Integrated Inventory and Monitoring

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Abstract—Understanding and inventorying our ecological systems is key to addressing how issues, questions, and management actions will affect the composition, structure, and function of these systems. Taking an ecological systems approach to the inventory and monitoring framework, is one which we feel will allow answers to currently identified management questions and new ones as they develop. More efficient ways to delineate polygons and a more credible method to attribute the polygons from a sample design are needed. Small area estimation such as the k-nearest neighbor or most similar neighbor, currently being evaluated, could be useful in mapping structural characteristic statistical data in a more defensible manner than methods used in the past.

Introduction

Region 1 of the USDA Forest Service includes about 25 million acres in the states of Montana, northern Idaho, North Dakota, and northwest South Dakota. Approximately 8 million acres are classified as suitable forest land, 12 million acres are identified as nonsuitable forest land (including wilderness), and 5 million acres is nonforest land (grass and rangeland). The successful and sustainable forest and grassland management depends upon what we know about the land, water and air as well as about the people who reside near or depend upon public lands for their use or enjoyment.

Currently we gather independent data by resource functions, which lead to gaps in information and costly duplication of work. Rather, the focus of this inventory and monitoring system is on coordinating data collection to reduce the overall costs and provide more comprehensive information. Why is inventory important? In moving to consider landscapes as a whole, it is very important to know what exists and where it exists. The inventory will cover the entire land base and, in addition to estimates of timber volumes and land areas, will include information on a full range of vegetation types, as well as data on coarse woody debris, forest health, soil, range, and other relevant items.

A general planning model includes four basic steps; inventory and monitoring, assessments, decisions and implementation. The model is a process that the Forest Service has generally followed since the conception of forest planning. The same model can be displayed by adding a dimension for scale. Thus the need to define location-specific inventory information for a project decision versus generalized information for a regional decision. Regardless of the decision scale it's important for the information to link between scales; to provide the fine scale detail required for broad-based regional decisions and to set the context and location for implementing regional decisions at a project scale.

The direction for Forest Inventory and Analysis (FIA) is to "…make and keep current a comprehensive inventory and analysis of the present and prospective conditions of and requirements for the renewable resources of the forest and range lands of the United States…." FIA was also directed to "…as part of the Assessment effort… to develop and maintain on a continuing basis a comprehensive and appropriately detailed inventory of all National Forest Systems land and resources" (Forest Service 1992).

The National Forest System (NFS) direction is taken from the ecosystem management principles of health and sustainability as articulated in the Forest Service Natural Resource Agenda. The Northern Region Overview focus is on ecosystem health and recreation is closely tied to the Natural Resource Agenda. Ecosystem health and habitat restoration are the overriding priorities for management. These principles help insure we can meet the needs of the present without compromising the ability of future generations to meet their needs.

This paper addresses what we believe are key components of an ecological systems inventory framework:

- Multiresource inventories that are linked or integrated;
- Multiscale approach that is linked across scales;
- Spatial expression;
- Data attributes that are sensitive to a variety of issues and indicators;
- Ground sampled data linked with mapping;
- Temporal continuity and comparison;
- Multiownership inventories that are coordinated;
- Organizationally executable and affordable.

We explore these components through the challenge of designing an inventory system for a particular part of the ecological system. We have simply called it the "Vegetation" aspect or if using the Holosphere model used on the Sierra Nevada Monitoring Framework, it would be the Biosphere. In this paper, we present the overall design and products for a systematic vegetation inventory. Then we will discuss the particular issues or considerations for each of the components above. At this time, the issues are being addressed through a pilot effort.

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A Vegetation Example

We focus on management surveys here and indicate what Region 1 needs and how the Region will be compatible with the national strategic needs and how project-planning surveys may fit in.

For its management needs the Region wants to define mapped ecosystems, which will vary tremendously in size and which are delineated with a desired accuracy level. These mapped ecosystems need specific information for each hectare in each Forest, but the level of detail may vary between lands classified as forest, range, or wilderness.

Ideally, mapping would be used to delineate cover types (species composition), size and density classes into polygons with 80 percent accuracy. Grouping will be done to achieve meaningful subpopulations for which the desired accuracy is achieved and attributes are assigned. Beyond this, specific information is to be collected by ground sampling for certain sample locations and that information is then used to predict the same type of information for nonsampled locations using small area estimation techniques. It is realized that the predictions will often be quite unreliable and reliable estimates of error are also required. The Region is also committed to providing information for the strategic level needs of the Forest Service so that FIA collects the required strategic level information on a 5-km grid of sample plots located on each National Forest in the Region but only on lands defined as forest.

For both strategic and management purposes the general areas of inventory are (1) timber mensuration, (2) vegetation characterization, (3) presence/absence of selected wildlife species, (4) riparian communities, and (5) presence/absence of sensitive plants.

