. On the sustainable productivity of planted forests. In: Planted Forests. Contributions to Sustainable Societies. College of Forestry, Oregon State University, **Corvallis.**

51. Powers, RF. 1989. Retrospective studies in perspective: strengths and weaknesses. p. 4762. In: W. J. **Dyck** and C.A Mees (eds.) Research Strategies for Long-Term Site Productivity. **IEA/BE** A3 Report No. 8. FRI Bulletin **152.** New Zealand Forest Research Institute, Rotorua.

52. Powers, R.F., D.H. **Alban,** RE. Miller, AE. **Tiarks,** C.G. Wells, P.E. Avers, R.G. Cline, RO. Fitzgerald and N.S. **Loftus,** Jr. 1990. Sustaining site productivity in North American forests: problems and prospects. p. **49-79.** In: S.P. Gessel, D.S. **Lacate,** G.F. Weetman, and R.F. Powers (eds.) Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conference, July 24-28, **1988,** Vancouver, B.C. Univ. British Columbia, Faculty of **Forestry,** Vancouver.

53. Powers, R.F. and P.E. Avers. 1995. Sustaining forest productivity through soil quality standards: a coordinated U.S. effort. p. 147-190. In: C.B. Powter, S.A. Abboud and W.B. McGill (eds.) Environmental Soil Science. Anthropogenic Chemicals and Soil Quality Criteria. Proceedings of a symposium August 10-11, 1992, Edmonton, Alberta. Canadian Society of Soil Science, Brandon, Manitoba.
54. Powers, R.F. and G.T. Ferrell. 1996. The 'Garden of Eden' study revisited. Findings at 8 years. P. 8-31. In: Proceedings, Seventeenth Annual Forest Vegetation Management Conference, Redding, California, January 16-18, 1996. Forest Vegetation Management Conference, Redding, California.
55. Powers, R.F., D.J. Mead, J.A. Burger and M.W. Ritchie. 1994. Designing long-term productivity experiments. p. 247-286. In: W.J. Dyck, D.W. Cole, and N.B. Comerford (eds.) Impacts of Forest Harvesting on Long-Term Site Productivity. Chapman & Hall, London.
56. Powers, R.F. and K Van Cleve. 1991. Long-term ecological research in temperate and boreal perennial ecosystems. Agronomy Journal 83: 11-24.
57. Pritchett, W.L. 1979. Properties and Management of Forest Soils. John. Wiley & Sons, New York
58. Richter, D.D., D. Markewitz, C. G. Wells, H. L. Allen, R. April, P. R. Heine and B. Urrego. 1994. Soil chemical change during three decades in an old-field loblolly pine (*Pinus taeda* L.) ecosystem. Ecology, 75(5):1463-1473.
59. Robinson, RK 1973. Mycorrhizas and "second rotation decline" of *Pinus patula* in Swaziland. South African Forestry Journal 84: 16-19.
60. Sands, R., E.L. Gracen and C.J. Gerard. 1979. Compaction of sandy soils in radiata pine forests. I. A penetrometer study. Australian Journal of Soil Research 17: 101-113.
61. Sereni, E. 1974. Storia del Paesaggio Agrario Italiano. Gius. Laterza & Figli Spa, Rome.
62. Sheffield, R.M. and N.D. Cost 1986. Evidence of pine growth loss in Forest Service inventory data. p. 74-85. In: Atmospheric deposition and forest productivity. Proceedings of the Fourth Regional Technical Conference, Appalachian Society of American Foresters, Jan. 29-31, 1986, Raleigh, North Carolina.
63. Sheffield, RM., N.D. Cost, W.A Bechtold and J.P. McClure. 1985. Pine growth reductions in the southeast. Resource Bulletin SE-83, USDA Forest Service Southeastern Forest Experiment Station, Asheville, North Carolina. 112 p.
64. Sheppard, KR. 1986. Plantation Silviculture. Martinus Nijhoff, Dordrecht.
65. Smethurst, P.J. and E.KS. Nambiar. 1990. Effects of contrasting silvicultural practices on nitrogen supply to young radiata pine. p. 85-96. In: W.J. Dyck and C.A. Mees (eds.) Impact of Intensive Harvesting on Forest Site Productivity. IEA/BE T6/A6 Report No. 2, FRI Bulletin No. 159, Forest Research Institute, Rotorua, New Zealand.

