SUSTAINING FOREST PRODUCTIVITY THROUGH SOIL QUALITY STANDARDS:
A COORDINATED U.S. EFFORT

by

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6.1 INTRODUCTION

Soil is more than farmer's dirt, or a pile of good topsoil, or engineering material; it is a body of nature that has its own internal organization and history of genesis.

Hans Jenny
The Soil Resource

"What will save the soil, then?" I ask.
"As soon as there is no food on their plates,
people will start worrying about saving the soil."

Question posed to a forest soil scientist by Peter Steinhart
The Edge Gets Thinner

Along with water and air, soil is the most fundamental of resources. This unconsolidated skin of the earth is the source from which many other resources and our most valued commodities flow. And along with clean water and air, healthy and productive soil is vital to a healthy and productive society. On a human time scale, soil is nonrenewable. Thus, in the fullest sense, soil is a heritage to be protected and, where necessary, to be repaired or improved as we pass it from one generation to the next.

Clear though this principle may be to some of us, it seems opaque to most of modern society to whom soil-derived resources simply are products of grocery stores, furniture shops, retail lumber yards and news stands. That soil is as common as air makes is just as invisible. Or, when thought is given to it, soil is seen in a negative sense. Soiled clothing must be cleaned. Soiled hands must be washed. Through the centuries, even landscape artists saw soil as little more than a platform for positioning deities and gentry (Jenny 1968). Even today, a cultural veil separates the earth from the eyes of most of humankind.

Despite today's general apathy, many cultures have emphasized soil stewardship through religion and philosophy. Abraham, in his covenant with God, was instructed to "Defile not therefore the land which ye shall inhabit, wherein I dwell" (Num. 35:34). Confucius saw in the earth's thin mantle the sustenance for all life and the source of minerals treasured by mankind. A century later, Aristotle viewed soil as the central mixing pot for the other elements of matter--air, fire and water--in the formation of all things. Donne, in Devotions Upon Emergent Occasions, used soil's relationship to earth metaphorically as man's relationship to mankind in that "No man is an Iland, intire of it selfe; every man is a peece of the Continent, a part of the Maine; if Clod be washed away by the Sea, Europe is the lesse, as well as if a Promontorie were, as well as if a Mannor of thy friends or thine owne were." Leopold (1949) expressed it too, in his Odyssey of an atom. From rock to soil, flower to acorn, deer to Indian, all in a single year.

In a sense, soil scientists carry a burden of raising a concern for saving the soil that approaches the fervor spent on whales, seals, owls, and redwood trees.

6.1.1 Legislating Soil Stewardship

The Law. Irrespective of general apathy or ignorance, sustaining the long-term productivity of our forested lands should be an ethical and economic aim of enlightened forest management. For the USDA Forest Service, there is a legal reason, too. Among the World's nations, the United States and the Netherlands stand alone in their legal mandates for good land stewardship. In the Netherlands, the Dutch Soil Protection Act of 1987 requires that soil must not be treated in a way that degrades its capacity for such multiple functions as grazing, ground water recharge, or crop production (Moen 1988). In the United States, the Multiple Use and Sustained Yield Act of 1960, the National Environmental Policy Act of 1969, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976 (NFMA) all bind the USDA Forest Service with managing renewable resources without permanently impairing the productivity of the land (USDA Forest Service 1983).

Section 6.(g)(3)(c) of NFMA specifically charges the Secretary with ensuring research and monitoring of the effects of each management system to protect the permanent productivity of the land (USDA Forest Service 1983). Responding to this, the Secretary appointed an independent Committee of Scientists to form a framework for implementing the law. These efforts led to a Code of Federal Regulations for Forest Planning which, among other things, requires the Forest Service to monitor the effects of prescriptions, including "significant changes in land productivity" (Code of Federal Regulations 1985). In response, the Chief of the Forest Service directed each of the nine Forest Service administrative Regions to develop monitoring procedures for detecting a significant change in land productivity over a planning horizon (a timber rotation).

The Forest Service's first task was to define the scope of its monitoring responsibility. "Land Productivity" can be defined as the ability of a site to create goods or services of social value. Thus, land productivity might encompass a cornucopia of timber, wildlife, watershed, fisheries, and aesthetic values--each a legitimate measure of the land's "produce." Legitimate though they may be, they are not equally measurable. Some are intangible, others subjective or temporally unstable. Discussions with the Office of General Counsel eased the way to a more objective and usable definition (USDA Forest Service 1987)

6.1.1.2 Interpreting The Law. "Land Productvity" was defined as the soil's carrying capacity for vegetative growth within the constraints of local climate. "Vegetation" means the flora native to the region, but not necessarily that occupying the site before disturbance from management. "Carrying capacity" was defined as average periodic dry matter production when the site is stocked fully with the native flora of interest. Finally,"Significant Change" was defined as the minimal level of reduced carrying capacity that is detectable with operational monitoring technology. After much discussion, a working value of 15% was adopted (USDA Forest Service 1987). This does not mean that the Forest Service tolerates productivity declines of up to 15%, but merely that it recognizes problems with detection limits. Although smaller declines might be detected with a higher intensity of sampling, the consensus was that a decline would have to be at least 15% to be separated from extraneous variation under realistic levels of funding.

Obviously, vegetative growth is not the broadest measure of productivity. But what is better? Are any other measures more reflective of ecosystem health and potential? Clearly, reducing a soil's capacity to grow vegetation degrades the capacity of the site for sustaining the production of all other renewable resources.

6.1.2 A Site's Productive Potential

Although the definitions of productivity and significant change were clarified, assessing them under operational conditions isn't easy. Merely measuring current growth rates is not enough because rates vary both within and between plant species and are subject to changes as communities develop. Even in simple plant communities of a given age, competitive differences can cause confusion. For example, a community of forest trees spaced very widely will have less total tree growth per unit area than does a community where trees are spaced more tightly. However, if only merchantable growth is considered, the relationship is reversed because fixed site resources are apportioned among fewer trees. This is illustrated in Table 1 (Oliver 1990) where total stand volume is related inversely to tree spacing. Yet, when the focus is on larger trees of sawlog size, volume and spacing are directly related and the trend is reversed. The paradox is that depending on tree spacing and growth definitions, opposing conclusions could be reached about whether one land unit is more productive than another. In the Table 1 example, apparent productivities truly are different. But the land's productive potential--the inherent capacity of the site to sustain plant growth--has not changed at all.

Another problem facing productivity monitoring concerns the effects of other types of vegetation on tree growth. Tree volumes may be substantially less in stands with shrub understories than in adjacent stands without shrubs (Table 1). Poorer tree growth where shrubs are present creates the impression that productivity has been fundamentally reduced. But with or without shrub competition, the site's total resources have remained the same and the land's productive potential has not been altered. Failure to account for the effects of competing vegetation can lead to false conclusions and an immense problem for operational monitoring.

Measuring existing vegetation per se is a blind alley. Instead, we must turn to measures of site potential. Unfortunately, our knowledge of site potential is limited because it is conditioned by the way forests have been managed (Powers 1987, Stone 1975) (Figure 1). Where forests are merely exploited, as on many non-industrial private lands of

Table 1. Tree means and stand totals for 20-year-old *Pinus ponderosa* planted at five spacings with and without shrub understories (Oliver 1990).

Square Spacing (m)	Average Height With	Average Height Without	Average Dbh With	Average Dbh Without	Total Volume With	Total Volume Without	Merchant. Vol. With	Merchant. Vol. Without
	(m)		(cm)		(m^3/ha)			
1.8	7.0	7.6	10.4	11.9	72	92	0	0
2.7	7.3	9.1	14.2	17.0	66	103	0	0
3.7	7.9	10.4	15.5	20.6	46	88	0	5
4.6	7.6	10.4	15.2	22.4	26	65	0	14
5.5	9.1	11.0	19.0	26.2	31	67	2	37