A special feature of the Region 1 data requirement is that data elements to be collected are taken from information contained in Netweaver, a rigorous exercise by the region to determine information needs.

Multiscale Design

The Forest Service requires statistically valid inventory and monitoring designs for very large scale strategic surveys of vegetation on forest land. These are statewide estimates on a 5 or 10 year cycle documenting the condition of the forest resource and how it has changed. Survey types are (1) strategic scale surveys (national), (2) large-scale surveys (Forest level or below) for forest and nonforest lands called management surveys, and (3) project planning surveys (specific populations where a management practice is or might be applied). The question is can we integrate these types of surveys so that all three types use common information as much as possible? This is critical to the organization for efficiency in sampling, compatibility and comparability of data, and perceived ownership of data.

The FIA inventory employs a nonstratified grid across each state. This does not depend on maps but would result in a small sample size for subdivisions of a forest or smaller subpopulations. In all options below we have assumed that a mandated FIA data collection inventory grid of 5 km which we call the R1 5-km grid. We assume that this also includes the nonforest lands in the region although FIA does not measure plots there currently.

There appear to be two major options for intensifying the inventory: nonstratified sampling (the existing FIA grid locations or an additional intensification) and stratified sampling. The grid intensification does not provide any cost or sampling efficiency that could be gained with stratified sampling. With stratified sampling we have several design possibilities; fundamentally we want subpopulations of 'like' polygons so they are homogeneous to populate the 'like' nonsampled polygons with good predictability.

Region 1 wants an ecosystem management based inventory and monitoring system. For all options below we visualize screening the locations for possible factors related to rare and endangered species as well as for other issues of interest. This would be a key first step in many project-planning surveys. The neighborhoods of identified locations would then be sampled more intensively in a statistically valid manner that we also have to develop. In some cases purposive sampling will identify special locations not tied in an obvious way to our statistical sample. Those situations would be treated separately. For both these situations very low altitude photography may be a useful supplementary sampling tool.

Mapping

Region 1 has several options to create polygons where a polygon consists of a delineated boundary with attributes that characterize the vegetation for the polygon; those attributes are size class, density and species composition (cover type). Vertical structure is desired but very difficult to develop from remote sensing or aerial photography.

The first step is a mapping phase that will start with satellite imagery and training data to produce a classified pixel map. This basic pixel map is used to aggregate or combine the pixels into an initial vegetation polygon map using an automated process, and then refine the attributes and the boundaries needed with ancillary data such as digital ortho-quads, potential vegetation, Indian resource satellite (IRS 5-meter panchromatic), classified 1 meter data and resource aerial photography. An accuracy assessment will be performed on the polygon map and the results will be documented; users will evaluate the accuracy and determine if it's adequate for the level of analysis being preformed. This map is similar to a "stand" map as traditionally used in forestry but includes the nonforest vegetation also. A National Forest is expected to have polygons or stands with an average size of about 30 acres, with 30,000 to 50,000 total individual polygons. This initial map is considered map one.

The next step, mapping phase II, is aggregating the initial mapped polygons into a map that represents 20 subpopulations (aggregation of similar composition characteristics from map one) with the intention of improving accuracy and providing larger polygons for field sampling. This map two will be used to allocate field sample locations to the 300 subpopulations (21 composition classes, 5 size classes, and 4 density classes). This is for use at the Forest, planning zone, or province level where spatial reference of composition, structure and pattern is needed for the inventory variables.

A similar map product, map three, is envisioned based on aggregating map product two to define very general vegetation classes. This mapped aggregation would consist of approximately 60 subpopulations for long-term inventory and monitoring and assessments for broad ecological zones or subregions.

The mapping process to create maps one and two will probably be done at a Forest Zone (in other words, a multi-Forest level to take advantage of local experience and knowledge of the ecological system) and to gain acceptance of the maps and ground inventory products at the local levels. All Forests or Zones will follow the same classification format and procedures with Regional Office involvement for quality assurance. Following these procedures will ensure a consistent classification and the ability to create other map products.

As indicated in the introduction, there is a need to identify the inventory with spatial characteristics. The mapping is essential, but recognized as "tenuous" due to the potential changes that could occur in the mapping.

Other Map Efforts

The approach to be used currently centers on the National Ecological Mapping Hierarchy System (ECOMAP) to identify ecological zones for the inventory. ECOMAP is based on biophysical characteristics that only change on geologic time scales. The Sections are based on regional climate, topography, and geologic characteristics. We propose to use the sections to identify the ecological zones for inventory and monitoring. Subsections are based on surface geology, soil great groups, and potential vegetation and land-type associations (LTA's) are based on geologic soils and landform; there appears to be a consistent methodology nationally.