66. **Snowdon,** P. and M.L. Benson. 1992. Effects of combinations of irrigation and **fertilisation** on the growth and above-ground biomass production of **Pinus** radiata. Forest Ecology and Management 52: 87-l 16.
67. Squire, R.O., P.VY Farrell, D.W. Flinn and B.C. Aeberli. 1985. Productivity of first and second rotation stands of radiata pine on sandy soils. Australian Forestry 48: 127-l 37.
68. Stevens, P. A., D. A Norris, T. G. Williams, S. Hughes, D. W. H. **Durrant,** M. A. Anderson, N. S. Weatherley, M. **Hornung** and C. Woods. 1995. Nutrient losses after clear-felling in Beddgelert Forest: a comparison of the **effectrs** of conventional and whole-tree harvest on soil water chemistry. Forestry. **68(2):115-1** 31.
69. Stone, R.L. and G.M. Will. 1965. Nitrogen deficiency of second generation radiata pine in New Zealand. p. 117-l 39. ***In:*** C.T. Youngberg (ed.) Forest Soil Relationships in North America. Proceedings of the 2nd North American Forest Soils **Conferenc,** August 1963, **Corvallis,** OR. Oregon State Univ. Press, Corvallis.
70. **Switzer,** G.L. and L.E. Nelson. 1972. Nutrient accumulation and **cyling** in loblolly pine **(*Pinus taeda*** L.) plantation ecosystems: the first twenty years. Soil Science Society of America Proceedings 36: 143-147.
71. Sword, **M.A., A E. Tiarks** and J. D. **Haywood.** (In review). **Early** cultural treatments affect the vegetation competition, nutrition, tannin chemistry and productivity of loblolly pine on an upper **gulf** coastal plain site.
72. Tiarks, AE and J. D. **Haywood.** (In press). Effects of site preparation and fertilization on growth of slash pine over two rotations. Soil Sci. **Soc.** Am **J.**
73. Van Cleve, K and R.F. Powers. **1995.** Soil carbon, soil formation, and ecosystem development. p. **55-200.** In: W.W. **McFee** and J.M. Kelly (eds.) Carbon Forms and Functions in Forest Soils. Proceedings of the 8th North American Forest Soils Conference, May 1993, Gainesville, Florida. Soil Science Society of America, Madison, Wisconsin.
74. Vitousek, P.M. and W.A **Reiners.** 1975. Ecosystem succession and nutrient retention: **a** hypothesis. Bioscience 25: 376-381.
75. Waring, R.H. and W.H. Schlesinger. 1985. Forest Ecosystems. Concepts and Management. Academic Press, New York
76. Whalley, W.R., E. Dumitru and AR. Dexter. 1995. Biological effects of soil compaction. Soil and **Tillage** Research 35: **53-68.**
77. Wiedemann, E. 1923. Zuwachstruckgang und Wuchstockungen der **Fichte** in den mittleren und den unteren Hohenlagen der Sachsischen Staatsforsten. Tharandt. (U.S. Dep. Agric. Translation No. 302, 1936).
78. Wollum, AG. II and C.B. Davey. 1975. Nitrogen accumulation, transformation, and transport in forest soils. p. **67-106.** In: B. Bemier and C.H. **Winget** (eds.) Forest Soils and Forest Land Management. Proceedings of the 4th North American Forest Soils Conference, August 1973, Laval. **Laval** University Press, Quebec.

Table 1. Effect of presence (w/) or absence(w/o) of forest floor litter on temperature and moist& in the surface 15 to 20 cm of soil in boreal and temperate 2nd-year plantations (from Powers, in press)

	Soil temperature				Soil moisture			
	Boreal forest		Temperate forest		Boreal forest		Temperate forest	
Month	w/	w/o	wI	w/o	w/	w/o	w/	w/o
	(°C)				(%)			
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	20.1	23.7	20	25	23	16
August	10.1	11.4	18.5	23.7	25	27	20	13
Sent.	9.8	11.6	17.5	21.0	25	26	15	12

Table 2. 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 fourth (Challenge) and **second** (Vista&growing seasons. Soil depth is 10-20 cm. (from Powers, in press.)

	Challenge (clayey texture)				Vista (sandy texture)			
	Not Compacted		Compacted		Not Compacted		Compacted	
	w/ Weeds	w/o Weeds	WI **Weeds**	**w/o Weeds**	**w/ Weeds**	**w/o Weeds**	WI **Weeds**	w/o Weeds
Seedling . volume (cm^3)								
P. ponderosa	105	321	152	194	15	16	20	27
Abies wnwlor	4	18	6	10	2	3	3	5
Vegetative cover (%)	91	**trace**	56	trace	55	trade	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 . A.W.C. (%)*	**0**	**0**	-24	-24	**0**	**0**	**+65**	**+65**
Soil moisture-50 cm (. %)	29	32 "	30	33 "	—— (not measured) ——			
Predawn plant water potential (Mpa)								
P. ***ponderosa***	-0.88	-0.60	-0.87	-0.66	-1.61	-1.05	-2.05	-1.14
Abies concolor	**-1.74**	-0.54	-1.15	-0.63	-2.37	-1.13	-3.47	-0.93

*Available water holding capacity.

