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The Pacific Northwest Region Vegetation and Inventory Monitoring System

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Abstract

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A grid sampling strategy was adopted for broad-scale inventory and monitoring of forest and range vegetation on National Forest System lands in the Pacific Northwest Region, USDA Forest Service. This paper documents the technical details of the adopted design and discusses alternative sampling designs that were considered. A less technical description of the selected design will be given elsewhere. The grid consists of a regular, square spacing with 5.47 kilometers (3.4 mi) between grid points. The primary sampling unit (PSU), established at each grid sampling point, consists of a circular, 1-hectare (2.47-acre) plot. The PSU is subsampled with a set of different-sized fixed-area subplots, as well as line transects, to assess all components of vegetation. The design is flexible and can be used with many types of maps. The theory of point and change estimation is described, as well as estimates of variation that assess the statistical precision of estimates.

Keywords: Sampling, plot design, fixed-area plots, line intersect sampling, monitoring, National Forest System, Pacific Northwest.

Contents

Introduction

In the past, inventories of National Forest System lands (NFS) have been designed primarily for estimating potential outputs of and managing the forests for wood products. Some information on other resources was collected, but it was often insufficient to answer complex questions about these resources. In addition, professional groups other than timber managers have conducted surveys of other resources such as wildlife habitat, soils, recreational features, water, and so forth. These efforts were rarely integrated into a comprehensive resource inventory system, plus inventory and monitoring were rarely considered together.

National Forest System lands are managed for a multitude of objectives including providing a wide variety of commodities, uses, and scenic and social values that people derive from them. Inventory and monitoring systems must be designed to provide comprehensive information about the land and vegetation to answer a broad spectrum of existing and newly developing questions. For example, information needs on the occurrence, abundance, and distribution of Pacific yew (*Taxus brevifolia* Nutt.) or the occurrence of habitat suitable for the northern spotted owl (*Strix occidentalis* Caurina) would not have been anticipated 10 years ago. But such information is much more likely to be available in a broad land and vegetation database. Such broad inventory and monitoring schemes also must meet the informational needs of the USDA Forest Service (FS) for periodic national and Regional assessments, Regional and national planning, and developing and implementing forest plans for NFS lands.

In October 1992, the Washington Office of the FS ordered its western Regions to establish a grid of plots across all NFS lands that would be compatible with the Forest Inventory and Analysis (FIA) grids. In April 1993, the FS established policy implementing ecosystem management of NFS lands. In June 1993, the Washington Office directed the FIA units to implement mapped plot designs for all FIA plots in the United States (Robertson 1993). The key idea of this direction was to locate plots exactly on the ground as planned and map them for conditions of interest. Moving some subplots into the same condition class as that of the central subplot is not permitted. This direction was expected to be fully implemented in 1994.

Anticipating a need for a scientifically defensible yet practical design for ecological purposes, the Pacific Northwest Region of the NFS (Region 6) convened a panel of survey sampling experts who met in a series of five meetings to plan such an inventory and monitoring (IM) system. This paper summarizes the deliberations and conclusions of this advisory group, which recommended a comprehensive IM system for Region 6. We believe this is a key step in inventorying and monitoring forest land for ecological purposes. Under current monitoring, only large-scale change is estimated by using sampling units that are periodically remeasured. Various alternatives for implementing remeasurement, such as an annual forest inventory system (AFIS),[1] will be explored later. Professional and disciplinary groups, whether monitoring watersheds or other areas of interest, can use the database developed here as a starting point for their more specific monitoring projects.

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[1] Hansen, M.H.; Hahn, J.T.; Schreuder, H.T.; Befort, W.A. AFIS-1: implementation of an annual forest inventory system. Manuscript in preparation.

Purpose and Objectives

The purpose of this paper is to present a broad-scale vegetation inventory and monitoring system designed to meet the present and future resource information needs of Region 6 and the FS. The system must be integrated by capturing basic land information and describing vegetative structure and productivity in an ecological framework. In addition, the system must be responsive to changing needs for spatial and temporal information at various scales and levels of resolution.

The objectives of the system are to develop and maintain a defensible database of ground resource estimates that can be used to periodically assess vegetation and monitor change in vegetation over time. The data are compatible with any map base developed for NFS lands in Region 6. The database will be used to develop forest plans and assess resources, special studies, and impact analysis. Each objective is described in more detail below.

For monitoring, it is important to note that we have used the term "monitoring" to mean assessing broad-scale changes in resources over time. The scope is strictly broad-scale; that is, applying to large areas. Many specific types of monitoring are defined and used by the FS and other agencies (for example, implementation monitoring and effectiveness monitoring), and they are not part of the scope of this paper. A good discussion of inventory and monitoring, as well as definitions of specific types of monitoring, is given in MacDonald and others (1991:6-8). In this paper, we use the term "sampling strategy" to define sample design plus estimation, where sample design refers to the approach used to select the actual sampling unit locations (Schreuder and others 1993).

Developing Forest Plans

The panel had one critical objective, which was to develop an inventory and monitoring system that would meet the needs of forest planning and forest management decisionmaking. Major components had to include methods for acquiring representative data, methods for summarizing data to obtain estimates, and associated database support. Planners now need estimates of both the current status of resources and changes in resources over time to make planning decisions. The new process will be based on incorporating spatial information for current vegetation, potential vegetation, land form, and soils at both Forest and multi-Forest levels.

Assessing Resources

Another key objective of the system was broad assessment of resources. Such assessment provides consistent resource estimates for addressing subregional, regional, and national issues (for example, information required by the national Resources Planning Act [RPA] 1974) and an initial source of information to Ranger Districts for addressing management issues. Such issues normally are driven by users' concerns for the land and for its associated vegetation, both current status and change over time.

Special Studies

The system had to be flexible to allow for implementing broad-scale special studies compatible with the overall IM design. Examples of such special studies are determining the pattern of root rot occurrence, the frequency and extent of insect epidemics, and the quantity and spatial distribution of live vegetation and woody debris as it relates to forest succession. Although such special studies are observational in nature, they provide an effective tool for addressing some issues.