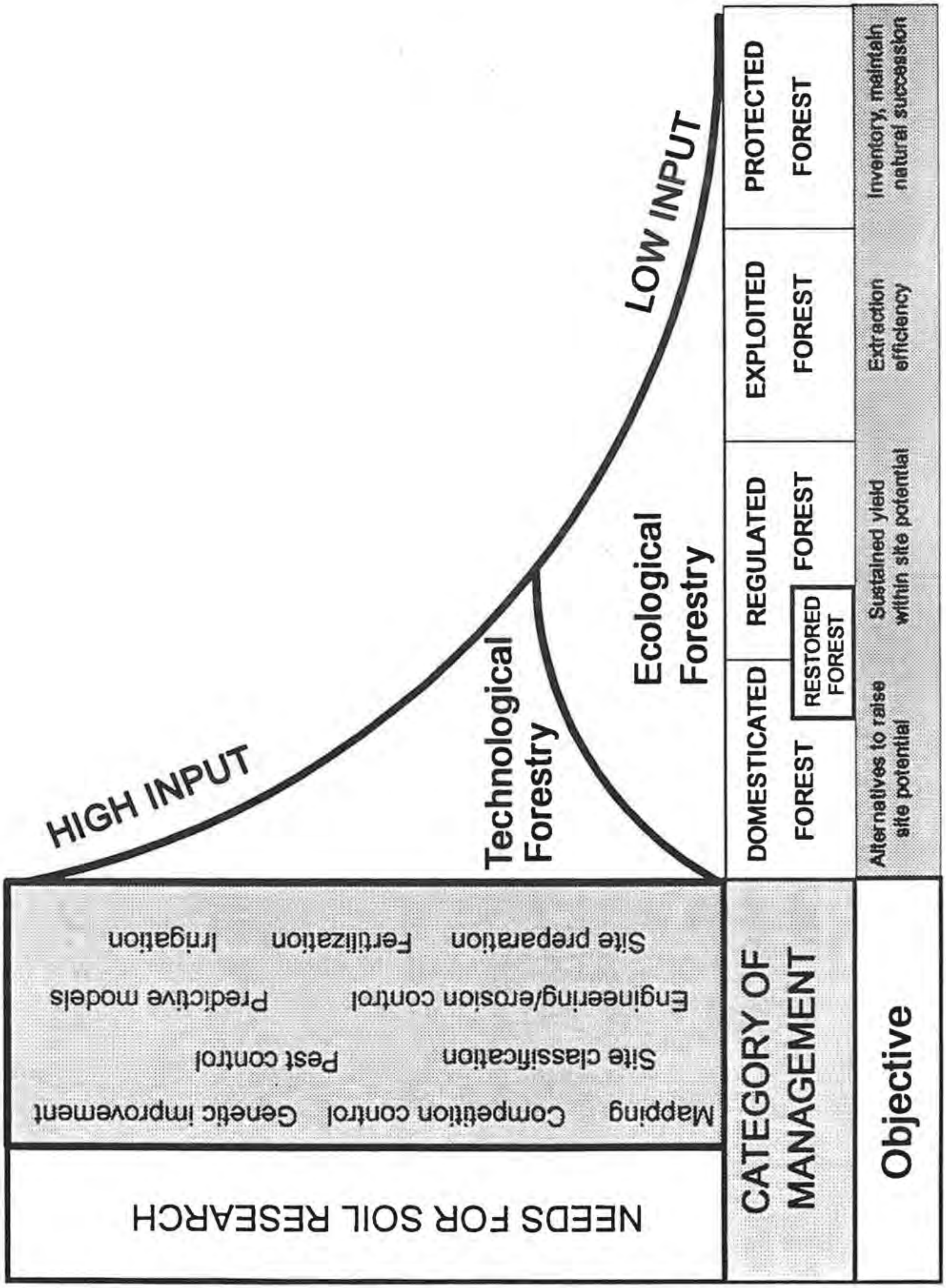

Figure 1. Site knowledge and soil information needs according to the level of technological input and category of management (Powers 1985, modified from Stone 1975).

the U.S. and the boreal region of Canada, knowledge about productivity is restricted at best to crude surveys of standing volumes. Technology is directed to efficiency of extraction, and very little is known about the site's potential for sustained growth. Where forests are regulated, as in most public and industrialized U.S. forests and portions of lower elevation British Columbia and the Atlantic Provinces, management has a working understanding of site potential in terms of site index and yield tables. There, the aim is to work within the inherent site potential and to find economic ways of capturing as much of the potential as possible. At the highest level of technological management intensity is the domesticated forest. There, inherent potential is viewed not as a limit, but rather as the foundation for raising productivity to a higher level by such intensive practices as soil modification.

While domesticated forestry is practiced extensively throughout much of the southern U.S., particularly on lands owned and managed by private forest industry, high cost, cumulative risks, and the inability to adjust crop cultures quickly to meet market demands means that most forests in the U.S. and Canada will be managed at lower levels of intensity. The aim there will be to work within the inherent site potential (Stone 1975). In a forestry context, at least for the present, this means working within concepts of site index and yield at culmination of mean annual increment. This is no panacea of course, because site index is simply an abstraction of potential productivity and must be related to yield functions to be useful in this sense (Powers 1987). Also, site index estimates are imprecise for stands much younger than 20 years, meaning that they cannot detect changes in early stand development following disturbance. Furthermore, stand yields reflect not only the productive potential of the site, but vagaries of stocking and competition (Table 1). And neither site index nor yield functions account for changes in non-tree vegetation. Although helpful, site index and yield have definite limitations.

6.2. THE FOREST SERVICE APPROACH

6.2.1 Soil Productivity as a Controlling Variable

The Forest Service knows that productivity standards cannot rely solely on tree growth. Instead, there must be a monitoring surrogate that is sensitive to changes in site potential, yet is buffered well against such factors as random fluxes in climate and stocking differences that affect vegetation from season to season and year to year. Soil is the best substitute. Within limits of climate, topography, and biology, soil sets the limits on productivity through its control of nutrients, moisture, and air supplies to plant roots. Furthermore, it is a controlling factor that is directly affected by management. "Soil productivity" has been coined to describe this, and the Forest Service's Watershed and Air Management staff has adopted a program for soil productivity monitoring that is based on the following rationale.

1. Management practices create soil disturbances.
2. Soil disturbances affect soil and site processes.
3. Soil and site processes control site productivity.

Monitoring soil and site processes directly is not feasible. Instead, monitoring strategy focuses on measurable soil variables that reflect important site processes. For example:

Site Process	Practicable Soil Monitoring Variables
Soil erosion	Soil loss thresholds, % soil cover, production, presence of rills, etc.
Nutrient availability	Forest floor presence, soil organic matter content, surface soil loss through erosion or displacement, etc.

Water availability	Infiltration, saturated hydraulic conductivity, soil bulk density, soil organic matter, plant water potential, soil moisture, etc.
Gas exchange	Soil bulk density, air permeability, puddling, presence of mottles, waterlogging, etc.
Root growth and nutrient uptake	Soil bulk density, soil strength, soil structure, water table depth, etc.

In putting this idea to practice, the Forest Service is establishing "soil quality standards" throughout its nine administrative Regions in the United States. Such standards are meant to be threshold values for operationally measurable soil properties that serve as early warning signals of impaired soil conditions. They are designed to help planning teams maintain or improve the health, suitability, or productive potential of soil. The standards become benchmarks for monitoring trends in soil condition, and for monitoring the implementation and effectiveness of soil and water conservation practices. For environmental assessments, standards are used in monitoring and evaluating the effects of management activities on the soil resource. Achieving these standards is taken to mean that the soil's potential for growing healthy and productive forest communities is sustained.

6.2.2 Setting Soil Quality Standards

6.2.2.1 The Principle. In its most elementary form, the principle behind the Forest Service approach is illustrated in Figure 2A. For any given soil and site, a change in a key soil variable (for example, a loss in porosity) will lead ultimately to a change in potential productivity when the site is at carrying capacity. For the hypothetical relationship in Figure 2A, the change is negative. However, one should note that not all soil variable changes lead to productivity declines. In many cases, productivity may be enhanced to a certain degree. Such is the case when moisture or nutrient constraints are modified by soil drainage, irrigation, or fertilization. Conversely, if the soil variable is not linked closely with productivity, changes in the condition of that variable will have little or no relevancy (potential productivity remains stable along the "line of no change" in Figure 2A). Obviously, the central feature of the concept is that the soil monitoring variable must be linked very closely with potential productivity when the forest has reached some specified stage of development.

The conceptual model in Figure 2A is simplistic. It implies that potential productivity is stable and known. In reality, there is a belt of uncertainty surrounding any productivity estimate that is due to climatic vagaries, the condition of the plant community, and to limits in our knowledge. Uncertainty about the true value of potential productivity leads to uncertainty about how much change a soil can withstand before productivity is affected. This uncertainty is shown as a shaded band about the line of no change in Figure 2B. Recognizing this, and based largely on collective judgement, the Forest Service has established a working hypothesis that a true decline in productivity would have to be at least 15% to be detectable. Therefore, the Watershed and Air Management branches of each Forest Service Region are charged with establishing soil quality threshold standards capable of detecting a 15% reduction in inherent soil productivy (USDA Forest Service 1987).

6.2.2.2 <u>The Practice</u>. Across the Nation, each administrative Region of the USDA Forest Service is establishing soil quality monitoring plans and soil quality thresholds (Table 2). Thresholds sometimes are rooted in scientific studies of direct applicability, but often they are based on the collective professional judgement of National Forest and Regional staff. In all cases, they are meant as interim guidelines that can be adjusted as knowledge improves. Some standards, such as those for compaction, are based on generalized models such as Froehlich and McNabb's (1984) linear model relating tree growth decline to increasing soil bulk density (Figure 3). There, a 15% decline in tree growth translates to about a 15% increase in bulk density. Erosion standards

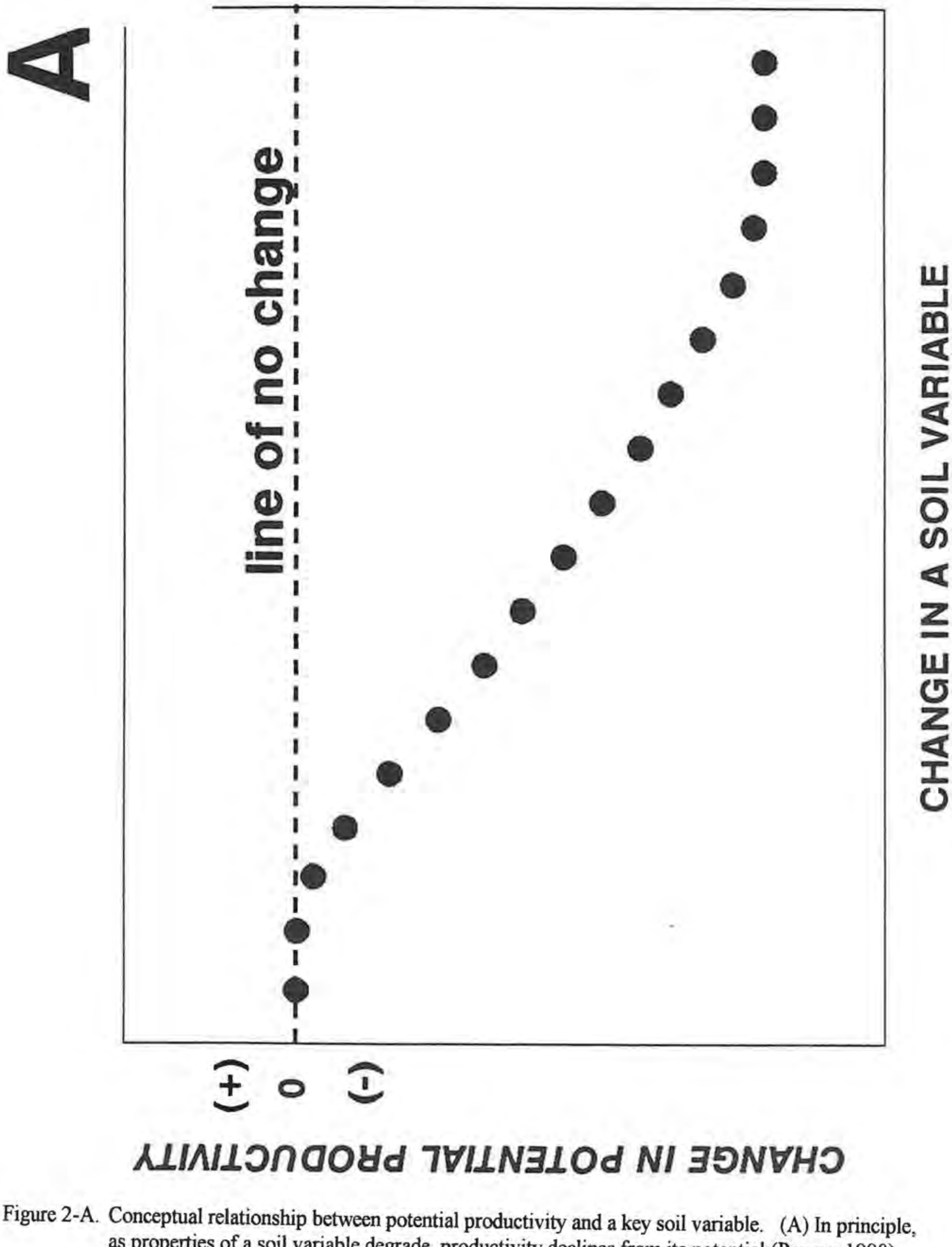

Figure 2-A. Conceptual relationship between potential productivity and a key soil variable. (A) In principle, as properties of a soil variable degrade, productivity declines from its potential (Powers 1990).

