(1435)

INVENTORIES OF STAND STRUCTURE: AN ECOSYSTEM PERSPECTIVE

Janet L. Ohmann
Pacific Northwest Research Station
P.O. Box 3890
Portland, OR 97208

and

Warren B. Cohen
Pacific Northwest Research Station
3200 SW Jefferson Way
Corvallis, OR 97331

ABSTRACT

Data on vegetation structure provide a focus for linking ecological, social, and economic values in an integrated framework for inventory, analysis, and decision-making. By incorporating current knowledge about ecosystem structure and function into inventory design and data collection, and by measuring structural attributes at a basic level, flexibility in responding to information needs is maximized. Inventory objectives are often met most efficiently and effectively using a combination of ground-based and remote sensing approaches. A wide variety of measures of live trees, coarse woody debris, canopy architecture, and understory vegetation can be employed as indicators of resource values as well as underlying ecological processes. However, measures of structural complexity and variability may be more important than mean stand conditions. The dynamic and often unpredictable nature of ecosystems underscores the importance of using results from inventory and monitoring to adjust natural resource management decisions.

INTRODUCTION

With growing concern about environmental quality and increased demand for a variety of products and amenities from forest lands, the need for information from integrated forest inventories has never been stronger. At the same time, researchers are finding tremendous complexity in ecosystems, including interrelations of component structures and processes, and links among structural and functional diversity, biological diversity, and long-term ecosystem productivity.

The forest stand has long been a focus of inventory specialists and ecologists. As one component of stand-level inventories, forest structure offers an opportunity to link ecological, social, and economic values in an integrated framework for forest inventory, analysis, and decision-making. Flexibility in addressing information needs about ecological systems and natural resources is enhanced by incorporating current knowledge about ecosystem structure and function into inventory design, and by measuring ecosystem components and processes at a basic level. In this paper we discuss the use of data on above-ground vegetation for many purposes. The content is biased towards developing integrated, multiple-resource inventories having an ecological basis. Presented concepts should assist resource managers and inventory specialists with wide-ranging backgrounds in developing inventories of forest ecosystems.

Relevant Ecological Concepts

Several concepts influence design of ecologically-based inventories. First, ecosystem *structure* (the physical organization or pattern of a system) is one of three interrelated attributes of ecosystems described by Franklin et al. (1981) and Noss (1990). Other primary attributes are *composition* (identity and variety of elements in a collection, such as species or genes) and *function* (ecological and evolutionary processes such as gene flow, disturbance, nutrient cycling). Inventory designs focused on structure must consider composition and function as well.

Ecosystems also occur at a *hierarchy of spatial scales.* Higher levels of organization in a hierarchy incorporate and constrain behavior of lower levels in ways that are not fully understood (Allen and Starr 1982, O'Neill et al. 1986). In this regard, broader scales of landscapes and regions provide context for designing and implementing stand-level inventories. Similarly, stands consist of a mosaic of finer-scaled ecosystems. Ecologists have found that this within-stand variability and pattern is often more important than average conditions as a control and an expression of ecosystem function.

Finally, ecosystems are *dynamic.* The often-unpredictable response of systems to disturbance introduces uncertainty to forest planning and management decisions. Information from inventories and monitoring can be used to evaluate and adjust decisions in a changing world. While temporal scale and variability therefore are key considerations in designing monitoring systems, this paper focuses on inventories conducted at a single point-in-time.

Needs for Information on Vegetation Structure

A broad array of data needs provide incentive for conducting integrated forest inventories. Data on vegetation structure have uses at many scales, ranging from prescribing stand treatments to analyzing resource trade-offs or environmental ramifications of proposed policies at the national level. Data may also be used in research and modeling at a range of spatial scales. Many public land managers have legal mandates and policy direction to consider multiple resources in their planning, inventories, and decision processes. In particular, the USDA Forest Service's new Ecosystem Management perspective emphasizes a broader framework for inventories and assessments to support ecologically-based management (Kessler et al. 1992, USDA Forest Service 1992). There is growing interest among private landowners, as well, in managing for multiple values.