Impact Analysis

An objective becoming increasingly important is impact analysis. Such analyses investigate potential relations among response variables, management practices, environmental factors, and other anthropogenic stresses. The acquired vegetation databases, both spatial and temporal, must be useful for such analyses. Evaluations may include documenting effects of catastrophic events, determining effects of land form on management practices, and monitoring change in vegetation and understanding why such change occurs.

Review of Literature

Surveys traditionally have been planned to provide estimates of current status. Such estimates have been so useful to management that additional objectives have evolved. The original objective of FIA inventories, for example, was to estimate the area of forest land by type, stand size, ownership, site quality, and stocking and to estimate merchantable wood volume by tree species and diameter class. Over time, additional information related to change over time was added, such as growth, mortality, timber removals, and success of regeneration.

Recently, interest has expanded in relations established by using natural resource survey data. Establishing such relations and drawing conclusions based on them is termed “analytical inference.” Such inferential use of sample survey data requires reliable data. Conclusions drawn by scientists from a comparison of the 1982 and earlier FIA surveys of Georgia and Alabama is a striking example of such inference. In that study, average growth rates in tree diameters decreased (Bechtold and others 1991, Ouyang and others 1993, Ruark and others 1991) for a screened data set, but the cause is still not known. Various hypotheses have been proposed, including regional changes in average stand structure of forests, anthropogenic stresses, and weather. As a result of the ensuing controversy, efforts were made to determine whether survey data could suggest cause-effect relations, and how they might more effectively serve analytical uses.

In the following subsections we briefly review several topics: sampling designs in use, estimation and analysis, analytical uses of survey data, and quality assurance of data collected.

Sampling Designs in Use

Around the world, many broad-scale forest inventories are based on a systematic arrangement of grids (Köhl 1994). These designs are adopted primarily for practical reasons of implementing and revisiting plots well distributed over a vast area. Three well-known examples in the United States are the FIA program, Forest Health Monitoring program of the FS, and the National Wetlands Inventory of the U.S. Fish and Wildlife Service.

All FIA units use double sampling for stratification. A large number of grid locations, either single points or a cluster of points, is located, typically on available photography, and locations are classified into strata (the simplest being forest and nonforest) (Birdsey and Schreuder 1992). Permanent, unobtrusively marked sample plots are then located on the ground on a grid, typically consisting of a cluster of 5 or 10 variable-radius plots sampling a 0.4-hectare (1-acre) plot. These plots are then measured for variables of interest, which are sometimes multiresource in nature. At present the timber variables receive the most attention (Birdsey and Schreuder 1992; Hahn and others, 1995). The Forest Health Monitoring program of the FS and the Environmental Protection Agency (EPA) uses a cluster of four fixed-area circular subplots to sample a circular 1-hectare plot; 0.0168-hectare subplots (radius = 7.32 meters or 24 ft) are mapped for forest conditions (Messer and others 1991; Scott and Bechtold 1995).

Since 1974, the U.S. Fish and Wildlife Service has inventoried the Nation's wetlands through its National Wetlands Inventory project. The statistical design implemented in the lower 48 States can be used to obtain reliable estimates for individual states or other geographical areas by intensifying the grid (Hall and others 1994).

Designs are given in Schreuder and others (1993) for sampling recreational use, wildlife populations, regeneration, understory vegetation, and timber variables. More practical, objective methods are needed for obtaining information on vegetation profiles (Schreuder and others 1993) and the biomass of range vegetation (National Research Council 1994).

Estimation and Analysis

Traditionally, interest in NFS lands has centered on the area and condition of the resources and how these change over time. Scott and Bechtold (1995) and Williams and Schreuder (1995) present the relevant estimation theory for mapped designs. The notation used is:

A = Total area in population (hectare).

F = Number of condition classes of interest.

t = Time period t (t = 1, 2).

A_{tf} = Area in condition class f at time t (f = 1, ..., F; t = 1, 2) (hectare).

Y_t = Total for variable of interest at time t.

ΔY =Total change in variable Y from time 2 to time 1.

Y_{tf} = Total for variable of interest in condition class f at time t (f = 1, ..., F; t = 1, 2).

k = Number of subplots in a cluster (k = 5 or 10 depending on FIA unit).

M = Number of plots in population.

m = Number of sample plots (clusters).

BAF = Basal area factor in variable radius plot (VRP) sampling = square meter/hectare (or ft^2/acre) of basal area represented by a tree when tallied at a single subplot.

Π_{ti} = Probability of selecting tree i at time t (t = 1, 2).

r_s = Radius of small fixed-area plot.

r_ℓ = Radius of large fixed-area plot.

Y_{ti} = Value of variable of interest for tree i at time t (t = 1, 2).

$\hat{Y}_{th}$ = Estimated total for variable of interest y on sample plot (cluster) h (h = 1, ..., m) at time t (t = 1, 2).

$a_j(f_t)$ = Approximate area in condition f (= a_ℓ if only one condition occurs) at subplot j and time t (t=1, 2).

d_{ti} = Diameter at breast height of tree i at time t.

g_{ti} = Basal area of tree i at time t.

i = Used to sum over trees on each subplot.

j = Used to sum over subplots.

h = Used to sum over clusters of plots.

a_S = Area of small fixed-area plot (hectare).

a_ℓ = Area of large fixed-area plot (hectare).

Estimating area and change—Estimators giving areas by condition classes [A(f)] in the population and change in these areas over time [ΔA(f)] are:

$$\hat{A}(f_t) = \frac{1}{m}\sum_{h=1}^{m}\frac{1}{k}\sum_{j=1}^{k}\frac{a_j(f_t)}{a_\ell}A \tag{1}$$

and

$$\hat{\Delta}A(f) = \hat{A}(f_2) - \hat{A}(f_1) \tag{2}$$

with variance estimates

$$v(\hat{A}(f_t)) = \sum_{h=1}^{m}(\hat{a}_h(f_t) - \hat{A}(f_t))^2 \Big/ \{m(m-1)\} \tag{3}$$

and

$$v\left[\hat{\Delta}A(f)\right] = v\left[\hat{A}(f_2)\right] + v\left[\hat{A}(f_1)\right] - 2\,\mathrm{cov}\left[\hat{A}(f_1), \hat{A}(f_2)\right] \tag{4}$$

where for cluster h

$$\hat{a}_h(f_t) = \frac{1}{k}\sum_{j=1}^{k}\frac{a_j(f_t)A}{a_\ell} \tag{5}$$

and

$$\mathrm{cov}\left[\hat{A}(f_1), \hat{A}(f_2)\right] = \sum_{h=1}^{m}\left[\hat{a}_h(f_1) - \hat{A}(f_1)\right]\left[\hat{a}_h(f_2) - \hat{A}(f_2)\right] \Big/ \left[m(m-1)\right]. \tag{6}$$