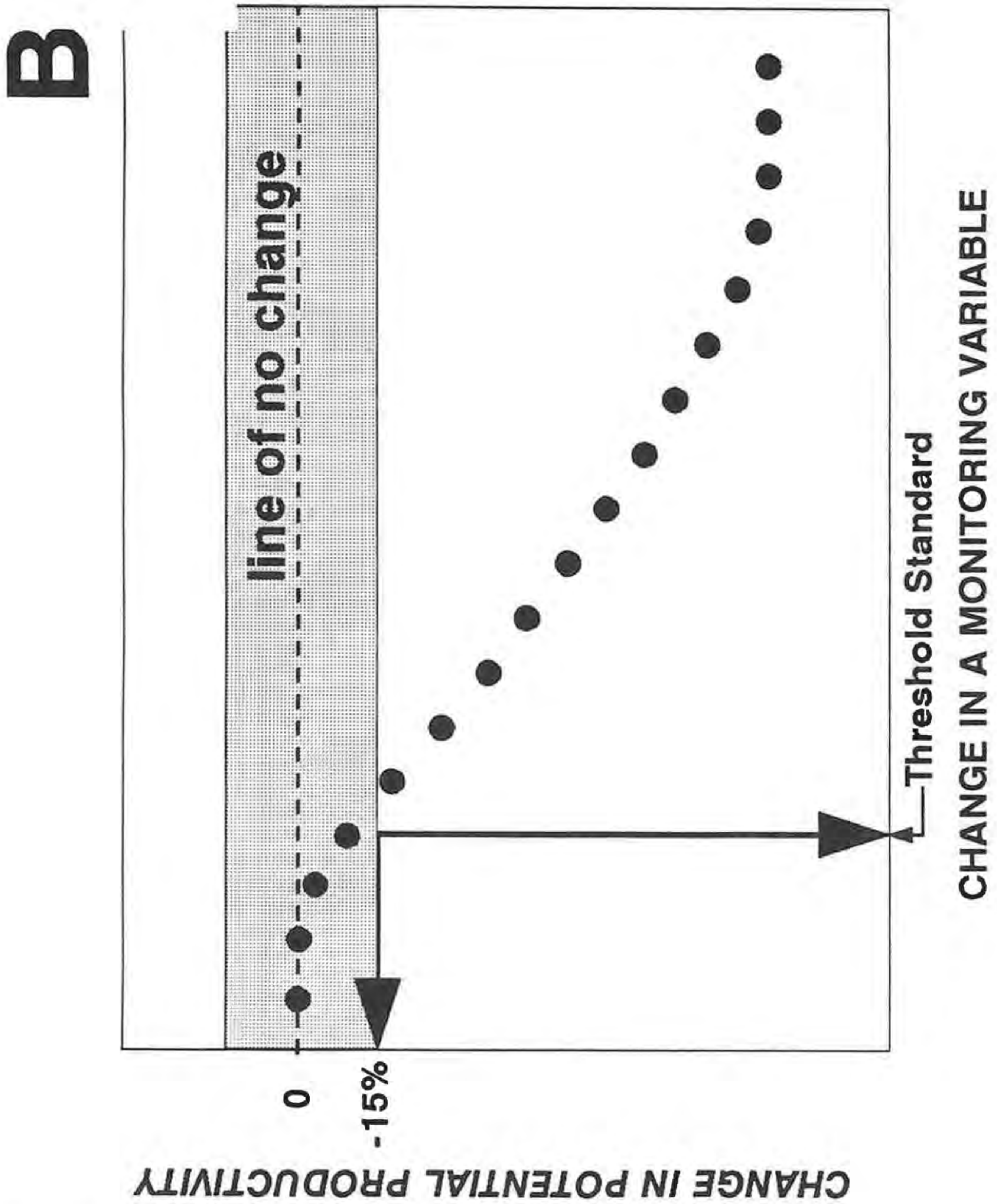

Figure 2-B. Conceptual relationship between potential productivity and a key soil variable. (B) In practice, variability exists about the estimate of productivity for an undisturbed site. Threshold soil quality monitoring standards indicate the degree of soil change needed to detect a 15% decline in potential productivity (Powers 1990).

Table 2. Soil quality standard threshold values for various disturbance variables for the nine administrative Forest Service Regions.

Disturbance Variable	FS Region	Threshold Value
Erosion (surface)	1	See "soil cover."
	2	Appearance of pedestalled rocks and plants. Deposition of soil uphill of objects. Formation of an erosion pavement or of channels greater than 2.5 cm deep on more than 15% of the area.
	3	Any of the area exceeds soil loss tolerance values as determined by the universal soil loss equation (USLE).
	5	See "soil cover."
	6	See "soil cover."
	8	Soil loss exceeds the allowable loss tolerance values set by the R-8 Guide on more than 15% of the area.
	9	Sheet and rill erosion exceeds the average annual soil loss tolerance over a rotation, or exceeds twice the threshold level on more than 20% of the area.
	10	Removal of 50% of topsoil or humus-enriched surface soil from 9.3 m^2 or more over more than 15% of the area.
Soil cover	1	Enough cover to prevent erosion from exceeding natural rates of soil formation on more than 15% of the area.
	2	Depending on erosion hazard class, effective ground cover is less than 30% to 50% the first year, and 50% to 70% the second.
	4	Too little to prevent erosion from exceeding natural rates of soil formation determined through the USLE.
	5	Forest floor covers less than 50% of area.
	6	Less than 20% cover on sites with low Erosion Hazard Ratings, 30% for moderate, 45% for high, and 60% for very high in first year after disturbance. Standards raise to <30%, 40%, 60%, and 75% in the second year.
	8	Cover guided by local standards.
	10	Less than 85% cover on slopes under 35%. Less than 95% cover on slopes greater than 95%.
Organic matter	1	Enough to sustain site productivity.
	3	Less than 22-34 Mg/ha organic matter throughout the area.
	4	Large woody debris insufficient to sustain site productivity as determined through research.
	5	~~Litter and duff covers less than 50% of area~~. Fewer than 12 decomposing logs/ha with diameters of at least 50 cm and lengths of 3 m.
	8	Soil organic matter less than 85% of that in upper 30 cm of undisturbed soil on more than 15% of the area.
Infiltration	3	Reduction of 20% from natural rates throughout area.
	5	Reduced to ratings of 6 or 8 as defined by Regional Erosion Hazard Rating System. Extent depends on cumulative watershed effects analysis.

Table 2. Concluded.

Compaction	1	Bulk density at depths of 5 to 30 cm raised to between 1.35 and 1.85 g/cm^3, depending on soil texture, on more than 15% of the area.
	2	Bulk density increased more than 15% over natural conditions, or densities exceeding 1.25 to 1.60 g/cm^3, depending on soil texture, on more than 15% of the area.
	3	15% bulk density increase over natural conditions for soil other than Andisols and 20% increase for Andisols throughout the area.
	4	Reduction of more than 10% in total soil porosity or a doubling of soil strength in any 5-cm increment of surface soil on more than 15% of the area.
	5	Reduction of more than 10% in total soil porosity over an area sufficiently large that it reduces productivity potential.
	6	15% bulk density increase, 50% macropore reduction, and/or a 15% reduction in air permeability over natural conditions for soils other than Andisols and 20% increase for Andisols on more than 20% of area.
	8	15% bulk density increase and more than 20% decrease in macroporosity over undisturbed conditions on more than 15% of the area.
	9	15% bulk density increase over undisturbed conditions on more than 20% of the area.
	10	15% bulk density increase over undisturbed conditions on more than 15% of the area.
Rutting and puddling	1	Ruts to a depth of 15 cm or greater on more than 15% of the area.
	2	See "compaction."
	6	Ruts reach at least 15 cm depth on more than 20% of the area.
	8	Ruts exceed 15 cm deep for a continuous distance of more than 15 m, ruts exceed 30 cm deep for more than 3 m, and ruts exceed 46 cm for any distance on more than 15% of the area.
	9	Ruts exceed 46 cm deep anywhere on site, or rut depths exceed 30 cm and extend for more than 3 m on more than 20% of the area.
	10	Ruts or foot prints in mineral soil or Oa horizon of an organic soil on more than 15% of the area.

