EPA/620/R-94/007
March 1994

FOREST HEALTH MONITORING

1991 GEORGIA INDICATOR EVALUATION AND FIELD STUDY

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NOTICE

The research described in this report has been funded by the U.S. Environmental Protection Agency. This document has been prepared at the EPA Environmental Research Laboratory in Corvallis, Oregon, through Contract Nos. 68-C8-0006 to ManTech Environmental Technology, Inc., 68-C0-0049 to Lockheed Engineering and Sciences Company, and 68-D0-0106 to Statistical Consulting Service. It has been subjected to the Agency's peer and administrative review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This report represents data from one year of field operations of the Environmental Monitoring and Assessment Program (EMAP). Because the probability-based scientific design used by the EMAP necessitates multiple years of sampling, there is uncertainty associated with these data. This uncertainty will decrease as the full power of the approach is realized. Similarly, temporal changes and trends cannot be reported, as these require multiple years of observation. Please note that this report contains data from demonstration studies in one geographic region. Appropriate precautions should be exercised when using this information for policy, regulatory or legislative purposes.

This report should be cited as follows: Alexander, S.A., M. Baldwin, W.A. Bechtold, D.L. Cassell, S. Cline, T. Droessler, J.W.. Hazard, J.G. Isebrands, V.J. Labau, K.H. Riitters, H. Schreuder, S.J. Steele, and M.S. Williams. 1993. Forest Health Monitoring: 1991 Georgia Indicator Evaluation and Field Study, EPA/620/R-94/007. U.S. EPA Environmental Research Laboratory, Corvallis, OR.

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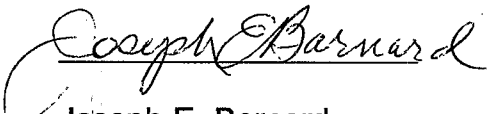
Approved by



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FOREWORD

The Forest Health Monitoring (FHM) 1991 Georgia Pilot study was undertaken to conduct field research for advancing forest monitoring science within the Environmental Monitoring and Assessment Program (EMAP). Indicator developmental and operational monitoring research was conducted simultaneously on plots. Indicator development objectives and criteria are detailed in the project plan entitled *FY91 Indicator Evaluation Field Study for Environmental Monitoring and Assessment Program - Forests (EMAP-F).*

The pilot study was designed to test methods for quantifying vegetation structure, photosynthetically active radiation (PAR), dendrochronology, and selected root fungi. Testing the methods included comparing different data collection procedures for individual indicators, estimating sampling efficiency (both of the sampling design and the sampling unit design), and evaluating spatial variability. In addition, the accuracy and precision of tree height instruments were determined as part of the pilot study.

The field work was conducted on a systematic grid consisting of 63 plots across the state of Georgia. Figure 1 shows a map of Georgia with county boundaries and demo plot locations. Although there were 63 potential plot locations, the land use for many was something other than forested (e.g., agricultural, urban, marsh). Several of the indicator studies utilized only 20 of the forested plots in western Georgia. Figure 1 shows the pilot plot locations.

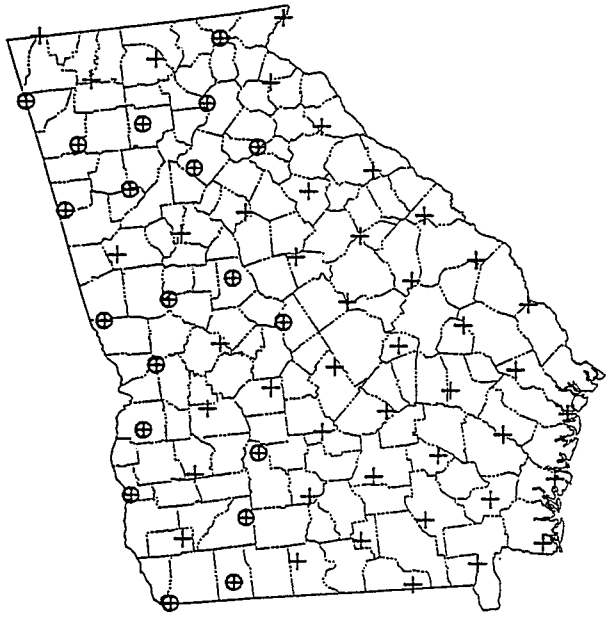

Figure 1. Locations of the 1991 Georgia Pilot plots. The 20 plots used by several indicators are circled.

EXECUTIVE SUMMARY

The following summary provides a succinct review of the objectives and results of the 1991 Georgia pilot by indicator. The lessons learned have been used in planning and improving the 1992 field activities.

VEGETATION STRUCTURE

The objective of the vegetation structure study was to compare the operational and informational characteristics of area-based and point-based methods for quantifying vertical and horizontal vegetation structure and to recommend a measurement system for vegetation structure for 1992 and beyond.

The general superiority of the quadrat method for sampling vascular plant species richness at both plot and regional levels was the most significant of several methodological differences found between the quadrat and pole methods. Comparisons of quadrat and pole diversity indices and species accumulation curves supported this finding. This finding is important because estimates of species richness are the most basic and sensitive measurements of the status of biotic diversity. Although estimates of species richness are basic and straightforward, they are not simple. Field personnel must have a working knowledge of the regional flora, the ability to identify vascular plants under field conditions based on experience or using regional taxonomic keys, and the ability to collect and press unknown plant specimens for later identification.

In constrast, even though superior to the pole method, the quadrat method implemented in this study usually sampled only 70 percent to 80 percent (range 66 percent to 107 percent) of a crudely estimated total plant species richness of the plot and regional level. Therefore, suggestions to reduce sample numbers per plot must be thoroughly evaluated before implementation, since the reliability of species richness and other diversity calculations increases with sample size. The quadrat method for measuring vegetation structure was recommended for use in future Forest Health Monitoring field seasons based on these findings.

PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR)

The primary objective of the PAR study was to develop an efficient and reliable method of using ceptometers and quantum sensors for measuring forest canopy light environments in various stand conditions. Several equipment problems were worked out so that PAR data collection can be considered reliable. The importance of measuring diffuse PAR in open areas in addition to ambient

PAR became evident. Statistics indicated that 7 points gave as good an estimate of PAR as 19 points, thereby reducing field work and time.

DENDROCHRONOLOGY

The objectives for dendrochronology were to determine if the sampling intensity and tree selection protocols were adequate for quantifing diameter at breast height (dbh) growth rates and trends on a regional basis. Based on the variance component analysis, the sample intensity is adequate. A graphical analysis of growth patterns showed that cores, grouped by species and age, showed similar patterns of growth within groups. Specific species should be sampled where possible (loblolly pine, for example), to minimize between-species variability in growth.

In addition, recommendations were made for improving equipment, field sampling, core handling, and preparation. The recommendations should improve core quality and expedite the measurement and analysis process. A specific recommendation was that cores should be prepared, measured, and analyzed by one laboratory.

ROOT DISEASE

One objective was to determine the presence and severity of root disease using two root sampling techniques: the two-root method and the cubic foot root collection method. The results showed that the two-root method was more effective than the cubic foot method in detecting root disease pathogens.

Another objective was to evaluate the cubic foot method for quantifying ectomycorrhizal fungi. The field sampling procedure was simple, but the laboratory work was cumbersome and labor intensive. The core sample was considered too large and the variability between cores was high. A smaller volume soil sample and/or a soil subsampling procedure were suggested to improve the procedure.

TREE HEIGHT

The objective was to determine if the accuracy and precision of tree height measuring devices were adequate for providing a measure of tree height change over time. The authors concluded that a 10 percent error in measuring tree height was common, especially for trees over 12 m in height. A 10 percent measurement error is unacceptable for accurately estimating height change over a 5-year period, therefore tree height is not recommended as an indicator at this time.

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ABBREVIATIONS AND ACRONYMS

ASCS	—	Agricultural Stabilization and Conservation Service
ASP	—	annosus sampling procedure
dbh	—	diameter at breast height
dm	—	decimeter
EM	—	ectomycorrhizal
EMAP	—	Environmental Monitoring and Assessment Program
EPA	—	U.S. Environmental Protection Agency
FAA	—	formalin, acetic acid, and alcohol
FHM	—	Forest Health Monitoring
GIS	—	Geographic Information System
GPS	—	Global Positioning System
MLRA	—	major land resource area
NLIN	—	(SAS) nonlinear regression procedure
MQO	—	measurement quality objective
PAR	—	photosynthetically active radiation
PDR	—	portable data recorder
QA	—	quality assurance
SAS	—	Statistical Analysis System
SCS	—	U.S. Soil Conservation Service
TPAR	—	transmitted photosynthetically active radiation
USDA	—	United States Deparment of Agriculture
VVS	—	vertical vegetation structure

ACKNOWLEDGEMENTS

The authors thank the following peer reviewers for their constructive criticisms: Mark Hansen, U.S. Forest Service, North Central Forest Experiment Station, St. Paul, MN. Greg Reams, U.S. Forest Service, Institute of Quantitative Studies, New Orleans, LA. Tim Strickland, U.S. Department of Agriculture, Competitive Grants, Washington, D.C.

Appreciation goes to Terry Droessler and Susan Christie (ManTech Environmental Technology, Inc.) for their contributions as editors.

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ABSTRACT

The Forest Health Monitoring (FHM) 1991 Georgia Pilot study was undertaken to conduct field research for advancing forest monitoring science within the Environmental Monitoring and Assessment Program (EMAP). Indicator developmental and operational monitoring research was conducted simultaneously on plots. The pilot study was designed to test methods for quantifying vegetation structure, photosynthetically active radiation (PAR), dendrochronology, and selected root fungi. The objective of the vegetation structure study was to compare the operational and informational characteristics of area-based and point-based methods for quantifying vertical and horizontal vegetation structure and to recommend a measurement system for vegetation structure for 1992 and beyond. The primary objective of the PAR study was to develop an efficient and reliable method of using ceptometers and quantum sensors for measuring forest canopy light environments in various stand conditions. The objectives for dendrochronology were to determine if the sampling intensity and tree selection protocols were adequate for quantifying diameter at breast height (dbh) growth rates and trends on a regional basis. The objectives for the root disease study were to determine the presence and severity of root disease using two root sampling methods (the two-root method and the cubic foot root collection method) and compare the methods, and also to evaluate the cubic foot method for quantifying ectomycorrhizal fungi. The objective of the tree height study was to determine if the accuracy and precision of tree height measuring devices were adequate for providing a measure of tree height change over time. The report presents the results and recommendations based on those results.

SECTION 1
STATISTICAL METHODOLOGY

D.L. Cassell and J.W. Hazard

1.1 Introduction

One of the objectives of these field activities was to assess statistically the reliability of measurements for pilot indicators. The developmental stage of the various pilot indicators dictated the statistical methodology, since, in some cases, concerns for logistics or feasibility were paramount.

Root sampling focused on feasibility and comparison of methods, as did tree height. The pilot studies for these measurements were thus not designed with variance component estimation in mind. Research on photosynthetically active radiation (PAR) has already included variance component estimation and semivariogram estimation in a previous pilot (Riitters et al., 1991), and focused on other avenues of research. The main goal of the vegetation structure leader was to compare quadrat and pole sampling with feasibility studies, thus the plot layouts are not optimal for semivariogram estimation.

Variance component analysis for estimation of sampling efficiency was performed on both vegetation structure methods, as well as on dendrochronology data. These results provide the ingredients for evaluating the efficiency of the sampling design and the sampling unit design. In addition, the spatial variability of both vegetation structure methods was examined. Spatial variability is important for two reasons. If the data for a measurement set are spatially correlated, the observations on those measurements cannot be assumed to be independent, which would affect the variance component analysis. Spatial correlation would also affect the variance estimates for the data if the indicator passed to demonstration or implementation phase.

1.2 Sampling Efficiency

Sampling efficiency was investigated using standard statistical equations to combine information obtained about sample variances with estimates of sampling cost to estimate optimum sample sizes for the different sampling stages. A hierarchical multi-stage sampling model was used in each case. Both methods of measuring vegetation structure used a three-stage sampling scheme incorporating plots, subplots, and measurement stations (see Section 2). For the vertical pole method, the measurement station was the pole point; for the quadrat method, the measurement station was the entire quadrat. For the dendrochronology method (see Section 4), a four-stage sampling scheme was used: plots, subplots, trees within subplots, and cores within a tree.

The cost components (Table 1-1) used in the evaluation are based on the average times required to set up and make measurements on a new plot location, a new subplot in a given plot, and further subsampling units. The subsampling costs are the times required for locating and measuring

vegetation structure pole points, siting quadrats and measuring flora within the quadrat, and locating and coring sample trees. These times were recorded as part of the logistics evaluations of the pilot measurements.

TABLE 1-1. ESTIMATED COST COMPONENTS FOR THE 1991 GEORGIA PILOT

Cost Component	Cost Estimate
Plot	3.33
Subplot	0.21
Vertical Pole Method	
Pole point	0.05
Quadrat Method	
Quadrat	0.40
Dendrochronology	
Subplot + Tree	0.66
Core	0.08

The variance estimates were made by computing mean squares for the variables in the various stages of the nested model. These mean squares were computed using the formulas in Sukhatme (1954) and Cochran (1977), and were then substituted into the optimum sample size equations provided in those texts. The sample size equations for a three-stage sampling design are:

Second stage: $m_{opt} = (c_1/c_2)^{1/2} * [(MS_2 - MS_3/k)/(MS_1 - MS_2/m)]^{1/2}$

Third stage: $k_{opt} = (c_2/c_3)^{1/2} * [MS_3/(MS_2 - MS_3/k)]^{1/2}$

where c_i and MS_i are the sampling cost and the estimated mean square, respectively, for the i^{th} stage of sampling; m and k are the actual sample sizes used in the second and third stages of the design respectively; and m_{opt} and k_{opt} are the respective estimated optimum sample sizes for these stages of the design.

If adequate quality assurance data are available to provide an external estimate of the measurement error at the final stage of sampling, then these sample size equations can be improved.

If the estimate of the measurement error variance for the final sampling stage is s_e^2, then the sample size equations for the three-stage sampling design (Cassell, 1992) become:

Second stage: $m_{opt} = (c_1/c_2)^{1/2} * [(MS_2 - (MS_3 - s_e^2)/k)/(MS_1 - MS_2/m)]^{1/2}$

Third stage: $k_{opt} = (c_2/c_3)^{1/2} * [(MS_3 - s_e^2)/(MS_2 - (MS_3 - s_e^2)/k)]^{1/2}$

where c_i, MS_i, m_{opt} and k_{opt} are as on the previous page.

The optimum first-stage sample size (i.e., the total number of plots) is not provided by these equations. This estimate can be made given a desired precision for a parameter over the population of plots under study, or given a total fixed cost for surveying the population. But such a solution should utilize alternate optimization techniques that are appropriate for the Forest Health Monitoring (FHM) Program first-stage sampling design. The resource allocation formulas here are appropriate for simple random sampling; the FHM design uses systematic sampling with post-stratification, which requires different formulas.

This emphasizes that the objective of this study—determining an optimum plot design once a plot location has been selected—gives little insight into the number of plots needed to characterize regional forest health at some specified level of precision. On the other hand, an optimum single-plot design is valid no matter how many plots are ultimately selected for measurement.

This estimation procedure does not assume that there are known bounds on the plot-level variability, but seeks to optimize the sampling distribution across the stages of measurement for the estimated cost components. If particular indicators develop guidelines for plot-level variability limits, then such limits will also be used to assess the arrangement of measurements within a plot.

Another important consideration is that the optimal plot design should be evaluated for the objective of estimating a population parameter over many plot locations, and not for the objective of estimating that parameter for any particular plot contained in that population. Optimal plot design for a regional survey does not imply that every site-specific estimate will meet other precision requirements. This tradeoff between obtaining precise answers for each site or for all sites in a population at once makes large-scale surveys practical and simultaneously limits the inferences that can be drawn about any one location.

A final consideration is that statistical optimality is not the only criterion for plot design. It may be necessary to ensure that some measurements "cover the area" so that they may be related to other measurements made on the plot. Or the design needed for an indicator may include special features to ensure accurate characterization of relevant subsets of the plot. Indicator development is an essential part of FHM, and the objectives of the indicator determine how the data are to be used and what other considerations must be incorporated into sample selection.

1.3 Spatial Analysis

The vegetation structure measurements (Section 2) were taken on an hexagonal grid for pole measurements, and in contiguous quadrats for the quadrat measurements. Semivariograms were calculated for species abundance measurements taken at these measurement stations, using standard formulas (e.g., Ripley, 1981). A semivariogram allows us to visualize the variability between observations as a function of the distance between the observations. In essence, the variance of two observations is computed as half the square of their distance. Then the variance for all pairs of data points a given distance apart is calculated as the average of these pairwise calculations.

This is a reasonable way to calculate the variance for a pair of numbers. If we choose two numbers, x and y, their mean z must be halfway between the two numbers. Thus the variance of the pair $\{x,y\}$ is given by:

$$(x - z)^2 + (y - z)^2$$

$$= [(x - y)/2]^2 + [(x - y)/2]^2$$

$$= \tfrac{1}{4} (x - y)^2 + \tfrac{1}{4} (x - y)^2$$

$$= \tfrac{1}{2} (x - y)^2$$

The semivariograms permit us to visualize at what distance the spatial correlation levels off (i.e., how far away the measurements can be when the correlation is roughly the same as for two points on opposite sides of the plot). This provides useful information for deciding whether two data points can be treated as statistically independent. When the data are independent, they appear to be scattered at random. Spatial structure may appear in many forms, including clustering of the data points, clustering of values of the data, or nonrandom order across the area.

SECTION 2
VEGETATION STRUCTURE

S. Cline and D.L. Cassell

2.1 Introduction

Gathering information about the status of forest biotic diversity and how it is changing is one objective of the Forest Health Monitoring (FHM) program. A vegetation structure indicator was proposed originally to provide better assessment of non-tree, understory vegetation. This understory vegetation comprises most of the plant species diversity in forests, is more sensitive to environmental gradients, and has higher turnover rates and thus a potentially faster reaction time to stress than trees (Daubenmire, 1968). Furthermore, vegetation structure is an important aspect of wildlife habitat structure, which was appealing because monitoring animal habitat in EMAP may be a cost-effective alternative to directly monitoring animal populations.

2.2 Objectives

Numerous candidate indicators representing compositional, structural, and functional aspects of biotic diversity could be measured, depending upon the objectives of the monitoring program (Noss, 1990). Given the importance of the effects of habitat alteration upon biotic diversity (U.S. EPA, 1990), structural features of landscapes and forest habitats are leading candidate indicators (Figure 2-1; Table 2-1).

The objectives for the vegetation structure indicator were:

- To compare the operational characteristics of a point quadrat (pole) method and an area quadrat method of measuring vertical and horizontal vegetation structure, including spatial variation, sampling efficiency, time and labor requirements, and measurement error.
- To compare the informational characteristics of a point quadrat (pole) method and an area quadrat method of measuring vertical and horizontal vegetation structure, including species accumulation curves, and species and structural diversity estimates.
- To recommend a refined and streamlined measurement system for vegetation structure for 1992.

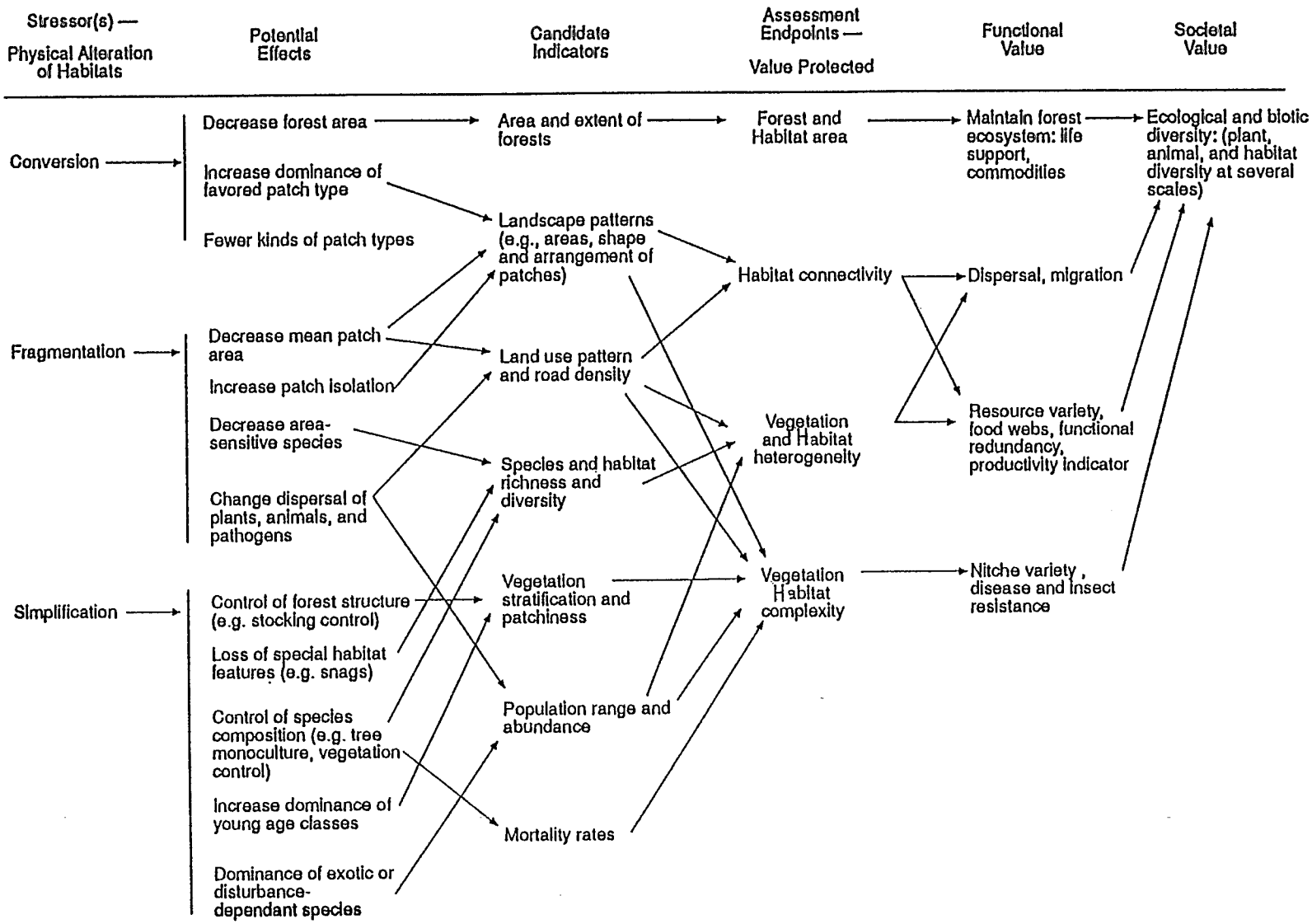

Figure 2-1. Forest Health Monitoring program ecological assessment model for biotic diversity.