Many efforts to develop an ecological basis for forest inventory have involved new applications of vegetation data collected in timber inventories, or the "piggy-backing" of new vegetation measures onto existing inventory designs (Schlatterer and Lund 1984, Rudis 1991, Lund 1986). Many activities have been aimed at wildlife habitat assessment, with habitats defined largely by vegetation structure (Ohmann 1992). However, inventory systems relying on models of wildlife-habitat relationships are still not well-tested (Thomas and Verner 1986). Interest in wildlife and their habitats is now encompassed by a broader issue of biological diversity. The loss of structural complexity in managed forests of all ages may threaten biodiversity in forest ecosystems (Hansen et al. 1991). Several related issues focus attention on methods of inventorying and mapping vegetation structure, most notably the debate over fate of old-growth forests. Vegetation structure is the most distinctive feature of developmental stages and age classes in natural and managed forests (Spies and Franklin 1991, Spies et al. 1988).

INVENTORY DESIGN CONSIDERATIONS

Inventory Design and Sampling Methods

Inventory design is driven by objectives that consider information needs, accuracy requirements, and cost. Information from multiple-resource inventories is must support a variety of analyses, including evaluating resource interactions. Imperfect knowledge about ecosystem processes further complicates efforts to identify and measure appropriate attributes. The challenge, then, is to incorporate concepts of ecosystem complexity into inventory designs that are affordable and simple to apply in practice.

Fortunately, many simple measures of forest structure can be used to estimate resource values as well as indicate ecosystem processes underlying forest biodiversity, health, and productivity (Noss 1990) (Table 1). The scientific credibility of using structural measures as indicators of broader ecological function rests on developing and validating reliable models. Ecologically-based inventory designs will also be furthered by adhering to the following guiding principles (Wikstrom and Hoekstra 1981): (1) collect data under an ecological classification system; (2) assure capability of aggregating data to different levels of resolution for analysis; (3) collect data from the same sample points (not necessarily at the same time) for interaction analysis; (4) distribute sample locations across ecosystem(s); (5) provide measurements of change and relationships in ecosystem(s). Also, data elements should be collected at a basic level to allow later classification under multiple schema.

In most cases maps, graphics, and summary statistics are all desired products, and inventory designs that combine remote sensing and ground-based techniques provide maximum efficiency and effectiveness. We emphasize ground-based approaches in this paper, but also discuss some important applications of remote sensing technology. Procedures can be applied to mapped polygons of vegetation that serve as inventory units themselves or as sampling units within more extensive surveys, or to plots measured as part of extensive, sample-based inventories.

Field Plot Design

Ground measurements of vegetation provide a high level of resolution and detail, but inventory objectives may not justify the cost. Nevertheless, some structural attributes can be assessed in no other way. Accuracy of field measurements is readily quantifiable using accepted statistical measures, and data can be collected to varying levels of accuracy.

Methods of sampling vegetation fall into four general categories: (1) point (e.g., point-intercept), (2) line (e.g., line-intercept), (3) area, or plot; and (4) plotless (e.g., point-center-quarter). Point data usually can be obtained quickly, and can be used to determine frequency and relative abundance of certain components. Line transect methods generate data on the composition, frequency, and abundance of structural elements, and on their horizontal arrangement. Plots are frequently used to describe the arrangement, density, and composition of structural elements within an area. Plot methods are usually time- and labor-intensive, but they provide relatively accurate data. Plotless sampling techniques produce density estimates as a function of distance. See Cooperrider et al. (1986), Greig-Smith (1964), LaBau and Cunia (1990), Lund (1986), and Mueller-Dombois and Ellenberg (1974), for more detailed discussions of sampling methods.

Table 1. Selected structural elements of forest vegetation, with some commonly used tree- and stand-level characteristics.