Table 2. Continued

Detrimental burning	1	Standards set locally. Loss of O horizon and signs of mineral soil oxidation should not occur on more than 15% of the area.
	2	Fine fuels entirely consumed, surface soil heated to redness, no organic structure recognizable, and/or no ash layer remains. Standards set locally but should not prohibit broadcast burning.
	3	Most woody debris and entire forest floor consumed to bare mineral soil and fine roots charred in upper 1 cm of mineral soil on any of the area.
	4	Standards set locally.
	6	Top layer of mineral soil heated to redness and next 1 cm blackened from charring on more than 20% of area.
	9	Consumption of the forest floor to mineral soil on an area of more than 4.6 m^2. Bare soil exposure exceeds 5% on more than 80% of the area.
	10	Most woody debris and entire forest floor consumed to bare mineral soil and fine roots charred in upper 1 cm of mineral soil on any of the area.
Displacement	1	Loss of either 5 cm or more of the surface soil, or one half of the humus-enriched A horizon, which ever is less, on more than 15% of the area.
	2	Soil loss from a continuous area of more than 9 m^2 on more than 15% of the area.
	3	Removal of lesser of 50%, or 5 cm, of A horizon from a contiguous area of 9.3 m^2 or more.
	4	Removal of lesser of 50% of humus-enriched surface soil or 5 cm of topsoil on more than 15% of the area.
	5	Organic matter in the upper 30 cm of soil is less than 85% of the soil organic matter found under natural conditions. Affects an area sufficiently large that productivity potential is reduced.
	6	Removal of more than 50% of topsoil or humus-enriched A1 and/or AC horizons from an area of 9.3 m^2 or more and at least 1.5 m wide.
	8	Removal of more than 50% of the humus-enriched A horizon over a continuous area more than 5.6 m^2 and more than 1 m wide for more than 15% of the area.
	9	Removal to a depth of one-half the thickness of the A horizon over an area of more than 5.6 m^2 and more than 1-m wide on more than 20% of the area.
	10	Removal of forest floor and 50% of topsoil from an area of 9.3 m^2 and at least 1.5 m wide on more than 15% of the area.

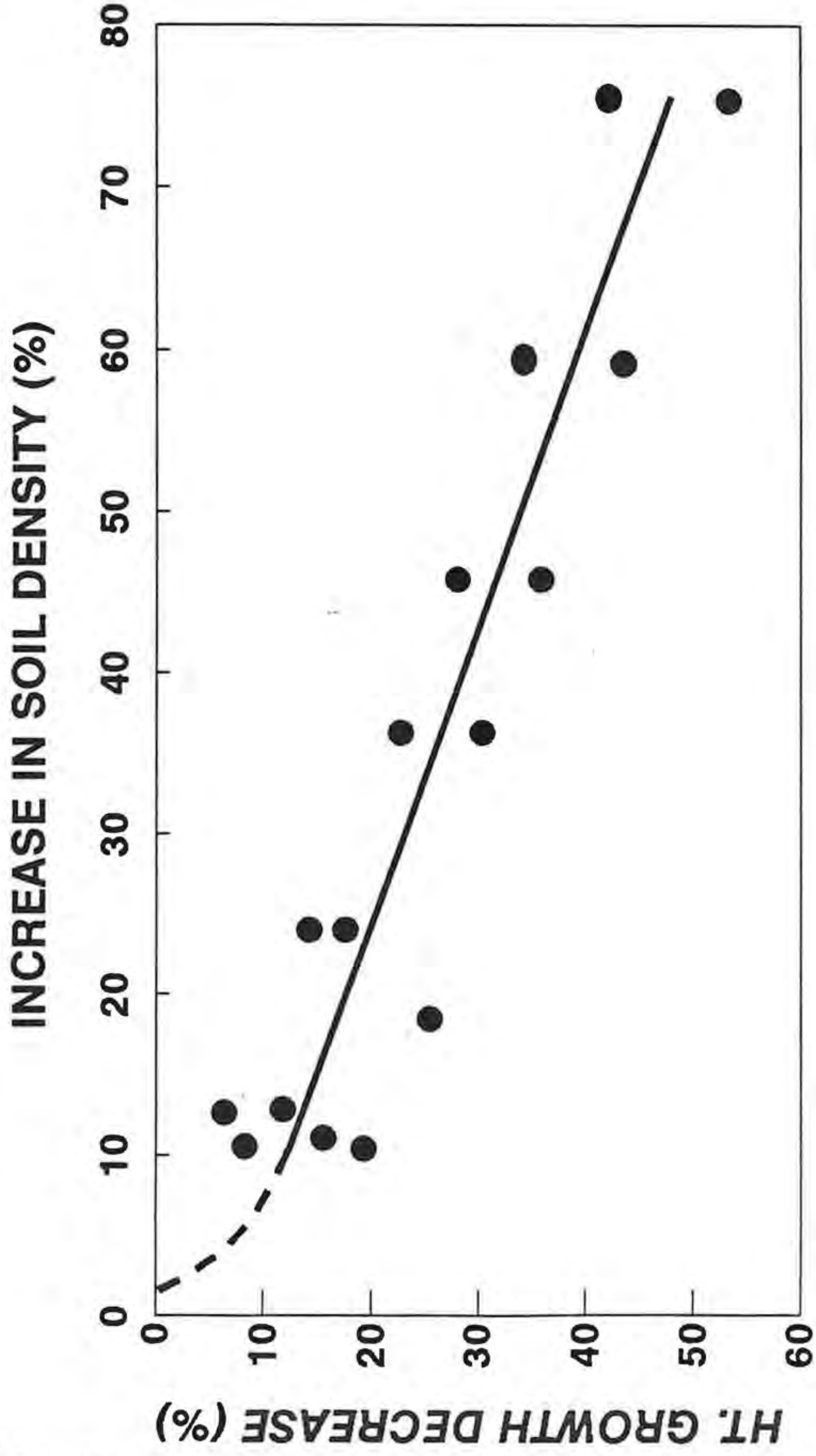

Figure 3. Relationship of soil bulk density increase to height growth decrease for a variety of sites (Froehlich and McNabb 1984).

largely are based on threshold tolerances from the Universal Soil Loss Equation (Wischmeier and Smith 1978) or potentially from such variants as the USDA Water Erosion Prediction Project (1987). In general, soil displacement and soil organic matter thresholds relate to our general understanding that soil fertility is most concentrated near the soil surface (Figure 4). Generic procedures for obtaining statistically reliable samples have been developed (Hazard and Geist 1984, Howes et al. 1983).

Soil quality monitoring is seen as a three-step procedure in the process of land management planning (Avers 1990). The steps are designed to address the following questions:

1. Implementation monitoring. Were prescribed soil management practices implemented as designed?
2. Effectiveness monitoring. Were the prescribed soil management practices effective in meeting management objectives?
3. Validation monitoring. Are the monitoring standards and guidelines appropriate for maintaining soil productivity?

Both implementation and effectiveness monitoring are the responsibility of soil scientists in the administrative arm of the Forest Service. The third stage, validation, is the responsibility of scientists in the research arm.

6.2.3 THE ROLE OF RESEARCH

6.2.3.1 Has Productivity Declined? Other than from mass wasting, is there sound evidence that soil productivity has declined from management activities? Findings from the United States tends to be confounded, or short-term and inconclusive (Powers et al. 1990). Many findings are based on retrospective analyses of data collected for other purposes. Characteristically, such studies are anecdotal and offer little insight into cause-and-effect mechanisms (Powers 1989).

The best report of an experiment designed specifically to test the deleterious impacts of management practices on soil productivity in

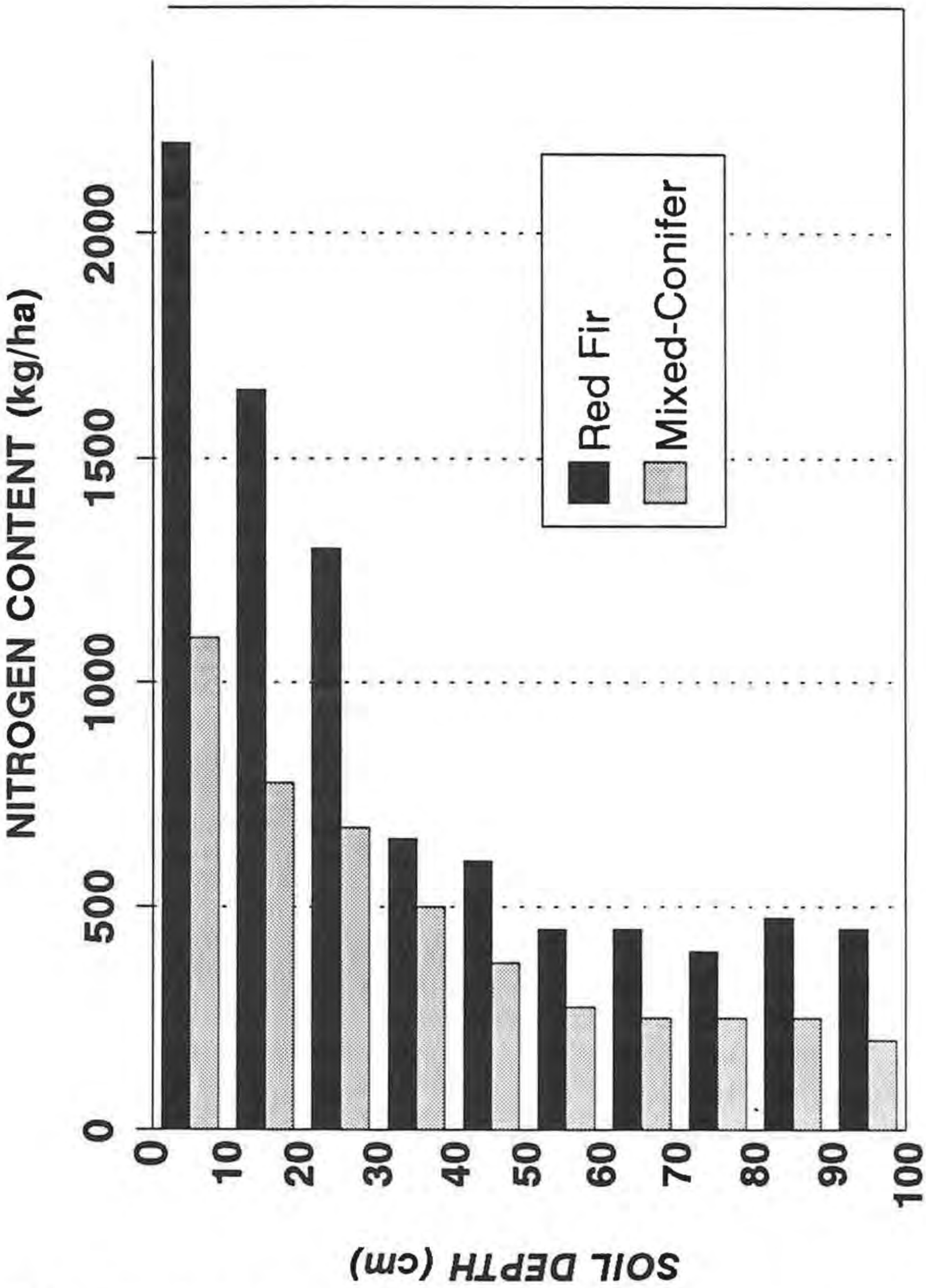

Figure 4. Content of total soil nitrogen and its distribution by depth averaged for two forest types in California.