TABLE 2-1. CANDIDATE INDICATORS OF BIOTIC DIVERSITY

A. **Coarse patch delineation:** Landscape/Region level

Remote-based variables from small-scale (1:45,000) photos

- forest area by class (conifer/deciduous/mixed)
- land area by use type
- landscape pattern (area, shape, juxtaposition, and connectivity of patches)

B. **Fine patch delineation based on external features:** Community/Ecosystem level

Remote-based variables from large-scale (1:6,000 or 12,000) photos

- subdivision of patches by forest type
- subdivision of patches by tree density and height
- overstory cover, roughness, and patchiness
- location and area of ecotones
- number of vertical strata

C. **Fine patch characterization based on internal features:** Population/Species level

Ground-based variables from fixed area plots

- tree species
- tree diameter and basal area
- tree density

Ground-based variables from pole and quadrat methods

- profile of understory vegetation cover
- patchiness of understory vegetation cover
- canopy cover
- species and growth-form composition
- species richness

2.3 Vegetation Structure Measurement Methods

2.3.1 Sampling Design

2.3.1.1 Plot Selection

We selected 20 forested hexagons from the EMAP one-quarter interpenetrating national sampling grid. The hexagons were distributed from the northern to the southern borders of western Georgia and included a variety of forest types and elevations in the mountain, Piedmont, and coastal plain provinces (Figure 1 in the Foreword). These sites presented realistic conditions to test the operational capabilities and analytical difficulties that will typically be encountered in pilots and regional demonstration studies in other mountainous regions of the eastern United States. The field sampling plot in each hexagon

is located by selecting the FIA photo grid point closest to the hexagon centerpoint that is associated with forest (Palmer et al., 1991, Chapter 5).

2.3.1.2 On-Plot Sampling Scheme

The standard FHM sampling plot was laid out in association with each hexagon; it is a set of four fixed-area plots (each 1/24 acre or 168 m^2) spread over about 1 ha (Figure 3-3; Palmer et al., 1991, Chapter 5). The point and area quadrats employed different sampling schemes over this four-subplot area. Pole point quadrats were set at 7 of the 19 points per subplot used to sample photosynthetically active ration (PAR) (Figures 2-2a and 3-3). Meanwhile, at least three 1-m^2 quadrats per subplot were laid out side by side on randomly preselected azimuths (Figure 2-2b; subsection 2.3.4.2 [quadrat layout]).

2.3.2 Logistics

2.3.2.1 Field Personnel Requirements

A botanist was responsible for vegetation structure and photosynthetically active radiation (PAR) measurements in the 20-plot landscape pilot substudy. A primary qualification of this person was a working knowledge of the flora in Georgia, including the ability to identify vascular plants under field conditions based on experience or using regional taxonomic keys, and to collect and press unknown plant specimens for later identification. One crew member assisted the botanist during pole point measurements.

2.3.2.2 Training

The botanist and a field auditor were trained in the vegetation structure methods in a formal session conducted the week before the start of the field season. Training consisted of an overview of the point and area quadrat methods in a classroom session and a half-day of field instruction and practice on plots selected to represent different forest structural and compositional features. The next day, the botanist measured vegetation structure as part of the pilot crew to test the crew interactions and work loads, to gain additional experience with the methods, and to estimate remeasurement errors under more realistic conditions. Finally, a debriefing session was held at the end of the training session to discuss results of "plot day" and remeasurement evaluations, and to make necessary adjustments in the vegetation structure procedures before field data collection.

2.3.3 Quality Assurance

The auditor conducted a field audit at the beginning of the second week of the field season. The auditor checked to see that the vegetation structure procedures were being followed, remeasured two plots, and checked plant identifications. In addition, the botanist remeasured one preselected point and area quadrat per plot to track data quality throughout the field season. The auditor and botanist remeasurements were used to quantify measurement error (subsections 2.4.2.1 and 2.5.1.4).

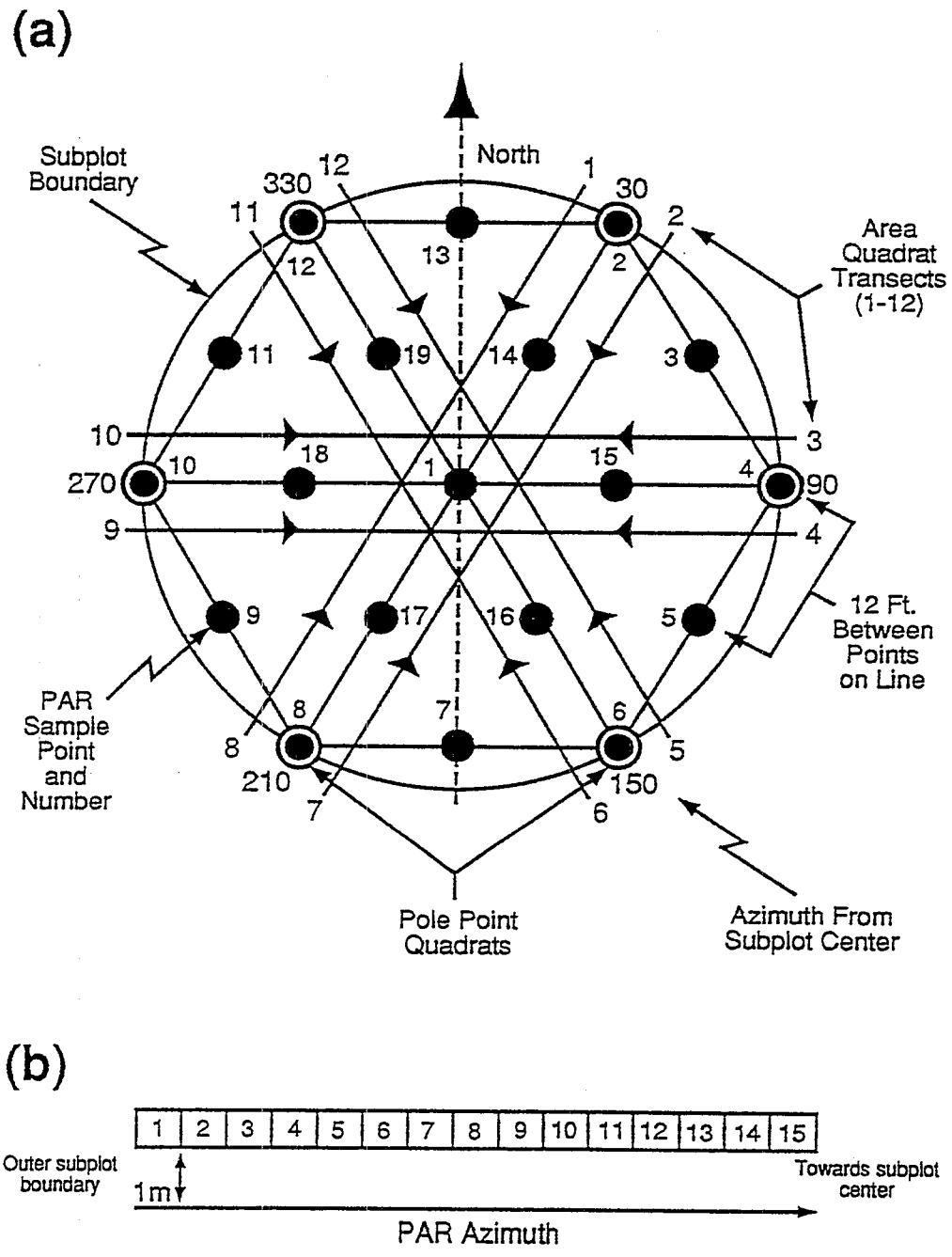

Figure 2-2. On-plot sampling scheme for (a) point quadrats and (b) area quadrats in relation to subplot.

2.3.4 Measurement Procedures

2.3.4.1 Point Quadrats

Summary of Method

The crew raised a 10-m telescoping pole vertically through the forest vegetation at preselected grid points, and recorded "hits" of live leaves, branches, and stems by species and height (to the nearest decimeter interval). The "pole" method provides objective, quantitative estimates of the vertical and horizontal distribution of vegetation cover and its species composition.

The pole method was implemented on each plot as follows: (1) set up the grid of measurement points on each subplot; (2) determine the division of crew member responsibilities; and (3) at each grid point, record ground surface substrate and any species of live vegetation that touch the fully extended pole.

Grid Layout

The crew collected data on all subplots at points 1, 2, 4, 6, 8, 10, and 12 of the 19-point, hexagonal sampling grid established for PAR measurements (Figure 2-2a). Where a point was obstructed by a tree bole, a very tall stump, or very large rocks, the point was moved further along the direction line until it was physically possible to place the pole on the ground. The distance moved and the height that the pole was elevated above the ground were then recorded. Number flags were used to mark each grid point and left in the ground for PAR measurements.

Crew Member Responsibilities

Crews consisted of two members: observers 1 (botanist) and 2 (assistant). At each point, observer 2 held the pole vertically while observer 1 estimated and recorded, on a standard form, the vegetation intersecting the pole.

Recording

Plot and subplot numbers were recorded, along with starting time and (later) time finished. Next, the substrate under the pole was recorded at the 000 height. The choices were as follows: mineral soil/sediment, rock, standing water/flooded, stream, dead wood, litter/duff, live roots, moss (by species or type, if known), and lichen (by species or type, if known).

Next, starting at the ground line and moving upward, live vegetation intersected by the pole was recorded to the nearest decimeter (dm) height interval by species. Thus, the completed data for each "hit" consisted of entries in a height and species column, and the data for a completed point consisted of a series of height-species entries for all hits between 000 and 100 dm.

Measurement Quality Objectives (MQOs)

The main sources of procedural error in the pole method were pole movements off vertical and inherent bend, or "play" as the pole was extended. These errors were exacerbated by some uncontrollable environmental and site conditions, including wind that caused pole and vegetation movement, steep slopes that made the pole hard to steady, and low and thick vegetation overhead that obscured the view of the pole tip at upper positions. A bubble level was attached to the pole as a leveling guide. The inherent bend in the pole was controlled by following strict protocols for placing, aligning, and raising the pole; this did not eliminate the play, but made it consistent between measurements (i.e., the same bend in the same direction).

For the training session, the MQOs were as follows: difference in total number of hits per point, ± 1; difference in 0.5-m intervals of recorded hits, ± 1; misidentification of plant genus, no differences; and misidentification of plant species, 5 percent.

2.3.4.2 Area Quadrats

Summary of Method

The general strategy was to assess the number and abundance of vascular plant species present on contiguous square meter quadrats (Mueller-Dombois and Ellenberg, 1974). Visual estimates of cover were made for each plant species in each of four strata on each quadrat. In stratum 1, all ground substrates and nonvascular plant species were recorded. Then, starting with stratum 2, the following were measured: small herbs, shrubs, and tree seedlings (stratum 2); large shrubs and tree saplings (stratum 3); small and large trees (stratum 4). The method provides quantitative estimates of the vertical and horizontal distribution of vegetation cover and its species composition.

Quadrat Layout

The quadrats were laid out on 1 of 12 randomly preselected transect lines running parallel (offset to either side by one meter) to one of the azimuths used to establish the point quadrats (Figure 2-2b). Beginning at the outer edge of the subplot, a square meter quadrat frame was laid down and plant measurements were made. The frame was then moved to the next contiguous square meter area along the transect line and the measurements were repeated. The crew measured three to six quadrats in this manner on each subplot. The number of quadrats sampled per subplot varied because the botanist was instructed to sample no more than one hour per subplot; thus, a variable number of quadrats were sampled depending upon vegetation density and diversity.

Crew Member Responsibilities

The botanist made all measurements for this method.

Recording

Plot and subplot numbers were initially recorded, along with starting time and (later) ending time. An index of cover abundance was estimated visually for every species and substrate identified within each stratum (Daubenmire, 1968, with Bailey and Poulton, 1968 modification). The cover classes were: (1) 0 to 1 percent (0.5 percent midpoint), (2) > 1 percent to 5 percent (3.0 percent midpoint), (3) > 5 percent to 25 percent (15.0 percent midpoint), (4) > 25 percent to 50 percent (37.5 percent midpoint), (5) > 50 percent to 75 percent (62.5 percent midpoint), and (6) > 75 percent (87.5 percent midpoint). Next, the cover of substrates within each quadrat was estimated by cover class. The substrates were the same as those used for the pole method. The strata were: (1) 0 m (ground surface), (2) > 0 to 1.5 m, (3) 1.5 to 10 m, and (4) > 10 m. Thus, the completed data for each stratum consisted of entries in substrate/species, strata, and cover class columns, and the data for a completed quadrat consisted of a series of species-strata-cover entries for all strata present.

Measurement Quality Objectives (MQOs)

The main sources of procedural error in the quadrat method were inconsistencies in enumerating all vascular plant species in the sampling areas and subsequently in identifying the plant species, and to a lesser extent, estimating vegetation cover classes, especially in stratum 4. These errors were exacerbated by several uncontrollable environmental and site conditions, including dense understory vegetation, phenological and maturity state of each plant species, and low and thick vegetation overhead that obscured the view of the taller vegetation. Errors in enumerating and identifying species were limited by hiring a botanist familiar with the flora in Georgia. Reference marks were placed on the sampling frame as guides during cover estimation.

For the training session, the MQOs were as follows: difference in total number of species per subplot, ± 10 percent or ± 2 species, whichever was less; difference in estimated cover of species, ± 1 cover class; misidentification of plant genus, no differences; and misidentification of plant species, 1 in 20 (5 percent).

2.4 Analytical Methods

2.4.1 Index Selection and Calculation

The structure of a biological community refers to its species composition and the pattern of species abundances, where abundance is expressed as frequency, biomass, productivity, or any similar importance value (Pielou, 1975). Community structure is known to reflect site environment and change predictably with environmental pollution or disturbance (e.g., Brenchley, 1958; Patrick, 1968; Kempton and Taylor, 1976). Thus, there is obvious appeal to a summary statistic or index that captures community structure and is sensitive to environmental changes such as pollution and disturbance. Advantages of such a summary include quantification, ease of interpretation and communication, and

ability to evaluate environmental impacts upon communities in different regions, since species names are discarded (Kempton and Taylor, 1974).

For this study, we selected Hill's (1973) series of diversity measures as summary statistics for the community structure of vascular plants sampled with the pole and quadrat methods on each pilot plot. We chose these indices because they are among the most widely used in the ecological literature and provide diversity numbers that are among the easiest to interpret ecologically (Ludwig and Reynolds, 1988). Hill's family of diversity is calculated as follows:

$$N_A = \left(\sum_{i=1}^{S} p_i^A \right)^{1/(1-A)}$$

where p_i is the relative abundance of the ith species. Three members of this series are in common use (i.e., $A = 0$, 1, and 2. When $A = 0$, $\mathbf{N}_0$ equals S, or species richness, the total number of species in the sample regardless of abundance. When $A = 1$, $\mathbf{N}_1$ equals the exponent of the Shannon index, $e^{H'}$ (Shannon and Wiener, 1949). When $A = 2$, $\mathbf{N}_2$ equals the reciprocal of the Simpson index, 1/D (Simpson, 1949) (Table 2-2). Each of these diversity measures expresses the "effective" number of species in a sample, a measure of the number of species weighted by their abundance. As A increases, less weight is placed on the rare species, so typically $\mathbf{N}_0 > \mathbf{N}_1 > \mathbf{N}_2$.

Plot-level Hill diversity indices were calculated by strata using pole and quadrat data (Table 2-2). Frequency data from all points, or cover data (class midpoints) from all quadrats, were accumulated across each plot to construct a species list and to determine the relative abundance (p_i) of each species for use in the diversity indices. Diversity calculations were made separately for each stratum. With this analytical approach, diversity measures indicate the community structure of organisms similar in habitat or microhabitat, size, life history traits, and resource utilization (Hurlbert, 1971).

The status or trend in the values of Hill's diversity measures is one way to assess ecological condition or environmental quality. For example, the studies of Brenchley (1958), Patrick (1968), and Kempton and Taylor (1976) show that communities in a polluted or recently disturbed environment are typically characterized by a few species having very uneven distributions; these sites would have relatively low Hill diversity values. In contrast, in more stable environments, communities tend to have a larger number of species with a much more even species abundance distribution; these communities have larger Hill diversity numbers. Interpretation of patterns or trends in diversity indices must be done with caution, however, because numerous environmental factors influence diversity and any strong relationship between diversity and some environmental impact is best described as correlative, rather than causative (Magurran, 1988).

TABLE 2-2. DEFINITION AND CALCULATION OF PLOT-LEVEL VALUES FOR EACH ELEMENT OF HETEROGENEITY AND COMPLEXITY OF VEGETATION

Elements	Definition	Formula	Aggregation to Plot-Level Value[a]
Richness	The number of species sampled in an area.	$\bar{S}$ = average number of species sampled per unit area.	Count number of species/quadrat sampled (n=12); average.
Evenness	The distribution of abundance among the species in a community.	p_i = relative abundance of species i; n_i/N.	Sum cover by species/quadrat (n=12); divide by total cover.
Diversity	Synthetic measures that are sensitive to both richness and evenness. Related to the uncertainty of identity of an individual randomly selected in an area. Uncertainty increases with richness and evenness.	$H' = -\Sigma p_i \ln p_i$ (Shannon-Wiener, 1949). $c = \Sigma p_i^2$ (Simpson, 1949)	Use p_i values generated for plots. Note: $c^{H'}$ and $1/c$ = the number of equally common species required to produce the same uncertainty as the sample.
Equitability	Relative diversity of sample in relation to maximum possible diversity of a community of S species.	$J' = H' / H'_{max}$	Use H' and H'_{max} generated for plots. Note: $H'_{max} = \ln S$.
Pattern Diversity	Variation due to the spatial arrangement of plant cover	Stratification = variability, as coefficient of variation, in total cover per stratum. Patchiness = variability, as coefficient of variation, in total cover of each sample.	Sum cover/strata (n=4); calculate $\bar{X}$, S, CV. Sum cover/quadrat (n=12); calculate $\bar{X}$, S, CV.

[a] Assumes FIA condition code is the same on all four subplots. If condition code changes, then average the subplots separately by condition code.

2.4.2 Statistical Analysis of Comparability of Pole and Quadrat Methods

2.4.2.1 Operational Characteristics

Spatial Variation

Semivariograms were computed for the quadrat and vertical pole data, using the method discussed in Section 1.3. For both data sets, the variables examined were the diversity indices, mentioned above, calculated for pole or quadrat within each stratum. The vertical structure measurements were taken on an hexagonal grid within each subplot, and in contiguous quadrats.

Sampling Efficiency

The sampling efficiency for the vertical structure and quadrat protocols was investigated using the statistical methodology discussed in Section 1.3. This efficiency analysis compares the variability accrued at each stage of sampling with the added costs of a sample at that stage. The analysis then produces estimates of the number of samples at each stage required to provide a given overall regional variance estimate at the lowest overall cost.

Time and Labor Requirements

The elapsed time to complete pole and quadrat measurements was calculated for each subplot and plot. Paired Student's t-tests (normal distribution) and the Wilcoxon signed ranks test (distribution free) were used to test the null hypothesis H_0: time needed to complete measurements did not differ by method.

Measurement Error

We analyzed two data sets: (1) data collected by the botanist and remeasured by the auditor, and (2) data collected and remeasured by the botanist. For each data set, the three diversity indices described in Section 2.4.1 were calculated using data from the original measurement and the remeasurement. Paired Student's t-tests (normal distribution) and the Wilcoxon signed ranks test (distribution free) were used to test the null hypothesis H_0: mean difference between remeasurements = 0.

2.4.2.2 Informational Characteristics

Species Diversity

Plot-level diversity values were calculated using data generated by the pole and quadrat methods. The measurement data collected with the pole were grouped in the same height strata as the quadrat data, so that the resulting diversity calculations were comparable. The pole and quadrat diversity calculations were compared for strata 1 (ground layer, 0 m), 2 (> 0 to 1.5 m), and 3 (> 1.5 to 10 m), but not for stratum 4 (> 10 m). Paired Student's t-tests (normal distribution) and the Wilcoxon

signed ranks test (distribution free) were used to test the null hypothesis H_0: mean difference in diversity values based on pole and quadrat methods = 0.

Species Accumulation Curves

Plot Level. To evaluate how well the vegetation structure methods sampled the species richness of each plot, species accumulation curves were constructed by stratum for each plot using point (pole) and area quadrats (stratum 4 quadrat only). Each plot consisted of the mean number of plant species accumulated in relationship to sample area or size. The mean number of plant species was calculated from 100 sequences of samples drawn at random. For example, for a given plot and stratum, 12 quadrats were drawn at random without replacement (e.g., quadrats 2, 9, 4, 8, 10, etc., and the cumulative number of plant species was recorded for each quadrat. This process was repeated 100 times. Then the cumulative number of species in the 100 quadrats drawn first, second, third, etc., were averaged and plotted in relationship to quadrat sequence.

Then the SAS nonlinear regression procedure (NLIN) was used to fit several different models to the species accumulation curves to determine which model form fit the data best. The models used were: (1) mean species richness (MSR) = a + b * 1n quad (or point) no. (logarithmic), (2) MSR = a * EXP b/quad (or point) no., and (3) MSR = a * {1–EXP[–b*quad (or point) no.]} negative exponential). The latter two equations have defined asymptotes, but the first one does not. The goodness of fit of each model was evaluated by comparing the models' residual mean squares by stratum by plot, and ranking them in ascending order. Finally, once the best fitting equation had been identified for each curve, it was used to estimate the number of plant species sampled if 40 point or area quadrats were measured. The percentage of species sampled with current methods in relation to expanded sampling (n = 40) was used as a general guideline for estimating how well current methods sample total plant species richness.

Regional Level. The procedure used to generate plot-level curves was then repeated for the western Georgia region. First, the total number of substrates and plant species in each stratum was determined by plot. Then, for a given stratum, the 20 plots were drawn at random without replacement (e.g., plot nos. 3208571, 3308563, 3108551) and the number of plant species accumulated in relationship to the number of sample plots. This process was repeated 200 times and the cumulative numbers of species drawn first, second, third, etc., were averaged and plotted in relationship to plot sequence. As before, the SAS NLIN procedure was used to fit the same models to the species accumulation curves. Similarly, the percentage of species sampled with current methods in relation to expanded sampling was used as a general guideline for estimating how well current methods sample total plant species richness in the region.

2.5 Results and Discussion

2.5.1 Operational Characteristics

2.5.1.1 Spatial Variation

Semivariograms permit us to visualize the spatial correlation structure, that is, how far away the measurements can be when the correlation is roughly the same as for two points on opposite sides of the plot. This provides information useful in deciding whether two data points can be treated as statistically independent.

