United States Department of Agriculture

Forest Service

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Subject: National Study of Long-Term Soil Productivity

To: Regional Foresters and Station Directors

Enclosed is the final generic study plan on "Evaluating Timber Management Impacts on Long-Term Soil Productivity: A Research and National Forest System Cooperative Study" by Robert Powers, et al. This study plan has received extensive review by Stations and Regions and we appreciate your comments.

This generic study plan provides a framework for the development of detailed cooperative study plans by Stations and Regions. We encourage and support all Regions and Stations to participate. The Pacific Southwest (R-5), Southern (R-8), and Eastern (R-9) Regions along with Pacific Southwest (PSW), Southeastern (SE), Southern (SO), and North Central (NC) Stations are initiating installation of the study this fiscal year. National coordination is being handled jointly by the Washington Office (WO) Timber Management Research (TMR), Forest Environment Research (FER), Watershed and Air (WS&A) Management, and Timber Management (TM) Staffs. If you have any questions, please call Pete Avers, WS&A Staff (FTS 235-8178), or Nelson Loftus, TMR Staff (FTS 235-8200).

James C Overbay

JAMES C. OVERBAY
Deputy Chief
National Forest System

Jerry A. Sesco

JERRY A. SESCO
Deputy Chief for Research

Enclosure

cc:
WO-TMR
WO-WS&A
WO-TM
WO-FER

STUDY PLAN

FOR

EVALUATING TIMBER MANAGEMENT IMPACTS ON LONG-TERM SOIL PRODUCTIVITY: A RESEARCH AND NATIONAL FOREST SYSTEM COOPERATIVE STUDY

by

Robert F. Powers
Principal Research Silvicultrist, PSW

David H Alban
Principal Research Soil Scientist, NC

Gregory A. Ruark
Principal Research Soil Scientist, SE

Allan E. Tiarks
Principal Research Soil Scientist, SO

Charles B. Goudey
Regional Soil Scientist, R-5

Jerry F. Ragus
Regional Soil Scientist, R-8

Walter E. Russell
Regional Soil Scientist, R-9

PREFACE

"Evaluating Management Impacts on Long-Term Soil Productivity: A Research and National Forest System Cooperative Study" is part of a joint effort by TMR, WS&A, FER, and TM to provide national direction and coordination to research and management activities relative to sustaining forest productivity on National Forest lands.

The proposal for this joint study was developed by several of the authors while on detail to the WO and presented to the Deputy Chiefs for the National Forest System and Research and the Staff Directors of WS&A, TM, TMR, and FER. This group recommended preparation of the enclosed generic study plan for implementation over a 5-year period starting in FY 1989. The objectives and methodology in the study plan are based on a National Forest System and Research co-authored paper entitled, "Sustaining Site Productivity in North American Forests: Problems and Prospects" presented to the 7th North American Forest Soils Conference in Vancouver, BC, July 1988.

The plan is to create a network of comparable studies on National Forest lands involving all National Forest Regions and Research Stations. Results from this joint NFS-Research effort will help the Forest Service address public concerns about policies and programs related to forest management and long-term productivity; address research needs identified in Forest Plans; develop fundamental information on soil-forest productivity relationships; and meet monitoring and assessment requirements of the National Forest Management Act of 1976.

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Timber Management Research
Watershed and Air Management
Forest Environment Research
Timber Management

EVALUATING TIMBER MANAGEMENT IMPACTS ON LONG-TERM SOIL PRODUCTIVITY:

A RESEARCH AND NATIONAL FOREST SYSTEM COOPERATIVE STUDY

EXECUTIVE SUMMARY

The impact of timber management practices on sustained site productivity (the wood-growing capacity of commercial forests) is emerging as a legal and scientific issue. This is particularly relevant to timber management operations of the U.S. Forest Service--an agency bound by law to manage the land in a way that does not impair its long-term productivity. Responding to the National Forest Management Act of 1976 and the federal regulations that followed, each Forest Service Region is developing "threshold" soil quality standards for detecting significant declines in soil productivity (the soil component of site productivity) caused by management practices. Where possible, these standards are based on published research. Often, standards must be based on professional judgement because research has not been conducted.

A framework is needed for understanding how soil disturbance affects long-term productivity. Research shows that the main factors related to sizable declines in productivity are losses in site organic matter and soil porosity--properties routinely impacted during harvesting and site preparation. But beyond these generalizations, little is known about how large a loss a site can tolerate before long-term productivity is impaired. Nor is there more than a superficial understanding of how site organic matter and soil porosity are tied to the many processes controlling productivity. Developing such understanding is central to sound timber management.

Traditional lines of study offer modest hope for major gains in knowledge. Rather, a new coordinated thrust is needed to understand how management practices affect soil productivity across a broad range of sites. Such a thrust is described by a major, cooperative national effort between Forest Service Research and the National Forest System aimed at:

1. Measuring the effects of soil and site disturbance on long-term productivity.

2. Validating soil quality standards and developing effective monitoring techniques for evaluating the long-term impacts of management practices.

3. Understanding how soil and site disturbances affect the fundamental processes controlling productivity.

To accomplish his, a minimum of nine treatments--three levels of organic matter removal crossed with three levels of soil compaction--will be applied following clearcutting at benchmark sites characterizing major commercial forest types and representative soils. Each treatment plot will be regenerated promptly, and growth will be monitored over time, along with other soil and site processes. The experimental design creates major opportunities for collaborative work with other scientists, and plots will have lasting demonstration value. Three levels of control are described to ensure the success of the project.