North America is that by Compton and Cole (1991) for Douglas-fir (Pseudotsuga menziesii). Ten-year findings of a series of organic removal treatments following clearcutting on two sites are summarized in Table 3. The experiment was designed to test the hypothesis that increasing the amount of organic removal on sites low in soil nitrogen (N) leads to a decline in the productivity of the next forest. To avoid compaction, no equipment was allowed on the plots. Following treatment, plots were planted with Douglas-fir. The same treatments removed more N from the better site than the poorer because the better site had a much greater N capital. But expressed as a proportion of ecosystem N, the poorer site suffered the greatest relative loss. After 10 years, trees on the complete removal plots were about 30% shorter than those on the bole-only treatment. Fertilizing plots with N at year 5 led to rapid growth increases, supporting the hypothesis that growth decline was due to N removal, and not organic matter removal per se. (Cole 1992).

Work overseas has shown conclusively that losses of site organic matter, particularly on sandy soils and droughty sites, can trigger poor growth. Wiedemann's (1935) report of litter gathering in Pinus sylvestris forests of eastern Germany is a classic example. There, poor forest growth occurred on community-owned forests where, for decades, peasants had practised litter raking to provide bedding straw for farm animals. Growth in adjacent, estate-owned forests where litter gathering was not permitted averaged a full site class better.

In South Australia, Keeves (1966) showed that Pinus radiata planted on sandy soils grew much more poorly in the second rotation than in the first. Squire et al. (1985) demonstrated that the decline was due to the burning of logging slash following the first rotation. This led to both moisture and nutrient stress in the next forest, and the effect was evident by the time of crown closure. Productivity of successive plantations could be maintained either by retaining logging slash and avoiding burning (Squire et al. 1985), or by intensive silvicultural techniques such as cultivation, weed control, and fertilization (Cellier et al. 1985).

Table 3. Nutritional effects of organic matter removal on nitrogen budgets and plantation growth on two Douglas-fir sites in Washington (Compton and Cole 1991).

Treatment[a]	Total in Ecosys.[b]	Removed in Harvest	Leached in 3 Yrs.	Total Lost (%)	10-Year Relative Ht. Growth (%)
	(kg N/ha)				
Site Quality III					
Uncut	3,293	0	0.3	0	Not planted
Bole only	3,293	478	4.4	15	100
Whole tree	3,293	728	0.5	22	92
Complete	3,293	950	0.6	29	71
Site Quality IV					
Uncut	1,032	0	1.0	0	Not planted
Bole only	1,032	161	2.1	16	100
Whole tree	1,032	318	4.7	31	81
Complete	1,032	522	5.5	51	69

[a] Uncut (all vegetation left standing), Bole only (all logging slash retained), Whole tree (boles and crowns removed), Complete (whole tree plus understory and forest floor removed). Soil compaction was avoided by keeping machinery off the plots and removing organic materials using full suspension.

[b] Soils sampled to a depth of 50 cm.

In New Zealand, Dyck and Skinner (1990) have shown how windrowing first rotation P. radiata logging slash and an estimated 2.5-cm of pumice topsoil by tractor has led to growth losses in the second rotation. At 7 years, pines planted in windrows had volumes averaging 41 m^3/ha, while those planted between windrows averaged only half of that. Combining data on an areal basis produced average plantation volumes of 28 m^3/ha--only 84% of those in an adjacent plantation where logging slash had been retained. Differences were even greater by age 17, when volume in the windrowed plantation had fallen to 65% of that in the adjacent stand.

Such studies illustrate the significance of site organic matter in sustaining soil productivity. In the short run, surface organic residues provide a physical barrier to soil moisture evaporation--a particularly importent factor in drier ecosystems before canopies have closed (Squire et al. 1985). During droughty summers in California, plant-available soil moisture lasts several weeks longer where surface residues are retained following timber harvesting than where they are absent (Powers unpublished). Surface materials also reduce soil particle dispersion from raindrop impact. Erosional losses where soil surfaces are exposed following prescribed burning can be 40% to 1200% greater than erosion from logging alone (Megahan 1987). In California, the mechanical exposure of mineral soil increased soil movement 3-fold in friable soils and 20-fold in compacted (Powers, unpublished).

Organic matter also supports soil productivity through the development of soil structure. Plant residues are the primary source of fixed carbon providing energy to surface and tunneling soil fauna that shred, digest, and transport organic materials beneath the surface. Earthworms feeding on surface litter create vertical, faeces-lined tunnels to the subsoil, promoting the entry of gravitational water, the movement of capillary water, and the exchange of surface and subsurface gases. Such altered, mixed materials provide energy substrate to microbes which drive ecosystem processes and promote soil stability. For example, microbially-produced polysaccharides promote soil aggregate formation through H-bonding and cation coordination (Stevenson 1982). Because polysaccharides themselves are degraded easily by other microorganisms, fresh inputs of organic matter are needed to maintain aggregate stability, soil structure, and resistance to erosion.

Organic matter also is a reservoir for such nutrients as N and phosphorus (P) (Table 4) and probably is the main source of labile nutrients in closed-canopy forests. Nowhere is this more evident than in forest floors of temperate and cooler climates. There, forest floor mass is only a fraction of that in living vegetation, but its nutrient content is second only to that in the mineral soil (Table 4) (Powers and Van Cleve 1991). Therefore, major losses of site organic matter inevitably affect nutrient availability that may lead to nutrient stress. In young stands, nutrient deficiencies may not appear for several years because nutrient releases from roots and residual litter usually exceed the low uptake needs of very young vegetation (Smethurst and Nambiar 1990). However, deficiencies may appear as canopies close and readily available nutrient reserves are depleted. This will be most evident on sites with low nutrient storage but supplied well with water (Table 3).

Other nutritional effects of organic matter include chelation and ion exchange reactions. Organic acids produced during decomposition can form chelates with polyvalent metal ions such as aluminum (Al), rendering such metals innocuous at concentrations known to be toxic in the ionic form (Hue et al. 1986). Oxalate, common in most forest soils, adsorbs readily to Al-oxide surfaces, displacing P (Goldberg and Sposito 1985) and increasing its content in the soil solution (Fox and Comerford 1992).

Clearly, organic matter is a major factor affecting soil productivity, but it is not the only factor. On finer-textured soils, losses of soil aeration porosity through compaction may surpass the effects of organic matter losses. A unique experiment in New Zealand (Dyck and Skinner 1990) demonstrated that basal area growth of P. radiata was halved if bulk density was increased in the surface soil by 13% or in the finer-textured subsoil by only 4% (Figure 5). This indicates that Froehlich and McNabb's (1984) linear model of growth depression with increasing bulk density (Figure 3) is probably too simplistic.

Table 4. Ranges in total nitrogen (N) and phosphorus (P) contents found in young, mature *Abies*, *Pinus*, and *Pseudotsuga* ecosystems in North America. From Powers and Van Cleve (1991) as modified from Kimmins et al. (1985).

Ecosystem Component	Abies		Pinus		Pseudotsuga	
	N	P	N	P	N	P
	(kg/ha)					
Trees						
Above ground	80-686	12-83	180-556	12-31	84-728	18-112
Below ground	24-72	4-12	12-117	2-21	30-90	5-18
Understory	2-50	t[a]-14	1-54	t-5	5-66	1-9
Forest floor	666-2,300	9-103	80-1,240	9-103	110-1,249	19-115
Soil to 1-m	5,237-14,000	3,212-6,317	1,753-5,554	146-4,457	1,770 ~~14,170~~-15,400	3,878-3,900

[a] t = trace.