The semivariograms looked similar for all strata except stratum 2. In all the strata except stratum 2, there was no sign of significant spatial structure at the resolution of the sampling, due in part to the irregularity of occurrences for strata 3 and 4, which led to large numbers of missing values in the data. The lack of apparent spatial structure for stratum 1 in the quadrat measurements may indicate that the correlation structure is not particularly evident at distances of a meter or more. This does not indicate that there cannot be spatial structure at distances shorter than one meter.

The semivariograms for stratum 2 consistently showed more correlation between the closest data points than between the most distant ones for both measurement methods and for all three diversity measures. This correlation structure indicates that for the data from stratum 2, we cannot consider the diversity observations for adjacent measurement stations to be independent.

The evidence of interdependence among diversity observations for stratum 2 data from adjacent measurement stations suggests that it might be beneficial to move the measurements farther apart within each subplot, as has already been done for quadrat measurements in pilots conducted during the 1992 field season (the three quadrats per subplot were 7.8 m apart). Furthermore, the evidence indicates that we must be cautious about assuming statistical independence of observations within a subplot for the diversity indices for stratum 2. The consequences for subsequent analyses are discussed in the following paragraphs.

2.5.1.2 Sampling Efficiency

The cost components (Table 1-1) used in the evaluation are based on the average times required to set up and make measurements on a new plot location, a new subplot in a given plot, and further subsampling units. The subsampling costs are the times required for surveying the diversity at the various layers at a measurement station, whether that measurement station is a quadrat or a vertical pole point. These times were recorded as part of the logistics evaluations of the pilot measurements.

For both the vertical habitat structure and the quadrat methods, a three-stage sampling scheme was used: plots, subplots within plots, and measurement stations within subplots. The variables analyzed using this technique are the three diversity measures discussed previously, aggregated within

strata for each measurement station. Diversity measures were not calculated for stratum 1 (the substrate under pole points), so only strata 2 and 3 were examined for the vertical pole measurement. Due to a large number of stations with no observations for strata 3 and 4 on the quadrats, it was not feasible to calculate $e^{H'}$ or 1/D for these stations; thus strata 3 and 4 were examined for the quadrats using only the measure *S*. Remember that for both measurement methods, stratum 2 showed a spatial correlation structure and hence the variance estimates and resulting computations for stratum 2 must be viewed as approximate.

The measurement error estimates were calculated for the quadrats only, since quadrat-level quality assurance data bases were available. Thus the vertical pole data were evaluated using the equations presented in Section 1 that do not take measurement error into account and the quadrat data were evaluated using those equations in Section 1 that incorporate measurement error. The measurement error variances for the quadrats were estimated from two sources. The field crew member remeasured one quadrat per plot, and the original and remeasured data were compared to obtain a remeasurement variance.

Also, two complete plots were remeasured during an audit and 24 quadrats were measured by both the auditor and field crew member. These data were examined for signs of spatial structure before any variance estimates were computed. Although there were signs of spatial structure in the data, the differences between the original and audit measurements at each quadrat did not show any spatial correlation structure. This is to be expected, since the difference in two measurements at a quadrat should be due only to measurement error, including crew-to-crew variability, and should not be affected by the spatial structure of the vegetation at *other* quadrats on the plot.

The two measurement error estimates were pooled to generate a more reliable error estimate with more degrees of freedom, using the formula:

$$s_e^2 = \frac{(n_1 - 1)*s_1^2 + (n_2 - 1)*s_2^2}{n_1 + n_2 - 2}$$

where s_e^2 is the error variance used in the calculations, s_i^2 (i = 1,2) is the two variances calculated from the audits and the remeasurements, and $n_i - 1$ is the respective degrees of freedom for those error estimates. This formula is equivalent to using a Kalman filter (Chatfield, 1989) to combine the two error estimates. It also has the form of the standard maximum likelihood estimates for a pooled variance to be used in a one-way analysis of variance with two levels.

Tables 2-3 and 2-4 show the mean squares and measurement error estimates used in the analyses for vertical structure and the quadrats. See Table 1-1 for the costs of the sampling stages.

TABLE 2-3. MEAN SQUARE AND ERROR ESTIMATES FOR VERTICAL STRUCTURE

	Plot Mean Square	Subplot Mean Square	Residual Mean Square	Error Variance
		Pole		
Stratum 2				
1/D	2.38	0.612	0.753	
$e^{H'}$	2.75	0.690	0.808	
S	3.27	0.846	0.880	
Stratum 3				
1/D	0.773	0.701	0.297	
$e^{H'}$	0.918	0.908	0.376	
S	1.26	1.30	0.552	
		Quadrat		
Stratum 1				
1/D	0.324	0.0698	0.0621	0.0288
$e^{H'}$	0.471	0.162	0.0946	0.0513
S	3.08	4.21	1.04	0.477
Stratum 2				
1/D	4.74	4.22	2.36	0.607
$e^{H'}$	10.92	8.22	3.50	0.741
S	46.86	11.38	8.94	0.548
Stratum 3				
S	11.46	5.19	1.37	0.282
Stratum 4				
S	6.27	0.0440	0.0875	0.0663

Using the formulas in Section 1.2, the mean squares and variances (Table 2-3) were used to compute the estimates shown in Table 2-4. These estimates are the optimal number of subplots and the optimal number of measurement stations per subplot. A measurement station is defined as a vertical pole point for the pole method or a quadrat-level diversity estimate for the quadrat method.

TABLE 2-4. ESTIMATED OPTIMAL SUBSAMPLE SIZES

	Number of Subplots	Stations within Each Subplot
Plot		
Stratum 2		
1/D	1.90	2.50
$e^{H'}$	1.88	2.43
S	1.93	2.27
Stratum 3		
1/D	4.18	1.38
$e^{H'}$	4.43	1.36
S	4.54	1.38
Quadrat		
Stratum 1		
1/D	1.74	0.55
$e^{H'}$	2.33	0.39
S	5.61	0.27
Stratum 2		
1/D	3.96	0.50
$e^{H'}$	3.61	0.45
S	1.76	0.72
Stratum 3		
S	2.75	0.34
Stratum 4		
S	0.31	0.55

Rounding up the estimates, we see that, given an appropriate number of plots, four subplots per plot and one or two quadrats per subplot are enough for regional estimation. Similarly, four or five

subplots with three vertical pole measurements per subplot would provide enough information for regional estimation. More data per subplot are currently being collected, with an appropriately smaller plot-level variance estimate. So, based on these calculations, the plot design appears to be adequate for this indicator.

2.5.1.3 Time and Labor Requirements

The quadrat method required one person, whereas the pole method required two people. Consequently, the elapsed times were multiplied by the number of persons needed for each method, to arrive at person-time, an estimate of the total effort required to complete measurements on each plot. Analysis of paired subplot person-times (n = 70) showed that the pole method took significantly longer (43 minutes) than the quadrat method (25 minutes; paired t-test, t = –7.17, prob. > t 0.0001). The mean elapsed time per subplot (n = 20) was 92 minutes for the quadrat method and 155 minutes for the pole method.

2.5.1.4 Measurement Error

Botanist Measurements Remeasured by Auditor

The diversity indices *S*, $e^{H'}$, and 1/D calculated for each stratum from botanist and auditor measurements were not significantly different (paired t-tests, prob. > t ranged from 0.162 to 0.795). The *S* values for stratum 1 were the only measurements that approached significant difference (t = 1.926, prob. > t 0.067). This difference was related to the identification of substrates and nonvascular plants in stratum 1, not vascular plant species.

Botanist Measurements Remeasured by Botanist

The diversity indices *S*, $e^{H'}$, and 1/D calculated for each stratum from botanist measurements and remeasurements were not significantly different (paired t-tests, prob. > t ranged from 0.141 to 1.000). Again, the *S* values for stratum 1 were the only measurements that approached significant difference (t = 2.092, prob. > t 0.055).

2.5.2 Informational Characteristics

2.5.2.1 Species Diversity Indices

The null hypothesis H_o: mean difference in diversity values based on pole and quadrat methods = 0 was rejected for *S* in all three strata and for $e^{H'}$ in stratum 3 (Table 2-4, paired t-tests, prob. > t ranged from 0.0001 to 0.023). In strata 1 and 2, *S* values based on the quadrat method were greater than those based on the pole method; the higher diversity numbers with the quadrat method suggests better performance than the pole method in capturing the species richness of stratum 2. In contrast,

in stratum 3, both *S* and $e^{H'}$ values based on the quadrat method were less than those based on the pole method, suggesting better performance with the pole than the quadrat method. Meanwhile, 1/D values did not differ significantly between methods, although the differences in strata 2 and 3 approached significance at the 0.05 level (Table 2-5, paired t-tests, prob. > t ranged from 0.084 to 0.096).

TABLE 2-5. DIFFERENCES IN HILL DIVERSITY NUMBERS FROM THE QUADRAT (Q) AND POLE (P) METHODS BY VEGETATION STRATUM[a]

	HILL DIVERSITY NUMBER		
Stratum	***A* = 0 (S)**	***A* = 1 ($e^{H'}$)**	***A* = 2 (1/D)**
1	Q > P P = 0.0001	Q = P P = 0.2105	Q = P P = 0.3417
2	Q > P P = 0.0001	P = Q P = 0.8007	P = Q P = 0.0835
3	P > Q P = 0.0132	P > Q P = 0.0234	P = Q P = 0.0958

[a] Paired t-test.

Two patterns emerge from these results. First, as *A* changes from 0 to 2, (i.e., as the weights given to rare species decline), the significance of the differences between methods decreases. Thus Hill diversity numbers based on lower *A* values are more likely to distinguish smaller differences between methods. Second, as the stratum changes from 1 to 3, superior performance in capturing species richness shifts from the quadrat method to the pole method. Thus, if species diversity is relatively high, as in stratum 2, the quadrat method should be employed; but if species diversity is relatively low, as in stratum 3, the pole method may be employed.

2.5.2.2 Species Accumulation Curves

Plot Level

Methods Comparability. We compared species accumulation curves from the quadrat and pole methods to determine which method was better at capturing the vascular plant species richness of each stratum. At each plot, there is some unknown plant species richness *S*. Typically this total species richness is not fully captured by sampling; however, the method that captures relatively more plant species may be judged better or superior because its sample *S* is relatively closer to a total *S* for the plot. By this criterion, we judged the quadrat method to be superior to the pole method in strata 1 and 2, but within stratum 3, the sample *S* was similar for both methods [Figure 2-3(a-d)].

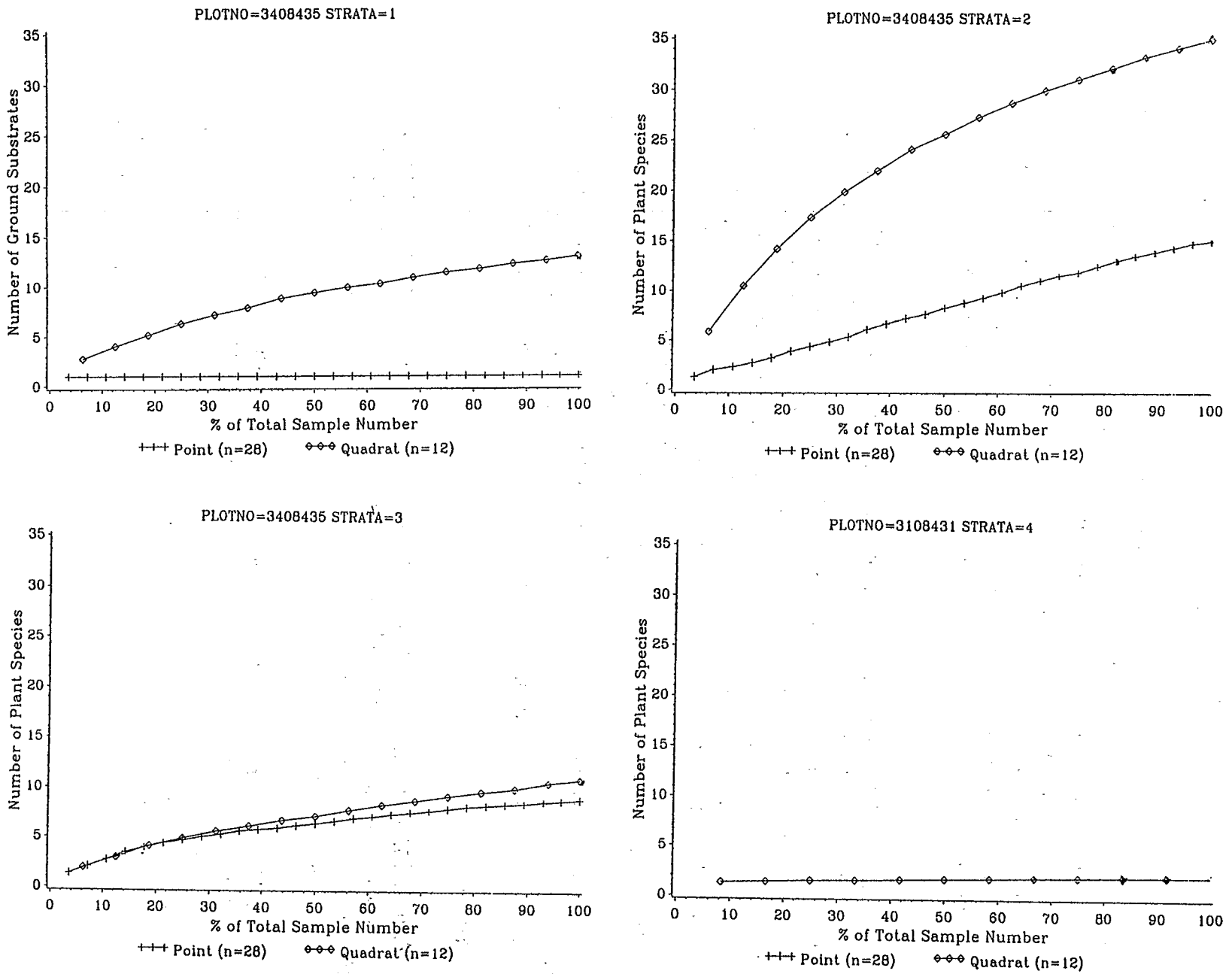

Figure 2-3. Typical examples of species accumulation curves based on the pole and quadrat methods: (a) stratum 1, (b) stratum 2, (c) stratum 3, and (d) stratum 4 (quadrat only).

Goodness of Fit of Model. We further analyzed the species accumulation curves of the quadrat method by testing for goodness of fit to several different empirical models. In subsection 2.4.2.2, we explain that the known values for comparison were the species numbers predicted at n = 40 quadrats, using three nonlinear equations. The asymptotic, negative exponential function described the species accumulation curves best in strata with high species richness, such as strata 2 and 3 (mean plant species richness of 33 and 9, respectively). In contrast, the non-asymptotic, logarithmic function was slightly better than the negative exponential function in strata with low species richness, such as strata 1 and 4 (mean plant species richness of 6 and 3, respectively). The best fitting, parameterized models served two functions: (1) a convenient summary description of each species accumulation curve and (2) a mechanism for estimating species richness in relation to changing sample size (see next paragraph).

Efficiency of Sampling Vascular Plant Species Richness. We evaluated the efficiency of the quadrat method in sampling plant species richness in different strata by dividing the species richness observed using the current sampling strategy (mean quadrats per plot = 11.5) by the predicted species richness with 40 quadrats per plot, expressed as a percent. The best fitting nonlinear models, described in the previous paragraph, were used to predict species richness values. The mean efficiencies of the current quadrat sampling strategy in relation to the logarithmic function were 77 percent for stratum 1, 72 percent for stratum 2, 72 percent for stratum 3, and 66 percent for stratum 4. Meanwhile, the mean efficiencies of the current quadrat sampling strategy in relation to the negative exponential function were 96 percent for stratum 1, 87 percent for stratum 2, 94 percent for stratum 3, and 99 percent for stratum 4. Lower mean sampling efficiencies were indicated for the logarithmic function than for the negative exponential function, because the negative exponential function was asymptotic, but the logarithmic function was not. Thus, estimating conservatively, at least 70 percent of the vascular plant species richness was sampled with the current quadrat sampling strategy.

Regional Level

Methods Comparability. Regional species accumulation curves from the quadrat and pole methods supported the plot-level results by showing the clear superiority of the quadrat method for sampling regional plant species richness in stratum 2, and the similarity of the methods for sampling within strata 1 and 3 [Figure 2-4(a-d)].

Goodness of Fit of Models. The regional species accumulation curves of the quadrat method were also tested for goodness of fit with the same empirical models used for plot-level data. The negative exponential function described the species accumulation curves much better than either the logarithmic or the alternative asymptotic function in all but stratum 1, for which the logarithmic function was slightly better. The mean regional species richness was lowest in stratum 1 (15), followed by strata 4 (30), 3 (77), and 2 (305). These results followed the similar patterns found for the plot-level curves.

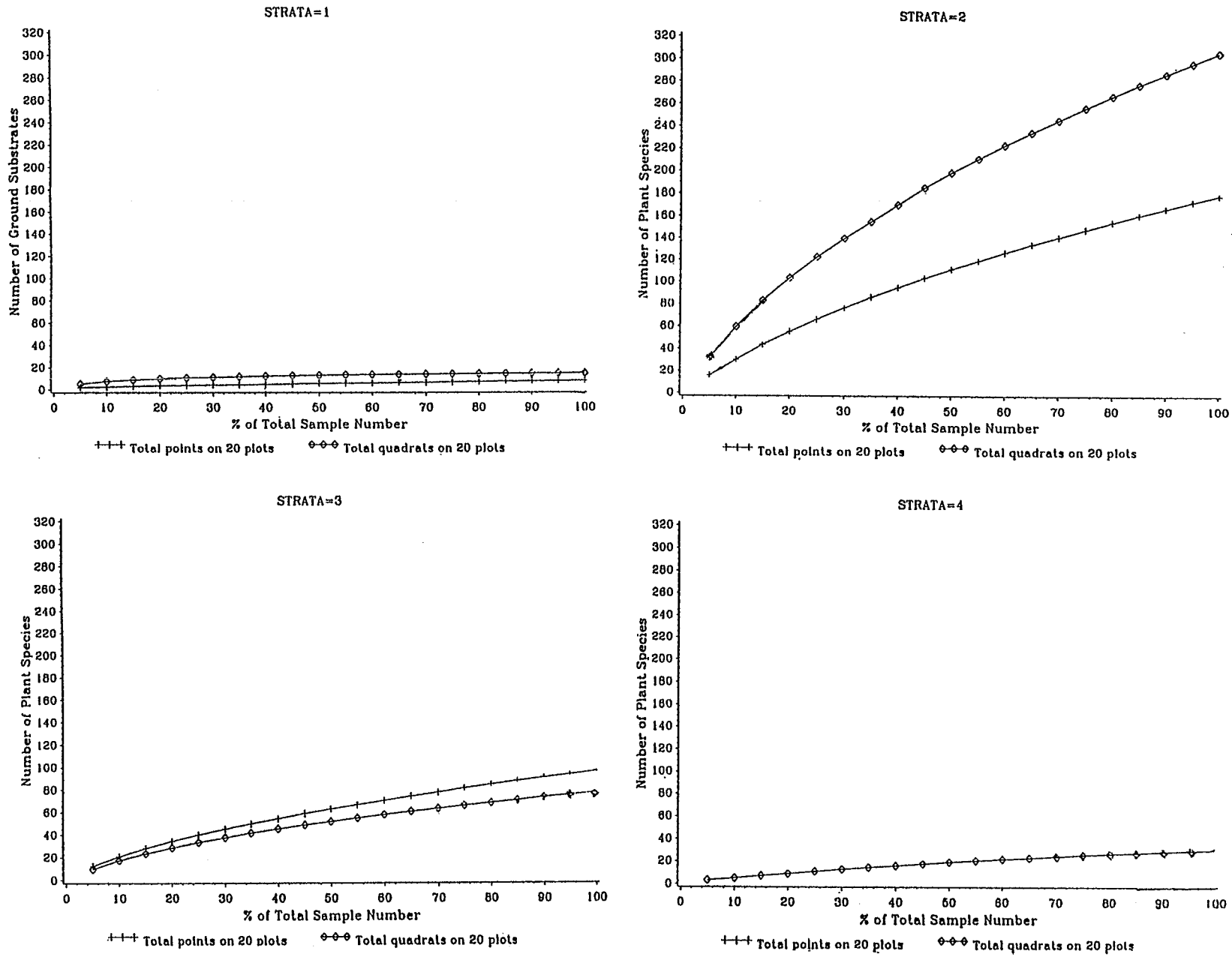

Figure 2-4. Regional species accumulation curves based n the pole and quadrat methods: (a) stratum 1, (b) stratum 2, (c) stratum 3, and (d) stratum 4 (quadrat only).

Efficiency of Sampling Vascular Plant Species Richness. We evaluated the efficiency of the current quadrat method in sampling regional plant species richness in different strata by the same procedure used for the plot-level results. Using predicted values from the negative exponential function, the mean efficiencies were 107 percent for stratum 1, 79 percent for stratum 2, 85 percent for stratum 3, and 70 percent for stratum 4. Using predicted values from the logarithmic function, which had much poorer fits except for stratum 1, the mean efficiencies were 79 percent for stratum 1, 76 percent for stratum 2, 75 percent for stratum 3, and 75 percent for stratum 4. Thus, all nonlinear models suggested similar mean sampling efficiencies, and overall results indicate that about 75 percent of the regional vascular plant species richness was sampled with the current sampling strategy.

2.6 Summary of Results and Recommendations

2.6.1 Operational Results

Measurements based on four subplots per plot and one or two quadrats per subplot were deemed optimal for regional estimation of the S, $e^{H'}$, and 1/D diversity indices. Similarly, four or five subplots with three vertical pole measurements per subplot were optimal for similar regional diversity estimations based on the pole method. Thus, the current plot design and the current number of samples per subplot were adequate, although perhaps fewer measurements could be taken on each subplot for the vegetation structure indicator. Although any of these diversity indices can be calculated based on any number of samples, the reliability of such diversity calculation increases with sample size (Magurran, 1988). Species accumulation curves at both the plot and regional levels indicated that even with current sample sizes, plant species richness was undersampled, varying from 66 percent to 98 percent of total plant species richness, depending upon stratum. Consequently, the suggestion of reducing samples per subplot must be thoroughly evaluated before implementation.

The quadrat method actually required less total effort (person-time) than the pole method, since the quadrat method required only one person and the pole method required two people. Therefore, the quadrat method has a distinct practical advantage since the field work can be completed more quickly and it is easier for groups to collect compatible data.

Quadrat diversity calculations were both reproducible (observer versus auditor) and repeatable (observer versus observer). Even though pole remeasurements were not available from 1991, 1990 analyses showed that trained crews could reproduce one another's measurements (Riitters et al., 1991). So, although both field methods have known procedural errors, the errors do not significantly affect the reproducibility of the diversity indices derived from their respective data.