Soil water potential exceeds **-1.5 MPa.

Table 3. Effect of competing weed growth on elemental concentration in ponderosa pine needles and relative volume growth at 5 years (from Powers and Ferrell 1996). Means within columns followed by different letters are significantly different ($P<0.05$)

$SI_{Age\ 50}$ (m)	Precip. (mm)		Concentration in Needles ($g\ kg^{-1}$) N	P	K	S	Al	Relative growth (%)
17	1015	w/ Weeds	8.8a	1.0a	6.7a	0.57a	0.16a	100a
		w/o	10.2b	1.2b	8.7b	0.66b	0.15a	307b
23	1140	w/ Weeds	9.5a	0.7a	4.4a	0.60a	0.16a	100a
		w/o	12.8b	0.8a	5.6b	0.75b	0.16a	240b
30	1780	w/ Weeds	11.3a	1.0a	6.3a	0.77a	0.18a	100a
		w/o	11.0a	1.0a	6.5a	0.77a	0.18a	152a

Table 4. **Effect of organic matter removal (OM) at harvest and weed control (WC) on soil K levels (0-10 cm** depth) at age 5 and pine seedling volume and foliar potassium levels at age 6 at an **LTSP site in Louisiana. The main effects of weed control are significant at the 5%** level

Organic matter removal	Pine volume ($m^3\ ha^{-1}$)	Foliar K ($g\ kg^{-1}$)	Soil K ($cmol^{+}\ kg^{-1}$)
$WC_0\ OM_{Boles\ only}$	11.36	4.76	0.066
$WC_0\ OM_{Whole\ tree}$	8.03	4.63	0.063
WC0 OM_{Total}	6.96	5.96	0.061
$WC_{Total}\ OM_{Boles\ only}$	23.65	6.32	0.043
$WC_{Total}\ OM_{Whole\ tree}$	16.43	7.20	0.048
$WC_{Total}\ OM_{Total}$	14.83	6.77	0.055

Table 5. Effect of organic matter (cast needles) additions at planting and weed ***control on the*** volume and potassium levels in foliage and soil (O-10 cm depth) at age **5 in Louisiana. Means within** a column followed by the different letters are significantly different at 5% level. (Sword. et-al.. in review)

Weed Control & Organic Matter Treatments	Pine volume (m^3 ha")	Foliar K (g kg-')	Soil K (cmol' kg-')
WC_0 OM_0	7.8a	4.40a	0.096a
WC_0 $OM_{needles}$	13.0b	4.40a	0.086a
WC_{Total} OM_0	20.3c	5.97b	0.065b
WC_{Total} $OM_{needles}$	20.6c	6.06b	0.047b

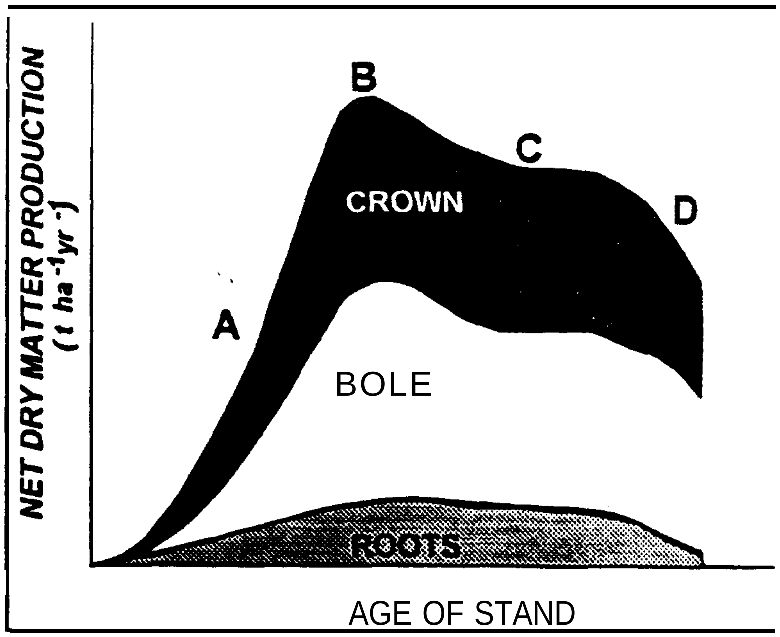


Figure 1. Typical pattern of evenaged stand development showing annual partitioning of productivity into roots, bole, and crown. Major phases are (A) rapid increases in productivity and nutrient demand as trees occupy site resources; (8) peak productivity and nutrient uptake at crown closure; (C) relatively stable productivity to maturity with increasing maintenance respiration (note that crown mass is fixed. Much of the stand's nutrient demand is met through internal recycling); (D) rapid decline as stand senescences from natural causes (Powers, in press, modified from Waring and Schlesinger 1985).