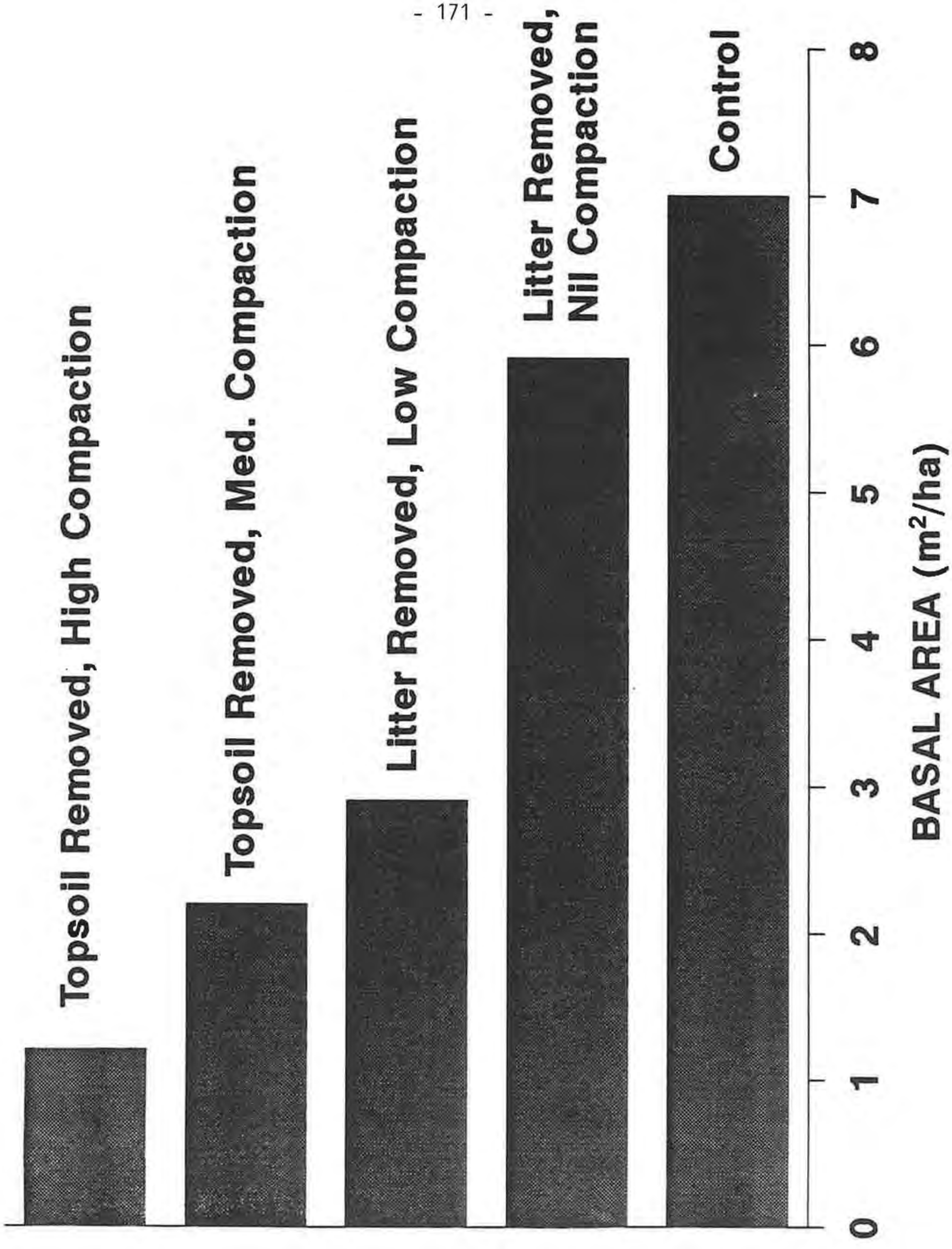

Figure 5. Average stand basal area at six years for a Pinus radiata plantation in New Zealand receiving a series of soil stress treatments (Dyck and Skinner 1990, supplemented with more recent data).

Soil densification affects productivity in several ways, including mechanical resistance to root penetration. Plant roots grow through the soil by following voids and by moving particles aside when pore diameters are narrower than those of elongating roots. If pores are large enough, root growth can continue. Using average pore size as a guide, Daddow and Warrington (1983) calculated theoretical growth limiting soil bulk densities where root growth should cease because of mechanical resistance. Growth limiting bulk densities varied by soil texture, ranging from 1.4 g/cm^3 in clayey soils to 1.8 g/cm^3 in sandy loams. Growing roots can exert forces of between 0.5 and 2.4 MPa to overcome particle resistances and enlarge soil voids (Wiersum (1957). Greacen and Sands (1980) found root densities of pines were extremely low in soils with strengths at or above 3 MPa--values which are not at all unusual in compacted soils.

Mechanical resistance is not the only problem posed by compacted soils. Simmons and Pope (1988) have shown that compaction must be interpreted in terms of soil strength and aeration porosity. Under moist conditions, reducing air-filled pore volumes below 0.1 m^3/m^3 creates anaerobic conditions that limit root growth in hardwood seedlings. Under drier conditions, aeration porosity is adequate, but soil strength may restrict root penetration into new soil volumes and increase the tortuosity of the flow path for water and nutrients to roots. Sands (1983) has demonstrated the cumulative impact of mechanized equipment on soil strength in sandy soils (Figure 6) where strengths in the subsoil approach 3 MPa, the threshold for root growth. Impacts extend deep enough into the profile that they probably are irreversible (Sands 1983). Even if compaction is not severe enough to inhibit plant growth altogether, it will shorten the growing season to a fraction of its potential. As soils dry in the summer, soil strength will reach a threshold that limits root processes much sooner on compacted sites (Figure 7).

The physical, chemical and biological means by which organic matter and soil porosity regulate productivity are suggested the conceptual model in Figure 8 (Powers et al. 1990). Clearly, process rates

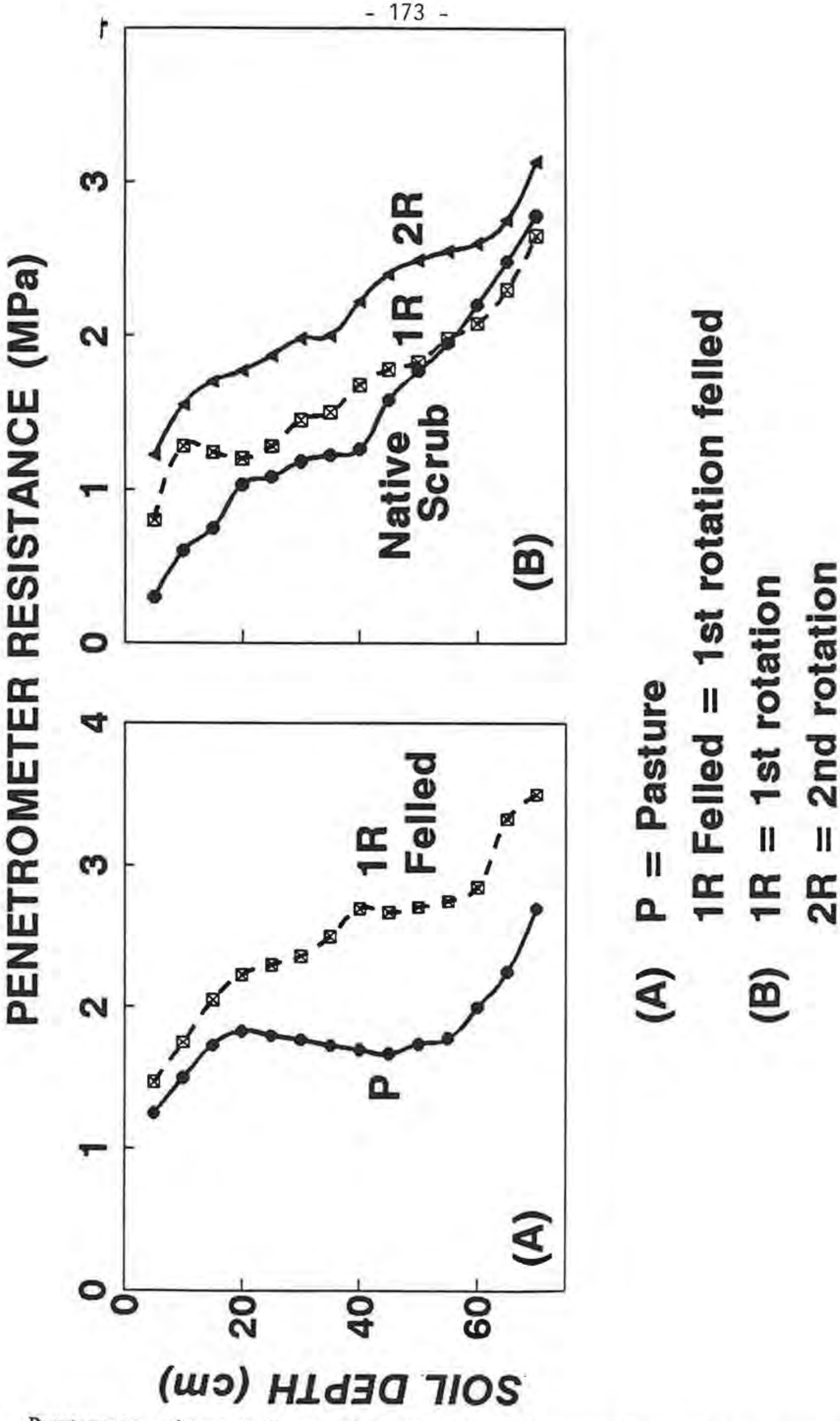

Figure 6. Penetrometer resistance (soil strength) as affected by land uses for adjacent sites on the same soil type in Australia (Sands 1983). Effects of each successive land use are cumulative.