2.6.2 Informational Results

Species richness (*S*) varied significantly between pole and quadrat methods. For strata 1 and 2, *S* estimates were greater with the quadrat method than with the pole method; opposite results were found for stratum 3. Meanwhile, the $e^{H'}$ and 1/D indices were methodologically comparable.

Species accumulation curves indicated the quadrat method sampled plant species richness better than the pole method for strata 1 and 2 at both the plot and regional levels. In contrast, the pole method was similar or slightly superior to the quadrat method in sampling species richness within stratum 3.

Species accumulation curves based on quadrat sampling were best described overall by the negative exponential function, especially in strata with higher species richness, such as strata 2 and 3. Meanwhile, the logarithmic function was similar or slightly better than the negative exponential function in strata with low species richness, such as strata 1 and 4.

The quadrat method typically sampled an estimated 70 percent to 80 percent (range 66 percent to 107 percent) of total plant species richness at the plot and regional levels, depending upon stratum and predictive equation. The effect of undersampling was greater for strata 2 and 3, where species richness was higher, compared to strata 1 and 4.

2.6.3 Recommendations

We recommend the quadrat method for measuring vegetation structure in future Forest Health Monitoring field seasons. The overall plant species richness and diversity in forests might be more efficiently estimated by implementing one or more of the following sampling refinements:

1. Sampling strata 1 and 4 less often (e.g., every second or third quadrat) because of lower species richness.

2. Sampling stratum 3 more intensively (e.g., use pole to determine presence/absence and as reference during cover estimates), but less often (e.g., alternating quadrats), because of moderate species richness.

3. Sampling stratum 2 more often (e.g., four or five quadrats per subplot), to more fully capture (> 80%) species richness.

SECTION 3
PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR)

J. G. Isebrands, S. J. Steele, and K. H. Riitters

3.1 Introduction

Measurements of solar radiation intercepted by the canopy are fundamental to the interpretation of the productivity and function of plant communities (Norman and Campbell, 1989). Photosynthetically active radiation (PAR) is the quantity of light between the 400-700 nm wavebands of the spectrum, and is the part of the spectrum used by plants for photosynthesis. We can estimate the percentage of PAR transmitted by a plant canopy by calculating the ratio of PAR under the canopy to ambient incoming PAR. This ratio can be related to canopy condition as well as leaf area index and can be combined with growth measurements to estimate growth efficiency, an important indicator of forest health (Waring and Schlesinger, 1985). We can also combine PAR with companion measurements of vegetation structure and/or remote sensing to assess canopy condition with a multivariate indicator approach.

Reliable measurements of transmitted solar radiation are difficult to achieve on the ground, and are typically characterized by significant temporal and spatial variability. Ambient PAR measurements vary, depending upon cloud conditions, time of day, and solar angle (i.e., location and time of season). Thus, obtaining a reliable estimate of %TPAR over a range of temporal and spatial conditions is a challenge. The Georgia pilot study was designed to test the feasibility of using a portable integrating radiometer called a ceptometer (Decagon Devices, Inc., Pullman, Washington) for estimating PAR and transmitted PAR across the various forest types and stand conditions in Georgia.

3.2 Objectives

The general objective of this and related research was to develop and evaluate PAR as an indicator of canopy condition that can be used in monitoring the health and ecological condition of U.S. forests. This objective includes evaluating alternate methods of making PAR measurements and developing knowledge that will enable the Forest Health Monitoring (FHM) program to interpret the data.

The regional pilot and demonstration tests focus on developing a suite of concurrently measured indicators, including PAR, in an operational setting. This rationale leads to the following specific objectives of the PAR Georgia Pilot study:

1. Develop an efficient and reliable method of using a ceptometer and quantum sensors for measuring forest canopy light (PAR) environments under different stand conditions.

2. Develop and test procedures for linking PAR measurements to vegetation structure measurements.

3. Develop and test procedures for linking ground measurements of PAR to photointerpreted measures of stand and canopy attributes.

The Georgia Pilot field study helped accomplish the first specific objective by providing the data needed to (1) evaluate and recommend new or modified field sampling procedures, instrument modifications, and field data handling procedures for measuring PAR with a ceptometer based on experiences gained from the 1990 20/20 pilot study, and (2) recommend efficient sampling procedures to achieve specified precision for various forest types and stand conditions. The Georgia Pilot met the second objective by measuring PAR and vegetation structure on common sample points on the subplots on the same day and relating the measurements quantitatively. The third specific objective of linking photo- and ground-based measures is a longer term objective. The spatially-referenced PAR measurements will be correlated with forest canopy attributes derived from the 1:12000- and 1:6000-scale photography when those photos are available.

3.3 Related 1991 PAR Studies

Photosynthetically active radiation was initially measured as part of the 1990 FHM 20/20 study in the Northeast and Southeast. Results of that study indicated that PAR could be measured reliably with a ceptometer on days with uniform sky conditions (e.g., clear or cloudy), but that variable conditions were more problematic. This experience prompted us to modify the methods employed in the Georgia Pilot.

Figure 3-1. Locations of PAR research sites and pilot sites in 1991 Forest Health Monitoring.

In 1991 a smaller scale PAR companion pilot study was conducted in California and Colorado to test the applicability of PAR methods to western forest stands and conditions. Other PAR activities were conducted by a PAR indicator team consisting of interested scientists from throughout the country. Their goal was to evaluate PAR as a potential indicator for the FHM Program. In 1991, research PAR studies were conducted in Wisconsin, Michigan, Tennessee, North Carolina, Colorado, and Idaho (Figure 3-1). In total, the PAR team measured PAR on a wide variety of forest types, including hardwoods and conifers, at many different geographical locations in the East (Table 3-1) and the West.

TABLE 3-1. EMAP-FHM PAR INDICATOR: 1991 GEORGIA PILOT PLOT SUMMARY

Plot #	Hex #	Date Sampled	Forest Type	Cloudiness Index PAR/Hour 1200-1400 Hrs
1	3408521	6-17	Oak-Gum-Cypress	102585
2	3408435	6-19	Oak-Pine, Oak-Hickory	69524
3	3308385	6-25	Oak-Pine, Oak-Hickory	44172
4	3308481	6-30	Loblolly	57274*
5	3308476	7-1	Oak-Pine, Oak-Hickory	103845*
6	3308563	7-2	Loblolly	98646
7	3308318	7-8	Oak-Gum-Cypress	57513
8	3208365	7-9	Loblolly	112296
9	3208571	7-13	Loblolly	73166
10	3108368	7-19	Loblolly	114347
11	3108551	7-22	Loblolly	82615*
12	3108431	7-23	Oak-Pine, Oak-Hickory	89370*
13	3008467	7-24	Oak-Pine, Oak-Hickory	71676

* Ambient station on less than one hour; value extrapolated to one hour

3.4 Methods

The PAR measurements were to be made on 20 locations selected in the western half of Georgia. The plot selection rules were dependent on the needs of all participating indicators, as well as on logistical constraints. To meet the objectives of the PAR portion of the pilot project, the 20 selected stands were to be representative of available locations (to provide estimates of expected regional variability of terrain, forest type, and stand conditions). The PAR measurements were made during a six-week timeframe beginning about June 15, after full canopy development and before canopy senescence. Measurements were taken at only 13 locations, due to logistics, weather, and equipment problems (Figure 3-2; Table 3-1).

The on-plot sampling scheme for PAR measurements was done on an ambitious sampling grid superimposed on the standard FHM four-point fixed area subplot clusters. Under-canopy PAR was measured at 19 points on each subplot for a total of 76 sample points per plot (Figure 3-3). Moreover, to achieve uniformity, the PAR team adopted this standard PAR sampling grid for all PAR studies across the country. Under-canopy PAR measurements were made with a ceptometer. Specific operating details can be found in the FHM Field Methods Guide. Synchronized ambient PAR measurements were also made in the open at each site with quantum sensors. Transmitted PAR was then calculated as the ratio of PAR under canopy to PAR in the open, expressed as a percentage.

The PAR measurements were made during a standard sampling window from 1100 hrs to 1300 hrs standard zone time (i.e., 1200 and 1400 hrs daylight savings time). This window was necessary to ensure accurate measurement of the percentage of transmitted PAR at each site.

3.5 Results

Figure 3-4 shows a typical PAR data set from a plot in Georgia; under-canopy PAR and ambient PAR are plotted for each of the 76 sample points. The data are from hexagon number 3408521 which contains an oak-gum-cypress forest type. Figure 3-5 shows transmitted PAR (calculated from data in Figure 3-4) for the same plot. This graph illustrates the kind of variability in canopy condition that the PAR indicator can detect within a FHM plot.

Table 3-2 summarizes all the transmitted PAR data by plot location on a subplot and plot basis. The data can be cross referenced to Table 3-1, which summarizes all locations according to hexagon number, date, location, forest type, and cloudiness index on the dates sampled.

In Georgia, we experienced some early problems with our instrument reliability, but most were corrected immediately. For example, the ambient PAR station did not function well when it was moved often or when it experienced intense heat. Inexpensive dataloggers and fabricated quantum sensors were used at the beginning of the field season rather than standard factory equipment. The quantum sensors had to be replaced by factory equipment in the first week; the datalogger was not replaced

and continued to cause problems throughout the year. The Decagon ceptometer performed well for all plots except one. After minor repairs, that problem was corrected and no further problems occurred. The PAR equipment was inoperable only during heavy rain.

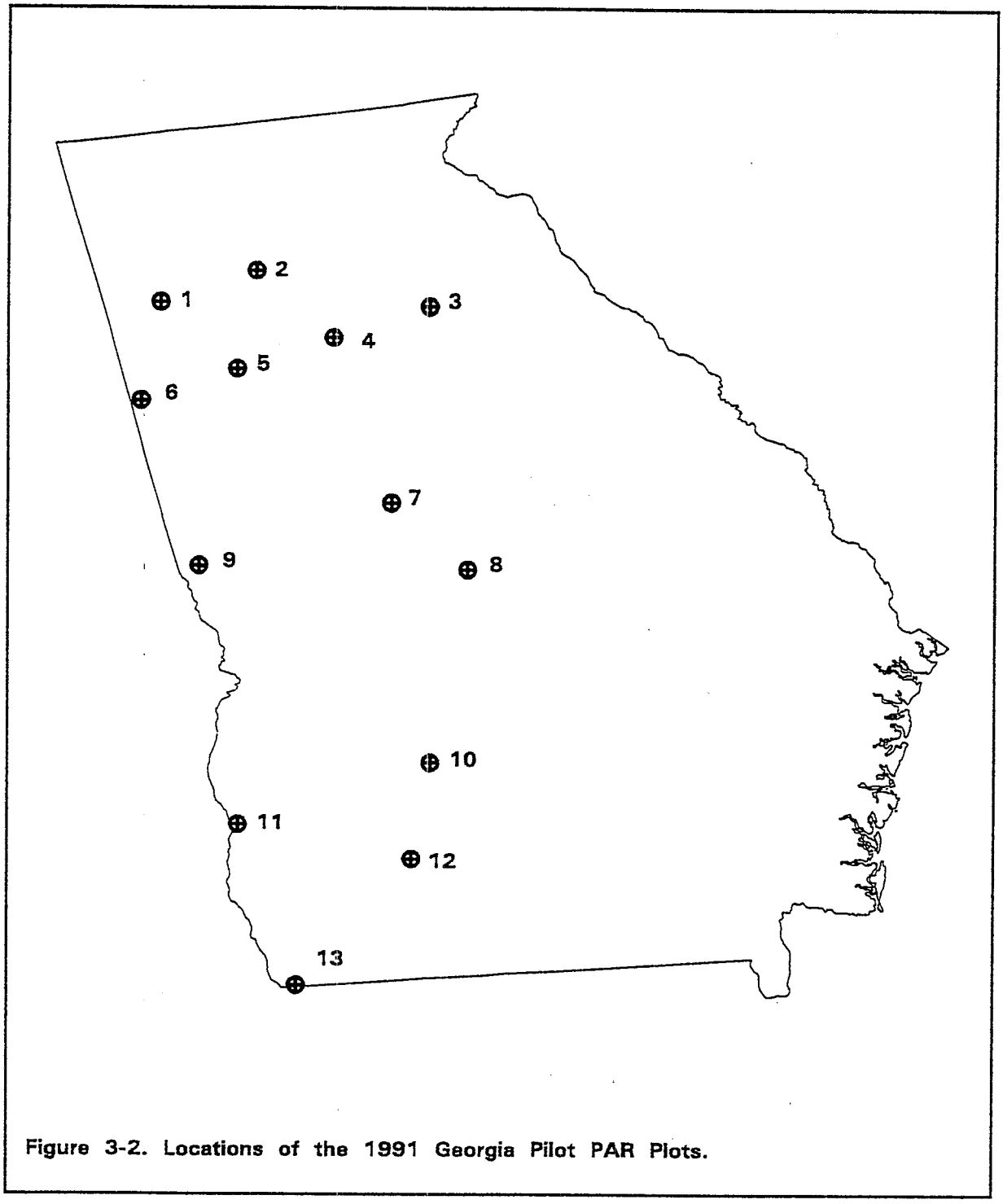

Figure 3-2. Locations of the 1991 Georgia Pilot PAR Plots.

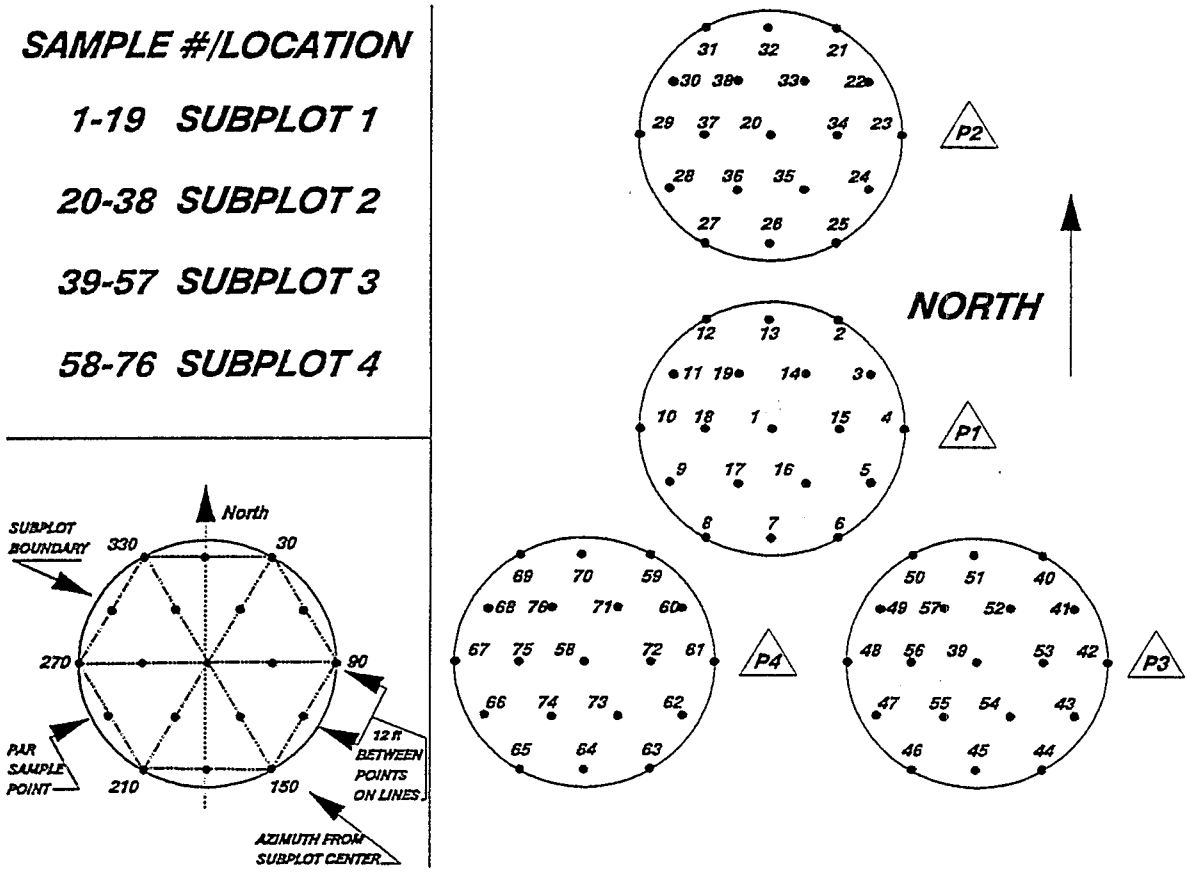

Figure 3-3. PAR sampling scheme for Georgia pilot study in 1991. Subplot example on left shows sampling point layout according to azimuth. Diagram on right shows 19-point grid for each subplot of the 4 fixed area subplot cluster. A total of 76 points were sampled per location.

As mentioned earlier, 13 of the 20 proposed locations in the Georgia pilot have complete PAR data. The seven missing plots resulted from:

- Four ambient station datalogger malfunctions.
- One rainy day.
- One ceptometer malfunction.
- One absence of a suitable ambient station.

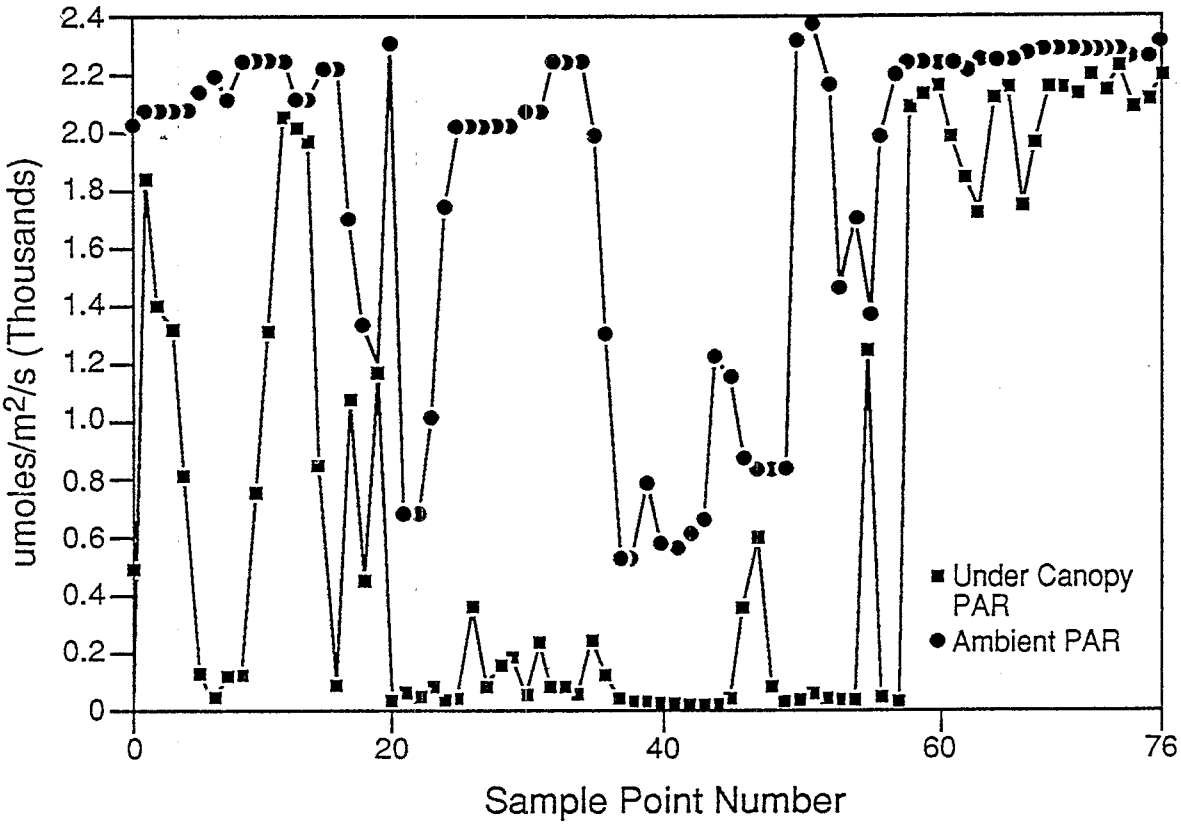

Figure 3-4. Under-canopy and ambient PAR on a plot (3408521) in the 1991 Georgia pilot showing the amount of variability within plots.

In the pilot studies, as well as at the other research sites, we investigated the optimal number of PAR sampling points needed per subplot. Although 19 sample points were measured throughout all 1991 studies, we wanted to determine how well we could estimate PAR with a smaller sample size, based on only the center and 6 corner points of each subplot hexagon (e.g., points 1, 2, 4, 6, 8, 10, and 12 of subplot 1 in Figure 3-3). The advantages of using seven sample points were that the sampling time would be considerably less and the environmental impact would be lower during sampling, due to less trampling of understory vegetation. Based on the means, standard errors, and variances shown in Table 3-2, our 1991 studies clearly showed that seven points gave as good an estimate of transmitted PAR as 19 points. This result meant that in 1992 we could reduce our sample points by two-thirds and reduce the PAR indicator timeframe from 2 hours to 1 hour or less, and, at the same time, do minimal understory vegetation damage to the site.