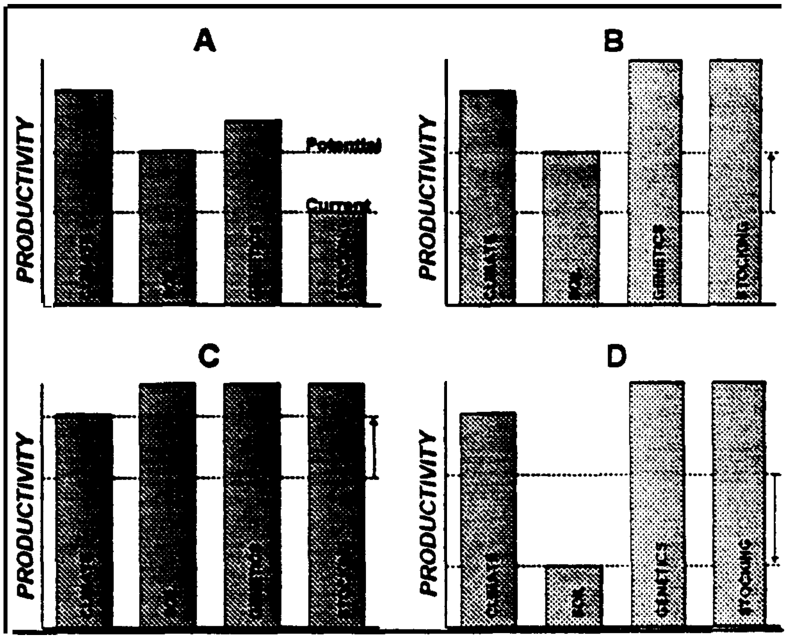


Figure 2. Relationship between current and potential productivity of a plantation as constrained by climate, soil, genetics and stocking. (A): An understocked stand is performing at less than potential as limited by the natural properties of the soil. **(B):** Improvements in genetics **and** stocking 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 (Powers, in press).

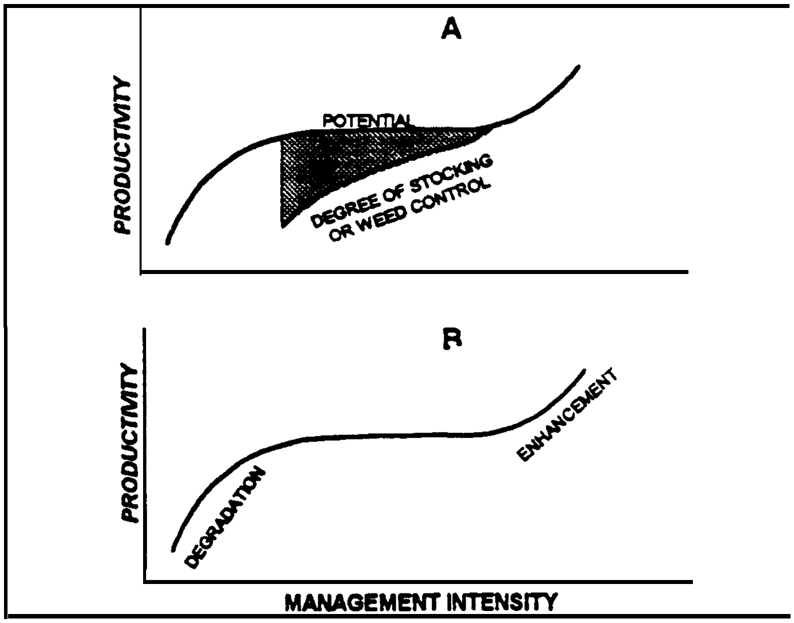


Figure 3. Relationship of management intensity to site productivity. (A): The degree to which the natural potential of a site is captured depends on stocking and weed control. (B) A site's potential productivity isn't static, but may be degraded by careless management (erosion, compaction), or enhanced by favorable soil treatment (fertilization, drainage, irrigation, subsoiling) (Powers, in press).