EVALUATING TIMBER MANAGEMENT IMPACTS ON LONG-TERM SOIL PRODUCTIVITY:

A

RESEARCH AND NATIONAL FOREST SYSTEM COOPERATIVE STUDY

INTRODUCTION

Sustaining long-term site productivity (the wood-growing capacity of commercial forests) is a fundamental goal of forest management in North America and a legal requirement of the U.S. Forest Service. The success of our variety of silvicultural systems depends on sustaining each site's ability to grow vegetation. In some highly productive wood growing areas, rotations are shortening, residue use is rising, and site preparation is intensifying. Mechanized harvesting methods involving larger, more mobile machinery are used increasingly to extract whole trees. Removing more organic matter accelerates the loss of nutrients and organic materials important to soil resiliency and microbial activity. Heavy equipment used to prepare sites for regeneration raises the risk of soil compaction. These and other emerging practices may threaten long-term soil productivity (the soil component of site productivity). The sparse and fragmented scientific evidence, reviewed by Powers and others (1988), suggests this may be occuring. Thus, sustained, long-term soil productivity of forest land is emerging as a legal and scientific issue. As the world's largest forest management and forest research agency, the U.S. Forest Service has lead responsibility for resolving this matter.

A Cooperative National Study--This study plan describes a Forest Service Research and National Forest System cooperative effort aimed at (1) quantifying the effects of soil disturbance from management activities on soil productivity; (2) validating soil quality monitoring standards and developing monitoring techniques; (3) evaluating the fundamental relationships between factors of the soil, long-term productivity, and forest management practices. This generic plan outlines the core experimental design, treatments, and basic measurements. It serves as a template for more detailed plans developed by Principal Research Investigators, Regional Soil Scientists, and Regional Silviculturists within each Forest Service Region and approved by a National Technical Committee. Three levels of coordination are described to ensure the achievement of national and regional objectives.

BACKGROUND

National Forest System Regulations--The Multiple Use-Sustained Yield Act of 1960 binds the Forest Service to achieve and maintain outputs of various renewable resources in perpetuity without permanent impairment of the productivity of the land. Section 6 of the National Forest Management Act of 1976 (NFMA) charges the Secretary of Agriculture with ensuring research and continuous monitoring of each management system to safeguard the land's productivity. The Code of Federal Regulations for Forest Planning that followed NFMA requires the Forest Service to measure effects of prescriptions, including "significant changes in land productivity." The USDA Office of General Council interprets "land productivity" to mean the inherent capacity or potential of a soil to produce vegetation. Therefore, The Forest Service is bound by Federal law and regulations to maintain or enhance a soil's inherent capacity to grow vegetation.

Each Region is directed to develop soil quality standards that indicate a loss in productive potential of 15 percent or greater over a planning horizon (FSH 2509.18). Soil was selected as an indicator of a site's productive potential for two reasons. First, along with climate and topography, soil is a basic, fundamentally important resource that controls both quantity and quality of such renewable forest resources as timber, wildlife habitat, and water yield. Second, soil is a non-renewable resource that is affected directly by forest management practices--particularly those surrounding timber harvest and site preparation. Thus, monitoring the condition of the soil following forest management operations can provide an index of the potential productivity of the site. This soil monitoring strategy assumes that (1) the proper soil variables are being measured, and (2) there is a relationship between those variables and potential productivity.

RESEARCH EXPERIENCE

Research has shown that changes in long-term productivity are related to changes in site organic matter and soil porosity (Powers and others 1988), which are the main "soil" factors mediating the site processes controlling productivity (Fig. 1). Long-term records from the southern hemisphere and central Europe indicate site productivity has been lowered by certain management practices affecting these variables. In South Australia, Keeves (1966) found that growth rates in second-rotation stands of Pinus radiata were about 40-percent lower than in the first rotation following clearcutting and slash burning. Squire and others (1985) traced this decline to increases in moisture and nutrient stresses when the forest floor was removed during slash burning. Retaining logging slash reversed this effect and increased productivity in second rotations above that in first rotations.

Sands (1983), also working with _P_. _radiata_ in southern Australia, found sizable increases in soil compaction and strength on sites converted from pasture to first- and second-rotation pine plantations. Root growth essentially ceased at soil strengths of 3,000 kPa--penetrometer resistances that were found in some plantation soils. He concluded that maintenance of desirable physical soil properties depended strongly on the maintenance of soil organic matter. Wiedemann (1935), summarizing effects of litter raking on growth of _Pinus sylvestris_ on mesic sites in eastern Germany, found productivity was lowered nearly two site classes where litter had been routinely removed. Soil density also increased. This was confirmed recently in New Zealand's pumice region. Removing needle litter annually for 17 years reduced volume growth of _Pinus radiata_ by 12 percent, and produced nutrient deficiencies in the foliage (Ballard and Will 1981). As a consequence of these and other studies, a soil classification system has been proposed recently for New Zealand that relates long-term productivity decline to nutrient loss and soil compaction (Hunter and others 1988).

In the U.S., direct evidence of productivity decline has been short-term or retrospective. Froehlich and others (1986) and Helms and others (1986) found that stem volumes of pines growing on compacted skid trails and landings were about one-fifth less than volumes of those growing on less-compacted soils nearby. However, initial soil conditions were unknown, and results were partially confounded by differences in stocking and weed competition. Most U.S. research has centered on nutrient losses (particularly nitrogen) under varying harvest intensities and site preparation methods. Wells and Jorgensen (1979) point out that physical soil properties are affected by timber management practices as readily as nutrient properties, and potentially they are just as important to sustained productivity. These properties are influenced simultaneously by most--if not all--forest management field practices (McColl and Powers 1984). Accordingly, a sound soil monitoring program must consider physical and chemical soil properties together.

Work is needed at both the fundamental and applied level to quantify the effects of soil disturbance on productivity--not only in a timber management sense, but in a more fundamental sense as well. We know little about the inherent carrying capacity of forest sites for producing vegetation. Yet, the capacity of a site for producing vegetation is a good index of its ability to produce other resources useful to society. The processes affecting this carrying capacity can be understood only through deliberate manipulation--an approach that is distinct from most ecosystem process work, which has centered on narrowly defined objectives in unmanipulated stands (McColl and Powers 1984).