TABLE 3-2. 1991 EMAP-FHM GEORGIA PILOT MEANS OF % TPAR (19 Pts vs 7 Pts)

Plot #	No. of Sample Points	Sub-plot 1[1]	Variance[6]	Sub plot 2	Variance	Sub-plot 3	Variance	Sub-plot 4	Variance	# Of Points	Total Plot	Variance	Sky Cond.[9]	Forest Type Group[10]
1	19 7	49.1 (8.1) 45.9 (14.0)	[1252.3] [1372.5]	7.9 (1.0) 7.7 (1.6)	[19.2] [17.1]	14.4 (5.9) 10.6 (5.3)	[857.9] [196.6]	92.7 (1.4) 91.4 (2.6)	[38.1] [45.4]	76 28	41.0 (4.6) 38.9 (7.4)	[1624.1] [1549.7]	2	600
2	19 7	13.1 (3.7) 15.6 (8.7)	[258.3] [535.3]	14.5 (2.8) 14.7 (4.0)	[144.1] [114.1]	19.2 (2.0) 16.1 (2.6)	[77.7] [46.2]	20.3 (3.3) 22.5 (6.7)	[203.5] [315.3]	76 28	16.8 (1.5) 17.2 (2.9)	[173.6] [234.6]	3	400/ 500
3	19 7	5.8 (0.1) 6.0 (0.2)	[0.3] [0.2]	4.6 (0.1)[2] 4.8 (0.1)[5]	[0.1] [0.1]	7.8 (0.2) 7.2 (0.4)	[0.7] [1.1]	9.6 (0.4) 8.3 (0.4)	[2.5] [1.1]	70 28	7.2 (0.3) 6.7 (0.3)	[4.4] [2.3]	3	400/ 500
4	19 7	4.7 (0.4) 4.8 (0.6)	[2.4] [2.3]	6.2 (0.4) 5.4 (0.5)	[2.6] [1.8]			4.4 (0.2)[4] 4.4 (0.4)[5]	[0.5] [0.9]	54 20	5.1 (0.2) 4.9 (0.3)	[2.5] [1.7]	2	300
5	19 7	30.9 (5.5) 37.4 (8.7)	[573.4] [531.6]	4.5 (0.5) 5.7 (1.1)	[5.2] [8.7]	19.3 (3.7) 14.9 (6.5)	[259.3] [298.4]			57 21	18.2 (2.6) 19.3 (4.6)	[387.6] [437.6]	2	400/ 500
6	19 7	17.7 (3.2) 19.3 (6.0)	[190.4] [247.5]	8.8 (1.6) 4.4 (0.5)	[45.5] [1.9]	30.5 (5.4) 44.1 (8.6)	[542.9] [509.0]	21.1 (4.6) 28.2 (8.7)	[393.9] [526.3]	76 28	19.5 (2.1) 24.0 (4.2)	[343.0] [500.7]	2	300
7	19 7	4.7 (0.3) 4.7 (0.5)	[1.4] [1.6]	6.9 (0.2) 6.6 (0.4)	[1.1] [1.3]	5.6 (0.3) 5.6 (0.3)	[1.6] [0.6]	7.5 (0.2) 7.4 (0.2)	[0.5] [0.4]	76 28	6.2 (0.2) 6.1 (0.3)	[2.3] [1.9]	3	600
8	19 7	53.9 (9.0) 65.7 (14.3)	[1536.1] [1428.9]	23.5 (3.8)[4] 22.2 (6.9)[5]	[225.4] [237.9]	54.6 (9.5)[6] 45.0 (13.5)[5]	[1092.4] [914.8]	23.8 (5.0) 27.6 (11.4)	[477.0] [916.6]	66 24	38.0 (4.0) 41.2 (6.9)	[1030.6] [1133.0]	1	300
9	19 7	26.6 (3.8) 18.6 (3.4)	[268.2] [81.45]			19.5 (1.0) 20.5 (1.8)	[18.4] [22.1]	9.0 (0.6) 10.2 (1.1)	[7.7] [8.5]	57 21	18.4 (1.6) 18.4 (1.6)	[148.0] [54.2]	1	300
10	19 7	47.5 (5.2) 48.3 (5.1)	[513.3] [183.0]	48.5 (6.2) 45.2 (10.8)	[734.9] [818.9]	66.8 (5.2) 70.1 (8.7)	[508.3] [524.7]	80.0 (8.0)[7] 85.0 (14.4)[5]	[959.4] [1041.8]	72 28	59.6 (3.4) 60.4 (5.5)	[809.3] [787.0]	2	300
11	19 7	40.2 (4.3) 40.1 (9.3)	[349.7] [599.5]	28.0 (3.4) 32.3 (8.0)	[216.3] [448.0]	46.9 (2.8) 41.2 (3.1)	[153.2] [68.2]			57 21	38.4 (2.3) 37.9 (4.1)	[293.3] [351.3]	2	300
12	19 7	41.4 (5.9) 40.3 (9.9)	[666.5] [692.1]	30.2 (4.8) 27.3 (2.7)	[434.8] [49.2]	43.3 (5.0) 54.9 (8.4)	[475.1] [488.2]	26.1 (4.0) 25.3 (5.2)	[300.0] [185.5]	76 28	35.3 (2.6) 37.0 (4.1)	[504.2] [459.7]	1	500
13	19 7	78.5 (4.0) 75.3 (9.4)	[308.4] [619.2]	93.6 (2.8) 89.1 (5.6)	[144.7] [219.4]	54.6 (3.1) 49.1 (5.7)	[184.1] [229.2]	68.8 (2.6) 70.8 (3.9)	[124.0] [106.8]	76 28	73.9 (2.3) 71.1 (4.1)	[387.4] [474.2]	1	400/ 500

[1] Number in parenthesis is the standard error of the mean
[2] # of Sample Points = 13
[3] # of Sample Points = 5
[4] # of Sample Points = 16
[5] # of Sample Points = 6
[6] # of Sample Points = 12
[7] # of Sample Points = 15
[8] Number in brackets is the variance of the mean
[9] Sky Condition Codes: 1 = clear, 2 = less than 50% of ambient readings under 900 $um/m^2/s$; 3 = more than 50% of ambient readings under 900 $um/m^2/s$; 4 = all ambient readings under 900 $um/m^2/s$.
[10] Forest Type Group: 300=loblolly/shortleaf pine; 400/500=upland hardwoods; 600=oak/gum/cypress

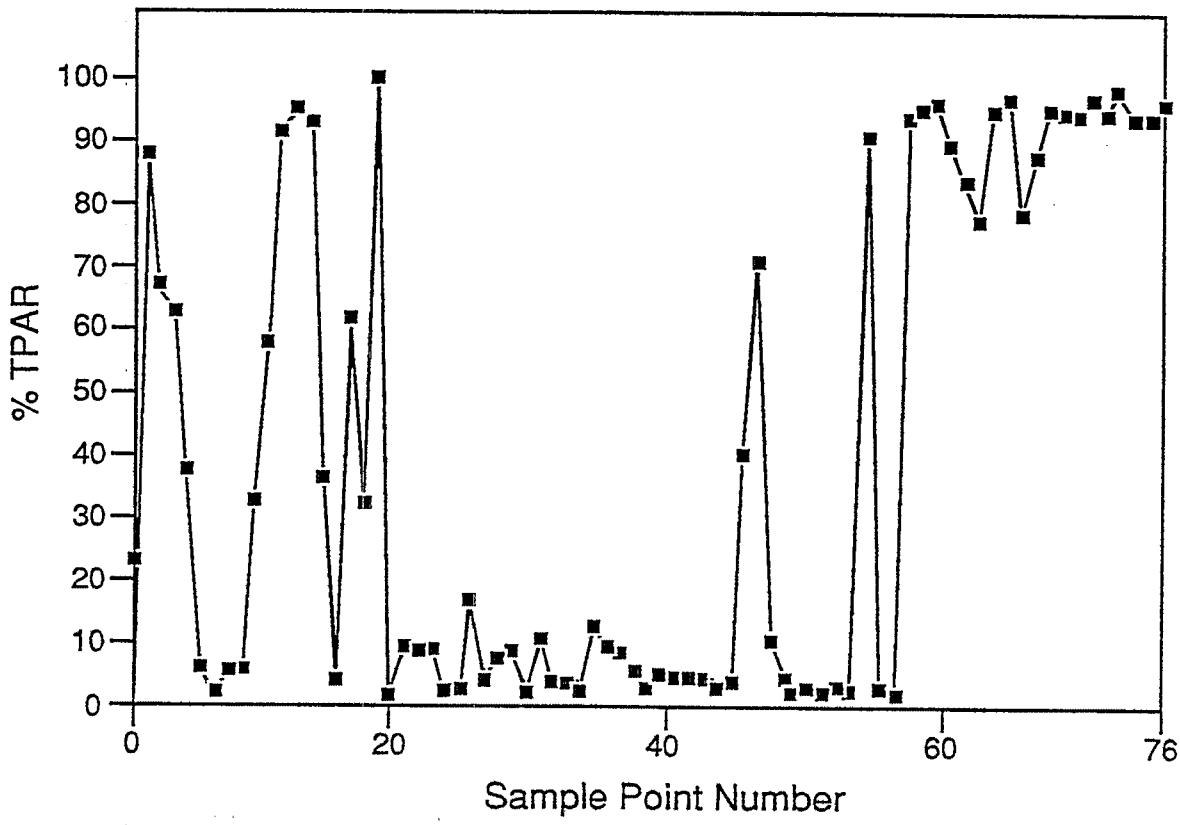

Figure 3-5. Percent Transmitted PAR from data in Figure 3-4; %TPAR = under-canopy PAR/ambient PAR x 100. Note the variability over the entire plot.

Our off-frame PAR studies in 1991 showed that transmitted PAR can be dramatically affected by cloudiness. It was already well known that PAR is affected by sun angle, which varies by geographical location and time of year. These factors influence important indicator criteria such as index period stability and signal-to-noise ratio. Plots of a cloudiness index (e.g., integrated PAR over measurement period) for the Georgia Pilot are given in Figure 3-6. Values over 100,000 indicate clear days; as expected in Georgia, most days encountered by the crews were cloudy. Cloudiness index is a continuous variable that was measured on every site. Therefore, cloudiness could be used as a covariate or a regression parameter to adjust the transmitted PAR values from the Georgia Pilot, reducing noise in the data.

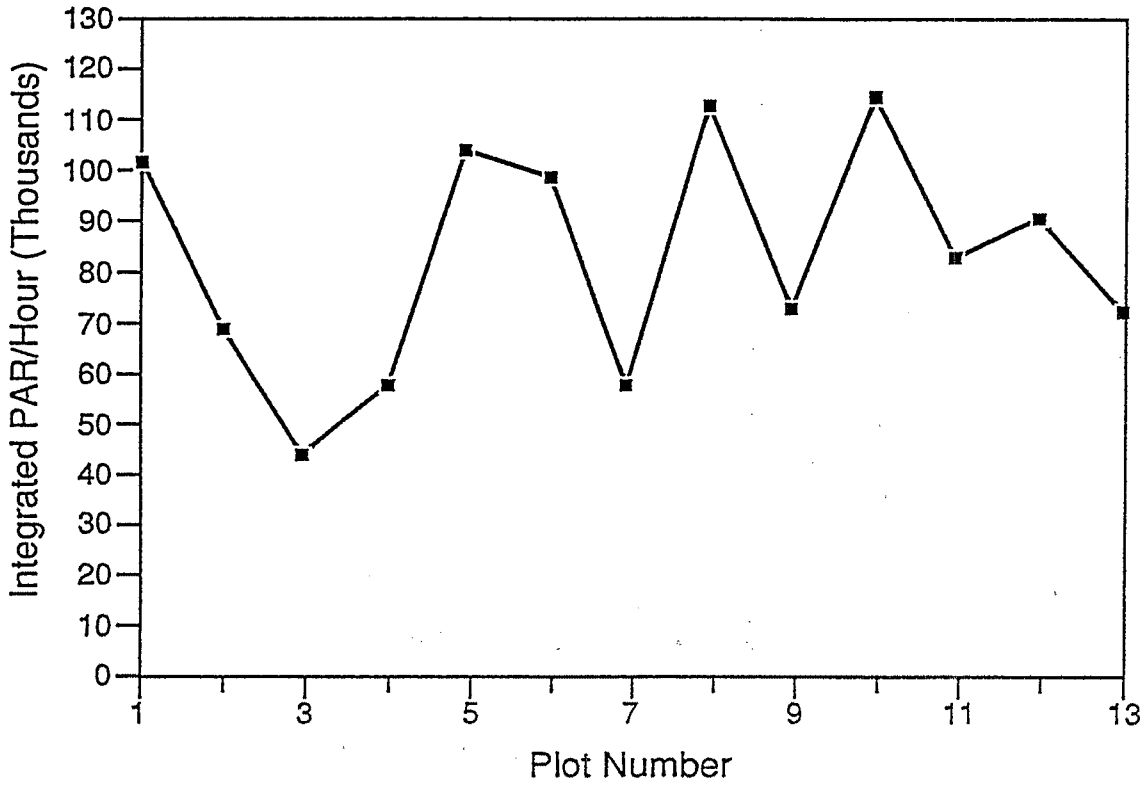

Figure 3-6. Integrated PAR/hour on the 1991 Georgia pilot PAR plots. Units are micromoles/meter^2/hour.

Data from the pilots and the other PAR research indicated that diffuse PAR should be measured in the open areas in addition to ambient PAR. Our off-frame preliminary results suggest that diffuse PAR can be used to estimate canopy condition and leaf area index without the variability experienced on cloudy days with ambient PAR only. Diffuse PAR allows us to calculate beam fraction, which is equal to 1 – (diffuse PAR/ambient PAR). Diffuse PAR is measured quite simply by shading a companion quantum sensor co-located in the open areas with the quantum sensor for measuring ambient PAR, with a small disk. Beam fraction was very stable over a wide range of cloudiness conditions in the off-frame PAR studies and is being measured in all 1992 PAR studies.

Additional PAR team activities in 1991 included:

- Comparing of different algorithms used in defining ambient PAR and mean-value estimators of transmitted PAR.

- Comparing of different methods and models for estimating LAI. The transmitted PAR data was incorporated into different models and the LAI estimates were compared to results received from a plant canopy analyzer on the same sites (LI-COR, Inc.; Lincoln, Nebraska).

- Examining shoot-level measurements and how they related to stand-level PAR transmission measurements to see if these measurements can assist in detecting significant change in PAR transmission over time.

In summary, the information gained from the Georgia and Western pilots and the other PAR research findings have advanced the PAR indicator methodology significantly. In 1992, we have incorporated better, more reliable equipment and included a shading device to collect diffuse PAR at the ambient PAR station. Moreover, we are taking the measurements on only 7 points per subplot rather than the 19 previously used. We hope that these advances will enable PAR to become more repeatable, reliable, and responsive to changes over time in a variety of forest ecosystems throughout the country.

SECTION 4
DENDROCHRONOLOGY

T. Droessler

4.1 Introduction

The tree cores extracted in Georgia in 1991 were used for determining annual diameter at breast height (dbh) growth. Dendrochronology, the systematic study of annual increment obtained from growth rings in trees, was being considered as an indicator in 1991.

4.2 Objective and Scope

The objectives for dendrochronology were to determine if the sampling intensity and tree selection protocols were adequate for quantifying dbh growth rates and trends on a regional basis (in this case, for the state of Georgia or regions within).

4.3 Methods

4.3.1 Sampling

Briefly, a plot consists of a cluster of four subplots, with a center subplot (subplot 1) and three outlying subplots at 0, 120, and 240 degrees (subplots 2, 3, and 4, respectively). The subplot radius was 7.3 m (24 ft) and the distance from the center of subplot 1 to the centers of the outlying subplots was 36.6 m (120 ft). Figure 3-3 shows a schematic of the plot layout. See the FHM Field Methods Guide for a more detailed description of plot structure, layout, and sampling methods.

Tree cores were collected on subplots 2 and 4 according to the following protocol. A random compass bearing was obtained from a portable data recorder and followed to the intersection of the subplot boundary at 7.3 m (24 ft), forming an inner sampling boundary. An outer sampling boundary was positioned at 11.0 m (36 ft). Proceeding in a clockwise direction between the sampling boundaries, the first dominant or co-dominant live tree 12.7 cm or greater (5 in) was identified as the sample tree. The azimuth and distance of the sample tree from the subplot center were recorded.

Tree cores were extracted at a fixed height, usually 1.37 m (4.5 ft). If the sample tree was on a slope, the first core was extracted parallel with the slope. If the tree leaned, the core was extracted 90° from the lean. A second core was extracted 90° from the first core. The cores were to contain the pith and be free of knots, pitch pockets, and compression wood. Additional cores were extracted if

necessary. A second dominant or co-dominant sample tree was located within the described sampling boundaries by proceeding in a clockwise direction from the first sample tree. A maximum of eight cores were extracted at a plot (two cores per tree from two trees on two subplots). The cores were stored in labelled straws and the straws stored in a tube. The tubes were mailed to the U.S. EPA laboratory in Las Vegas, Nevada, for tracking, drying, and storage.

4.3.2 Preparation and Measurement

The preparation included drying, stabilizing the core by mounting it in a wood stick, and machine and hand sanding the core so the growth rings were clearly visible on an even, flat surface. Stokes and Smiley (1968) present a formal description of tree core preparation. Cook and Kairiukstis (1990) provide several sections dealing with core handling.

Tree cores were glued into wooden mounts, machine and hand sanded, and dated by counting from the bark to the pith. The year adjacent to the bark was known as 1991.

Ring widths were measured to the nearest 2 μm (0.0001 in), with an incremental measuring machine equipped with a linear glass encoder. The encoder was interfaced with a microcomputer containing software that recorded ring widths by year for each core. As each ring width was measured, it was simultaneously plotted on the screen against a composite of other cores at the same location.

A stereomicroscope in combination with a monitor was used to measure ring widths. The magnified core image was transmitted to a monitor via a video camera. An electronic cross-hair projected onto the monitor screen was the reference point for measuring a ring width. No attempt was made to determine the number of rings not sampled or the distance to an estimated pith position.

4.3.3 Quality Assurance Procedures

All cores were first hand-dated from the bark end to the pith end, with decade years marked directly on the core surface. As the cores were measured, the measurement year was compared to the marked decade for agreement and visually compared to a composite plot of all previously measured cores on the same plot. Any obvious discrepancies were examined and, if necessary, corrected at the time of measurement. A minimum of five percent of the cores were randomly selected and measured by two technicians. The correlation between the independent measurement data for each core was calculated. In addition, the cores were shipped to the U.S.D.A. Forest Service Institute for Quantitative Studies in New Orleans for an independent measurement.

4.3.4 Analyses

The data used for analysis consisted of 138 tree cores from 84 trees from 33 plots. Total tree age was not estimated from the cores because the pith was usually not included. The length of record ranged from 2 to 99 years.

Van Deusen (1992) used two grouping levels to enhance a graphical display and analysis of growth trends in natural loblolly pine (*Pinus taeda L.*) in the southeastern United States. The first grouping was based on similar median stand age estimated from the cores. The second grouping was by 10-year age classes. The graphical results indicated that several trends could be distinguished from the cores.

For the 1991 Georgia tree cores, the raw increment by year was plotted for each core so that the consistency within and between trees on a subplot and plot could be visually compared. The within-tree cores exhibited similar growth magnitude and trends, although with some variability. The average increment by year, calculated from two cores per tree (if two cores were taken), was plotted by tree. Next, the data were subset to pine species for which the length of record was 19 years or greater. The average increment by year plots were compared between pine trees of approximately the same age on a subplot and were found to exhibit similar growth patterns. The plot average increment by year was then calculated and plotted.

4.4 Results and Discussion

4.4.1 Quality Assurance

Nine cores were randomly selected for remeasurement by a different technician. The correlation coefficient between the two measurements was 0.99 for eight of the nine cores and 0.78 for the remaining core.

The independent laboratory measurement by the U.S.D.A. Forest Service laboratory in New Orleans encountered a few potential false rings. Since a potential false ring does not obscure regional trends in growth, the data were considered adequate for the purpose of this report.

4.4.2 Regional Growth Patterns

Figures 4-1 and 4-2 are representative of two common pine growth trends for trees approximately 40 years and 90 years old, respectively. Figure 4-1 depicts a tree with high early growth rates which then sharply decline; the growth trend would be expected to level off in the next few years. Such a trend would be expected for a tree facing increasing competition from stand dynamics typical of

plantations. Figure 4-2 shows a tree with a steady or level growth trend with periods of increasing and decreasing growth rates about the trend; such a trend would be typical of natural pine stands.

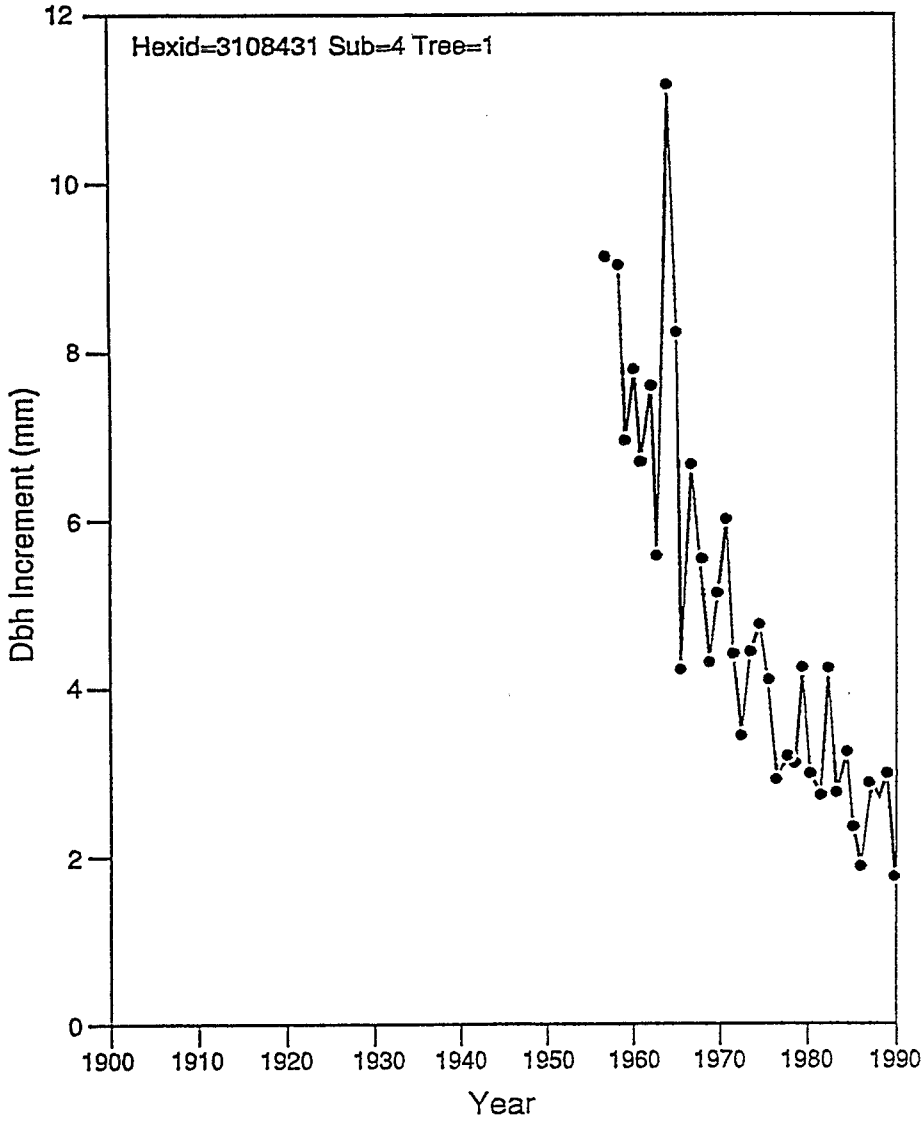

Figure 4-1. Example 40-year growth trend.

A formal analysis of growth trends is beyond the scope of this report. The graphical approach was sufficient for showing the utility of tree cores for depicting regional growth trends from which expectations of future growth rates could be determined.