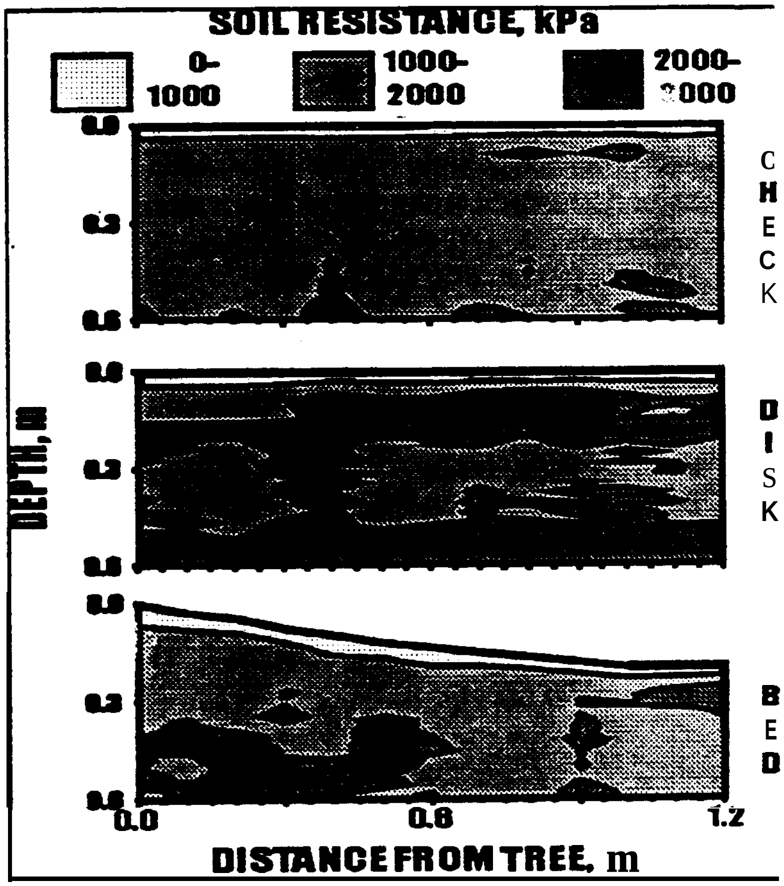


Figure 4. Penetrometer measurements of soil strength on burn only, **disked** and bedded treatments measured 33 years after site preparation. Measurements were made every 10 cm along 6 transects on each of 4 blocks and every 1.5 cm vertically.

Figure 5. Conceptual model of the roles of soil porosity and site organic matter in regulating the processes controlling site productivity within the constraints of climate and genotype (Powers, et al. 1990).

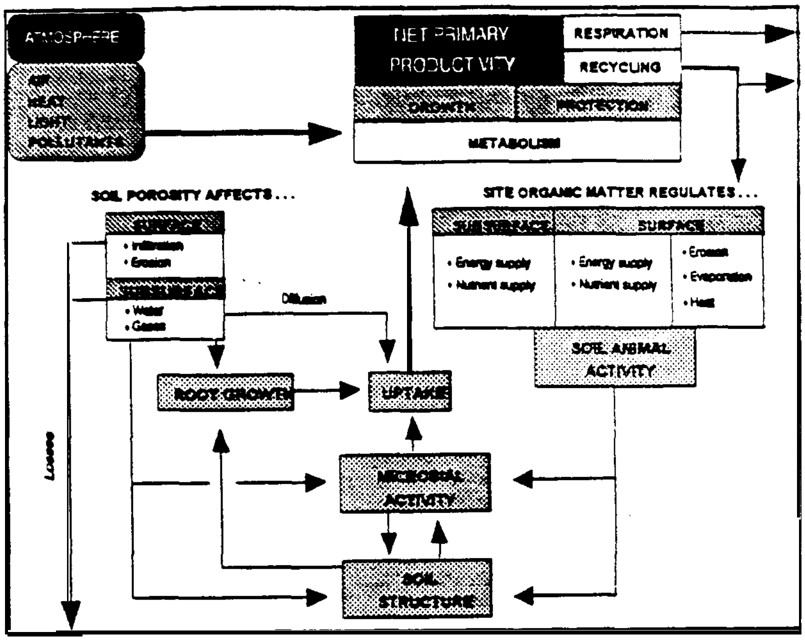


Figure 6. **Growth** patterns **of** current plantations **can** be compared with patterns from previous stands on the same site. Superior growth in the current plantation could be seen to indicate site improvement. Inferior growth could indicate site degradation.