JUSTIFICATION

National Forest System--Our ability to maintain a site's productive capacity faces increasing public challenge through Forest Land Management Plan (FLMP) and timber sale review comments and appeals. Results from this cooperative study will provide credible responses to these challenges, and will address related research needs identified in FLMP's across the Nation. Initially, existing soil quality monitoring standards will be compared with interim findings and can be adjusted to reflect the most recent research results. With time, more substantive results will be available to deal with future planning.

Most FLMP's require soil quality monitoring. Direction for monitoring and setting soil quality standards is provided in FSH 2509.18. Standards set in FLMP's are based on the best current information. Depending on location, however, this ranges from published research to local observations. Where research information is limited, standards are based on professional judgement. Consequently, we need to verify our soil quality standards and tie them more closely with soil productivity ratings. This study is designed to accomplish both objectives.

Research--Our technological capabilty to disturb soil is advancing faster than our understanding of its impact on long-term productivity. The oldest designed experiments in the U.S. rarely included the degree of soil disturbance possible using today's equipment. Addressing both fundamental and applied aspects of long-term productivity is beyond the scope of private and university forest research organizations (Morris 1988), but is clearly within the mission and ability of Forest Service Research.

While case studies show that the productive potential of a site can be degraded by losses of organic matter and total soil porosity, the most definitive work has been done outside the U.S. on sandy soils with mesic to xeric moisture regimes. Work on finer-textured soils and in cooler and moister climates tends to be short-term, limited in scope, retrospective, and often confounded. Because of this, results from existing research cannot be extended broadly to tackle the questions facing National Forest managers. Nor have studies been designed to find causes, or general principles, that produce observed effects. The oldest U.S. studies simply were not designed to address the long-term impacts of management practices on soil productivity.

Joint Needs--Traditional lines of study offer modest hope for major advances in understanding long-term soil productivity. A new approach is needed if we are to understand how management practices affect soil processes and potential productivity across a broad spectrum of sites. This can best be tackled by designing experiments causing systematic and sizable changes in fundamental soil properties affecting ecosystem processes (Powers 1987). This cooperative study alters site organic matter and total soil porosity over a range of intensities encompassing those possible under management. Emphasis is placed on the controlled manipulation of these two fundamental variables, rather than on operational practices which are difficult to control, confound several variables, and may become obsolete. The result is a network of comparable experiments examining the widest practical variation in soil disturbance and physiological stress in vegetation over a very broad range of sites and climates. Where practicable, operational trials situated near the research sites will be monitored as well.

Establishing and monitoring this network directly addresses the needs of National Forest management and creates a research opportunity of unusual scope and significance. This network of study sites will provide the scientific basis for validating soil quality standards established by the National Forest System. Improved, cost-effective monitoring methods will be developed and tested as well. The experimental design provides researchers with an opportunity to compare stand production with more fundamental measures of productivity. As suggested by the conceptual model in Figure 1, basic soil and growth processes and vegetation development can be measured and integrated with climatic data to construct models that extend results to a broad array of sites. The work fosters close cooperation between Research and National Forest Systems, and opens doors for important collaboration with university scientists.

COORDINATION

All Regions and Stations are encouraged to participate. Selection of soil types, timber types, and target National Forests will be the responsibility of each Region and Station working together. Active coordination and commitment between Research and the National Forest System is vital at the National, Regional, Forest, and District levels to ensure the success of this joint program. Study sites should be included in the Forest Monitoring Plan. Particularly close ties are required between Principal Investigators and Regional Soil Scientists to ensure that latest research findings are incorporated into Regional soil monitoring practices. An experienced field crew, dedicated to this study and supervised by the Principal Investigator, is recommended to oversee field work. Because this experiment deliberately imposes a gamut of stress conditions in vegetation, considerable pest and disease interactions are possible. Therefore, contacts and field visits with research and practicing entomologists, pathologists, and wildlife specialists should be frequent.

National coordination and review will be provided by Timber Management Research, Forest Environment Research, Timber Management, and Watershed and Air Management Washington Office staffs. Coordinating activities will include: (1) development of priorities and funding opportunities; (2) review of Station/Region implementation plans; and (3) highlighting of accomplishments. National Technical and Regional Steering Committees will be responsible for the establishment and conduct of the studies.

National Technical Committee--A National Technical Committee will consist of Principal Investigators and Regional Soil Scientists who presently are involved or who plan to be involved soon in installation and maintenance of studies and interpretation of study results. This Committee, chaired by a Principal Investigator, will have five main responsibilities:

1. Provide for a review of study proposals to assure that scientific methods are consistent and appropriate to meet program objectives.

2. Provide for the establishment of a national data base of research results.

3. Inform the Oversight Committee of progress, needs, opportunities, and substantive findings.

4. Coordinate and prepare results for publication.

5. Review, evaluate, and incorporate modifications to the proposals.

Regional Steering Committee--A Regional Steering Committee consisting of the Experiment Station Principal Investigator, Regional Soil Scientist, and Regional Silviculturist will develop cooperation and collaboration with National Forests, Ranger Districts, and other researchers. They will identify individual study sites, prepare specific study plans based upon this general plan, and implement the studies. This committee shares responsibility with National Forests and Ranger Districts for ensuring public awareness of the program.

METHODS

Site selection--The Regional Steering Committee will specify timber types, soils, relief, stand conditions, and area needed for the study, and will work with Forest Silviculturists and Soil Scientists, and Ranger District personnel to identify potential field study sites within their Region. Such sites must be relatively uniform in productive potential, native vegetation, stand structure, soil parent material and other soil properties important to growth, as well as aspect and topographic position. Soils must be common to the timber types of that Region. Emphasis will be placed on stands near rotation age with stocking and forest floor characteristics expected of stands under management. Sites will be visited by the Principal Investigator and Regional Soil Scientist, or their representatives, for final approval as candidate sites.