Estimating amount and change—The basic estimator of the total amount Y of any resource at a given time is:

$$\hat{Y} = \frac{1}{m}\sum_{h=1}^{N_h} y_{hi} \Big/ \Pi_{hi} = \sum_{h=1}^{m}\hat{Y}_h \Big/ m \tag{7}$$

with an unbiased estimator of variance

$$v(\hat{Y}) = \frac{(M-m)}{M}\sum_{h=1}^{m}\left(\hat{Y}_h - \hat{Y}\right)^2 \Big/ \left[m(m-1)\right]. \tag{8}$$

For estimating change, the following formulae are recommended.

Overall change ΔY —

$$\Delta\hat{Y}_1 = \sum_{f=1}^{F} \Delta\hat{Y}_1(f) = \sum_{f=1}^{F}\left(\hat{Y}_{2f} - \hat{Y}_{1f}\right) = \hat{Y}_2 - \hat{Y}_1 \tag{9}$$

where $\Delta\hat{Y}_1(f), \hat{Y}_{2f}, \hat{Y}_2$ and $\hat{Y}_1$ are the estimated total change for variable y in condition f, estimated totals at time 2 and time 1 in variable y in condition f, and estimated totals for time 2 and time 1 for variable y for plants not in the sample plot at time 1 but present at time 2 (ingrowth, I), respectively.

Ingrowth I—

$$\hat{I}_1 = \sum_{f=1}^{F} \hat{I}_1(f) = \sum_{f=1}^{F}\left[\frac{1}{m}\sum_{h=1}^{m}\frac{1}{k}\sum_{j=1}^{k}\left(\sum_{i\in i(f_2)}\frac{Y_{2i}}{\Pi_{2i}}\right)\right]. \tag{10}$$

Survivor growth Δ **S**—

$$\Delta\hat{S}_1 = \sum_{f=1}^{F} \Delta\hat{S}_1(f) = \sum_{f=1}^{F}\left[\frac{1}{m}\sum_{h=1}^{m}\frac{1}{k}\sum_{j=1}^{k}\left(\sum_{i\in s(f_2)+s_{on}(f_2)}\frac{Y_{2i}}{\Pi_{2i}} - \sum_{i\in s(f_1)}\frac{Y_{1i}}{\Pi_{1i}}\right)\right]. \tag{11}$$

Mortality M—

$$\hat{M} = \sum_{f=1}^{F} \hat{M}(f) = \sum_{f=1}^{F}\left[\frac{1}{m}\sum_{h=1}^{m}\frac{1}{k}\sum_{j=1}^{k}\left(\sum_{i\in m(f_1)}\frac{Y_{1i}}{\Pi_{1i}}\right)\right]. \tag{12}$$

Removals R—

$$\hat{R} = \sum_{f=1}^{F} \hat{C}(f) = \sum_{f=1}^{F}\left[\frac{1}{m}\sum_{h=1}^{m}\frac{1}{k}\sum_{j=1}^{k}\left(\sum_{i\in c(f_1)}\frac{Y_{1i}}{\Pi_{1i}}\right)\right]. \tag{13}$$

where $\hat{I}(f)$, $S_2(f)$, $\hat{M}(f)$, and $\hat{R}(f)$ are estimators of ingrowth, survivor growth, mortality, and removals respectively for condition f. If additivity of the estimates is not required, a more efficient estimator of overall change Δ Y is:

$$\Delta\hat{Y}_2 = \Delta\hat{S}_1 - \hat{C} - \hat{M} + \hat{I}_1 \tag{14}$$

where

$$\Delta\hat{S}_1 = \sum_{f=1}^{F} \Delta\hat{S}_1(f) = \sum_{f=1}^{F}\left[\frac{1}{m}\sum_{h=1}^{m}\frac{1}{k}\sum_{j=1}^{k}\left(\sum_{i\in s(f_2)}\frac{Y_{2i}}{\Pi_{1i}} - \sum_{i\in s(f_1)}\frac{Y_{1i}}{\Pi_{1i}}\right)\right]. \tag{15}$$

The classical variance estimator for these parameter estimates is (Williams and Schreuder, 1995):

$$V(\hat{Y}) = \sum_{h=1}^{m} \left(\hat{y}_h - \hat{Y} \right)^2 \Big/ \left[m(m-1) \right]. \tag{16}$$

In addition, Williams and Schreuder (1995) give formulas for estimating the percentage of plots with more than one condition class, the length of the boundaries between the condition classes, corresponding changes in these parameters over time, and the relevant variances. Instead of using the classical variance estimators as described, an alternative is to generate a large number of bootstrap estimates, which allows more reliable confidence intervals to be constructed (see Ouyang and others 1992).

Analytical Uses of Survey Data

Skinner and others (1989) consider P. Lazarsfeld as the key figure influencing modern developments in the analysis of surveys. Lazarsfeld viewed survey analysis as being primarily concerned with relations between variables. He was primarily interested in methods for causally analyzing contingency tables.

Deming (1975) distinguished between enumerative (descriptive) and analytical studies as follows: In an enumerative study, the number of units of a population belonging to a certain class is estimated, whereas in an analytical study, a basis for action on the causal system or process to improve the result or effect has to be found. In other words, interest in enumerative surveys is in estimating population parameters, whereas in analytical surveys it is in explanatory (or predictive) models (Skinner and others 1989). Analytical uses of survey data then involves model building and model testing.

To further clarify the distinction between enumerative and analytical studies, consider the case where a 100-percent sample of a population is collected. In an enumerative study, such a sample provides the complete answer to the question posed, subject to the limitations of the method of investigation; that is, an enumerative survey has the property that if all N units are observed without error, population parameters are determined exactly (Smith 1983a, 1983b). Such populations are called finite popuations by statisticians. In contrast, inference on the effect of a treatment on a 100-percent sample of a stand of trees is still inconclusive in an analytical problem because this stand represents an often ill-defined, essentially infinite population of such stands. Such populations are called superpopulations by statisticians.