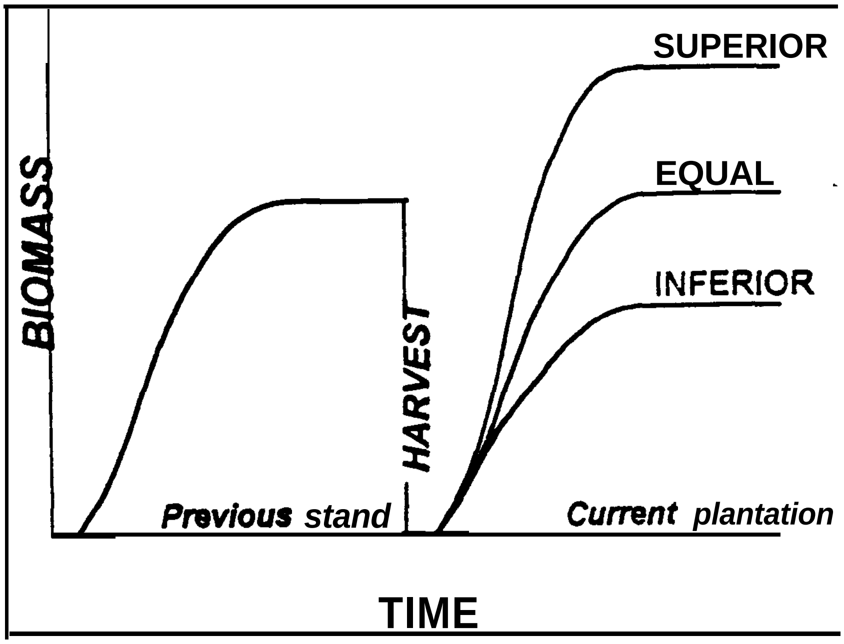


Figure 7. Bulk densities of the surface soil in Louisiana immediately after compaction (Age 0) and after 5 years of recovery, with and without grass cover.

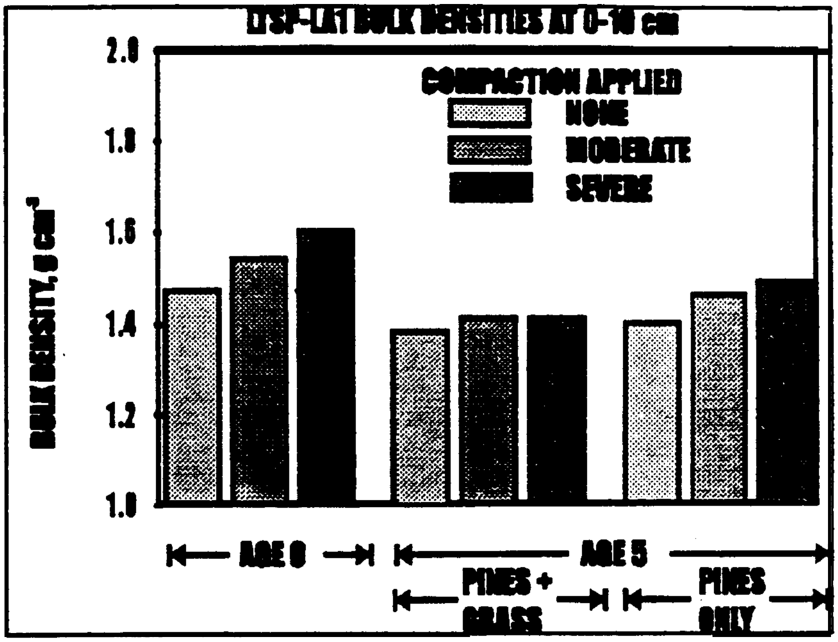


Figure 8. Two field designs for experiments on the long-term impacts of management practices on site productivity and the processes controlling it. **(A):** the standard LTSP design used by the USDA Forest Service. Each plot is 0.4 ha with vegetation control/no control as a split plot. (B): an alternative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