Study sites will be selected from the list of candidates with the aim of covering the breadth of soil-site conditions found within a timber type. The general approach will be to group candidate sites along a gradient in a physical soil property or properties believed to be linked directly with potential site productivity (for example, effective rooting depth, water holding capacity, drainage class, texture, etc.). The importance of any particular property will vary by region. Three study sites with similar soils would be drawn randomly as replicates from each of the "low," "medium," and "high" soil groupings, producing a minimum of nine study locations. Sites may be added at gradient positions intermediate between the "low," "medium," and "high" positions--a concept shown graphically in Figure 2.

A preliminary soil survey will be directed by the Forest Soil Scientist to locate study areas within a uniform set of soil properties, such as may be represented by soil series or family. A grid method of sampling with shovel of bucket auger at a 20-m grid interval is recommended. The site will be mapped for soil properties thought to be regionally important to tree growth and definition of the soil unit. Statistical tests such as drift trend analysis (Davidoff and others 1986) may be used to ensure the key soil properties do not vary in a significant trend across the site. Following selection, boundaries will be established for nine treatment plots, 65 m on a side, in areas shown to be relatively uniform by the preliminary survey, and typical of the soil properties and soil series of interest. Study site characteristics (see "Measurements") will be described for each plot before harvest.

Treatments--Nine treatment combinations of the following levels of organic matter removal and soil compaction will be assigned randomly to the core treatment plots.

Organic Matter Removal

- OM_0 Boles removed, only
- OM_1 Boles and crowns removed (whole tree harvesting)
- OM_2 Boles, crowns, and forest floor removed (all above-ground biomass)

Soil Compaction

- C_0 No compaction
- C_1 Intermediate compaction (half-way between C_0 and C_2)
- C_2 Compaction to about 80% of the difference between hypothetical growth-limiting bulk density (Daddow and Warrington 1983) and bulk density existing at 10-20 cm prior to treatment.

The pattern of soil compaction can vary with depth and amount of land surface affected. In terms of plant response, the pattern of soil compaction may be as important as degree. During operation of most equipment, only the surface few centimeters are compacted. However, when exceptionally heavy equipment is operated on moist soil, compaction may extend deeper, restricting rooting depths (Voorhees et al. 1986). The depth to which soil is affected depends on soil texture, soil water content, organic matter content, weight of equipment, and the distribution of the load on the soil. In this plan, the compaction will be confined to the surface layers and horizons because:

1. The majority of fine feeder roots are found in the surface horizons.

2. Root and other organic debris on the surface distribute applied loads more evenly in forest settings than in tilled agricultural fields.

Compaction will be applied by a rubber-tired machine with the capability of varying the load. A pneumatic roller is an example of the kind of equipment that may be used. The number of passes and amount of loading on the machine needed to reach a given level of compaction will be found by trial and error. On a small portion of the site not included in the plots, the machine will be driven across the soil under various loads and number of passes. Bulk densities and water contents will be measured to gauge the required load. The plots will be compacted prior to timber harvest to reduce work in moving organic residue. On plots where the litter layer is to be retained, a swath will be carefully lifted or rolled aside and the soil compacted. The litter will then be replaced with minimal disturbance. Another pass by the compaction machine under minimal load will be made over the litter to reestablish the interface between the forest floor and soil surface.

On whole-tree harvesting plots, all trees will be felled directionally so that boles or whole trees can be removed with minimal soil disturbance. Biomass will be removed soon after felling in the OM treatments in a way that minimizes soil disturbance. The Principal Investigator will choose the most effective procedure for each site. A possible treatment arrangement is shown in Figure 3. This cluster of nine treatment plots will be separated from adjacent stands by an outer buffer strip at least 20 m wide. Other treatments--such as ameliorative practices or conventional harvest and site preparation techniques--may be installed on adjacent areas at the prerogative of the Regional Steering Committee, provided that they do not confound or alter the core treatment design. Plots will be monumented at each corner with permanent posts and described according to Curtis (1983). A standard weather station will be installed at each site to monitor air temperature, relative humidity, radiation, and precipitation. These weather stations will be compatible with other stations installed throughout the Forest Service, if possible.

Generally, treatment plots will be planted at about 2.5 m by 2.5 m spacing (Fig. 4) with seedlings of the appropriate timber type and a mixture of the best available genetic stock (for example, half-sib families adapted to the site that have demonstrated a superior growth performance). The aim is to favor superior growth without narrowing genetic diversity. Natural regeneration (seeding and coppice) may be substituted where it is the usual method of regeneration. Each treatment plot will be split in half, creating two subplots of at least 338 trees in 13 rows of 26 trees (slightly more for a plot design such as in Fig. 4B). A 160-tree measurement plot will be established from the forth row of trees inward in each subplot, as shown in Figure 4. Following establishment, one subplot will be kept weed-free, using herbicides as needed. In the other subplot, regional vegetation will be encouraged to grow with the trees--the aim being to promote complete vegetative recovery as rapidly as site conditions permit so as to approach full site carrying capacity. As shown in Figure 4, this creates a means for side-by-side comparisons of (1) stand productivity vs. total vegetative productivity; (2) the effect of competing vegetation on tree growth.

Auxillary Treatments--Regional Steering Committees are encouraged to install adjacent plots to examine treatments of regional interest, such as broadcast burning, windrowing, soil amelioration, partial cutting, etc. Such treatment plots should be characterized and monitored similarly to those in the core set of nine treatments.