Structural Element	Tree-level measurements	Mean stand characteristics	Variability Characteristics
Tree boles (live, snags, down logs)	Size (diameter, basal area, height or length); decay class; position on ground	Diameter (quadratic mean); density (number of stems, basal area, stand density index, stocking); volume; biomass	Spatial distribution; standard deviation of bole diameter
Tree canopy	Crown dimensions (width, height, depth)	Density (crown cover); layer heights; canopy volume; biomass	Vertical layering; standard deviation of tree height; horizontal pattern
Understory (shrubs and herbs)	Height; cover; weight	Cover; biomass	Horizontal pattern
Multi-element	Multiple	Stage of development	Structural Complexity Index

inventories. As the number of variables increases, problems of plot size, shape, number, and distribution, and the value of information obtained, become more critical because of cost (Lund 1986). Also, it becomes increasingly difficult to optimize plot design (Wiant and Yandle 1980, Zeide 1980) as elements are added. In general, relatively large plots encompassing smaller, nested plots are commonly used in broad-scale and multi-resource inventories (Lund 1986). A combination of plot, line, and point methods may also be used.

ASSESSING MEAN STRUCTURAL CONDITIONS

Tree Boles

Measures of the size, density, and distribution of tree boles (live, dead, standing, and fallen) in a forest have many applications. Tree boles are a valuable timber and wildlife resource. Abundance and characteristics of live trees and dead tree boles (coarse woody debris) also are important in many ecological and physical processes in forest ecosystems (Harmon et al. 1986).

Live Trees. Methods for sampling live trees are well established. Variable-radius sampling is popular, but the method loses its efficiency when sampling elements uncorrelated with tree basal area. Point or line sampling may be useful in surveys that won't be repeated, and where maximum efficiency is desired. Fixed-area plots are advantageous in continuous forest inventories where measuring change is a primary objective. Computations of tree-level volume and biomass generally utilize allometric equations that describe relations to easily-measured attributes.

Stand summary statistics are computed by expanding tree-level measurements (diameter at breast height (DBH), basal area, and height) based on plot size and number. Measures of interest include quadratic mean diameter and per-acre stand volume, biomass, and stem density (Table 1). Vegetation density can be expressed in absolute or relative terms. Relative measures compare absolute measures to a standard of interest, such as normal stands used in yield table development. Relative measures permit useful comparisons of stands of differing stages of development and (sometimes) species (Maclean 1979). Relative measures also convey a more precise representation of tree stocking and canopy closure than do absolute measures such as stem density or basal area (McTague and Patton 1989). Reineke's (1933) stand density index (SDI) is applicable to even-aged, single-species stands. Crown competition factor (CCF) (Gingrich 1967) may be used in uneven-aged, mixed-species stands. As an alternative, Maclean (1979) offers an approach where the stocking contribution of each tree is calculated individually, as though it were growing in a normal stand of like trees. Tree-level contributions can be aggregated by stand component for many analytical purposes.

Snags. Snags (standing dead trees), one component of coarse woody debris (CWD), should be routinely inventoried if the welfare of wildlife species that use snags is of concern. Unfortunately, there is little information about accurate and efficient methods of determining snag characteristics (Bull et al. 1990, Ohmann 1992, Thomas and Verner 1986). Sampling of snags is problematic because of their relatively low densities, irregular spatial distributions, and irregular recruitment over time from natural and human-caused disturbances (Spies et al. 1988). These attributes also complicate attempts to use inventory data to assess snag habitat for wildlife species (Ohmann 1992).

The appropriate size, number, and configuration of field plots depends on inventory objectives, size of the area to be sampled, existing snag density, desired precision, and the particular ecosystem under study. Bull et al. (1990) compare fixed-radius and variable-radius plots of various sizes with complete counts. They recommend using 1-ac or factor-5 plots to determine snag density in areas of several thousand acres where the known snag density is 0.7-2 snags/ac. However, variable-radius sampling may be a problem in dense stands because of low snag visibility, or if measuring change on permanent plots is an objective. The authors recommend complete counts where snags are scarce (<0.2/ac).

Down Logs. Down logs (fallen trees) present similar sampling challenges. Line-intercept (or planar-intersect) sampling (Brown 1974) is a popular and efficient sampling method for computing log volume, biomass, and density. See Brown (1974) for guidelines on sampling intensities and field procedures. If measured as part of an integrated, multi-resource inventory, however, lines should sample the same ground area and forest condition as plots used to sample other elements. Fixed-radius plots may be employed as well, and may be better suited to characterizing spatial distribution and monitoring change.