Traditional sample surveys have been used primarily for enumerative purposes; that is, estimation for finite populations. But such surveys are often also used for analytical purposes by adopting a superpopulation model; this is vividly illustrated by Brewer and Mellor (1973) and Holt and Smith (1976). The alternative uses of survey data emphasize the need to recognize that it is the inference to be drawn that is inherently enumerative or analytic, and not the survey itself.

In some of the social and demographic sciences, the enumerative uses have been subordinate to the analytical ones (Kendall and Lazarsfeld 1950). In forestry and other renewable natural resource disciplines, the reverse is usually true.

Analysis of data from large, complex sample surveys can be quite difficult (Landis and others 1982). Difficulties result from complications introduced by unequal probability sampling, imputation for nonresponse, regression estimation and use of several levels of sampling and poststratification, and conflict with the assumptions made in classical statistical analysis of mutually independent sample observations drawn by simple random sampling. In addition, survey data may contain substantial and confounded measurement errors, although classical models assume no or simply distributed observational errors (Simmons and Bean 1969). There also is the question of what superpopulation the sample represents, which is even more pertinent in classical statistical experimentation.

Beyond developing explanatory or predictive models, scientists and managers are also keenly interested in cause-effect relations. In considering the conditions necessary to establish a cause-effect relation, and how difficult is it to achieve these conditions, Mosteller and Tukey (1977) note that two of three criteria (consistency, responsiveness, and mechanism) must be satisfied. Consistency implies that the presence and magnitude of the effect (y) is always associated with a minimal level of the suspected causal agent (x). Responsiveness is established by experimental exposures to the suspected causal agent and reproducing the symptoms. Mechanism, as it relates to the subject of this paper, is established by demonstrating a biological or ecological process that causes the observed effect. Only consistency can be confirmed by observation alone. Hence, surveys are useful primarily in identifying potential cause-effect relations.

There are many examples, particularly in epidemiology, of falsely claiming to have established cause-effect relations. Epidemiologists sometimes cannot conduct experiments on people and cannot randomly assign healthy people to exposure to potentially noxious substances. Because of these limitations, medical research often has not followed scientific principles. Recently, however, rigorous clinical trial methods have enjoyed a major resurgence in medical research. Feinstein (1988) advocates the following principles for observational studies in epidemiology: stipulate a research hypothesis prior to analysis, study a well-specified cohort having a statistical factor in common (for example, a tree diameter-class), collect high-quality data, study possible explanations, and avoid personal biases in detecting possible relations.

Although inventories in forestry traditionally have emphasized point and change estimation, analytical uses of inventory data are becoming more important. An example is the effect of treatments on a specific resource. This is particularly likely to be of importance for NFS inventories where there is a need to examine the effect of treatments applied under operational conditions. Note that effective analytical use requires reliable point and change estimates.

Use of survey data either to identify potential cause-effect relations or to establish them is controversial (Schreuder and Thomas 1992). For sample plots, there are still many uncontrollable variables (weather, insect epidemics) and essentially unmeasurable variables (rainfall, pollution), so many explanations are readily available for an observed effect (such as a change in the population of a bird species). Nevertheless, there is no alternative but to use survey data to identify possible cause-effect relations. Schreuder and McClure (1991) suggest modifications to FIA designs to improve detection of change and identify its possible causes. The broad objectives underlining the modifications to FIA proposed by Schreuder and McClure (1991) are to generate descriptive statistics, detect changes in such statistics, and analyze the data to identify possible cause-effect relations. But even with these modifications, the emphasis in FIA surveys would still be to collect descriptive statistics efficiently, especially for timber. The fact is that it is difficult to even identify reasonable potential cause-effect relations, let alone establish cause-effect in the natural resource fields. Simplicity in survey design is more likely to lead to success in this regard (Schreuder and others 1993).

Quality Assurance

Quality assurance refers to the quality control imposed on the collection and processing of data to obtain the most reliable data set and statistics possible for the amount of money spent on the survey. The most detailed quality assurance program for natural resource inventory and monitoring activities probably is the one used by Forest Health Monitoring as required by the Environmental Monitoring and Assessment Program (EMAP) of the EPA (U.S. EPA 1992). Forest Health Monitoring embraces the concept of total quality management (TQM), which is a process of continuous improvement and innovation led by managers. Total quality management fully integrates management philosophy, planning, and operating methodology. The philosophy behind TQM is aimed at achieving total employee commitment to quality. To achieve this, TQM focuses on:

- Identification of customers of the survey. All customers must be identified, and effective and continuous communication of their requirements must be maintained.
- Standards and performance. Proactive rather than reactive measures of performance must be used.
- Leadership commitment. This commitment is essential and can be documented well by establishing a TQM “culture” during training.
- Employee recognition. A key ingredient to the success of TQM is to establish and implement criteria and mechanisms for recognizing the effort, creativity, and achievement of employees.
- Training. This is listed separately in U.S. EPA (1992), but rigorous training of crews who collect data certainly needs to be emphasized in TQM. EMAP makes the point that such training should focus on the development of organizational and interpersonal skills as well as technical proficiency.
- Development of a clearly written code of practice for data collection. This too is not listed separately under TQM, but it seems to fit there. This code of practice is essential for training and for ready reference during data collection.

Specific quality assurance objectives for Forest Health Monitoring are (U.S. EPA 1992):

- Compatibility of data. For purposes in Region 6, this means compatibility of data within and among Forests and with cooperators such as FIA and BLM.
- Meeting specified levels of uncertainty that the users are willing to accept. Such statements should be definitive and either quantitative or qualitative.
- Documentation of data collection methods. Such documentation ensures that information on data quality, statistical design, algorithms, protocols, and analytical procedures are available for comment.
- Verification and validation of data. A systematic approach to verification and validation ensures that all data are subjected to basic standards of accuracy to verify their authenticity and reliability.