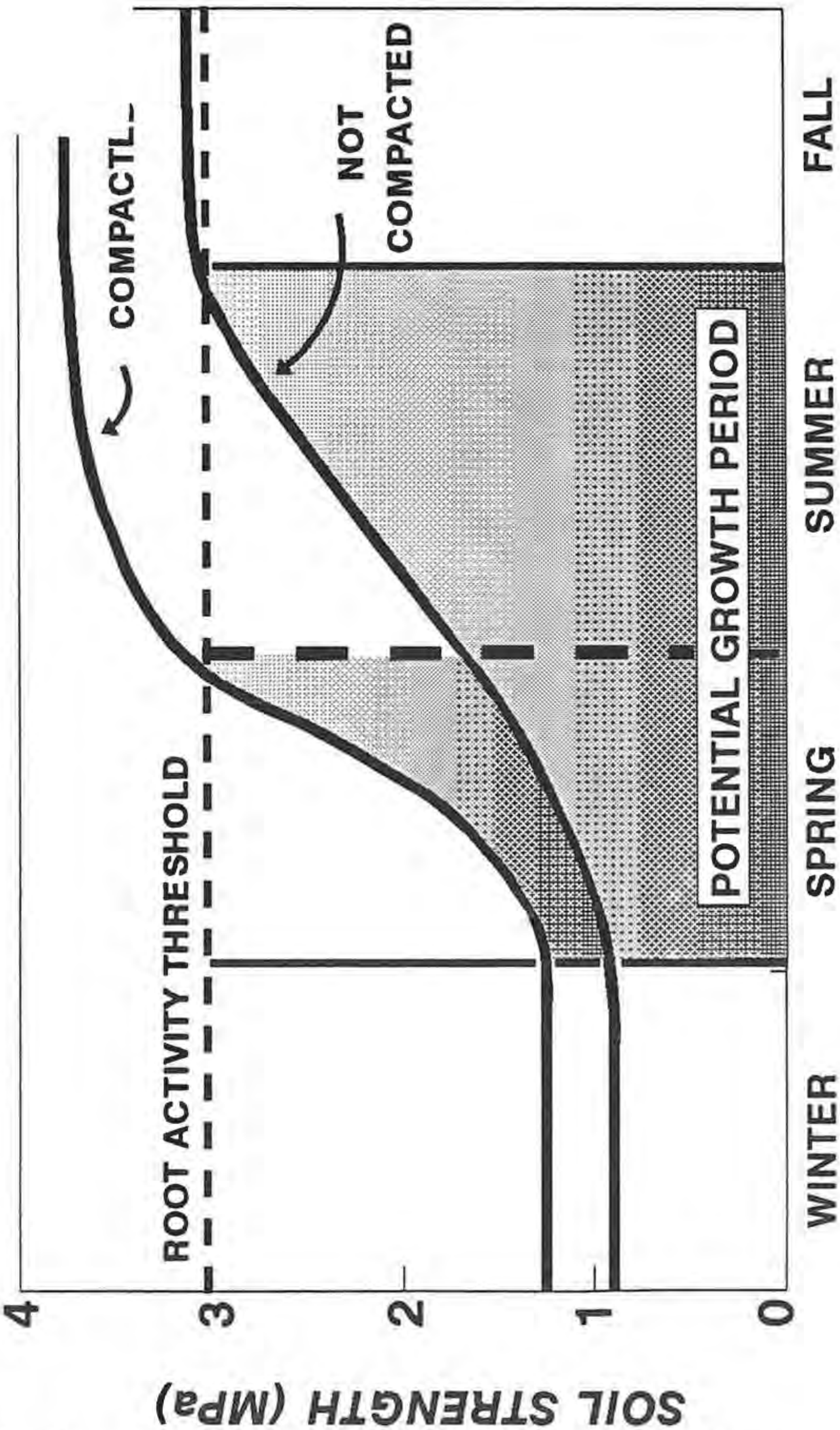

Figure 7. Conceptual model of how compaction affects soil strength and potential growing season (shaded area). Regardless of soil texture, root activity (growth, water and nutrient uptake) is presumed to slow and essentially cease as soil strength within the rooting zone approaches 3 MPa.

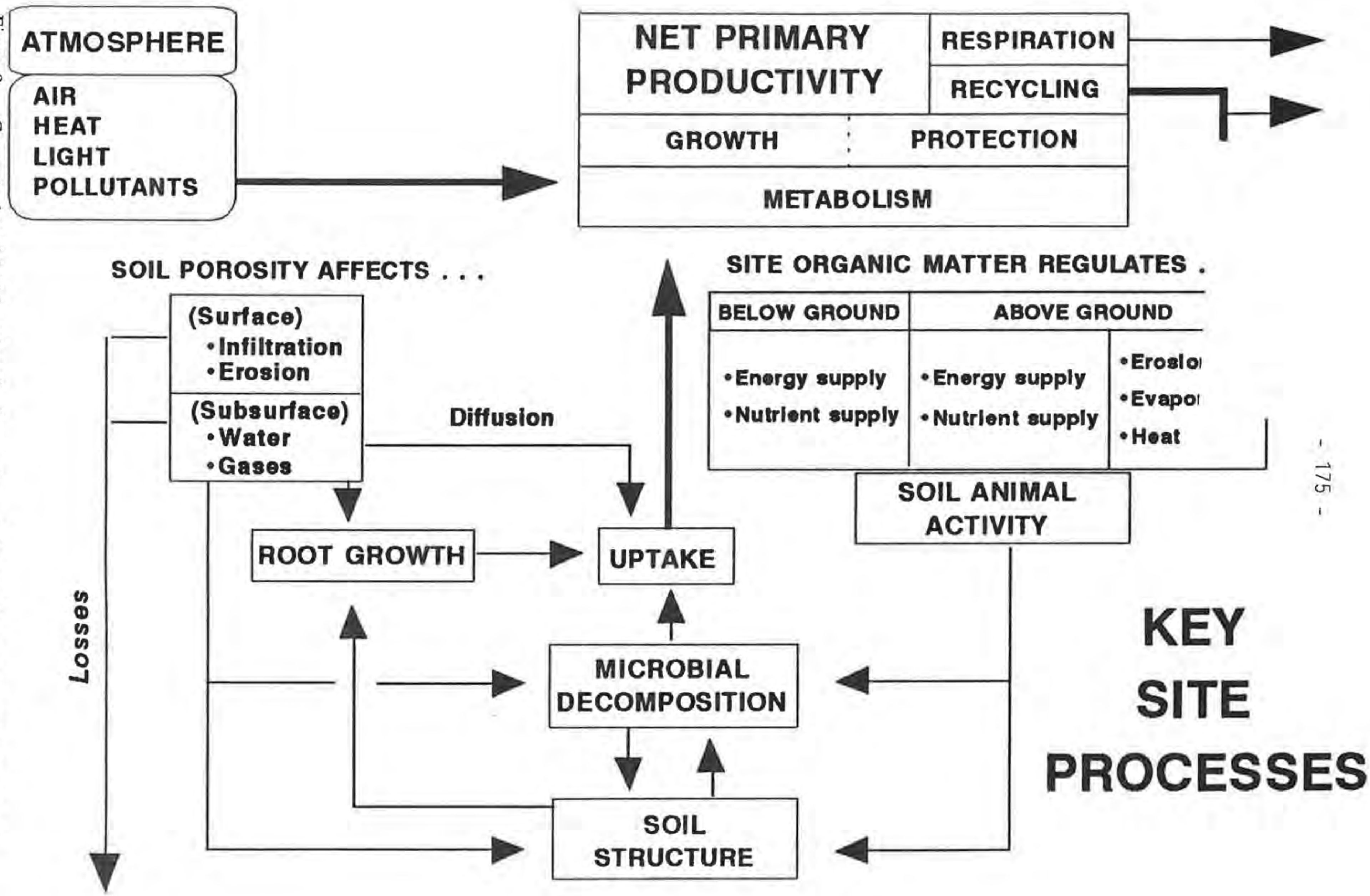

Figure 8. Conceptual model of the roles of soil porosity and site organic matter in regulating the site processes controlling productivity (Powers et al. 1990).

and productivity will be changed if site organic matter and soil porosity are altered substantially. But how much change is too much? Are some sites more resilient than others? Beyond conceptual models, we lack a specific understanding of what a given change in organic matter or porosity means for each site relative to long-term soil productivity. Uncertainty and skepticism will persist until we establish and maintain studies that help us document and understand the long-term effects. This gap in our knowledge means that soil quality standard thresholds described in Table 2 risk legal challenge because they are based largely on "best professional judgement."

6.2.4 A COOPERATIVE NATIONAL STUDY

In 1989, a formal program of cooperation between research and administrative arms of the Forest Service was launched to address this problem through a national network of long-term soil productivity studies (LTSP) (Powers et al. 1989). A fundamental purpose of this is to help us understand how soil porosity and site organic matter jointly affect site processes controlling productivity through the conceptual model in Figure 8. An applied purpose is to validate soil quality standards and monitoring methods used by National Forest Systems. Specific objectives are to: (1) quantify the effects of soil disturbance on soil productivity; (2) establish site-specific calibrations such as are hypothesized in Figure 2; (3) validate standards and techniques for soil quality monitoring; and (4) improve our understanding of fundamental relationships between soil properties, long-term productivity, and forest management practices. Complementary "Research" and "Development" aspects include:

RESEARCH How does soil disturbance affect--	DEVELOPMENT Facilitate soil monitoring by--
o Carbon allocation o Water and nutrient use	o Calibrating changes in soil properties against both stand productivity and total vegetative productivity

- o Soil biotic activity
- o Resistance to pests
- o Fundamental productivity
- o Evaluating/developing field monitoring methods
- o Developing means for extending results broadly

6.2.4.1 Coordination. National and regional coordination is achieved through three levels of control. First, national coordination and review for LTSP is provided by Washington Office staffs from Forest Management Research, Forest Environment Research, Timber Management, and Watershed and Air Management. Further coordination exists through a National LTSP Technical Committee of Principal Investigators from Forest Service Research and Regional Soil Scientists from National Forest Systems. Their main responsibilities are to establish and maintain research protocols, review study progress, and inform the Washington Office of significant findings, problems, and opportunities. Finally, a Regional LTSP Steering Committee consisting of the local Principal Investigator from Research and the Regional Soil Scientist and Silviculturist from National Forest Systems have responsibility for site selection, study establishment, and site maintenance. Their job also is to establish close working ties with National Forests, Ranger Districts, and other researchers. These ties are not merely to exchange information, but to foster a sense of partnership in the effort. Scientific aspects of LTSP are the responsibility of the local Principal Investigator. Supplemental research occurs through a group of collaborating scientists from nearly a dozen U.S. universities who are exploring ways for financing integrated studies on carbon cycling. International ties also have formed with British Columbia's Ministry of Forests and New Zealand's Forest Research Institute.

6.2.4.2 Research Protocol. A broad array of soil porosity and site organic matter manipulations are applied on benchmark soils within the major commercial forest types of the United Sates. Work began in 1989 in Louisiana and California, and now has expanded to Idaho, Michigan, Minnesota, Mississippi, Missouri, North Carolina, Oregon, and Texas (Figure 9). Within each region and forest type, about a dozen timbered sites will be selected for treatment. Sites are characterized before treatment according to a standard protocol (Powers et al. 1989). Then a core series of organic matter and soil porosity treatments are applied to 0.4 ha treatment plots. This treatment core includes the following main effects and their interactions:

Organic Matter Treatment	Soil Porosity Treatment
o Boles removed, only	o No compaction
o Whole trees removed	o Intermediate compaction
o All vegetation and forest floor removed	o Severe compaction

This produces nine factorial combinations that capture the range of site organic matter and soil porosity changes apt to occur under present or future forest management (Figure 10). Treatments were not chosen with any conventional management practice in mind. Nor are findings meant to apply exclusively to even-aged management systems. Instead, an experimental design is established in which site organic matter and soil porosity can be regarded as continuous variables in the development of general predictive models when data are combined. The product will be site-specific projections of the probable biological outcomes when site organic matter and soil porosity are altered. Where space permits at each LTSP installation, other treatments are added. These include conventional harvest and site preparation techniques and such ameliorative practices as tilling and fertilization. From this, one can compare the effects of operational practices, determine the value of timely mitigation, and examine possibilities for enhancing soil productivity.