Hydrological units (HUC's) are based on the concept of watersheds with a consistent national framework for level four category units (4th code HUC); about 2,100 exist across the country. Level 5 and 6 HUC's are smaller and without a consistent national framework for definition. HUC's are not always true watersheds and approximately 50 percent of the HUC's are composite watersheds.

It is reasonable to assume that more maps may be desired; for example a recreation use map or a wildlife habitat map. The ECOMAP subsections and landtype associations will be used as a further stratification for inventory and analysis. Hydrologic units will be most useful in the analytical phase and during monitoring.

Statistical Estimation

Sample Designs

Assume a map of vegetation polygon subpopulations. Group these subpopulations into strata of like polygons. Then select a sample of polygons from each subpopulation. Subsample the selected polygons or select a "grid" sample from each subpopulation (which means that the number of sample units from the selected polygons is a random variable that may be undesirable given that we want to use small area estimation to populate the unsampled polygons in each subpopulation). The advantage is that we focus as much as possible on the smallest subpopulations of interest and assign near-optimal probabilities of selection to units in those subpopulations that are of most interest (this assumes that R1 can decide on putting subpopulations in an order of priorities). The key disadvantages are that sample selection has to wait till the vegetation polygon map exists, the map will change almost continuously and if the map used turns out to be incorrect to a large degree, we may be sampling very differently from expected.

Another issue that may be a disadvantage is that there are certain features of the polygon we would like to map such as structure but it seems unlikely at this time to be able to do so. Hence such features need to be sampled for on the ground, causing difficulties in populating the nonsampled polygons well. With 13 National Forests and 300+ current vegetation classes we have a rough estimate of 500,000 polygons and about 2,000 subpopulations with about 300 polygons per subpopulation with the R1 5-km grid yielding about 1.5 plots per subpopulation (not sure these add up). We are therefore aiming at breaking sample size n into 13 n (F, subpopulations). There are other stratified options that will not be discussed here.

Criteria for Evaluating Design Alternatives

1. Ability to create vegetation polygon map.
2. Ability to make estimates for all critical subpopulations.
3. Comparison of number of strata.
4. Ability to estimate change between two inventory periods.
5. Special designs to accommodate special issues (rare species, etc.).

A pilot test is being implemented as an initial step toward implementation, where the map products are being developed in 1999 for a large area (400,000 acres) of land in the Idaho Panhandle National Forest and assessed for their accuracy. This area was picked for its considerable heterogeneity as well as the willingness of key local people to collaborate. Then in 2000 a large ground sample will be collected in each of the ecosystems to determine whether the objectives can be achieved for the pilot study area.

The Northern Region management inventory (which is likely to be also useful for the strategic survey) would be pilot tested through all phases of data collection, estimation, and analysis. This includes evaluating the ability of managers to make decisions based on the data, model development and testing, and modifications needed prior to full implementation.

To accommodate the strategic needs of the FS and to allow for integration or merger with FIA sampling, the following plot design will be used, a generalization of the FIA plot design. The FIA plot consists of four $\frac{1}{24}$-acre circular subplots each of which is subsampled by a small $\frac{1}{300}$-acre circular subplot for regeneration. We plan to use a one-hectare plot subsampled by four circular subplots of about $\frac{1}{4}$ acre centered at the same locations as the four FIA subplots. Transects will be used within the one hectare plot for down woody material and understory measurements. Further refinement and testing of the plot design will be completed with the pilot test.

Incorporating the existing FIA plot design with the added one-hectare and ¼ acre plots will provide the ability to account for large trees, snags, and other rare occurring characteristics.

Estimation

Much of the estimation theory in this section was adapted from Region 6 written but unpublished directions by permission from John Teply, Program Manager, Region 6 Inventory and Monitoring. We assume that the 4 subplots on the hectare are a random sample of the one-hectare plot for variance estimation. This is required both for classical and bootstrap variance estimation. A nuisance that arises with almost any type plot but certainly with the circular plots used is that parts of the plots will fall outside the population of interest or are inaccessible to sampling either because of difficulty of terrain or in order to reach part of the sample in a practical manner we need to access via private land. Not all landowners will allow access through their land to measure information on NFS land.

To account for the different sizes in actual plot areas by sample locations we decided that the most appropriate estimator to be used in estimating population totals is:

$$\hat{Y}_s = A\left[\sum_{i=1}^{n}\sum_{j=1}^{m_i}\hat{A}_{ij}Y_{ij}\right] / \left[\sum_{i=1}^{n}\sum_{j=1}^{m_i}\hat{A}_{ij}\right] \quad (1)$$

where $\hat{Y}_s$ is the estimator for subplot size s, $\hat{A}_{ij}$ and Y_{ij} are the estimated sampled area and value of interest (expanded to a ¼ ha estimate) respectively in subplot j of plot i, n is the number of plots in the sample, and m_i is the number of subplots in the sample for plot i. How the $\hat{A}_{ij}$ and m_i are determined is described in a separate write-up (Max and others 1997). To estimate parameters involving a combination of sizes, we would then have:

$$\hat{Y} = \sum_{s}\hat{Y}_s \quad (2)$$

with summation over the subplots involved.