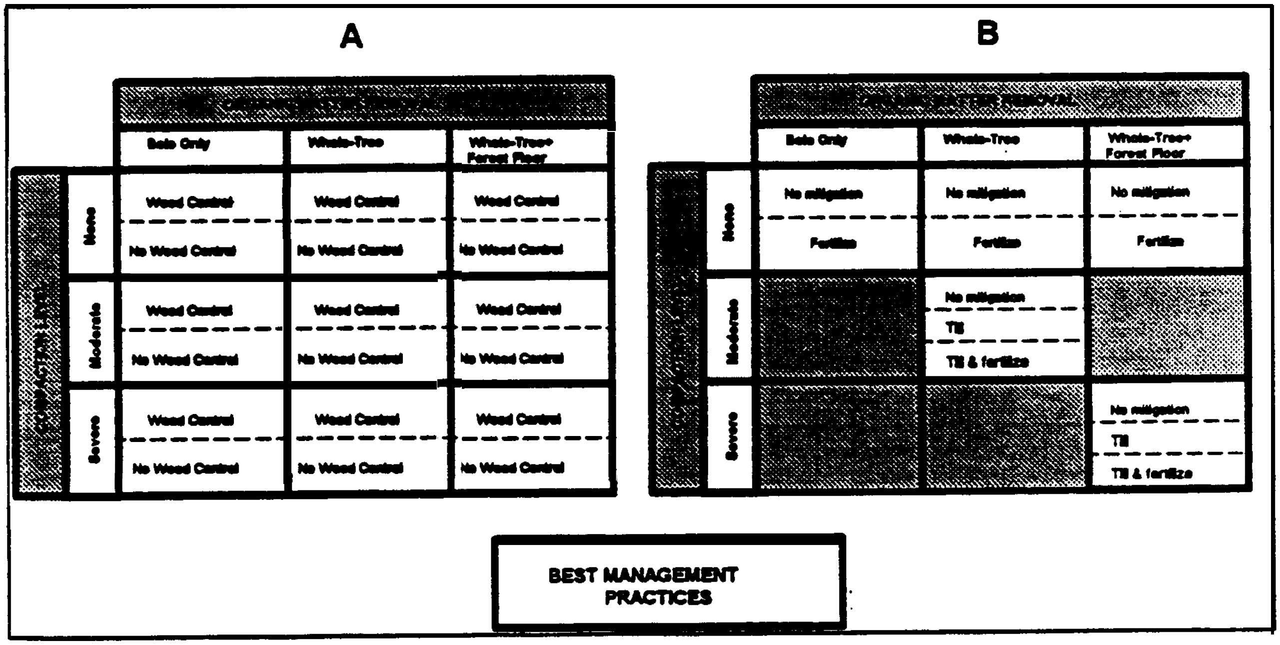


Figure 9. Actual layout of one block of the study showing treatment placement. Blowup of one plot shows the location of water table sampling wells for geostatistical interpretation.

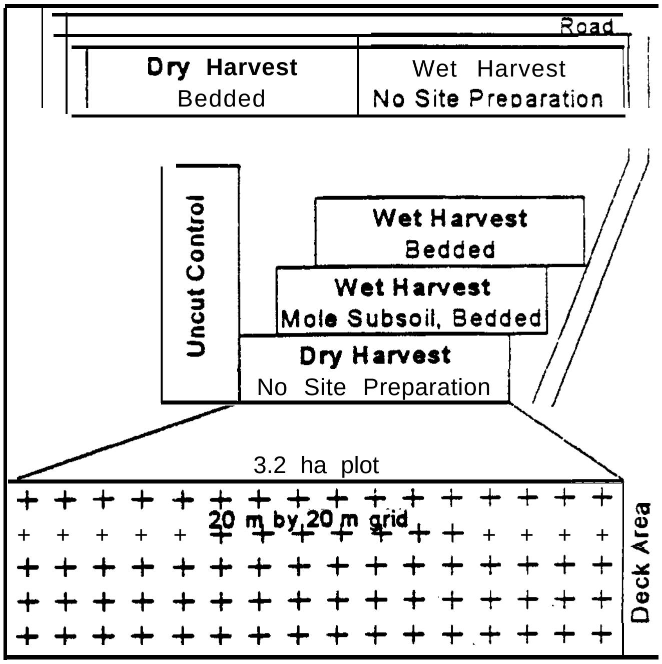


Figure 10. Spatial distribution of organic matter and soil disturbance after harvesting.