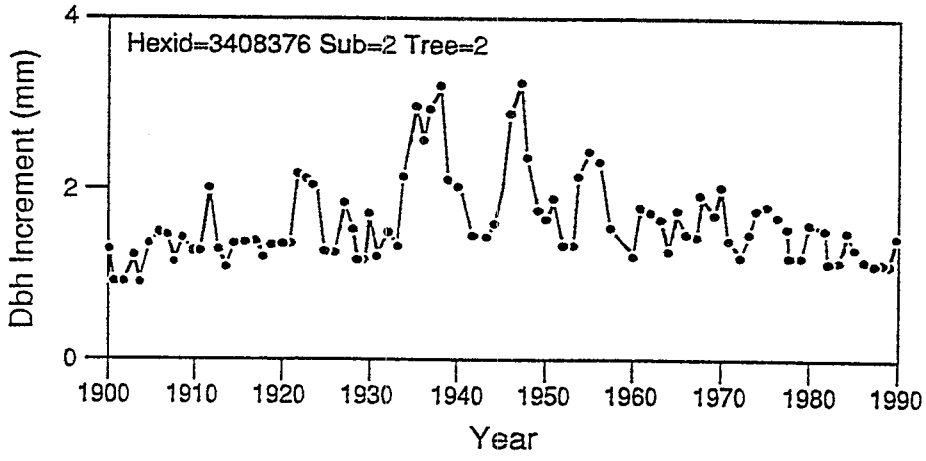

Figure 4-2. Example 90-year growth trend.

4.4.3 Statistical Considerations

The sampling efficiency for the dendrochronology protocols was investigated using the statistical methodology discussed in Section 1, Statistical Methodology. This efficiency analysis compares the variability accrued at each sampling stage with the added costs of a sample at that stage. The analysis then produces estimates of the number of samples at each stage to provide a given overall regional variance estimate at the lowest overall cost.

The cost components (Table 4-1) used in the evaluation are based on the average times required to set up and make measurements on a new plot location, a new subplot in a given plot, and further subsampling units. The subsampling costs are the times required for locating and coring sample trees. These times were recorded as part of the logistics evaluations of the pilot measurements.

For dendrochronology, a four-stage sampling scheme was originally proposed: plots, subplots within plots, trees within subplots, and cores within trees. The variables analyzed using this technique are the average core increments for the last five, ten, and fifteen years, with 1990 being the last full year available.

Analysis of variance components for the four-stage model led to a design alteration. Essentially all the variability between subplots was explained by tree-to-tree variability. Not only were the mean squares not significantly different from zero, but the variance estimates were consistently negative. This led to an alternative model: plots, trees within plots, and cores within trees. The cost component of trees within plots (Table 4-1) encompasses the time required to establish the subplot and select an appropriate sample tree. Over 80 percent of this time is due to the time required for sample tree selection.

Table 4-1 shows the costs, mean squares, and measurement error estimates used in this analysis. The measurement error estimates were calculated from duplicate readings on tree core increments.

TABLE 4-1. COST, MEAN SQUARE, AND ERROR ESTIMATES FOR DENDROCHRONOLOGY

Effect	Cost ($)	5-Year Average	10-Year Average	15-Year Average
Plot	3.33	14.40	32.62	4.94
Subplot/Tree	0.66	5.85	4.76	1.58
Core	0.08	0.369	0.324	0.121
Meas. Error	–	0.000634	0.000138	0.000091

Using the formulas given in Section 1, these values gave the following estimates for the optimal number of trees and cores per tree (Table 4-2).

TABLE 4-2. ESTIMATED OPTIMAL SUBSAMPLE SIZES

	5-Year Average	10-Year Average	15-Year Average
Trees per Plot	1.49	0.86	1.30
Cores per Tree	0.73	0.76	0.81

Rounding up, we see that given an appropriate number of plots, two trees per plot and one core per tree would provide an adequate estimate for regional estimation. Thus the current design is obtaining enough material for dendrochronological purposes. There is currently not enough information to determine if the variability at the plot level meets program needs, and so two trees with only one core per tree may not be adequate for all program goals. No information is available to determine if an adequate sample is being obtained for elemental analysis.

4.5 Conclusions and Recommendations

4.5.1 Equipment

Obtaining high-quality increment cores requires adherence to several guidelines. The increment borer equipment must be sharp and free of sap and dirt. The borer must be carefully started

in the tree with even pressure to prevent corkscrewing. Using an increment borer starter is highly recommended for maintaining consistent directional pressure on the borer to prevent corkscrewing. Corkscrewing was evident on many of the cores. A core usually breaks at each bend in the corkscrew when being glued in the mounting stick.

4.5.2 Field Sampling

The objectives for dendrochronology were to determine if the sampling intensity and tree selection protocols were adequate for quantifying dbh growth rates and trends for the state of Georgia. The pine cores were much easier to extract, handle, prepare, and measure than cores from most other tree species. Cores from oak were more difficult to extract and often had reaction wood that made measuring increments difficult.

If all plots were completely forested, all sample trees cored, all cores completely labelled, and all cores appropriate for analysis, a maximum of 264 cores would have been available from the 33 plots. The cores from hardwood trees were much more difficult to accurately date and measure than the cores from softwoods. Hardwood cores had a greater frequency of potentially missing or false rings. The ring boundaries were often obscured by reaction wood, making accurate measurement of increment difficult.

The pith was frequently missed by one to many rings. Since the original intent for extracting the cores was for tree core elemental analysis and not dbh increment, a core that included the pith was not as critical. If the core misses the pith by many rings (cm), obtaining an accurate measure of increment becomes increasingly difficult towards the pith. In addition, the increment obtained when approaching the pith is not from the same radius from bark to pith. The increment is from an arc of radii extending from the original radius to a radius 90° to the side of the pith from which the core was actually taken. For example, if a core misses to the right of the pith, the measurements near the pith represent increments from radii up to 90° to the right of the bark-to-pith radii.

Many of the mounted cores did not have complete label information. All codes from the field label were to be transferred to the mounting stick. Evidently the field labels were not completed properly. All information required on a label should be recorded before leaving the site. The hexagon, subplot, tree, and core numbers, and species must always be completely filled in for proper sample identification and tracking beginning in the field and continuing to analysis.

4.5.3 Handling and Preparation

Cores should be handled as little as possible between extraction and measurement. Each core should be placed in a straw or some storage container in a consistent manner (pith end first), leaving the bark attached. Many of the cores had the bark end removed, making it difficult to determine if just the bark or the bark and last one to several years were removed. Bark ends may have broken off after

the core had been shipped from the field. Each handling results in more broken cores and the potential for broken segments to be lost, get out of proper sequence, or be mixed with portions of cores from other trees. Two mounted cores consisted of portions of cores from different species.

The cores used in this study were shipped from the field to Las Vegas for tracking, drying, and storage. Some cores were glued in crude holders. The cores were shipped to Virginia Polytechnic Institute and State University for gluing into core holders. The core holders were made by making saw cuts into a wood stick so that the core could be glued into the rectangular slot. The rectangular slot provided less surface area contact than a rounded slot for the core to be completely stabilized for surfacing. A good core holder has a curved slot routed out that matches the size of the core. The core should snap into place when being glued in the holder. No amount of sanding, measurement, or analysis will overcome problems with an improperly extracted, dried, and/or mounted core.

A tree core measurement laboratory should be identified to which cores can be sent for drying, mounting, dating, and measurement. The quality control then becomes the responsibility of a clearly identified laboratory.

SECTION 5
ROOT DISEASE

S.A. Alexander and M. Baldwin

5.1 Introduction

As part of the pilot research project entitled *FY91 Indicator Evaluation Field Study for Environmental Monitoring and Assessment Program - Forests (EMAP-F)*, we examined root samples in plots in western Georgia for root disease. Sampling began June 16, 1991, and lasted through September 4, 1991. We used two root sampling techniques: the two-root method (Section 6 of the FHM Field Methods Guide), in which two roots of the sample trees were directly sampled; and the cubic foot method (Section 9 of the FHM Field Methods Guide), in which roots were taken from a cubic foot of soil near a sample tree, but not specifically identified with a particular tree. A soil core was taken from the center of the cubic foot sample for quantification of ectomycorrhizae. Root and soil core samples were stored, refrigerated, and shipped on ice weekly to the Forest Pathology Laboratory at Virginia Polytechnic Institute and State University (VPI&SU).

In 37 plots, a total of 120 trees were sampled by the two-root method; 21 of those plots were also sampled by the cubic foot method. Root isolations were made specifically for *Leptographium procerum* (Kendrick) Wing., *Armillaria(Fr.:Fr.)* Staude spp. and *Heterobasidion annosum* (Fr.:Fr.) Bref. To maintain quality assurance, a training workshop was held for FHM field crews in Asheville, North Carolina, June 10–14, 1991. A field audit of the procedures was conducted on July 1, 1991. The field crew was debriefed on October 1 and 2, 1991. Details of the training and debriefing can be found in the FY91 Field Study Operations Report.

5.2 Evaluation of Root Disease Indicator

5.2.1 Objectives

The objectives were to: (1) determine the incidence of root disease; and (2) compare the two detection methods.

5.2.2 Materials and Methods

The two-root samples received at the Forest Pathology Laboratory at VPI&SU were logged in with the date they were received and assigned an index number. This number is part of a sequential indexing system designed for sample tracking and data recording. A metal identification tag with the index number accompanied each sample through processing. The samples were stored under refrigeration until processed. There were four root chips per sample, two from each of two roots per

sample tree. Chips were at least 2.5 cm^3 to provide enough tissue for fungal isolations. Samples were washed under running tap water for five minutes to remove dirt and debris, air dried on paper toweling for 15 minutes, and then flamed briefly with 95% ethanol to sterilize the surface. The edges and bark of each chip were removed using sterile pruners to expose clean wood. Blocks of wood approximately 1 cm^3 were removed and aseptically placed on sterile agar growing media. This processing employed one general medium (2% malt extract agar) and three media selective for *L. procerum* (McCall and Merrill, 1980), *Armillaria* spp. (Russell, 1956) and *H. annosum* (Alexander and Skelly, 1973).

One block from each root chip was placed on each plate. All samples were plated within one week of receipt. Plates were incubated at 20°C for three weeks and examined under a binocular dissecting microscope (7x to 60x) for the presence of pathogenic fungi. Pure cultures were obtained through conidial transfer and deposited in the VPI&SU Forest Pathology Laboratory culture collection. The original plates were re-examined after 60 days for slow growing fungi before being autoclaved and discarded.

5.2.3 Results

L. procerum was isolated from three trees on three separate plots. *H. annosum* was isolated from two trees on two separate plots. No *Armillaria* species were isolated.

5.3 Root Sampling for Evaluation of Root Diseases and Mycorrhizae

5.3.1 Objective

The objective was to determine whether the cubic foot root collection method for detection of pathogens, as described by Alexander (1989), can be used to obtain samples appropriate for quantifying ectomycorrhizal fungi. We also compared this method to the two-root technique for pathogen detection.

5.3.2 Materials and Methods

5.3.2.1 Root Disease Quantification

The cubic foot method was adapted from the Annosus Sampling Procedure (ASP) (Alexander, 1989). Because the ASP was developed for detection of annosus root disease in pine plantations, we used this method only when the sample tree was a pine species. We selected an area of 30.5 cm^2 (12 in^2) one to four meters from the sample tree, in the direction of other pine trees, if present, to maximize the number of tree roots sampled. The duff layer was removed and the square excavated to a depth of 30.5 cm. All tree roots 0.32 cm (0.12 in) and larger were collected and placed in a plastic bag. Soil was returned to the hole and the duff layer replaced. The soil core and root samples were

placed on ice for shipment to the Forest Pathology Laboratory at VPI&SU. In all, crews sampled 21 plots.

Samples were logged in when received and assigned the same index number as the accompanying two-root sample described in Section 5.2. They were stored under refrigeration and evaluated for root disease within seven days of receipt. Pine roots were examined for disease symptoms of white stringy rot, resin soaking, and staining. All other types of roots were discarded. The number of symptomatic roots and the total number of roots were recorded. After the roots were washed and surface sterilized with a 10% bleach solution, a 1-cm segment of each root was aseptically plated onto each of the four media used for the two-root method. Sample plates were incubated and examined as described in Section 5.2.

5.3.2.2 Mycorrhizal Quantification

Within the square described in 5.3.2.1, a soil core 76 mm (3 in) in diameter and 152 mm (6 in) deep was taken through the litter layer and placed in a plastic bag. Mycorrhizal soil cores were washed for 10 minutes in a North Carolina State University Semi-Automatic Soil Elutriator onto a 0.7-mm screen to remove the soil from the roots. The wet roots were placed in plastic bags and frozen until they could be counted. At that time, the bags were removed from the freezer and thawed in warm water; the contents were placed in water in a standard glass petri dish 100 mm in diameter. Roots were examined under a binocular dissecting scope (7x to 60x) and the active ectomycorrhizal (EM) tips were counted. Criteria used to determine active and inactive EM were taken from Harvey et al. (1976). Individual tips were counted whether they were single or part of a complex structure. For each sample, tips representative of each morphological type were preserved in formalin, acetic acid, and alcohol (FAA) for later staining and microscopic confirmation of Hartig net. No attempt was made to quantify the different morphological types. The logging and washing process took approximately one hour per sample; it took an average of four to five hours per sample (range: 1-20 hours) to count EM tips. We sampled 20 plots.

5.3.3 Results and Discussion

Of the 20 plots sampled, eight contained roots showing disease symptoms. The mean number of roots in cubic foot samples from these eight plots was 20 ± 11, of which 2 ± 1 were symptomatic. The only symptom observed was resin soaking. None of the root pathogens of concern were isolated using the cubic foot method. A qualitative comparison of the root sampling methods indicates that the two-root system may be as effective as the cubic foot method in detecting root disease pathogens. No pathogenic fungi were isolated directly from symptomatic roots in cubic foot samples from eight of the plots, even though the two-root method confirmed root disease in two sample trees from two of those plots.

TABLE 5-1. ECTOMYCORRHIZAL TIPS PER LITER OF SOIL

Plot Number	n	EM Tips per Liter
3408435	2	991 ± 101
3308476	1	2,964
3308481	2	248 ± 152
3308563	3	606 ± 566
3208365	4	1,136 ± 614
3208446	3	1,021 ± 713
3208417	2	841 ± 741
3108551	2	1,697 ± 42
3108431	4	2,403 ± 1,753
3108368	4	1,792 ± 2,292
3008386	4	430 ± 366
3108311	1	5,144
3008175	2	1,386 ± 319
3208273	1	2,518
3208148	2	1,673 ± 202
3208571	1	2802
3308323	3	1,375 ± 620
3408148	3	233 ± 175
3408382	2	967 ± 503
3408218	2	574 ± 303

The mycorrhizal study was intended to perform an overall evaluation of the procedure. The field sampling method was easily performed over the soil types and conditions found in the study. Laboratory processing of the samples was cumbersome and time consuming. One sample alone took 20 hours to count. The mean number of EM tips in the 20 plots sampled was 1,540 ± 1,150 per liter of soil (Table 5-1). These numbers were within ranges that could be expected over a variety of soil types and stand ages. Harvey et al. (1979) found a range of 200 to 1,700 EM tips per liter in three forest habitat types in western Montana. The variability of the mycorrhizal counts was too high to make comparisons among the plots. This was to be expected, since ectomycorrhizal populations are known to be highly variable in distribution within an area (Marks et al., 1967; Alexander, 1985), and few

samples were taken. In addition, within-sample variability has been shown to be very high. Alexander (1985) estimated that, based on core diameter, 44 to 431 cores would need to be taken in a sitka spruce plantation to minimize within- and between-sample variability. Core size (0.6895 L) was very large, and the distribution of EM within the samples was irregular, preventing subsampling. Work is needed to reduce the core size and/or develop a suitable subsampling procedure. The number of samples taken per plot will have to be increased to compensate for the high degree of variability.

SECTION 6
EVALUATION OF DIFFERENT INSTRUMENTS FOR MEASURING TREE HEIGHT

W.A. Bechtold, V.J. LaBau, H. Schreuder, and M.S. Williams

6.1 Introduction

Tree height growth is a potential indicator of forest health, since height growth may be restricted by anthropogenic or natural factors that impose stress on forests. The existing instruments for measuring standing tree height are adequate for most applications, if the tree base and top are well defined and clearly visible. However, the variance and bias of the height estimates could be large for tall trees in dense stands or for trees that do not have well-defined tops. These errors in measurement could be as large or larger than tree growth between two successive measurements.

An opportunity to evaluate some of the currently available height measurement instruments (including a laser-driven instrument) for forest health monitoring presented itself in the summer of 1991. Tree climbers, who were employed to collect foliage samples for chemical analysis, measured the true height of standing trees. Readings from several different height measuring instruments were compared to the values obtained by the tree climbers. We used these data to determine if any of the instruments were accurate enough to make using tree growth as an indicator of forest health practical.

6.2 Methods

6.2.1 Study Planning and Preparation

All data collected were from Forest Health Monitoring (FHM) plots in Georgia. True heights for all trees were taken while crews collected foliage samples from the tree crowns. One crew member climbed as far as possible up each tree. From that point, the climber used a pole to measure the remaining distance to the top of the tree. To determine when the pole was at the top of the tree, sightings were taken from the ground and by the crew member in the tree. When all crew members were in agreement, they calculated the total height from the ground to the top of the pole. Although some measurement error existed in this method, no alternative method could have been implemented that would have met the time and cost constraints, and still represented realistic measurement situations, such as varying terrain, canopy, tree height distributions, and species mix.

Readings from a Laser Height Finder (Jasumback, 1991), a Suunto Clinometer (Husch et al., 1982), a Spiegal Relaskop, an Enbeeco Clinometer, and a Spiegal Tele-relaskop (Bitterlich, 1978; Husch et al., 1982) were recorded at the same locations using a tripod to steady each instrument. This

procedure required adapting a tripod mount for the Suunto Clinometer, which is designed to be hand-held. All other instruments had thumb-screw systems to accommodate tripods.

A mix of scales on the instruments was used so that no two instruments successively utilized the same scale. The Suunto Clinometer and the Enbeeco used the percent scale, the Relaskop used the topo scale, and the Tele-relaskop and the Laser Height Finder used the degree scales. This mix of scales was intended to interrupt the tendency to drive the current readings to be the same as those obtained with the previous instrument. The following formulas give the scale conversion for each of the instruments:

- Clinometer [Percent Scale]
  Height = (Top reading + Base reading) x (Level Distance/100)

- Relaskop [Topographic Scale]
  Height = (Top reading + Base reading) x (Level Distance/66)

- Tele-relaskop [Degree Scale]
  Height = [Level distance x tan(Top reading)] + [Level distance x tan(Base reading)]

- Enbeeco [Percent Scale]
  Height = (Top reading + Base reading) x (Level distance/100)

- Laser [Degree Scale]
  Height = [Level distance x (tan(Top reading)] + [Level distance x tan(Base reading)]

Before these computations could be made, all level distances had to be computed, since the distances collected in the data set were slope distances. The formula for converting slope distance to level distance is:

Level Distance = Slope Distance x [cos(slope)], where slope = cotan(percent slope/100).

As an example, given a slope distance of 73 feet on a 4% slope, Level Distance = 73 x {cos[cotan(4/100)]} = 73 x (cos 2.29) = 73 x .9992 = 72.94 feet (22m).

6.2.2 Data Set Descriptions

The original data set contained instrument readings from six different observers, but only one observer collected enough data to permit reasonable comparisons among all five instruments. Therefore, most of the analyses that follow are based on the data collected by the single observer. To determine if differences between observers impacted the results, all analyses were repeated with a pooled data set that included all observers. Detailed output from the pooled data sets are not presented in this report, but the few differences are noted in the results. In addition, only 15 observations were made with the Laser Height Finder, which was an preproduction model and not

available until late in the field season. Due to the small number of observations collected, it was difficult to make any definite conclusions about the Laser Height Finder.

6.2.3 Evaluation Techniques

Four linear models were fit to the data to test the bias and efficiency of the height measurements, and to determine if there is an upper limit to the reliability of the instruments. The models were first fit using all species of trees together, then softwood trees only. Hardwoods were removed to examine the effect of extracting additional variability caused by poorly defined central stems typical of many hardwood species. Tables 6-1 through 6-4 show the results of the regression analysis.

Ideally, the correlation between true height and measured height is 1, thus the first model was specified as

$$h_t = \beta h_m + \varepsilon, \qquad [1]$$

where h_t is the true height and h_m is the measured height. The error terms, ε, are assumed to be normally distributed with mean 0 and variance σ^2.

The assumption of equal variance in the error term is highly suspect. A reasonable assumption is that the error in measurement increases with tree height. Therefore the model

$$e^{ht} = e^{\beta hm} + \varepsilon_1 \qquad [2]$$

was fit to remove the effect of the heteroscedasticity.

For completeness, intercept terms were added to [1] and [2], yielding

$$h_t = \alpha + \beta_{hm} + \varepsilon \qquad [3]$$

and

$$e^{ht} = e^{\alpha+\beta hm} + \varepsilon_1. \qquad [4]$$

Analysis of the coefficients from values given by models [1]–[4] was used to test if a bias in estimation existed for any of the instruments. Confidence intervals for models [1] and [2] allowed the hypothesis

$$H_0 : \beta = 1$$

to be tested. For models [3] and [4], the hypothesis

$$H_0 : \alpha = 0, \beta = 1$$

was tested.