To facilitate data verification and validation, U.S. EPA (1992) recommends use of portable data recorders, electronic data verification, and remeasurement of some field plots as follows:

- Crews should remeasure a representative sample of their own plots so that estimates of their "within-field" precision can be determined.
- All field crews should measure a series of reference plots so that measures of accuracy and "between-crew" precision can be determined.
- Remeasurement, by a check crew, of a representative sample of plots completed by field crews. This, too, can measure crew accuracy and between-crew precision.

Methods

Based on the specified sampling objectives, design criteria, directions from the FS Washington Office, literature, personal experience, and the concern in Region 6 for a single inventory database with consistent resource estimates, the approach summarized below was adopted.

Approach Adopted

The general approach to IM adopted by Region 6 is explained in the following series of statements. These statements document the principles and key features of the IM system.

- Continue the development of Regional Geographic Information Systems (GIS) databases for historical vegetation, current vegetation, and potential natural vegetation across all FS lands, using all levels of technology including state-of-the-art modeling and satellite imagery.
- Pursue developing techniques for continually updating GIS databases.
- Establish a 5.47-kilometer (3.4-mile) square grid across all NFS land regardless of administrative classification or forest allocation. This grid is compatible with that used by the Pacific Northwest Research Station FIA unit and is expected to be adequate to meet FIA sampling error standards for each National Forest in Region 6. This grid system was implemented in 1993 on all NFS land. Ecological land units (Bailey 1994, USDA Forest Service 1993) should be identified and mapped on the sample units. Establishing this grid in the field is expected to be completed by the end of 1996.

- Through partnership with FIA, develop standards and procedures for measuring ground sample units to include data necessary to meet information needs at all levels of the FS. Coordinate operational inventory activities with FIA, including data collection, quality control, data compilation and analysis, and reporting. The work for any activity may be accomplished by one or both administrative units or by contractors, according to the intra-Agency agreement.
- For land management planning, Forest plan implementation, and monitoring changes in land and vegetation for all NFS lands excluding wilderness, use a more intensive grid (four times more intense) of a 2.74-kilometer (1.7-mile) square. Using this approach, Region 6 personnel have the option to repeatedly poststratify the databases as necessary to provide critical information to forest managers. Information will not be constrained by strata definitions adopted in a typical prestratified inventory.
- If the standard grid (2.74-km [1.7-mi] square) for data acquisition does not meet all the vegetation or modeling needs of the forest planning effort (it is a given that it will not), install a supplemental 1.37-kilometer (0.85-mile) grid. It is at this stage that other data sources may be incorporated into the information base. For example, the occurrence of Pacific yew was a specific need dictating a particular GIS mapping overlay. Such a grid “intensification” can be tied to any use or map as a basis for supplemental sampling.
- Sample all vegetation on all NFS land. In addition, data needed to estimate biomass and carbon loading should be collected.
- Maintain flexibility in design to facilitate addressing future questions. This is accommodated by establishing a self-weighting, equal probability, systematic grid of sampling units on the ground.
- Maintain the ability to formally incorporate existing information of acceptable quality from other survey sources, such as special range, wildlife, recreation, and soil surveys.
- Provide a formal framework for designing and implementing special studies.
- Ensure that (1) the sampling units do not change over time because of subjectivity in the way they are defined, (2) estimates are statistically valid and defensible, and (3) statistical estimates of reliability are provided with the most important estimates.

Mapping

Use of maps for estimating area—Historically, Region 6 has used several methods to derive area estimates for a variety of purposes. These methods, regardless of how the data were acquired, ranged from plot expansion, in sampling, to determining area from maps. No effort was made to estimate the error associated with any of the area estimates or the effect of that error on a particular forest resource estimate. This has been a continual concern for forest planners and should be of concern to all forest managers.

Technological changes in the management of natural resources and expansion of issues encompassing the total landscape have necessitated that the design of inventories be flexible enough to be compatible with maps created from a wide range of sources; for example, Landsat imagery and aerial photography used for ecological units, predictive modeling, and even arbitrary delineations of the land base. This flexibility does not make it easier to provide resource estimates or make planning and decisionmaking easier or more certain.

Mapping strategy selected—Various maps of the resources are acceptable, but any map used must be evaluated, quantitatively, for accuracy. Methods for assessing accuracy of maps are currently being developed (Czaplewski 1992, 1994) and will be incorporated into the IM system when available.

Sampling Frame and Plot Design

To select a probabilistic sample, several sampling frames and designs are possible. All those considered preceded the Robertson (1993) letter and are included here for completeness. We first discuss alternative sampling frames and then alternative designs for the ground plot installations.

Sampling frames—The three frames considered were:

- Existing vegetation polygons (similar to historical stand maps).
- Ecological polygons (also called ecological units [USDA Forest Service 1993]).
- Systematic grid of primary sampling units (PSUs). Each PSU contains a cluster of plots and line transects to subsample the PSU.

The advantages and disadvantages of each of these frames are given below.

Existing vegetation polygons (VP)—

Advantages:

- Allow easy inclusion of information from other (local) management surveys.
- Facilitate impact analysis because they comprise units that are more meaningful to resource specialists.
- Provide estimates of variation among polygons, within given classes, and within polygons.
- Provide a basis for grouping similar vegetation polygons into meaningful strata to improve efficiency.

Disadvantages:

- Likely to be unstable over time, particularly the boundaries. Clearly, vegetation changes over time, and there is concern that the vegetative classification system may not be repeatable given new remote sensing information (for example, new Landsat data) and newly developed models.
- May be relatively inefficient, from a sampling perspective, because a VP should be relatively uniform or homogeneous within itself. Subplots within the VP would not sample much variation if the classification is done accurately.

Ecological polygons (EP)—

Advantage:

- Likely to provide a better base for “ecologically based” management because they are more consistent with the management planning process, both in developing and implementing the plan.

Disadvantages:

- Likely to be a lack of objectivity in defining the EPs, particularly in establishing their boundaries. This will lead to variability, among field crews and even within individuals, in defining boundaries.
- Possible major change in definitions of EPs over time. This could affect boundaries on the ground and pose problems when estimating trends.