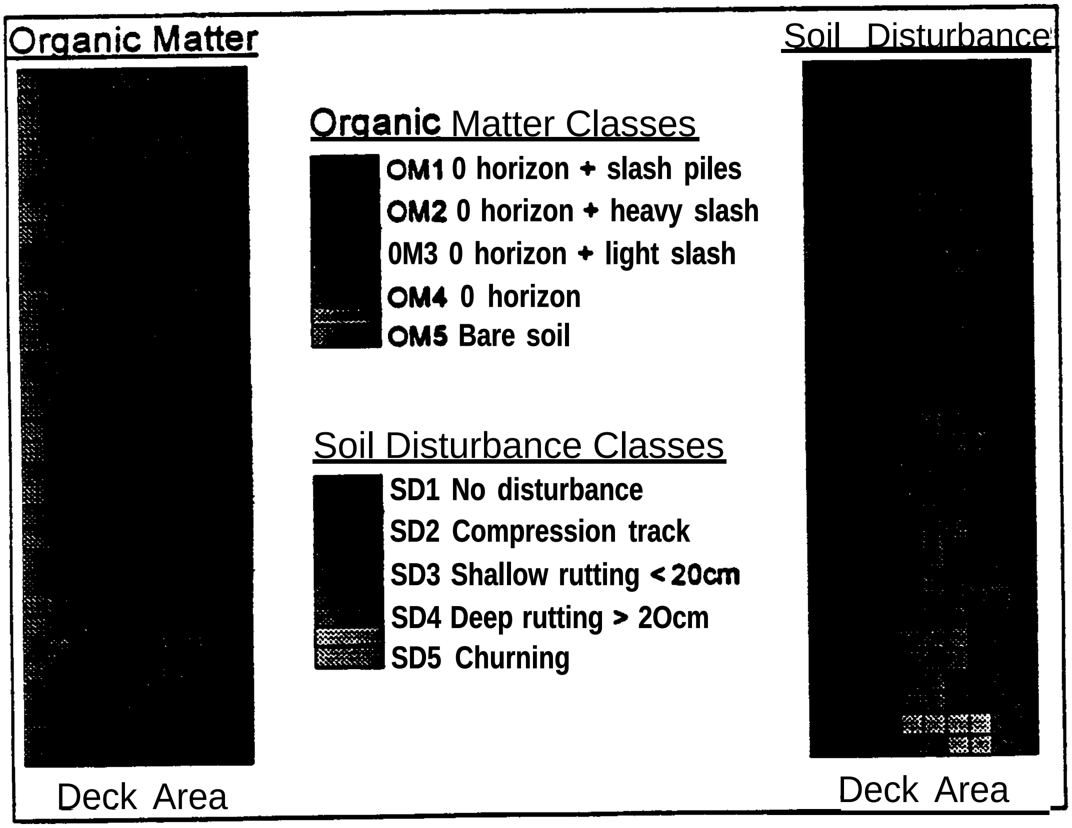
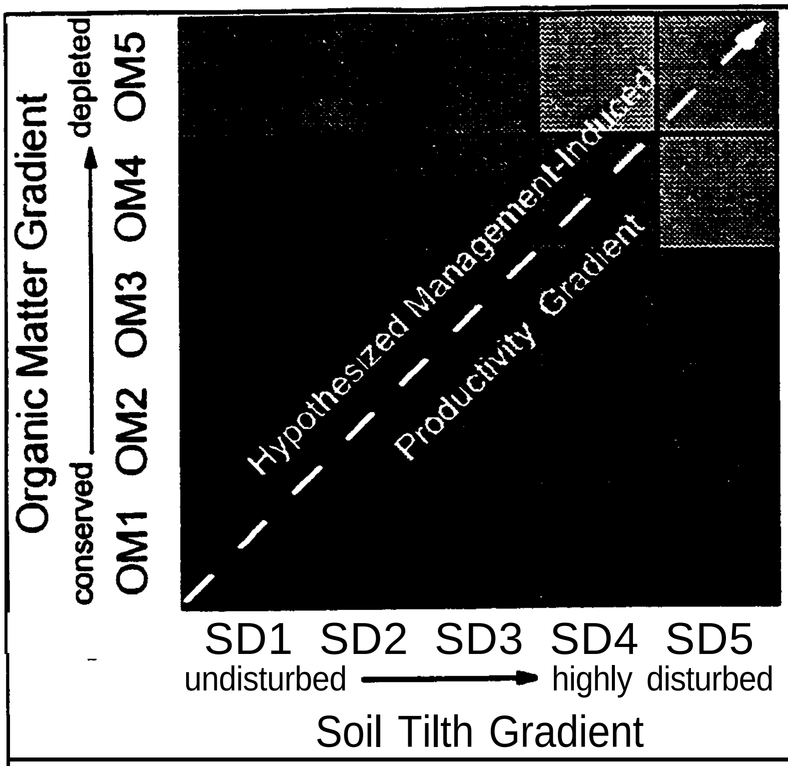


Figure 11. Organic matter and soil disturbance gradient imposed by harvesting. Response surface shows a hypothesized management-induced productivity gradient.



__Organic Matter Classes__

OM1 0 horizon + slash piles
0M2 0 horizon + heavy **slash**
OM3 0 horizon + light slash
0M4 0 horizon
OM5 Bare Soil

__Soil Disturbance Classes__

SD1	No disturbance
SD2	Compression track
SD3	Shallow rutting < 20 cm
SD4	Deep rutting > 20 cm
SD5	Churning