Tree Canopy

Overstory canopy closure, or *crown cover*, is perhaps the most widely applied measure of canopy structure. Canopy closure is used to predict habitat quality for wildlife, timber volume, abundance and diversity of understory vegetation, forage production, and snow and rain interception. Unfortunately, many wildlife-habitat relationship models incorporate crown cover as a stand-density variable, while timber models generally describe stand density in terms of stocking, basal area, or trees-per-acre. Greater standardization in modeling approaches would improve multi-resource inventory and analysis.

Field techniques for estimating overstory cover range from ocular estimates to use of simple devices such as the moosehorn and spherical densitometers, to use of various photographic methods (Chan et al. 1986, Bunnell and Vales 1990). Forest inventories may also employ line- or point-intercept sampling, or measurement of crown widths (O'Brien 1989). Ocular estimation methods are simplest and most common, but are often inaccurate. Methods such as point-intercept or fisheye photographic analysis are more accurate but also more time-consuming (Chan et al. 1986).

Many of these methods record an angular view of the canopy, thus including much of the depth of crowns of surrounding trees rather than just the tree crowns directly overhead. Choice of view angle should be consistent with the portion of the environment of interest. Narrow angles of view are preferable if canopy gaps are of interest. In fact, a vertical projection of cover is the least biased, and is the kind of cover utilized in most timber and wildlife models. The moosehorn and ocular estimation approximate vertical projections (Bunnell and Vales 1990).

Understory vegetation

Measures of understory vegetation are useful in describing stand development, vegetative diversity, wildlife habitat, and range condition. Cover of shrub and herb layers is most commonly assessed using ocular estimates for fixed-area plots, or using line- or point- intercept methods.

Stage of Development

In many inventories the ultimate purpose of collecting data on vegetation structure is to classify stage of forest development. Following major disturbance, stand development follows a relatively predictable sequence of successional stages (Oliver and Larson 1990). Classification of these stages are used in ecological characterization and in resource management. Most classification systems rely on stand means for attributes such as tree size and density, though wildlife and timber models typically utilize different measures of stand density.

ASSESSING STRUCTURAL COMPLEXITY AND VARIABILITY

The structural complexity of forest vegetation, including vertical canopy layering, variation in tree size, and horizontal patchiness of canopies, is important to a variety of ecological processes. Structural variability distinguishes stages of forest development and influences habitat selection by many animals. Structural complexity plays an important role in overall diversity of plant and animal communities (Hansen et al. 1991). Various aspects of structural diversity can be assessed using several ground-based and remote sensing approaches.

Canopy Height Diversity

Vertical layering of vegetation has often been only vaguely defined. Several techniques for measuring foliar height diversity are very laborious and are useful for intensive analysis and research, but impractical for broad surveys and inventories. A simpler approach is to ocularly estimate the number of canopy layers or the canopy volume in different layers. This can be done relatively rapidly, but it is subject to observer bias and many stands do not contain discrete canopy layers. Alternatively, any of several indices that describe the vertical diversity of tree canopies can be applied to measures of space occupied by tree canopies. For example, heterogeneity indices developed to compute species diversity (reviewed by Christensen and Peet (1984), and Magurran 1988) can be applied to canopy structure as well.

Spies and Cohen (1991) have developed an index of canopy height diversity (CHD) that is based on the volume of "ecological space" occupied by trees in a stand, and is general enough in theory to apply to a broad spectrum of ecological processes and organisms. Ecological space is defined as the sum of the imaginary cylinders surrounding individual trees, with cylinder height equal to tree height and cylinder diameter equal to crown diameter. The CHD can be calculated from DBH measurements and a rough knowledge of DBH-height relationships and DBH-crown area relationships, thus avoiding observer bias. Furthermore, CHD more closely tracks stand development, as defined by stand age, than indices based on basal area or other measures of tree density. However, index formulation is somewhat complex and non-intuitive, and the index may not apply to all forest ecosystems.

As an alternative measure of structural complexity, Spies and Cohen (1991) found that the standard deviation of tree DBH in a stand is also highly correlated with stand age, at least in natural Douglas-fir forests. While standard deviation of tree DBH may be a good indicator of diverse stands and is simple to calculate and intuitively straightforward, it is not as easily linked to ecological process and habitat conditions as measures of crown volume.