Measurements--A core set of measurements must be taken at each installation, both pre- and post-harvest, in order to ensure comparability among sites (Table 1). These are the responsibility of the Principal Investigator, and are not meant to preclude other measurements. Specific mensurational and analytic techniques must be reviewed and approved by the National Technical Committee. Breast-height diameters will be recorded for all trees in measurement subplots, and other measurements (height, volume, mass) will be recorded for a representative sample. Study sites will be classified according to an integrated ecological classification system in Regions where such systems are commonly used.

Soil data:

1. Soil profiles will be described in each measurement plot to the degree needed to define the soil unit, and forest floor and soil core sampling will occur at 10 to 30 randomly selected positions. Pretreatment samples may be composited to reduce analytic costs. After a preliminary sampling and determination of soil organic matter, the exact number of samples required will be selected to obtain a standard error of the mean of ± 10 percent, or as near to that as is practicable within budget constraints.

2. Infiltration rates will be determined by double-cylinder infiltrometer (Klute 1986) at a central point in each plot before treatment. Following treatment, rates will be determined at multiple positions determined randomly in (1) above.

3. Core samples (Ruark 1985) will be taken at these points for physical analysis of the 0-10, 10-20, and 20-30 cm depth classes, including bulk density, saturated hydraulic conductivity, and moisture release. Soil strength also will be measured by penetrometer (Klute 1986).

4. A 4-point composite sample will be collected near each core sample for chemical analysis including pH, organic matter, exchangeable cations, extractable P, and total N and S using standard procedures (Soil Survey Staff 1984, Page and others 1982, Klute 1986). **Individual studies may call for additional sampling and physical and chemical analyses.** Analyses will be based on a minimum of three composite samples from each plot.

5. Principal Investigators are encouraged to examine other variables and techniques of scientific value, such as soil loss, root dynamics, N mineralization, or expressions of organic matter quality. New leads should be shared rapidly with other members of the National Technical Committee.

Vegetation data:

1. Sites will be classified before treatment according to the classification system used by each individual Region (potential natural vegetation, habitat type, plant association, species composition, etc.).

2. Survival, height, diameter, and crown length of planted trees will be measured according to Curtis (1983) at the 1st, 3rd, and 5th year after planting, and at 5-year intervals thereafter. Height and percent cover of other regional vegetation will be measured by species at the same intervals.

3. Cumulative standing biomass (oven-dry basis) and leaf surface areas will be estimated at 5-year intervals for all vegetation by species through periodic biomass harvesting on small plots (perhaps in buffer strips), and regression to estimate biomass from non-destructive tree measurements (Baskerville 1965).

4. Plant damage will be recorded at each measurement interval using PDMS tree classification codes (Curtis 1983).

5. Dry weight and nutrient content of current- and year-old, upper-crown foliage of trees and perennial understory vegetation will be measured. Collections will be timed to periods of greatest potential stress and made at 5-year intervals.

6. Prepare a complete species list of existing vegetation before treatment and monitor changes over time. Record the following attributes as a minimum:

1. Canopy cover
2. Canopy height
3. Biomass production of current growth.

Silvicultural Tending--"Trees-Only" subplots will be kept weed-free throughout the rotation using appropriate herbicides. A thinning schedule will be developed for each site according to the growth characteristics of trees in each treatment and using best silvicultural practices. Records will be kept of volumes, biomass, and nutrient content removed at each thinning so as to develop a complete record of gross productivity.

Statistical Analysis--A block of 9 core treatments repeated at 3 locations within each of 3 soil strata leads to a mixed-effects ANOVA model for a given forest type (Table 2). Orthogonal comparisons planned _a priori_ appear in Table 3.

Nine combinations of organic matter removal and compaction treatments produces the following general regression model, given a minimum of three locations within three soil property strata:

$$Y_{ijk} = u + S_i + SL_{j(i)} + T_k + SxT_{ik} + SLxT_{j(i)k} + e$$

where Y = a response variable (such as soil productivity) for a given forest type

S = a fixed soil stratification variable (such as water-holding capacity), i = 1-3

L = a random location effect (nested in S), j = 1-3

T = a fixed treatment effect (org. matter x compaction), k = 1-9

SxT = a fixed soil x treatment interaction

LxT = a random soil x location x treatment interaction.

e = experimental error.

This serves as a simple general model for predicting the effects of changes in site organic matter and soil porosity on soil productivity. More sophisticated multivariate models will be developed to relate productivity to more fundamental "causal" factors. Response variables may include the soil and vegetation variables identified previously, and tree biomass or volume, or total vegetation biomass will be used to denote soil productivity. Soil variables correlating well with productivity measures will be identified for use in operational monitoring.

RESPONSIBILITIES

Costs of this cooperative effort will be funded jointly by NFS and Research. In general, NFS will be responsible for establishing and maintaining the sites. Research will be responsible for data collection, periodic measurements, data analysis, and publication. Detailed study plans between Stations and Regions will specify more clearly the funding and management responsibilities.

Because of the central roles organic matter and soil porosity play in controlling key site processes (Fig. 1), many research opportunities will exist once the study site templates are installed. Examples of potential research topics include water use efficiency, root dynamics, soil faunal dynamics, nitrogen mineralization, nutrient uptake and return, carbon allocation into growth vs. defense compounds, host-pest interactions, etc. Multidisciplinary collaboration will be encouraged.

IMPLEMENTATION

Once funded, approximately 14 months are needed to locate and install a series of study sites within a timber type. The first strong indication of long-term treatment effects can be expected in 5 to 10 years after planting on average sites. Figure 5 shows a probable timeline.

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Table 1.--Minimum measures of organic matter, soil porosity, and productivity to be taken on all plots.