Systematic grid of primary sampling units (PSUs)—

Advantages:

- Totally objective.
- Consistent over time.
- Likely to be relatively efficient from a sampling perspective; that is, a cluster of sampling locations (over a reasonably large PSU) should cover considerable variation.
- Simple in concept and implementation.
- Provide self-weighting PSUs.
- Accommodate any form of poststratification.

Disadvantages:

- Less compatible with “ecologically based” management.
- More difficult to accomplish impact analysis.
- More difficult to include information from special inventories or impact analysis surveys because these most likely focus on specific polygons or ecological response units.
- Altering sampling intensities and keeping a consistent grid limits the flexibility of the design.

Plot designs—All five plot designs considered are cluster designs in the sense that a larger PSU is defined, at least conceptually, and then is subsampled. The size and shape of the several plot designs, as well as the subsampling details, differ considerably. The PSUs for these designs are as follows:

1. One-hectare (2.47-acre) circular plot.

2. One-hectare (2.47-acre) rectangular plot.

3. A satellite system of seven subplots in a hexagonal arrangement.

4. A satellite system of five subsample points in a symmetric arrangement covering 2.5 hectares (6.2 acres).

5. A transect (linear) arrangement of five subsample points with supplemental sampling for particular insect, disease, and tree conditions.

Each of these plot designs is described in detail below, including the proposed plan for subsampling the PSU.

Alternative (1)—Satellite system of five subplots sampling a fixed-area, circular PSU of 1 hectare (2.47 acres).

- Contains five nested, fixed-area, circular subplots with size changing given the variable of interest; for example,

    Grass and forbs—3-meter (9.8-ft) radius

    Regeneration—trees <12.7-centimeters (5-in) in diameter at breast height (d.b.h.), 3-meter (9.8-ft) radius

    Trees 12.7-25.4 centimeters (5-10 in) in d.b.h., 6-meter (19.7-ft) radius

    Trees 25.4-101.6 centimeters (10-40 in) in d.b.h., 18-meter (59.1-ft) radius

    Trees >101.6 centimeters (>40 in), entire area of 1 hectare (2.47 acres)

- The subplots are laid out in a symmetrical design.
- Some response variables, such as tree mortality, can be tallied for the entire hectare or any representative subset of the plot.
- Transects can be laid out from subplot locations; for example,

    5 at about 10-meter (32.8-ft) intervals for down woody material

    5 at about 10-meter (32.8-ft) intervals for shrub cover

- No substitution or movement of the plot is allowed for changing vegetation conditions in the field.

Alternative (2)—A rectangular, fixed-area PSU subsampled by rectangular subplots located linearly within the PSU.

- PSU has dimensions of 10 by 1000 meters or 20 by 500 meters (32.8 by 3280.8 ft or 65.6 by 1640.4 ft).
- Contains fixed-area rectangular subplots with size based on the variable of interest; for example,

    Regeneration—trees <12.7 centimeters (5 in) in d.b.h., 5 by 5 meters (16.4 by 16.4 ft)

    Trees 12.7-25.4 centimeters (5-10 in) in d.b.h., 10 by 10 meters (32.8 by 32.8 ft)

    Trees 25.4-101.6 centimeters (10-40 in) in d.b.h., 10 by 20 meters (32.8 by 65.6 ft)

    Trees >101.6 centimeters (40 in) in d.b.h., entire area of 1 hectare (2.47 acres)

- Five subplots are laid out at regular intervals to collect information on live trees:

  Random starting point

  Plots may be tied to center of rectangle or along one side to allow for coincident boundaries (easier to monument)

- Mortality can be tallied for the entire hectare.
- Transects can be laid out along the direction of travel

  5 at about 40-meter (131.2-ft) intervals for down woody material

  5 at about 40-meter (131.2-ft) intervals for shrub cover

- No substitution or movement is allowed for changing conditions.
- Plot may have a random or systematic orientation.
- Allows for maximum variability of the response variables correlated with stand basal area within the PSU.
- PSU may end up crossing several vegetation conditions.

Alternative (3)—A satellite system of seven subplots in a hexagonal arrangement.

- The center plot controls the plot configuration and substitution rules.
- Satellite plots are a combination of fixed-area circular and variable-radius plots; for example,

  Regeneration—trees <12.7 centimeters (5 in) in d.b.h., 3.3-meter (10.8-ft) radius

  Trees 12.7-91.4 centimeters (5-36 in) in d.b.h., 7 BAF (metric; that is, 7 square meters/hectare [30.5 square feet/acre])

  Trees >91.4-centimeter (36 in) in d.b.h., 18-meter (59.1-ft) radius

- Distances among subplots are predetermined and fixed so route of travel is easy.
- No fixed area is associated with the plot design.
- Mortality can be tallied on satellite plots by using same rules as for live trees.
- Substitution (point rotation) is allowed for changing conditions.

Alternative (4)—A satellite system of five subsample points, arranged symmetrically, covering about 2.5 hectares (6.2 acres).

- Design is currently operational (Pacific Northwest Research Station-FIA unit in California).
- Subsample plots are a combination of fixed-area and variable-radius plots; for example,

  Regeneration—trees <12.7 centimeters (5 in) in d.b.h., 3.3-meter (10.8-ft) radius

  Trees 12.7-91.4 centimeters (5-36 in) in d.b.h., 7 BAF (metric; that is, 7 square meters/hectare [30.5 square feet/acre])

Trees 91.4 centimeters (36 in) in d.b.h., 18-meter (59.1-ft) radius

- Two line transects per subsample point are included in the plot design for measuring residue or physical and chemical properties. Each transect is 17 meters (55.8 ft) long.
- Mortality is tallied on subsample points under the same rules as for live trees.
- Lesser vegetation is tallied on a 5-meter (16.4-ft) radius circular plot at each subsample point.
- Root disease is mapped on a 17-meter (55.8-ft) radius circular plot at each subsample point.
- No substitution is allowed for changing conditions.

Alternative (5)—A transect (linear) arrangement of five subsample points with supplemental sampling for particular insect, disease, and tree conditions.