Variability in Tree Size

Inspired by the fact that many structural attributes of vegetation are highly correlated, Cohen and Spies (1992) developed a structural complexity index (SCI) that captures the overall structural diversity of a forest stand. They conducted a principal components analysis (SAS 1991) on over 200 natural stands using eight variables: standard deviation of DBH, mean DBH of upper-canopy trees, standard deviation of crown diameter, mean crown diameter of upper-canopy trees, standard deviation of tree height, mean height of upper-canopy trees, mean density of upper-canopy trees, and mean basal area of upper-canopy trees. The SCI for a stand is its score along the first principal component axis. The SCI can be calculated using simple field measurements (Spies and Cohen 1992).

Horizontal Diversity (Pattern)

Horizontal diversity, or *patchiness*, describes the regularity of vegetation distribution in a horizontal plane. It can be calculated for any vegetation layer in a stand, including shrub and herb understories. The variance associated with mean total cover across a number of vegetation plots is one measure of horizontal diversity.

Gap structure is another attribute of horizontal diversity. While gap structure and dynamics have been of great interest in research, a sampling protocol has only recently been developed (Runkle 1992). Gap structure can be surveyed using a variety of methods including complete surveys, a grid system of sample points, line-intersect sampling, or strip transects.

REMOTE SENSING APPROACHES

Most components of vegetation structure discussed thus far can be assessed using remote sensing as well as ground-based methods. Indeed, remote sensing has been successfully employed to assess stand structure since the end of World War II. Initially, aerial photo-interpretation techniques were developed to estimate tree size, density, species, basal area, and cover. Most of these techniques are still widely used today (Paine 1981). However, with the advent of satellite sensors and concomitant digital data in the early 1970s a whole new set of assessment techniques were required (Lillesand and Kiefer 1987). Thus, throughout the 1970s and 1980s the remote sensing research community developed a number of algorithms for extracting information on stand structure from satellite data. The models utilize both spectral and spatial (e.g., texture) properties of the imagery (Iverson et al. 1989, Cohen and Spies 1992). Satellite data are beginning to replace aerial photography in applications to forest inventory.

Satellite remote sensing is most applicable to assessing structure of the upper forest canopy. Understory vegetation and coarse woody debris are not readily observed, though they may influence reflectance. If these other characteristics are related to overstory features then they may be assessed using correlative models. The structural complexity and pattern in upper canopies is reflected in image texture. In this regard, efforts to estimate CHD using digital remote sensing data have been less successful than efforts to estimate SCI (Cohen and Spies 1992).

In addition, remote sensing technology and classification methods can be objectively, uniformly, and efficiently applied across extensive areas and multiple ownerships, including inaccessible sites. However, a strong reliance on ground- and

photo-based information for calibration and validation usually is essential to obtaining results of acceptable accuracy. Indeed, all classifications of digital data need to be assessed for accuracy in representing ground conditions before they can be used with confidence. Neither the sensors nor the algorithms are yet sufficiently developed to provide the level of detail and accuracy commonly attained on the ground or with air-photos. Accuracy results depend largely on the ecosystem under study, the structural attributes and number of classes, and the types of imagery and algorithms used. For some attributes, such as species composition, high degrees of accuracy should not be expected unless strongly associated with topographic and other site factors.

Continued research on sensor technology and on relations between stand and image properties is essential to delivering useful tools to forest managers and inventory specialists. For example, most models for estimating stand structure are correlative rather than mechanistic. Spectral properties that are strongly related to a stand attribute class can be used in developing a classification algorithm. Models that explicitly account for mechanisms driving scene reflectance will probably have greater utility in the future.

CONCLUSIONS

Approaches to measuring vegetation structure are many and varied. The process of weighing factors of cost, accuracy, feasibility, and effectiveness against multiple objectives for ecologically-based inventories can be quite complex. Nevertheless, there are ample opportunities to utilize simple, affordable measures of vegetation structure as indicators of resource values as well as of broader ecosystem health and function. Opportunities will increase with advanced knowledge about ecosystem structure and function, and improved technology for measurement and analysis. In the meantime, efforts to develop closer ties among research, inventory, and monitoring activities will be rewarded by improved decision-making by managers, planners, and policy-makers.