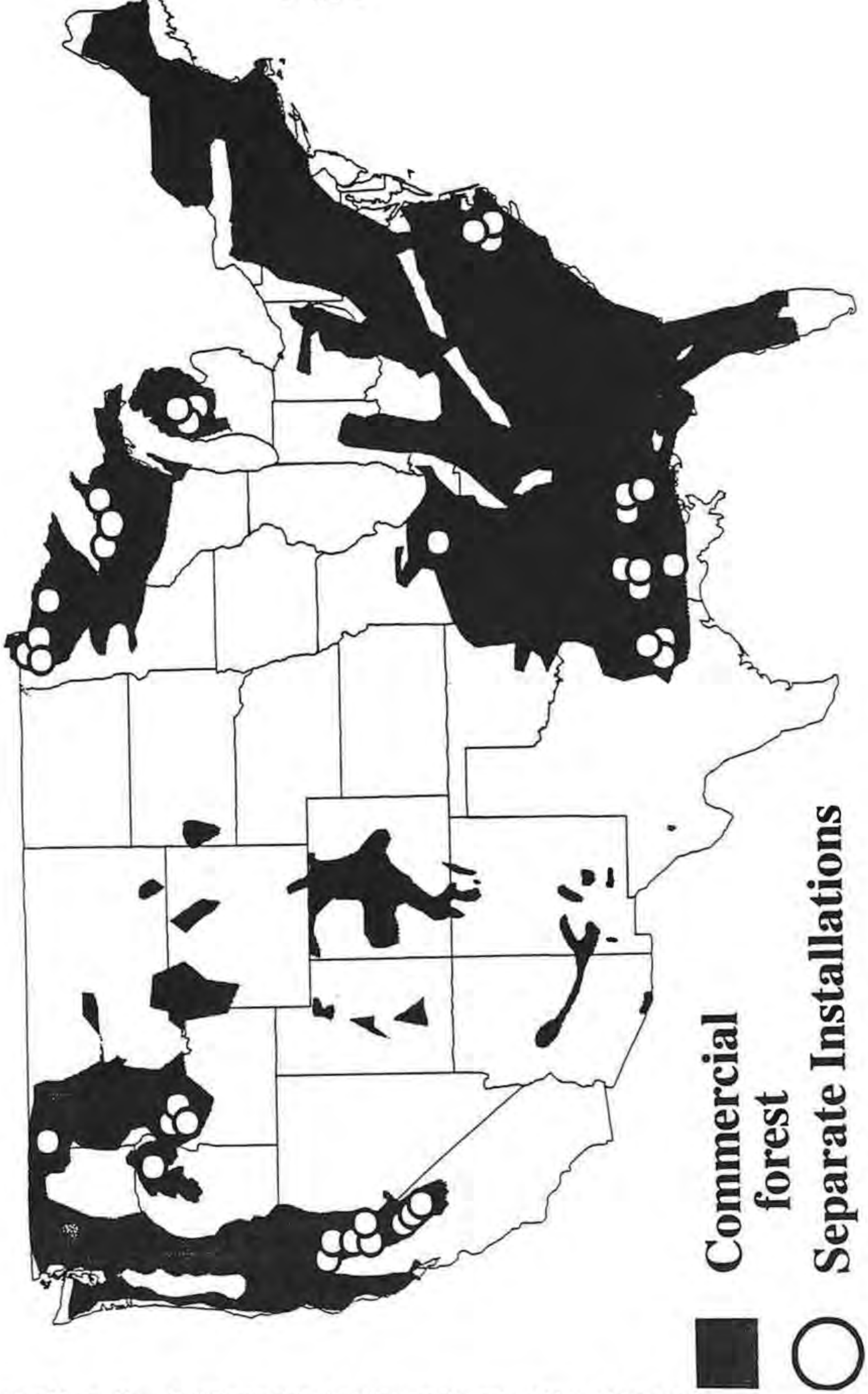

Figure 9. Location of Long-Term Soil Productivity installations through 1994 in relation to the commercial forest region of the United States (lands capable of producing 14 m^3/ha/yr at culmination of mean annual increment). Each LTSP installation is equipped with a recording climatological station.

Figure 10. Generalized layout of the 3 x 3 core arrangement of LTSP increasing stress treatments. Compaction levels reflect texture-dependent growth-limiting bulk density (Daddow and Warrington 1983). Each of the nine plots occupies 0.4 ha, and contains a split-plot subtreatment of vegetation control vs. no vegetation control. Ameliorative and operational treatments are included as space permits.

Each 0.4-ha treatment plot will be reforested with species of the appropriate forest type using a mixture of the best available genetic stock. The aim is to favor superior growth without narrowing genetic diversity. Each treatment plot will be split in half, creating two subplots with a measurement plot established centrally in each. One subplot will be kept weed-free. In the other, regional vegetation will develop with the trees. This provides the opportunity to study soil productivity and plant growth processes in simple and complex plant communities which are developing side-by-side. Installations will be maintained to at least the culmination of mean annual increment.

6.2.4.3 Site Measurements. Standard climatological stations and dataloggers will be installed at each LTSP installation to monitor air and soil temperature, wind speed and direction, relative humidity, total and photosynthetically active solar radiation, precipitation, and potential evapotranspiration. Stations will be compatible with others installed throughout the country, and will add to our monitoring base for detecting climatic change and its possible impacts on productivity. Variables measured on each plot include, but are not limited to, the following:

Variable	Measurement interval
o Climatological data	Continuously
o Soil moisture and temperature	Monthly
o Soil strength	Seasonally each 5 years
o Plant survival, damage from pests, growth, NPP	Years 1, 3, 5, 10, etc.
o Soil bulk density and porosity	5 years
o Water infiltratration and saturated hydraulic conductivity	5 years
o Soil organic matter content and	5 years
chemical composition	5 years
o Foliar chemistry and standing nutrient capital	5 years

o Biomass modeling and prediction   As vegetation develops

6.2.4.4 Process Measurements. Data from these periodic measurements will provide basic information on how stress affects water and nutrient use, carbon allocation, and resistance to pests. Because all treatment plots are adjacent with trees all at identical spacing and age, comparative growth rates offer precise measures of site productivity and avoid the confounding caused by stand (not site) factors mentioned previously. Comparing each treatment against the "nil disturbance" control will be the standard for judging whether soil changes have affected the potential productivity of the land. Wood and total tree biomass production in "trees only" subplots provide an assessment of how soil disturbance affects traditional measures of timber site productivity. "Total vegetation" subplots provide a more comprehensive measure of total site productivity. The first indication of long-term effects is expected to occur about the time of crown closure, when vegetation is fully capturing all the factors of site (Squire et al. 1985).

Beyond this, several key soil and site processes invite more detailed investigations. Many of these processes will be studied by individual Forest Service researchers, but the National LTSP study would be served more effectively by a comprehensive, nation-wide collaborative attack on some or all of the following topics:

o Soil erosion	o Plant biochemistry	o Residue dynamics
o Soil respiration	o Nitrogen fixation	o Soil faunal dynamics
o Process models	o Soil structure dynamics	o Microbial dynamics

To this end, a national group of university scientists has formed to develop the means for supporting collaborative LTSP research on fundamental aspects of carbon cycling. This group includes scientitst from the following institutions:

o The University of California	o Purdue University
o Michigan State University	o Texas A&M University

- o Michigan Technological University
- o The University of Nevada
- o The University of New Hampshire
- o Oregon State University
- o Virginia Polytechnic University
- o The University of Washington
- o The University of Wisconsin

6.2.4.5 Budget. The approximate budget for installataion and maintenance of each research site that includes the minimum nine core treatments is:

Task	Average cost	Responsibility
Installation and preliminary analysis	$50,000-65,000 in first year	National Forest Systems
Research	26,020 per year	Research
Maintenance	4,350 per year	National Forest Systems

6.3. SUMMARY

Our ability to maintain a site's productive capacity faces increasing challenge through public review of Forest Land Management Plans and timber sales. In response to NFMA, Forest Service Regions are developing threshold soil quality monitoring standards for detecting signs of declining soil productivity. Such standards are based on best available information. But until standards are validated, we can expect challenges from many sectors. In response, this national network of study sites provides researchers with a means for comparing stand production with more fundamental measures of productivity, and will provide the scientific basis for validating soil quality standards established by National Forest Systems. Basic models of soil and growth processes can be integrated with site and climatic data to extrapolate findings to a broad array of sites. Installing some LTSP sites on ecotones will help us judge possible impacts of changing climate on future productivity because ecotones will offer the first indications of climatic change. The LTSP effort is of such unusual scope that it creates landmark opportunities for developing a fundamental understanding of the functioning of managed forest ecosystems. Further, it is possibly the strongest vehicle yet for fostering close cooperation and collaboration between the scientific and administrative arms of the U.S. Forest Service, university and industry colleagues, and scientists in other nations.

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ENVIRONMENTAL SOIL SCIENCE

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AND

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OF

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CLRA
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Edited by
C.B. Powter, S.A. Abboud and W.B. McGill

Compiled by
Y.A. Kalra and W.W. Pettapiece

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PREFACE

The Environmental Soil Science conference was held August 8-13, 1992 at the University of Alberta, Edmonton, AB. It was sponsored jointly by the Canadian Land Reclamation Association (CLRA) and the Canadian Society of Soil Science (CSSS). The objective of the conference was to share theoretical and applied aspects of soil science. It also served to get participants from the sponsoring groups together to find areas of mutual interest. There were 330 participants from Austria, Bangladesh, Canada, England, France, Germany, India, Japan, New Zealand, Norway, Spain, the Netherlands, and USA.

Abstracts of the oral and poster papers were published in the Canadian Journal of Soil Science (Vol.72, No.3, August 1992. (p.299-353). Volunteer papers covered all aspects of land reclamation, soil science, and public participation in the environmental review process. Seventy six of the 164 volunteer papers were presented as posters.

The invited papers presented in the plenary sessions focused on soil quality and interaction of soils with anthropogenic chemicals, and are published in this proceedings. Publication of the proceedings has taken an unduly long time due to unavoidable circumstances and we apologize for the delay.

Grateful acknowledgement is expressed to our colleagues on the organizing committee (J.A. Robertson, Chair) for their contributions to the success of the conference.

Y.P. Kalra and W.W. Pettapiece, Compilers

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