- Subsample points are a combination of fixed-radius and variable-radius plots; for example,

  Regeneration—trees <12.7 centimeters (5 in) in d.b.h., 3.3-meter (10.8-ft) radius

  Trees 12.7-101.6 centimeter (5-40 in) in d.b.h., 7 BAF (metric; that is, 7 square meters/hectare [30.5 square feet/acre])

  Trees >101.6 centimeter (>40 in) in d.b.h., 18-meter (59.1-ft) radius

- Area sampled is about 2 hectares (4.9 acres), although no fixed area is associated with the plot design.
- Twenty supplemental points, spaced at regular intervals between the subsample points, follow the same sampling rules as for the five subsample points, but only for predetermined conditions; for example, root disease, bark beetles, dwarf mistletoe.
- Mortality is tallied on subsample points.
- Line transects can be included between points.
- No substitution of subsample points allowed for changing conditions.

Plot design selected—Beginning in summer 1993, Region 6 installed vegetation inventory plots on 5.47- and 2.74-kilometer (3.4- and 1.7-mile) grids across all NFS lands in Oregon and Washington. A version of the alternative (1) plot design was selected. The plot design is illustrated in figure 1. The main features of this design are as follows:

- PSU size (sample unit) is 1 hectare (2.47 acres).
- Each PSU consists of five subplots each representing 1/5 hectare (1/2 acre).
- Each subplot consists of three concentric, fixed-area plots used to limit measurement to certain tree diameter classes.
- On each 0.02-hectare (1/20-acre) fixed-area sample at each subplot, an ecology plot is installed based on the plant association guides developed for each Forest.

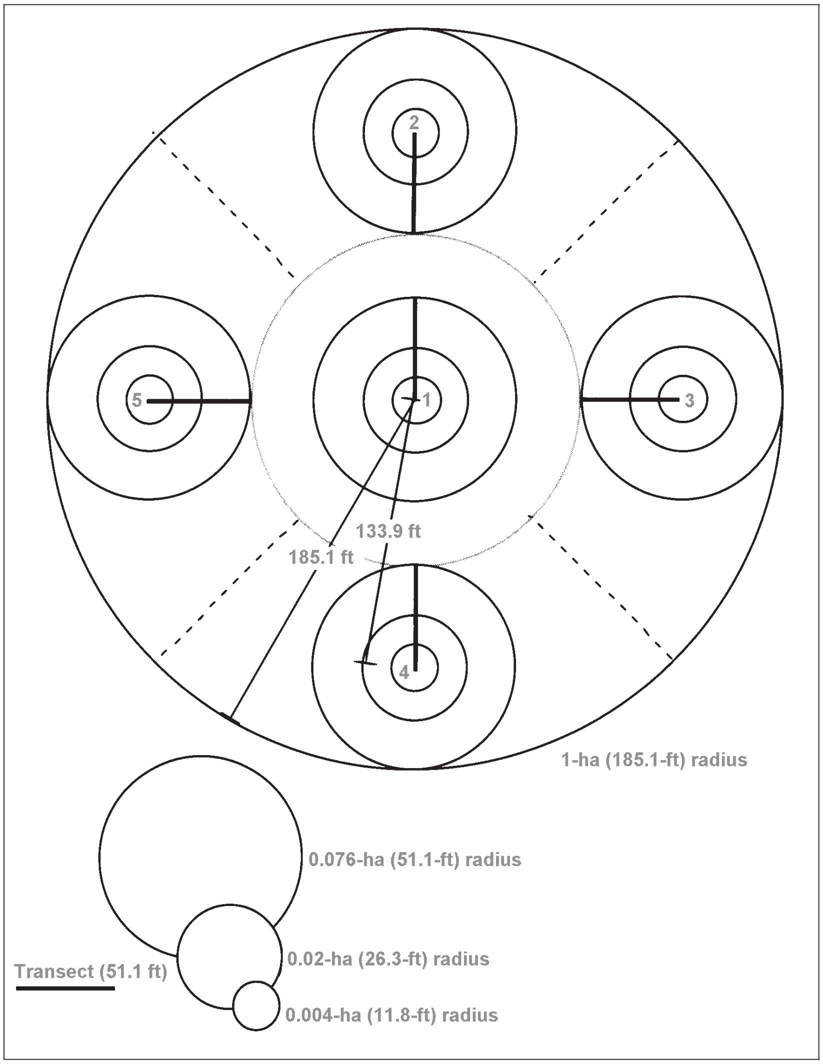

Figure 1—Basic ground plot design for one primary sampling unit, Pacific Northwest Region Vegetation Inventory and Monitoring System.

- On each subplot, a planar intersect sampling method is used to measure down woody material and ground cover.
- All plots and modifications of the basic plot design are permanently established for the purpose of remeasurement; that is, estimating long-term trends.
- The locations of all grid intersections in Region 6 of 1.37, 2.74, and 5.47 kilometers (0.85, 1.7, and 3.4 mi) were generated by using the GIS available in the Regional Office and were documented so that the actual locations can be repeatedly duplicated if necessary. Every intersection (PSU location) was consecutively numbered. This system is based on the original grid developed in 1960 by Region 6, Timber Management; the Pacific Northwest Forest and Range Experiment Station; and the Division of State and Private Forestry (Bernstein 1960).

The concentric plot sizes and associated diameter ranges are as follows:

— 0.004 hectare (1/100 acre) for seedlings <7.4 centimeter (3.0 in)

— 0.02 hectare (1/20 acre) for trees 7.6 to 32.8 centimeters (3.0 to 12.9 in)

— 0.08 hectare (1/5 acre) for trees 32.9 to 81.0 centimeters (13.0 to 31.9 in—east side)

— 0.08 hectare (1/5 acre) for trees 32.9 to 121.7 centimeters (13.0 to 47.9 in—west side)

— 1 hectare (2.54 acres) for trees >81.0 centimeters (32.0 in—east side) and >121.9 centimeters (48.0 in—west side) and for rare features such as occurrence of root rot or tally of mortality

Some specific attributes of the selected alternative are:

- This plot design does not allow for rotation or changes in the layout of any subplots, which conforms to the mandate of the Chief of the FS (Robertson 1993).
- By not allowing for rotation of subplots, any major change in vegetation must be mapped as part of the plot information.
- The plot design is flexible enough to be modified by a project or Forest to meet specific data requirements (for example, sampling for mortality, acquiring old-growth training sites), and it could have worked well for the Pacific yew inventory. The subplot sizes used to furnish the 1993 and 1994 data are being examined to determine if some modification is required. However, the 1-hectare (2.47-acre) circular plot still will be used as the PSU.