REFERENCES

Allen, T. F. H.; Starr, T. B. 1982. Hierarchy: perspectives for ecological complexity. Chicago IL: The University of Chicago Press. 310 p.

Brown, J. K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest an Range Experiment Station. 24 p.

Bull, E. L.; Holthausen, R. S.; Marx, D. B. 1990. How to determine snag density. W. J Applied Forestry 5:56-58.

Bunnell, F. L.; Vales, D. J. 1990. Comparison of methods for estimating forest overstor cover: differences among techniques. Can. J. For. Res. 20:101-107.

Chan, S. S.; McCreight, R. W.; Walstad, J. D.; Spies, T. A. 1986. Evaluating forest vegetativ cover with computerized analysis of fisheye photographs. For. Sci. 32:1085-1091.

Christensen, N. L.; Peet, R. K. 1984. Measures of natural diversity. In: Cooley, J. L.; Cooley J. H. Natural diversity in forest ecosystems: proceedings of the workshop. Athens, GA: Novemb 29-December 1 1982. P. 43-58.

Cohen, W. B.; Spies, T. A. 1992. Estimating structural attributes of Douglas-fir/wester hemlock forest stands from Landsat and SPOT imagery. Remote Sens. Environ. 41:1-17.

Cooperrider, A. Y.; Boyd, R. J.; Stuart, H. R. 1986. Inventory and monitoring of wildlife habitat. Denver, CO: U.S. Department of Interior, Bureau of Land Management. 858 p.

Franklin, J. F.; Cromack, K., Jr; Denison, W; Mckee, A. 1991. Ecological characteristics of old-growth Douglas-fir forests. Gen. Tech. Rep. PNW-118. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 48 p.

Gingrich, S. F. 1967. Measuring and evaluating stock and stand density in upland hardwood forest in the central states. For. Sci. 13:38-53.

Greig-Smith, P. 1964. Quantitative Plant Ecology. 2nd ed. London: Butterworths. 256 p.

Hansen, Andrew J.; Spies, Thomas A.; Swanson, Frederick J.; Ohmann, Janet L. 1991. Conserving biodiversity in managed forests. BioScience 41:382-392.

Harmon, M. E.; Franklin, J. F.; Swanson, F. J.; [and ten others]. 1986. Ecology of coarse woody debris in temperate ecosystems. In: MacFadyen, A.; Ford, E. D.; eds. Advances in ecological research. Vol. 15. New York, NY: Academic Press. P. 133-302.

Iverson, L. R.; Graham, R. L.; Cook, E. Q. 1989. Applications of satellite remote sensing to forested ecosystems. Landsc. Ecol. 3:131-143.

Kessler, W. B.; Salwasser, H.; Cartwright, C. W., Jr.; Caplan, J. A. 1992. New perspectives for sustainable natural resources management. Ecological Applications 2:221-225.

LaBau, V. J.; Cunia, T.; tech. eds. 1990. State-of-the-art methodology of forest inventory: a symposium proceedings. Gen. Tech. Rep. PNW-GTR-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 592 p.

Lillesand, T. M.; Kiefer, R. W. 1987. Remote sensing and image interpretation. 2nd ed. New York, NY: John Wiley & Sons. 721 p.

Lund, H. G. 1986. A primer on integrating resource inventories. Gen. Tech. Rep. WO-49. U.S. Washington, DC: U.S. Department of Agriculture, Forest Service. 64 p.

Maclean, C. D. 1979. Relative density: the key to stocking assessment in regional analysis--a Forest Survey viewpoint. Gen. Tech. Rep. GTR-PNW-78. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 5 p.

Magurran, A. E. 1988. Ecological diversity and its measurement. Princeton, NJ: Princeton University Press. 179 p.

McTague, J. P.; Patton, D. R. 1989. Stand density and its application in describing wildlife habitat. Wildl. Soc. Bull. 17:58-62.

Mueller-Dombois, D.; Ellenberg, H. 1974. Aims and methods of vegetation ecology. New York, NY: John Wiley & Sons. 547 p.

Noss, R. F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conservation Biology 4:355-364.