Pre- and post-treatment measurements dealing with--		Post-planting measurements dealing with--
Organic matter	Porosity	Productivity
Mass by component	Bulk density	Stocking
a. Logging slash	Soil strength	Height
b. Forest floor	Infiltration	Diameter
c. Mineral soil	Moisture release	Damage
Nutrients by component	Saturated hydraulic conductivity	Above-ground biomass in:
a. Logging slash		a. Trees (by component)
b. Forest floor		b. Other vegetation (by component)
c. Mineral soil		
		Species diversity

Table 2.--ANOVA showing expected mean squares for 9 treatments applied at 9 field locations (3 similar sites within low, medium, and high classes of soil properties).

Source of variation	Df	3 F i	3 R j	9 F k	Expected mean square	F test
Soil prop. i	2	0	3	9	$27v_S + 9v_{SL} + v_{err}$	S/SL
S x Location j(i)	6	1	1	9	$9v_{SL} + v_{err}$	cannot test
Treatment k	8	3	3	0	$9v_T + v_{SLxT} + v_{err}$	T/SLxT
S x T ik	16	0	3	0	$3v_{SxT} + v_{SLxT} + v_{err}$	SxT/SLxT
S x T j(i)k	48	1	1	0	$v_{SLxT} + v_{err}$	cannot test
Error l(ijk)	0	1	1	1	v_{err}	
Total	80					

Table 3.--Orthogonal contrasts for testing the effects of organic matter removal and soil compaction treatments on response variables of interest. Treatment codes are identified in Fig. 3.

Main effects test	H_o	Orthogonal coefficients for treatments--								
		1	2	3	4	5	6	7	8	9
Has level of organic matter any effect?	(1+4+7)/3 =	1/3	-1/3	0	1/3	-1/3	0	1/3	-1/3	0
	(2+5+8)/3 =	1/3	0	-1/3	1/3	0	-1/3	1/3	0	-1/3
	(3+5+9)/3	0	1/3	-1/3	0	1/3	-1/3	0	1/3	-1/3
Has level of compaction any effect?	(1+2+3)/3 =	1/3	1/3	1/3	-1/3	-1/3	-1/3	0	0	0
	(4+5+6)/3 =	1/3	1/3	1/3	0	0	0	-1/3	-1/3	-1/3
	(7+8+9)/3	0	0	0	1/3	1/3	1/3	-1/3	-1/3	-1/3

Table 4.--Direct costs, exclusive of permanent salaries, for establishing and conducting initial measurements on benchmark long-term productivity field study sites. Estimates are based on projected national averages.

Expense	Cost within a timber type		
	Per location	Per 9 locations	Per 12 locations
	------ thousands of dollars ------		
Installation	41.5	373.5	498.0
Initial research			
Equipment	15.3	137.7	183.6
Laboratory	17.0	153.0	204.0
Total	73.8	664.2	885.6

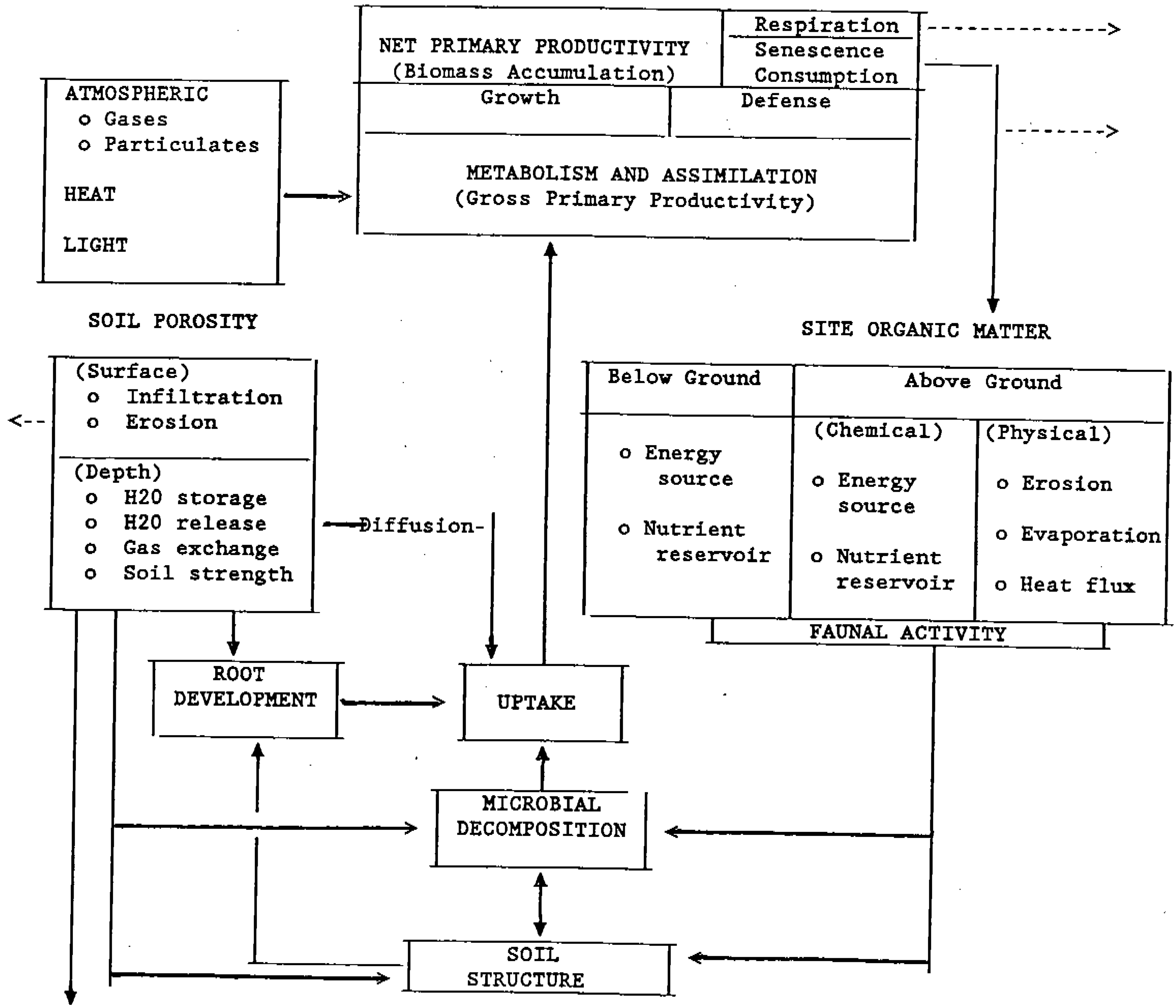


Figure 1.--Conceptual model of the role of soil porosity and site organic matter in mediating site processes controlling net primary productivity.