Quality Assurance

The following quality assurance procedures will be followed:

- A clearly understandable manual will be provided for Region 6 data collection crews.
- Potential customers of the inventory results will be identified and have an opportunity to comment on this paper and on proposed and actual products.
- All FS data collection crews (direct employees) will be given 10 days of training in plot establishment, measurement, and inventory procedures.
- Demonstrations of plot establishment and plot inspection shall be given to all contracted data collection crews.
- All data collection crews must measure successfully two out of three certification plots before they are allowed to work on an inventory project.
- The work of all data collection crews shall be inspected at a rate of one plot in five during the entire project and shall be evaluated by the same set of data acquisition standards as defined in their contract.
- All inspected plots shall become a part of the inventory database as well as part of the quality control database.
- Inspection of the work of all field inspectors shall be done through the Regional Office with assistance from other Forest inspectors.

Data Processing and Estimation

Rigorous quality control of the field data will be built into development of the final database. The estimation theory given for mapped designs in the “Review of Literature” will be used. The necessary computer algorithms are now being developed by the U.S. Department of Agriculture, Forest Service, Timber Management Service Center, Fort Collins, CO.[2]

Analyses

Procedures for analysis will be developed as data from the IM system become available. These will be keyed to the available standard statistical packages.

Acknowledgment

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Appendix 1
Plot Recording Sheet

Actual plot recording sheet used to record data in the Pacific Northwest Region Vegetation Inventory and Monitoring System.

Current Vegetation Data Form Tally Guide	Azimuth	Distance	Sampling Pt. #	SubPlot #	Quadrant	Veg. Code	Tree Number Previou	Tree Number Curren	Reconciliation	Species	Diameter	Ht./Length	Growth	Age	Crown Ratio	Crown Class	Crown Width Debris Depth	Damage/Severity			Defect	Cond./Use	Large End Dia.	Group Tally Features	Cover Type % Cover	Remarks
12-Apr-94 version 1.4	XXX	XX.X	XX	X	X	XX	XXX	XXX	X	XXXXXX	XXX.X	XXX	XXX	XXX	XX	X	XX	XX X	XX X	XX X	X	XX	XX	XXX	XX	
1 hectare (2.47 ac.)																										
Trees (>=32") East																										
Trees (>=48") West																										
Live	S	S	X	1		10		X		X	X	S			X	X		X	*	*	S					
GST	S	S	X	1		11		X		X	X	X	X	X	X	X	X	X	*	*	S					
Dead	S	S	X	1		20		X		X	X	S						X	*	*	S	X				
.076 ha. (1/5.3 ac.)																										
Trees (13-31.9") East																										
Trees (13-47.9") West																										
Live	S	S	X	2	X	10		X		X	X	S			X	X		X	*	*	S					
GST	S	S	X	2	X	11		X		X	X	X	X	X	X	X	X	X	*	*	S					
Site	S	S	X	2	X	13		X		X	X	X	S	X	X	X	S	None affecting height growth								
Dead	S	S	X	2	X	20		X		X	X	S						X	*	*	S	X				
Stumps (>= 13"dbh)			X	2		22				X								60 0						X		
.02 ha. (1/20 ac)																										
Trees (3-12.9")																										
Live	S	S	X	3	X	10		X		X	X	S			X	X		X	*	*	S			S		
GST	S	S	X	3	X	11		X		X	X	X	X	X	X	X	X	X	*	*	S			S		
Site	S	S	X	3	X	13		X		X	X	X	S	X	X	X	S	None affecting height growth						S		
Dead	S	S	X	3	X	20		X		X	X	S						X	*	*	S	X		S		
Stumps (5-12.9")			X	3		22				X								60 0						X		
Hardwood Clumps	X		X	3	X	60		X		X		X					X							X		
Indicator Species			X	3		40				X		X													X	
.004 ha. (1/100)																										
Trees (1.0-2.9")																										
Live	S		X	4	X	10		X		X	X	S			X	X		X	*	*						
GST	S		X	4	X	11		X		X	X	X	S		X	X	X	X	*	*						
Dead			X	4		25				X	0020													X		
Hardwoods			X	4		15				X	0020													X		
Seedlings			X	4		15				X	0001													X		
Non-Tally Ref.																										
Tree/Stumps/Object	X	X	X			99				X	X															REF
Transects																										
Down Woody																										
3" ID +			X	5		70				S	X	X										X	X			X
1-2.9" ID			X	5		70					0020													X		
.2-.9" ID			X	5		70					0005													X		
Cover Class		X	X	5		90						X													X	

X - Entry always required
S - Refer to manual for use
* - For multiple damaging agents

Subplot radius			
	1	1 ha.	(2.47 ac.; 185.1' r)
	2	076 ha.	(1/5.3 ac.; 51.1' r)
	3	.02 ha.	(1/20 ac; 26.3' r)
	4	004 ha.	(1/100 ac.; 11.8' r)
	5	Transect	

Max, Timothy A.; Schreuder, Hans T.; Hazard, John W.; Oswald, Daniel D.; Teply, John; Alegria, Jim. 1996. The Pacific Northwest Region vegetation and inventory monitoring system. Res. Pap. PNW-RP-493. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

A grid sampling strategy was adopted for broad-scale inventory and monitoring of forest and range vegetation on National Forest System lands in the Pacific Northwest Region, USDA Forest Service. This paper documents the technical details of the adopted design and discusses alternative sampling designs that were considered. A less technical description of the selected design will be given elsewhere. The grid consists of a regular, square spacing with 5.47 kilometers (3.4 mi) between grid points. The primary sampling unit (PSU), established at each grid sampling point, consists of a circular, 1-hectare (2.47-acre) plot. The PSU is subsampled with a set of different-sized fixed-area subplots, as well as line transects, to assess all components of vegetation. The design is flexible and can be used with many types of maps. The theory of point and change estimation is described, as well as estimates of variation that assess the statistical precision of estimates.

Keywords: Sampling, plot design, fixed-area plots, line intersect sampling, monitoring, National Forest System, Pacific Northwest.

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