TABLE 6-1. REGRESSION COEFFICIENTS, STANDARD ERRORS, 95% CONFIDENCE INTERVALS, AND R^2 VALUES FOR UNTRANSFORMED DATA AND ALL TREES

Instrument	Parameter	Standard Error	Confidence Interval	R^2	n
Clinometer					
Without Intercept (model [1])					
β	0.9888	0.0084	(0.9721, 1.0056)	0.9462	n=90
With Intercept (model [3])					
α	3.6659	1.3941	(0.8954, 6.4364)	0.9501	
β	0.9329	0.0228	(0.8876, 0.9781)		
Relaskop					
Without Intercept (model [1])					
β	0.9835	0.0090	(0.9655, 1.0016)	0.9372	n=90
With Intercept (model [3])					
α	3.6330	1.5225	(0.6074, 6.6586)	0.9410	
β	0.9283	0.0248	(0.8791, 0.9776)		
Tele-relaskop					
Without Intercept (model [1])					
β	0.9950	0.0160	(0.9628, 1.0272)	0.8990	n=51
With Intercept (model [3])					
α	4.4237	2.5880	(-0.7771, 9.6245)	0.9047	
β	0.9266	0.0430	(0.8403, 1.0130)		
Enbeeco					
Without Intercept (model [1])	0.9746	0.0088	(0.9570, 0.9921)	0.9505	n=76
β					
With Intercept (model [3])	3.3680	1.5062	(0.3666, 6.3693)	0.9537	
α	0.8835	0.0372	(0.8093, 0.9576)		
β					
Laser					
Without Intercept (model [1])					
β	1.0008	0.01858	(0.9609, 1.0406)	0.9250	n=15
With Intercept (model [3])					
α	4.4341	4.9531	(-6.2665, 15.1346)	0.9293	
β	0.9387	0.0718	(0.7836, 1.0938)		

TABLE 6-2. REGRESSION COEFFICIENTS, STANDARD ERRORS, 95% CONFIDENCE INTERVALS, AND R^2 VALUES FOR LOG TRANSFORMED DATA AND ALL TREES

Instrument	Parameter	Standard Error	Confidence Interval	R^2	n
Clinometer					
Without Intercept (model [2])					
β	1.0003	0.0021	(0.9961, 1.0045)	0.9702	n=90
With Intercept (model [4])					
α	0.2074	0.0669	(0.0745, 0.3403)	0.9731	
β	0.9485	0.0168	(0.9151, 0.9819)		
Relaskop					
Without Intercept (model [2])					
β	0.9984	0.0021	(0.9942, 1.0027)	0.9687	n=90
With Intercept (model [4])					
α	0.1228	0.0727	(-0.0216, 0.2673)	0.9697	
β	0.9678	0.0182	(0.9316, 1.0041)		
Tele-relaskop					
Without Intercept (model [2])					
β	1.0024	0.0048	(0.9926, 1.0120)	0.9215	n=51
With Intercept (model [4])					
α	0.3822	0.1312	(0.1046, 0.6599)	0.9321	
β	0.9065	0.0349	(0.8362, 0.9767)		
Enbeeco					
Without Intercept (model [2])					
β	0.9963	0.0023	(0.9918, 1.0008)	0.9726	n=76
With Intercept (model [4])					
α	0.1375	0.0735	(-0.0090, 0.2839)	0.9735	
β	0.9623	0.0183	(0.9257, 0.9988)		
Laser					
Without Intercept (model [2])					
β	1.0017	0.0041	(0.993, 1.010)	0.9597	n=15
With Intercept (model [4])					
α	0.2665	0.2086	(-0.1842, 0.7172)	0.9642	
β	0.9380	0.0501	(0.8297, 1.0462)		

TABLE 6-3. REGRESSION COEFFICIENTS, STANDARD ERRORS, 95% CONFIDENCE INTERVALS, AND R^2 VALUES FOR UNTRANSFORMED DATA WITH ALL HARDWOOD TREES REMOVED

Instrument	Parameter	Standard Error	Confidence Interval	R^2	n
Clinometer					
Without Intercept (model [1])					
β	0.9846	0.0096	(0.9655, 1.0037)	0.9480	n=68
With Intercept (model [3])					
α	3.9622	1.6137	(0.7403, 7.1841)	0.9523	
β	0.9262	0.0255	(0.8753, 0.9771)		
Relaskop					
Without Intercept (model [1])					
β	0.9837	0.0106	(0.9625, 1.0048)	0.9363	n=68
With Intercept (model [3])					
α	4.1243	1.8004	(0.5297, 7.7189)	0.9410	
β	0.9229	0.0284	(0.8661, 0.9797)		
Tele-relaskop					
Without Intercept (model [1])					
β	0.9983	0.0195	(0.9589, 1.0377)	0.8961	n=41
With Intercept (model [3])					
α	4.3524	3.1092	(-1.9418, 10.6467)	0.9012	
β	0.9335	0.0501	(0.8320, 1.0350)		
Enbeeco					
Without Intercept (model [1])					
β	0.9707	0.0098	(0.9511, 0.9903)	0.9535	n=59
With Intercept (model [3])					
α	3.6061	1.7017	(0.1984, 7.0138)	0.9569	
β	0.9197	0.0259	(0.8679, 0.9715)		
Laser					
Without Intercept (model [1])					
β	0.9899	0.0171	(0.9517, 1.0284)	0.9542	n=11
With Intercept (model [3])					
α	5.1553	4.3162	(-4.6086, 14.9192)	0.9605	
β	0.9185	0.0621	(0.7780, 1.0589)		

TABLE 6-4. REGRESSION COEFFICIENTS, STANDARD ERRORS, 95% CONFIDENCE INTERVALS, AND R^2 VALUES FOR LOG TRANSFORMED DATA FOR SOFTWOOD TREES ONLY

Instrument	Parameter	Standard Error	Confidence Interval	R^2	n
Clinometer					
Without Intercept (model [2])					
β	0.9996	0.0025	(0.9946, 1.0047)	0.9702	n=68
With Intercept (model [4])					
α	0.2321	0.0761	(0.0802, 0.3842)	0.9739	
β	0.9421	0.0190	(0.9042, 0.9801)		
Relaskop					
Without Intercept (model [2])					
β	0.9989	0.0025	(0.9938, 1.0040)	0.9694	n=68
With Intercept (model [4])					
α	0.1242	0.0834	(-0.0422, 0.2907)	0.9704	
β	0.9681	0.0208	(0.9266, 1.0097)		
Tele-relaskop					
Without Intercept (model [2])					
β	1.0031	0.0060	(0.9911, 1.0152)	0.9220	n=40
With Intercept (model [4])					
α	0.3595	0.1596	(0.0364, 0.6827)	0.9312	
β	0.9133	0.0403	(0.8318, 0.9949)		
Enbeeco					
Without Intercept (model [2])					
β	0.9956	0.0026	(0.9904, 1.0009)	0.9743	n=59
With Intercept (model [4])					
α	0.1370	0.0815	(-0.0262, 0.3002)	0.9755	
β	0.9620	0.0202	(0.9220, 1.0024)		
Laser					
Without Intercept (model [2])					
β	1.0000	0.0042	(0.9907, 1.0092)	0.9730	n=11
With Intercept (model [4])					
α	0.3349	0.1800	(-0.0723, 0.7421)	0.9805	
β	0.9199	0.0432	(0.8221, 1.0177)		

R^2 values were used as an indicator of goodness of fit. For this study, R^2 is defined as

$$R^2 = 1 - \frac{SSE}{SST}$$

where

$$SSE = \sum_{i=1}^{n} (h_{t_i} - \hat{h}_{m_i})^2$$

$$SST = \sum_{i=1}^{n} (h_{t_i} - \bar{h})^2$$

and $\hat{h}_{m_i}$ is the estimated height generated from the models described above, and $\bar{h}$ is the mean of the true heights.

To determine if there is a specific tree height at which ocular estimates are no longer accurate, a visual comparison of model errors was performed. The visual comparison entailed graphing the measured height versus the true height to determine if a significant error pattern could be identified. Figures 6-1 through 6-5 show the fit of model [1] to the data for all trees. Figures 6-6 through 6-10 show the fit of model [1] to the data with softwoods only.

After the bias and efficiency of each instrument had been evaluated, the next goal was to determine if any instrument was accurate enough to measure the growth of trees between successive growth cycles. Time constraints would not allow us to collect data at two time periods for comparison, so we evaluated the magnitude of the error for a single measurement. We determined that the growth of a tree could not be measured accurately enough if the amount of error associated with a single measurement was as large as or larger than the expected growth between successive measurements.

A comparison of model errors was performed by computing the average absolute error between the model estimates and the true heights by 10-foot (3.0 meter) height classes. These values were computed using the formula

$$\sum_{i=1}^{n_h} \frac{|\beta h_m - h_t|}{n_h},$$

where n_h is the number of trees in a given height class. Ten-foot (3.0 meter) height classes were used. Average errors in each height class provided a good indicator of how well tree growth could be measured with each of the instruments. If the average error in a given height class was large relative to the expected growth between successive measurement periods, no useful information about tree growth could be collected. Table 6-5 gives the error analysis results for all trees and Table 6-6 gives the analysis when data for hardwood trees were removed.

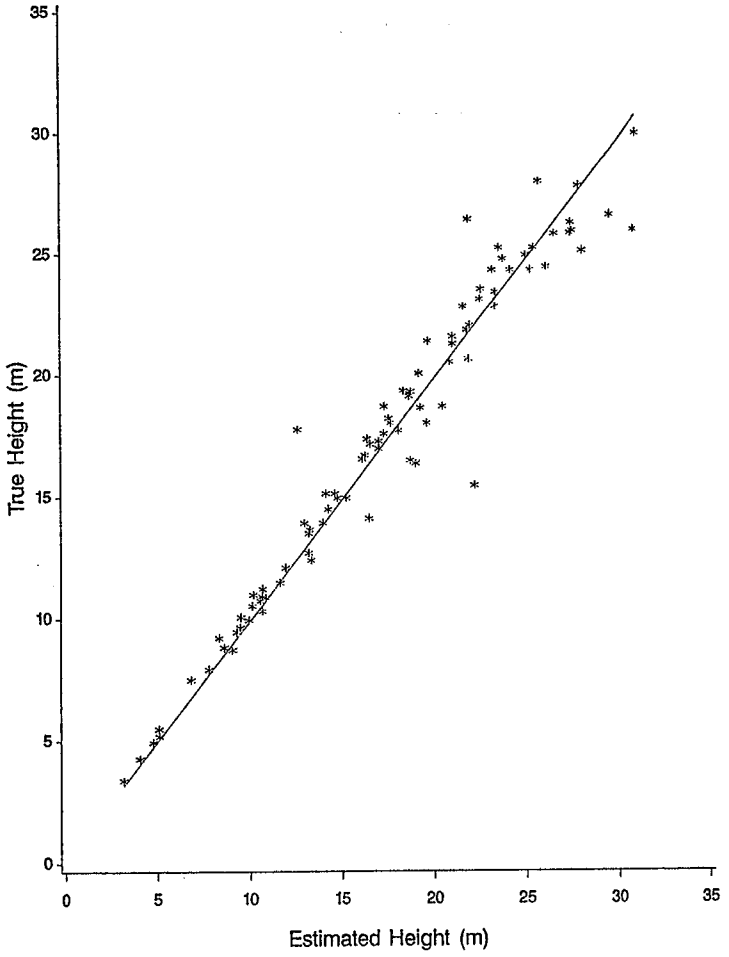

Figure 6-1. True height versus estimated height using the Clinometer (all species).

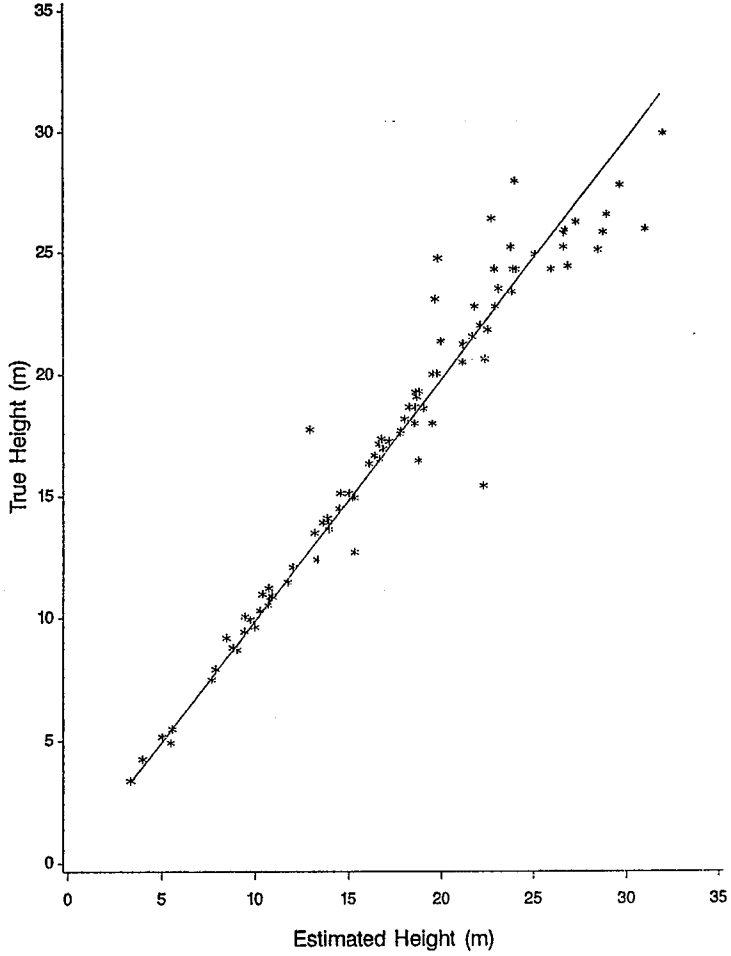

Figure 6-2. True height versus estimated height using the Relaskop (all species).

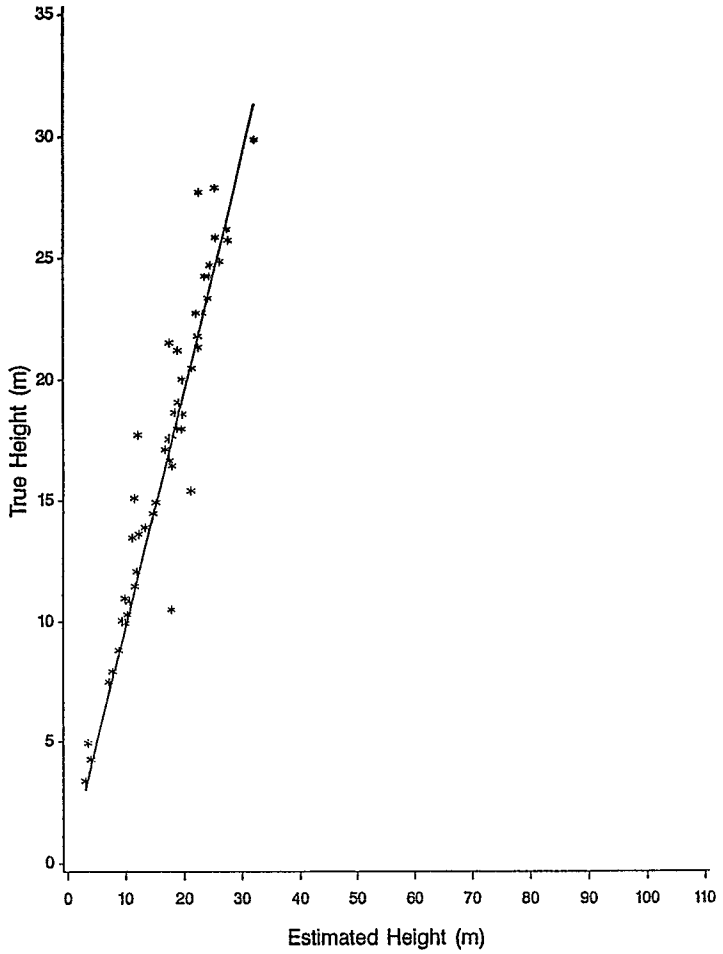

Figure 6-3. True height versus estimated height using the Tele-relaskop (all species).

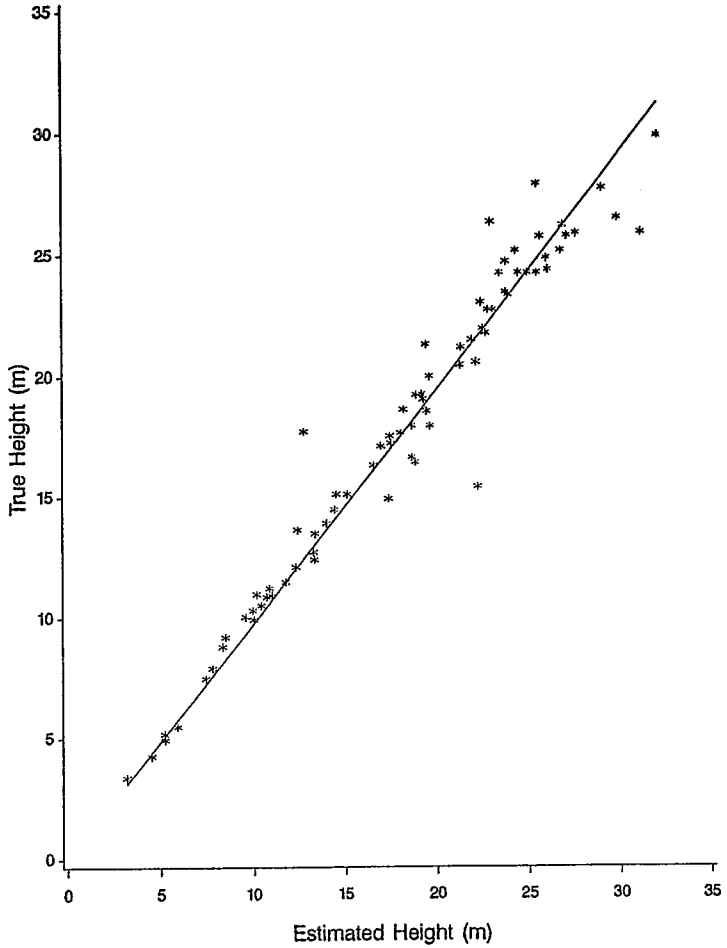

Figure 6-4. True height versus estimated height using the Enbeeco (all species).

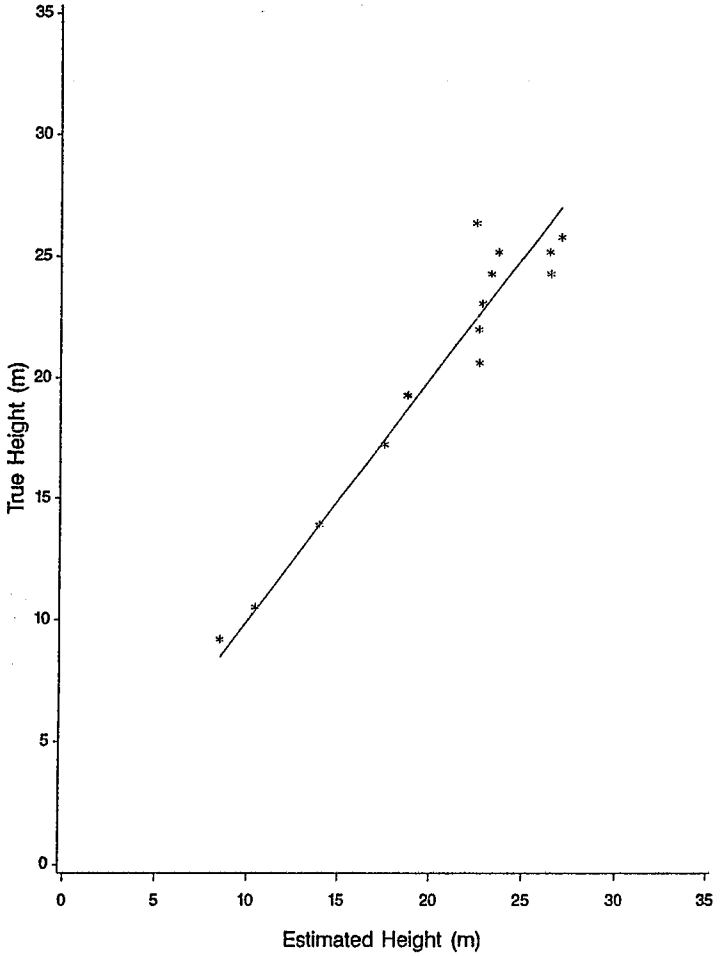

Figure 6-5. True height versus estimated height using the Laser (all species).

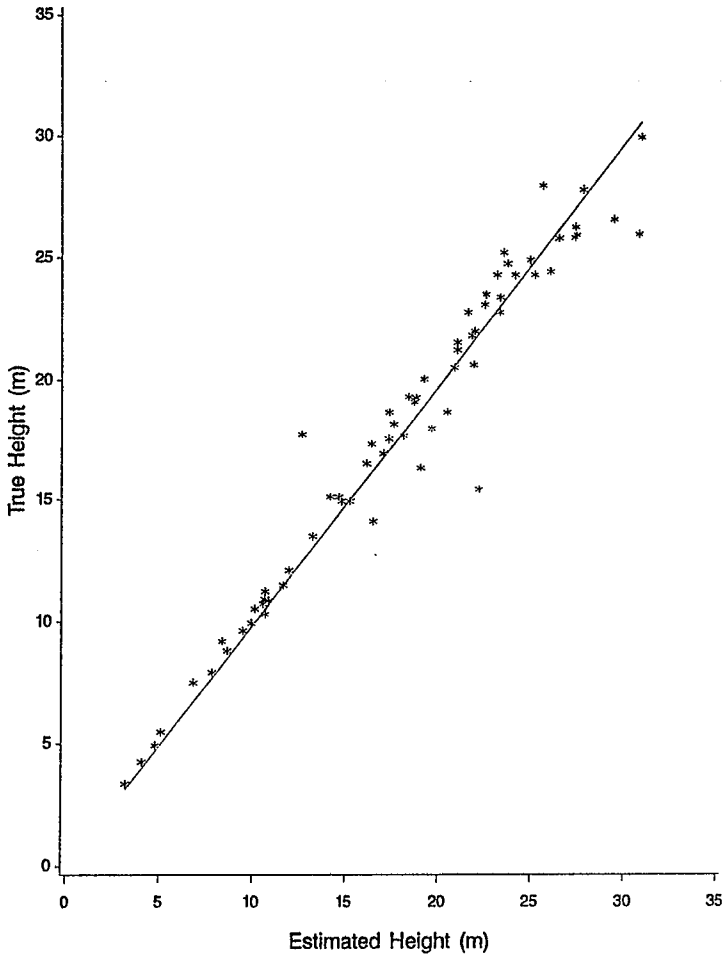

Figure 6-6. True height versus estimated height using the Clinometer (softwoods only).

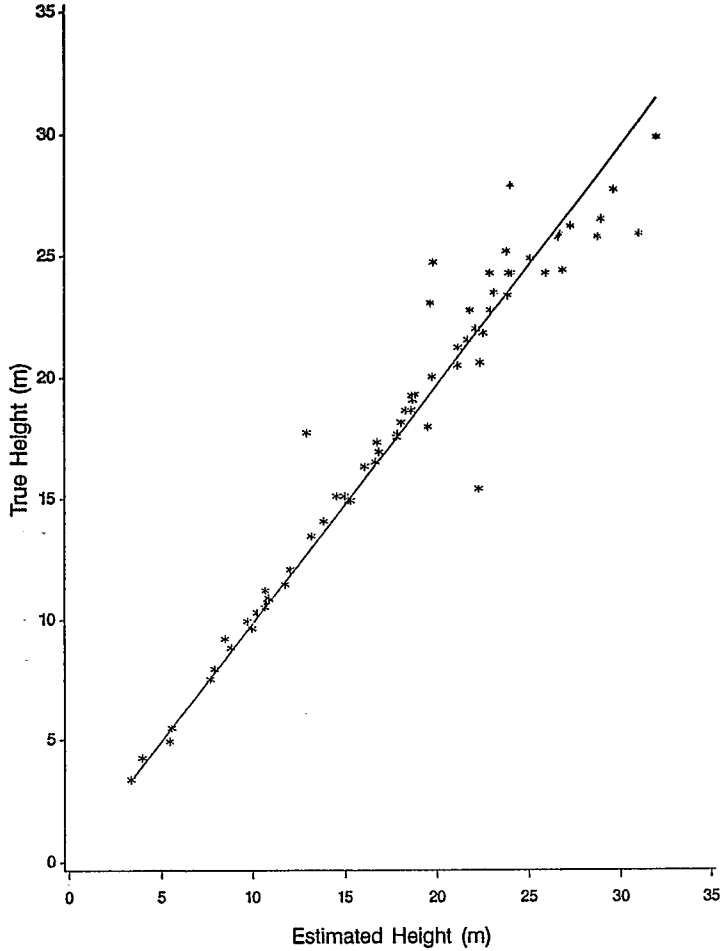

Figure 6-7. True height versus estimated height using the Relaskop (softwoods only).