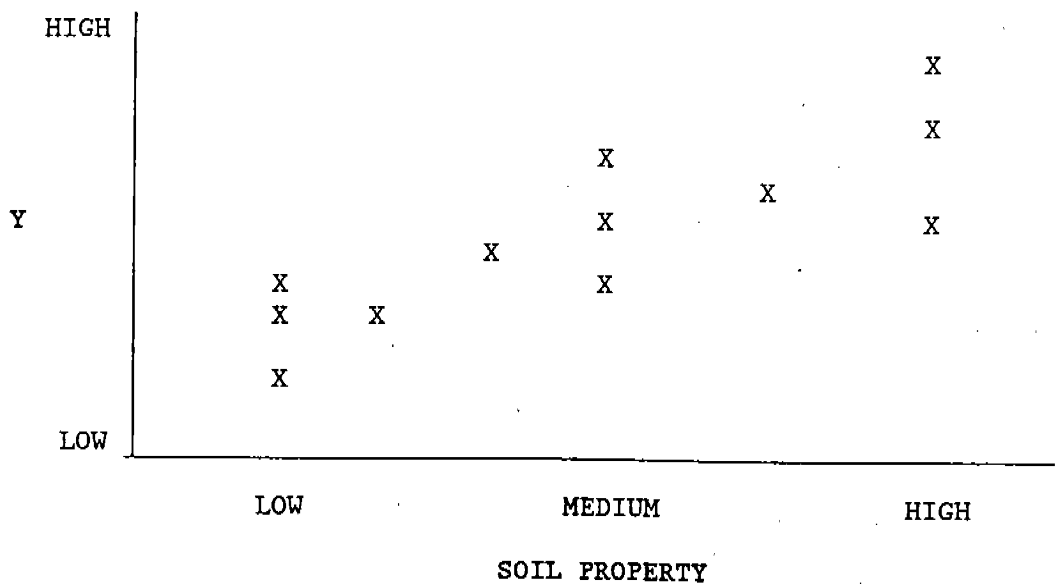


Figure 2.--Schematic positioning of 12 possible field installations (marked with "X") along a gradient in a physical soil property. The "Y" variable is a measure of productivity. Treatments are replicated three times at "Low," "Medium," and "High" positions along the soil property gradient.

ORGANIC MATTER REMOVAL

COMPACTION	OM_0	OM_1	OM_2
C_0	(1) OM_0C_0	(2) OM_1C_0	(3) OM_2C_0
C_1	(4) OM_0C_1	(5) OM_1C_1	(6) OM_2C_1
C_2	(7) OM_0C_2	(8) OM_1C_2	(9) OM_2C_2

Figure 3.--Generalized field layout of a 3 x 3 factorial arrangement of organic matter removal and compaction treatments. Plots probably would not be contiguous under field conditions. Other treatments or operational trials would be located nearby at the discretion of the Regional Steering Committee.