O'Brien, R. A. 1989. Comparison of overstory canopy cover estimates on Forest Survey plots. Res. Pap. INT-417. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 5 p.

Ohmann, J. L. 1992. Wildlife habitats of the North Coast of California--new techniques for extensive forest inventory. Res. Pap. PNW-RP-440. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 48 p.

Oliver, C. D.; Larson, B. C. 1990. Forest stand dynamics. New York, NY: McGraw-Hill, Inc. 467 p.

O'Neill, R. V.; DeAngelis, D. L.; Waide, J. B.; Allen, T. F. H. 1986. A hierarchical concept of ecosystems. Princeton, NJ: Princeton University Press. 253 p.

Paine, D. P. 1981. Aerial photography and image interpretation for resource management. New York, NY: John Wiley & Sons.

Reineke, L. H. 1933. Perfecting a stand density index for even-aged forests. J. Agric. Res. 46:627-638.

Rudis, V. A. 1991. Wildlife habitat, range, recreation, hydrology, and related research using Forest Inventory and Analysis surveys: a 12-year compendium. Gen. Tech. Rep. SO-84. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 61 p.

Runkle, J. R. 1992. Guidelines and sample protocol for sampling forest gaps. Gen. Tech. Rep. PNW-GTR-283. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 44 p.

SAS. 1991. Statistical Analysis System, version 6.03. Cary, NC: SAS Institute.

Schlatterer, E.; Lund, H. G.; compilers. 1984. Proceedings of the inventory integration workshop. Portland, OR: October 15-19, 1984. Washington, DC: U.S. Department of Agriculture, Forest Service. 165 p.

Spies, T. A.; Cohen, W. B. 1991. An index of canopy height diversity. Unpublished report on file at Pacific Northwest Research Station, Corvallis Forest Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331.

Spies, T. A.; Franklin, J. F. 1991. The structure of natural young, mature, and old-growth forests in Washington and Oregon. In: Ruggiero, L.F.; Aubry, K.B.; Carey, A.B.; Huff, M.H.; tech. coords. Wildlife and Vegetation of unmanaged Douglas-fir forests. Gen. Tech. Rep. PNW-GTR-285. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 90-109.

Spies, T. A.; Franklin, J. F.; Thomas, T. B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69:1689-1702.

Thomas, J. W.; Verner, J. 1986. Forests. In: Cooperrider, A. Y.; Boyd, R. J.; Stuart, H. R. eds. Inventory and monitoring of wildlife habitat. Washington, DC: U.S. Department of Interior Bureau of Land Management; 73-91.

U.S. Department of Agriculture, Forest Service. 1992. Proceedings of the national workshop taking an ecological approach to management. Salt Lake City, UT: 1992 April 27-30. Publ WO-WSA-3. Washington, DC: U.S. Department of Agriculture, Forest Service.

Wiant, H. V., Jr.; Yandle, D. O. 1980. Optimum plot size for cruising sawtimber in eastern forests. Journal of Forestry 78:642-643.

Wikstrom, J. H.; Hoekstra, T. W. 1981. Forest ecosystem analysis and inventory in the United States. In: Nishizawa, M.; ed. Proceedings, XVII IUFRO world congress, subject groups 4.01 4.02, 4.04, and 6.02. Kyoto, Japan: 1981 September 6-12. Ibaraki, Japan: Forestry and Forest Products Research Institute; 280-290.

Zeide, B. 1980. Plot size optimization. Forest Science 26:251-257.

STAND INVENTORY TECHNOLOGIES 92

Proceedings of the Stand Inventory Technologies:
An International Multiple Resource Conference

Held at
The World Forestry Center

September 13-17, 1992

Sponsored by:
The International Union of Forestry Research Organizations
World Forest Institute
USDA Forest Service Timber Management Staff and Tropical Forestry Program
Western Forestry and Conservation Association
Society of American Foresters
International Society of Tropical Foresters
American Society for Photogrammetry and Remote Sensing

Proceedings Editors:
H. Gyde Lund
Eric Landis
Toby Atterbury

ISBN 0-944426-97-2

Published by
American Society for Photogrammetry and Remote Sensing
5410 Grosvenor Lane • Suite 210
Bethesda, Maryland 20814

Printed in the United States of America