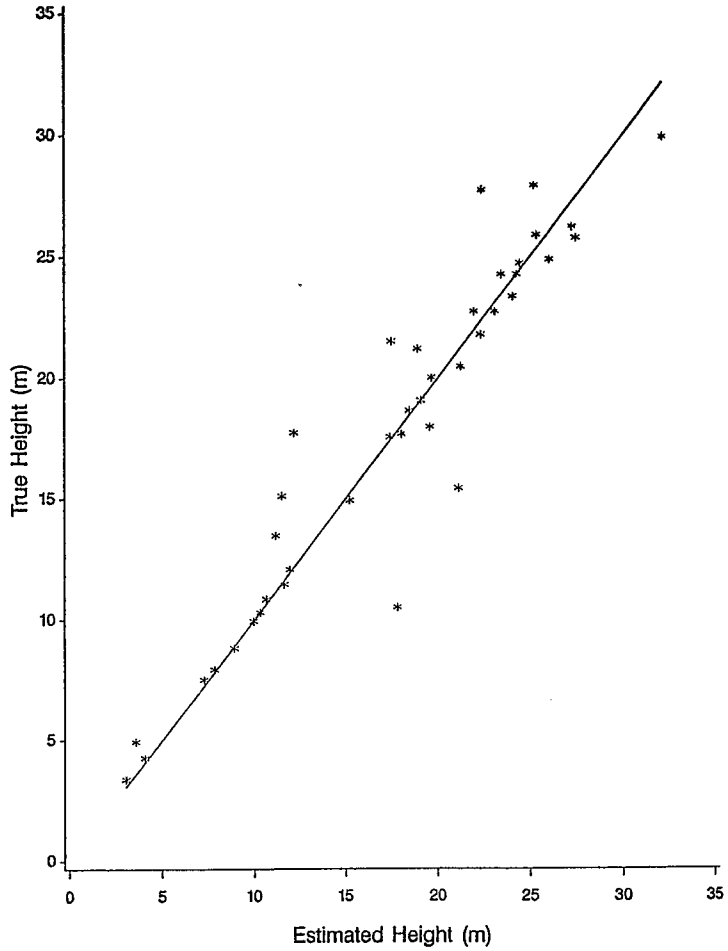

Figure 6-8. True height versus estimated height using the Tele-relaskop (softwoods only).

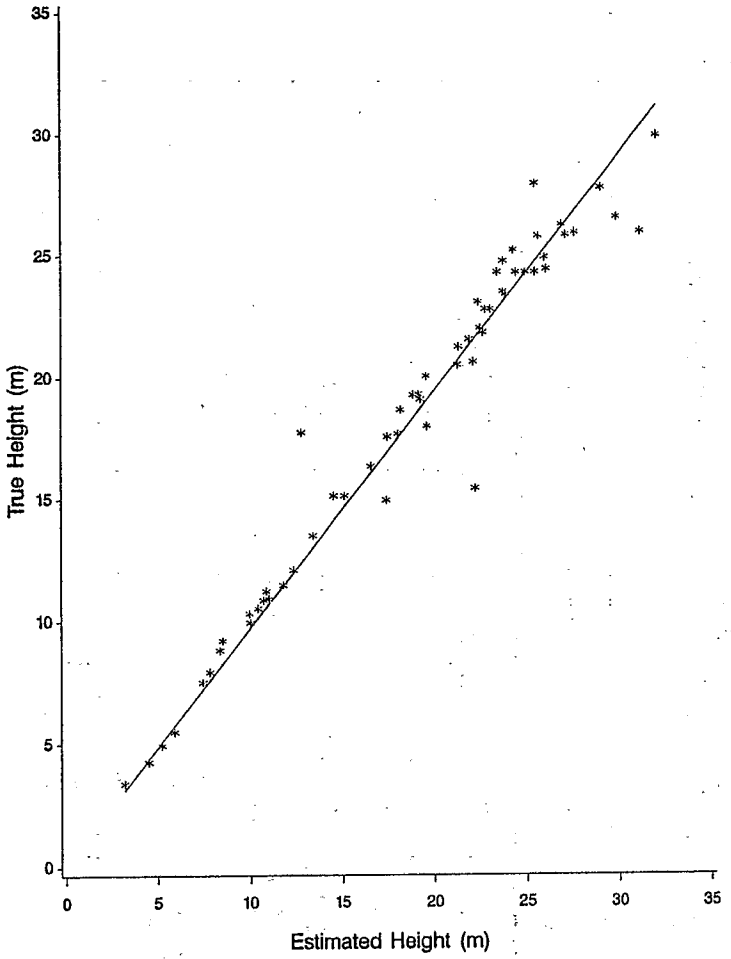

Figure 6-9. True height versus estimated height using the Enbeeco (softwoods only).

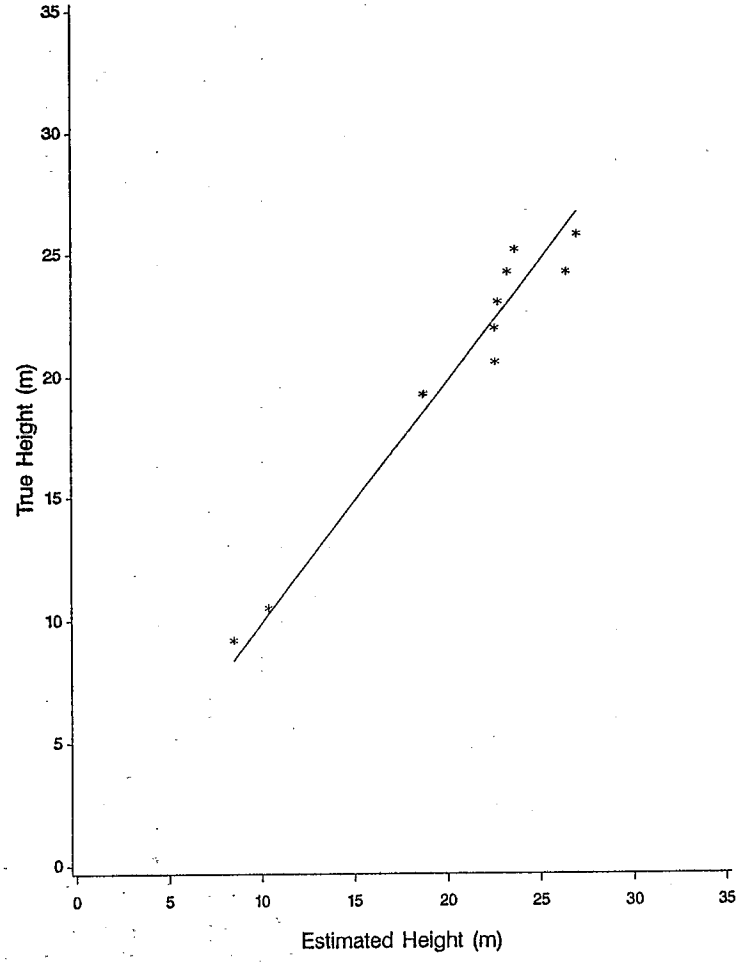

Figure 6-10. True height versus estimated height using the Laser (softwoods only).

TABLE 6-5. AVERAGE ABSOLUTE MODEL DEVIATION AND NUMBER OF TREES IN EACH 10-FOOT HEIGHT CLASS FOR ALL SPECIES, MODEL [1] FIT TO THE DATA[a]

Height Class ft (m)	Clinometer	Relaskop	Tele-relaskop	Enbeeco	Laser
10-20 (3.o- 6.1)	0.80, 5	0.71, 5	2.05, 3	0.61, 5	
20-30 (6.1-9.1)	1.20, 4	0.42, 4	0.50, 3	1.35, 3	
30-40 (9.1-12.2)	1.33, 4	1.15, 14	3.94, 8	1.51, 11	1.37, 2
40-50 (12.2-15.2)	2.22, 12	1.76, 12	4.56, 7	2.51, 10	0.03,1
50-60 (15.2-18.3)	5.09, 15	4.18, 15	6.03, 9	5.34, 11	0.64, 1
60-70 (18.3-21.3)	2.89, 11	2.12, 11	2.66, 6	2.06, 9	3.38, 3
70-80 (21.3-24.4)	2.69, 13	3.23, 13	3.37, 8	1.97, 13	3.32, 4
80-90 (24.4-27.4)	5.86, 13	6.96, 13	3.01, 5	5.16, 12	6.45, 4
90-100 (27.4-30.5)	3.84, 3	7.98, 3	11.31, 3	5.44, 3	

[a] The model used is $h_t = \beta h_m$.

TABLE 6-6. AVERAGE ABSOLUTE MODEL DEVIATION AND NUMBER OF TREES IN EACH 10-FOOT HEIGHT CLASS FOR SOFTWOOD TREES ONLY, MODEL [1] FIT TO THE DATA[a]

Height Class ft (m)	Clinometer	Relaskop	Tele-relaskop	Enbeeco	Laser
10-20 (3.0-6.1)	0.97, 4	0.70, 4	2.02, 3	0.65, 4	
20-30 (6.1-9.1)	1.46, 3	0.39, 3	0.48, 3	1.45, 3	
30-40 (9.1-12.2)	1.24, 11	0.93, 11	4.78, 6	1.33, 9	1.71, 2
40-50 (12.2-15.2)	2.74, 6	1.25, 6	6.78, 4	3.21, 4	
50-60 (15.2-18.3)	6.24, 10	4.98, 10	8.77, 5	7.48, 6	
60-70 (18.3-21.3)	3.07, 9	2.25, 9	2.40, 5	2.29, 8	3.56, 3
70-80 (21.3-24.4)	2.60, 12	3.04, 12	3.39, 7	1.65, 12	3.30, 4
80-90 (24.4-27.4)	5.02, 10	6.46, 10	3.08, 5	4.49, 10	4.44, 2
90-100 (27.4-30.5)	3.94, 3	8.00, 3	11.26, 3	5.29, 3	

[a] The model used is $h_t = \beta h_m$.

The top of the tree is sometimes not well defined, which means that picking a point at which to measure the top of the tree can be very subjective; two different people may choose different points as the top of a tree. For some of the trees in the data set, more than one crew member took measurements. Two crew members took a number of measurements on the same trees using all five instruments. We used a paired comparison to determine if these two crew members made significantly different estimates of tree height. The hypothesis tested was $H_0 : \mu = 0$, where μ was the average difference between height measurements. The average absolute error and median absolute error between the two observers was also compared. The formula used for the average absolute error was

$$\sum_{i=1}^{n} \frac{|h_{1i} - h_{2i}|}{n},$$

where h_{1i} and h_{2i} are the height measurements taken by the two different crew members for tree *i*. The median absolute error is the median of the $|h_{1i} - h_{2i}|$ values. Results of the tests between crew members are given in Table 6-7.

TABLE 6-7. PAIRED COMPARISON TEST RESULTS, AVERAGE AND MEDIAN ABSOLUTE ERRORS BETWEEN CREW MEMBERS, AND NUMBER OF OBSERVATIONS

Instrument	$H_0 : \mu = 0$	Average Abs. Error	Median Abs. Error	n
Clinometer	Accept H_0	2.97	1.2	29
Relaskop	Accept H_0	2.56	1.2	28
Tele-relaskop	Accept H_0	8.98	6.9	5
Enbeeco	Accept H_0	2.59	0.7	19
Laser	Accept H_0	1.71	0.9	7

6.3 Results and Discussion

Tables 6-1 through 6-4 show results for fitting models [1] through [4] to the data set with all species and to the data set with only softwood trees. The average absolute errors by diameter class are given in Tables 6-5 and 6-6.

For the Clinometer, the models without intercept terms (models [1] and [3]) had confidence intervals containing $\beta = 1$, regardless of whether all species or only softwood species were considered. In contrast, for models with intercept terms (models [2] and [4]), no confidence interval contained either $\alpha = 0$ or $\beta = 1$. R^2 values ranged from 0.9480 to 0.9739. When all species were considered, the R^2

values were consistently second largest. When only softwood trees were considered, the R^2 values were third largest, regardless of whether the data were transformed or which model was fit.

The results for the Relaskop were similar to those for the Clinometer. For the models without intercept terms (models [1] and [3]), the confidence intervals for β contained 1. When the intercept term was added (models [2] and [4]), the confidence intervals contained $\alpha = 0$ and $\beta = 1$ for both of the log transformed data sets, which may imply that the errors in fit were due to heteroscedasticity in the data. R^2 values ranged from 0.9363 to 0.9704. For all species, the R^2 values were always third largest. When only softwoods were considered, R^2 values were fourth largest.

For the Tele-relaskop, the confidence intervals contained $\beta = 1$ for the models without intercept terms. When intercept terms were added, the confidence intervals contained $\alpha = 0$ and $\beta = 1$ for the untransformed data using both the data set for all species and the data set for softwoods only. Using R^2 values as an indication of fit, the Tele-relaskop produced the worst fit for all models and data sets considered.

The Enbeeco was the only instrument that did not have confidence intervals containing $\beta = 1$ for all models without intercept terms. When model [1] was fit to the softwood data, the assumption that $h_t = h_m$ was rejected. When intercept terms were added, model [4] had confidence intervals containing $\alpha = 0$ and $\beta = 1$. R^2 values for the Enbeeco were consistently the largest when all tree species were considered. When only softwood trees were considered, the R^2 value for model [2] was the largest for all instruments and second largest when model [4] was fit.

The Laser has the distinction of being the only instrument whose confidence intervals contained $\beta = 1$ and $\alpha = 0$ under every model and data set. The R^2 values were fourth largest when all species were considered. R^2 values were the largest for the softwood data, except when model [2] was fit. In that case, the R^2 value was second largest.

The analysis of the absolute average error by diameter class is given in Tables 6-5 and 6-6. In all height classes less than 40 feet (12.2 m), the average absolute errors were generally less than 1.5 feet (0.5 m) with the exception of the Tele-relaskop, which in the 40-foot (12.2 m)class had error values of 3.94 for the data set for all species and 4.78 for the data set for softwoods only. For trees greater than 40 feet (12.2 m) tall, the error values increase. The error values range from 0.03 to 11.31 feet (0.01 to 3.45 m), with most values falling in the two- to five-foot (0.6-1.5 m)range. In most cases, removing the softwood trees from the data reduced the average absolute error. No instrument differed greatly from the others. The Tele-relaskop was the only instrument to produce average errors exceeding 10 feet (3.0 m).

The paired comparison test showed no significant difference between observers for any of the instruments. The average and median absolute errors showed similar results for the Clinometer, Relaskop, Enbeeco, and Laser. The Tele-relaskop had very large average and median absolute error

values, which could be due in part to the small number of observations available for two observers; it is consistent with the single observer results, however.

6.4 Conclusions

Results were similar for the Clinometer, Relaskop, and Enbeeco. The Tele-relaskop appeared to be slightly less accurate. Even though the results for the Laser indicate that it is the best instrument, the effectiveness of the Laser is still difficult to determine because of the limited amount of data available. In addition, the Laser height finder used in this study was an early preproduction model. Numerous design improvements have been made on current models, which may improve the accuracy of the Laser. The analysis of average and median errors indicates that errors of two to five feet (0.6-1.5 m) are common, especially for trees larger than 40 feet (12.2 m). This may be acceptable when the objective is to measure current height. However, when height growth is the objective, and the measurement cycle is as little as four to five years, average errors could exceed the amount of tree growth expected for many species and geographic areas. In addition, these errors could be conservative estimates of the expected error from repeated measurements, because tree heights would not necessarily be taken from the same point at each time period. Additional sources of variation could include new estimates of slope, slope distance, and tree lean at each time period. All these factors would increase the measurement error. With such large errors, height data obtained from standard instruments is not reliable enough at this time to make height growth a reliable indicator of forest health.

SECTION 7
REFERENCES

Alexander, I.J. 1985. Measuring mycorrhizal biomass: principles and problems. Pages 136-139 in R. Molina, ed. *Proc. 6th North American Conference on Mycorrhizae.* Bend, Oregon. 471 pp.

Alexander, S.A. 1989. Annosus root disease hazard rating, detection and management strategies in the Southeastern United States. Pages 111-116. *Symposium on Research and Management of Annosus Root disease in Western North America.* Gen. Tech. Rept. PSW-116. 177 pp.

Alexander, S.A., and J.M. Skelly. 1973. A comparison of isolation methods for determining the incidence of *Fomes annosus* in living loblolly pine. *Eur. J. For. Path.* 4:33-38.

Bailey, A.W., and C.E. Poulton. 1968. Plant communities and environmental relationships in a portion of the Tillamook burn, northwestern Oregon. *Ecology* 49:1-13.

Bitterlich, W. 1978. Single tree measurements by the Tele-relaskop—a highly efficient tool for forest inventories. Eighth World Forestry Congress, Jakarta, Indonesia.

Brenchley, W.E. 1958. *The Park Grass Plot at Rothamsted.* Rothamsted Experimental Station. Harpenden.

Cassell, D.L. 1992. Estimating optimal resource allocation for environmental monitoring networks. Pages 225-229 in *1991 Proceedings of the Section on Statistics and the Environment.* American Statistical Association, 1429 Duke Street, Alexandria, Virginia.

Chatfield, C. 1989. *The Analysis of Time Series, An Introduction.* Fourth edition. Chapman and Hall, New York.

Cochran, W.G. 1977. *Sampling Techniques.* Third edition. John Wiley and Sons, New York.

Cook, E.R., and L.A. Kairiukstis (eds). 1990. *Methods of Dendrochronology.* Kluwer Academic Publishers, Boston.

Daubenmire, R. 1968. *Plant Communities: A Textbook of Plant Synecology.* Harper & Row, New York.

Harvey, A.E, M.J. Larsen and M.F. Jurgensen. 1976. Distribution of ectomycorrhizae in a mature Douglas-fir/larch forest soil in western Montana. *For. Sci.* 22:393-398.

Harvey, A.E, M.J. Larsen and M.F. Jurgensen. 1979. Comparative distribution of ectomycorrhizae in soils of three western Montana forest habitat types. *For. Sci.* 25:350-358.

Hill, M.O. 1973. Diversity and evenness: a unifying notation and its consequences. *Ecology* 54:427-432.

Hurlbert, S.H. 1971. The nonconcept of species diversity: a critique and alternative parameters. *Ecology* 52:577-586.

Husch, B., C.I. Miller, and T.W. Beers. 1982. *Forest Mensuration.* Third edition. John Wiley & Sons,, New York. 402 pp.

Jasumback, T. 1991. *Laser Height Measurement. Timber Tech Tips.* Gov. Pub. 9124 2336-MTDC. USDA Forest Service Technical and Development Program.

Kempton, R.A., and L.R. Taylor. 1974. Log-series and log-normal parameters as diversity discriminants for the Lepidoptera. *J. Anim. Ecol.* 43:381-399.

Kempton, R.A., and L.R. Taylor. 1976. Models and statistics for species diversity. *Nature* 262:818-820.

Ludwig, J.A., and J.F. Reynolds. 1988. *Statistical Ecology. A Primer on Methods and Computing.* John Wiley & Sons, New York.

Magurran, A.E. 1988. *Ecological Diversity and Its Measurement.* Princeton University Press, Princeton, New Jersey. 179 pp.

Marks, G.C., N. Ditchburne, R.C. Foster. 1967. A technique for making quantitative estimates of mycorrhiza populations in *Pinus radiata* forests and its applications in Victoria. Pages 67-83 *Proc. Int. Union Forest Res. Org.* XIV 1967, Munich.

McCall, K.A., and W. Merrill. 1980. Selective medium for *Verticicladiella procera. Plant Dis.* 64:277-278.

Mueller-Dombois, D., and H. Ellenberg. 1974. *Aims and Methods of Vegetation Ecology.* Wiley & Sons, New York. 547 pp.

Norman, J., and G. Campbell. 1989. Canopy structure. Pages 301-325 in R. Pearcy, J. Ehleringer, H. Mooney, and P. Rundel, eds. *Plant Physiological Ecology.* Chapman and Hall, London.

Noss, R.F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Cons. Biol.* 4:355-364.

Palmer, C.J., K.H. Riitters, T. Strickland, D.L. Cassell, G.E. Byers, M.L. Papp, and C.I. Liff. 1991. *Monitoring and Research Strategy for Forests—Environmental Monitoring and Assessment Program (EMAP).* EPA/600/4-91/012. U.S. Environmental Protection Agency, Washington, D.C.

Patrick, R. 1968. The structure of diatom communities in similar ecological conditions. *Amer. Nat.* 102:173-183.

Pielou, E.C. 1975. *Ecological Diversity.* John Wiley & Sons, New York.

Riitters, K., M. Papp, D. Cassell, and J. Hazard (eds). 1991. *Forest Health Monitoring Plot Design and Logistics Study.* EPA/600/S3-91/051. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, North Carolina.

Ripley, B.D. 1981. *Spatial Statistics.* John Wiley and Sons, New York.

Russell, P. 1956. A selective medium for the isolation of basidiomycetes. *Nature* 177:1038-1039.

Shannon, C.E., and W. Wiener. 1949. *The Mathematical Theory of Communication.* University of Illinois Press, Urbana. 117 pp.

Simpson, E.H. 1949. Measurement of diversity. *Nature* 163:688.

Stokes, M.A., and T.L. Smiley. 1968. *An Introduction to Tree-Ring Dating.* University of Chicago Press, Chicago.

Sukhatme, P.V. 1954. *Sampling Theory of Surveys, with Applications.* Iowa State College Press, Ames.

U.S. EPA. 1990. *Threats to Biological Diversity in the United States.* PM-223X. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency, Washington, D.C. 57 pp.

Van Deusen, P.C. 1992. Growth trends and stand dynamics in natural loblolly pine in the southeastern United States. *Can. J. For. Res.* 22:660-666.

Waring, R.H., and W.H. Schlesinger. 1985. *Forest Ecosystems: Concepts and Management.* Academic Press, Orlando, FL.

*U.S. GOVERNMENT PRINTING OFFICE: 1994-550-001/00174 Region 5.