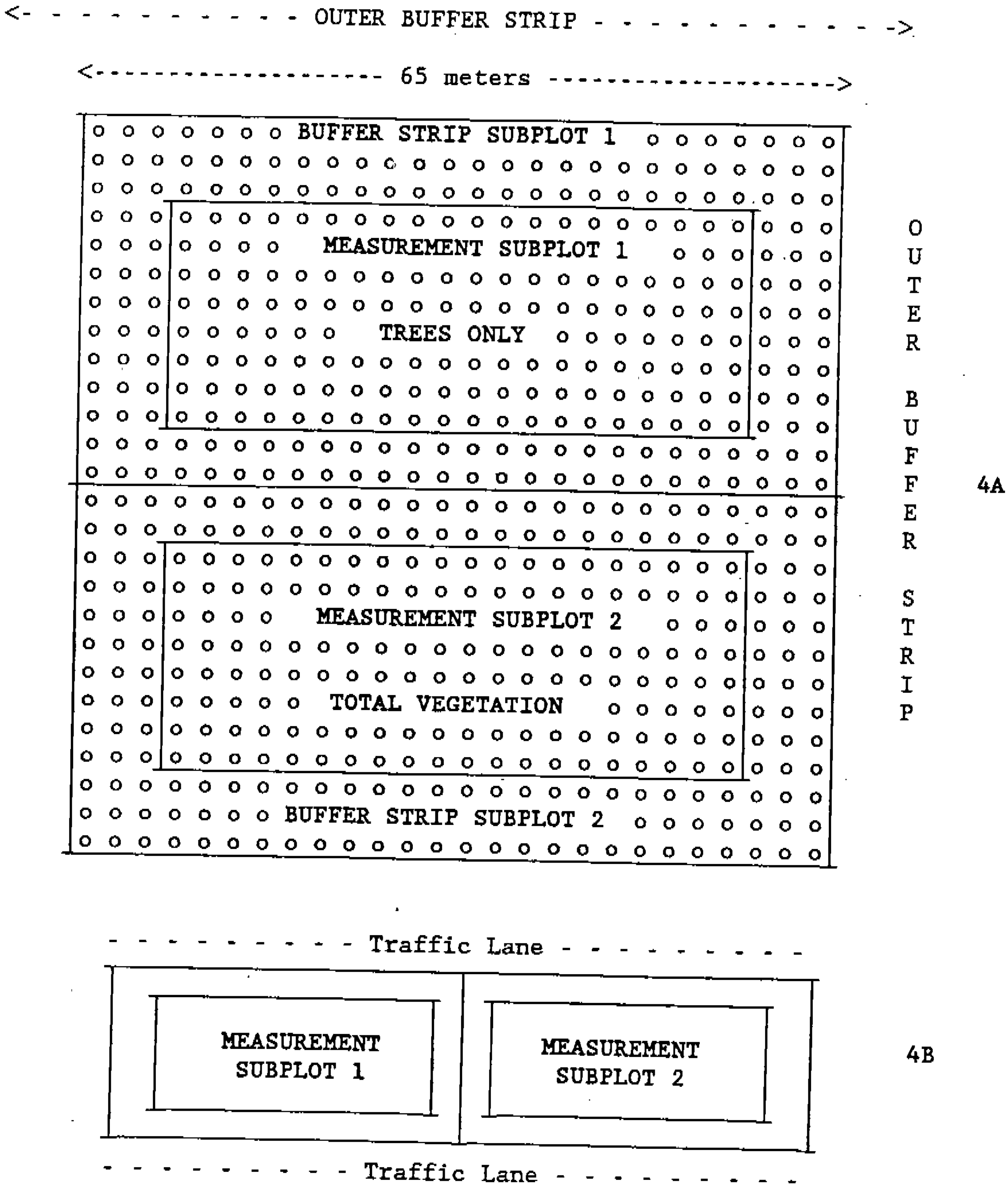
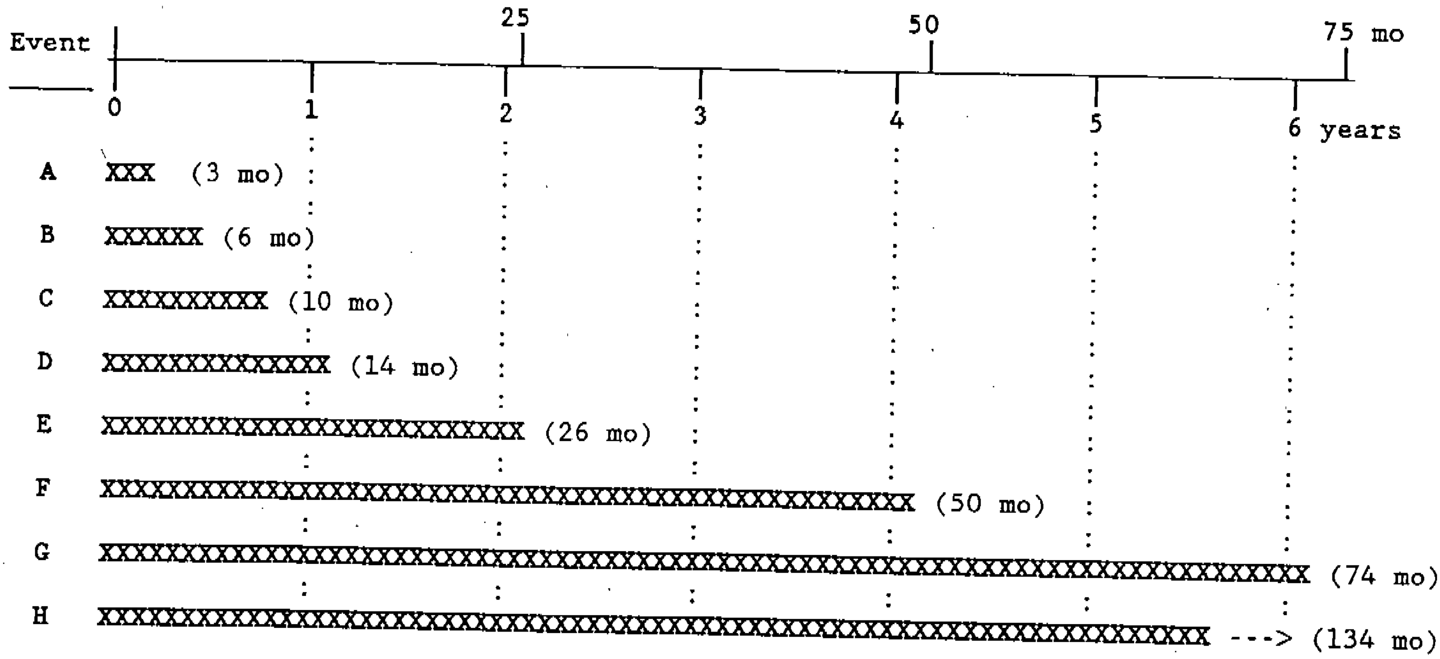


Figure 4.--Possible treatment plot and measurement subplot layouts. Tree locations marked by "o." Each measurement subplot contains three rows of buffer trees along its outer border. Figure 4A would be appropriate for full-suspension aerial harvesting systems. An alternative design (Fig. 4B) joins split plots along their short axis. Biomass can be removed by grapple from traffic lanes placed parallel to the long axis.



Event Codes:

A: Develop regional study plan with approval.

B: Identify candidate study sites.

C: Select study sites, preliminary sampling, develop contracts and special provisions.

D: Harvest, install treatments, plant, collect initial measurements.

E: First main post-treatment measurements.

F: Second main post-treatment measurements.

G: Third main post-treatment measurements. First biomass measurements.

H: Fourth main post-treatment measurements. Second biomass measurements. (Probably the first valid indication of long-term productivity trends).

Figure 5.--Sequence and timeline for locating, installing, and measuring study plots. Plots would be thinned according to best management practices and the stand characteristics of that treatment. Sampling would continue until rotation.