The basic rule for measuring plots that either intersect the boundary of the population or are partially inaccessible due to, say hazardous conditions, and adhere to the following basic principles.

1. Decisions concerning whether or not to measure a subplot or what part of a subplot to measure are made independently on each subplot of a PSU, regardless of subplot number, in other words, the PSU center, subplot number 1, is no different than any other subplot center.

2. If a subplot center is either inaccessible or not within the population boundary, then no measurements are taken on this subplot, since the subplot center cannot be established and referenced by standard field methods. In cases where part of the subplot is accessible or within the population boundary, even though the subplot center is inaccessible or outside the population, then this results in a part of the population that is selected to be included in the sample but is not measured. Hence this is a source of potential bias in the estimation process.

3. If the subplot center is accessible and within the population boundary, then all regular measurements are taken on that part of the plot that is accessible or within the population. The subplot must be mapped, with relevant measurements, in sufficient detail so that the amount of area of the subplot that was actually measured can be calculated accurately. This area provides the information essential for computing the proper area weight for the partially measured subplot.

4. For purposes of making decisions about measurement, a PSU can be thought of as consisting of four distinct and separate, although contiguous, subplots.

Inaccessible PSU's

In this section we address the situation where some, or possibly all, of a PSU is inaccessible. Inaccessibility is usually caused by hazardous conditions, for example the existence of cliffs, that prevent safe access to the area covered by the plot.

A. Subplots where subplot center is inaccessible

i. Entire area of subplot is inaccessible

Follow the basic principle, part (2). The entire subplot is not measured. This lack of measuring a part of the selected sample area is a source of potential bias in estimation.

If the subplot center that is inaccessible is subplot 1, the PSU center, then the location of the PSU must be monumented with respect to a subplot whose center is accessible. This is a deviation from standard field procedure in which the location of the PSU is referenced with respect to the PSU center coincident with the center of subplot 1.

ii. Some area of subplot is inaccessible

Follow the basic principle, part (2). The entire subplot is not measured because the center of the subplot is inaccessible and cannot be establish using usual field procedures. This lack of measuring a part of the selected sample area is, again, a source of potential bias in estimation.

If the subplot center that is inaccessible is subplot 1, the PSU center, then the location of the PSU must be monumented with respect to a subplot whose center is accessible. This is a deviation from standard field procedure in which the location of the PSU is referenced with respect to the PSU center, coincident with the center of subplot 1.

B. Subplots where subplot center is accessible

The basic rule is followed, in this case, without exception.

PSU's Intersecting Boundary

In this section we address the situation where a PSU intersects the boundary of the population. The population of interest, defined as simply as possible, is all National Forest System (NFS) land. The situation discussed here is where a

PSU intersects the boundary so that part of the PSU is on NFS land and part on some other ownership. The principles expressed in the basic rule, in this case, are designed to collect as much information as possible while avoiding the necessity of gaining access to the adjoining ownership for establishing subplot centers on the adjacent property.

A. Subplots where center is outside NFS land

i. No area of subplot intersects NFS land

Follow the basic principle, part (2). This subplot is not really part of the population, and there is no potential bias associated with not measuring any part of this subplot.

If the subplot center that is outside the population boundary is subplot 1, the PSU center, then the location of the PSU must be monumented with respect to a subplot whose center is within the population boundary. This is a deviation from standard field procedure in which the location of the PSU is referenced with respect to the PSU center, coincident with the center of subplot 1.

ii. Some subplot area intersects NFS land

Follow the basic principle, part (2). The part of this subplot within the population boundary is really part of the population. To access and measure this part of the subplot requires establishing the subplot center that actually is located on the adjacent property. To avoid gaining access to this adjacent property, we forgo measuring the part of the subplot on NFS land. There is a potential bias associated with not measuring the part of this subplot that is within the population boundary.

If the subplot center that is outside the population boundary is subplot 1, the PSU center, then the location of the PSU must be monumented with respect to a subplot whose center is within the population boundary. This is a deviation from standard field procedure in which the location of the PSU is referenced with respect to the PSU center, coincident with the center of subplot 1.

B. Subplots where center is on NFS land

The basic rule is followed, in this case, without exception.

Variance Estimation

Classical variance estimates can be obtained for $\hat{Y}_s$ using for example equation (5.12) on p.162 in Schreuder and others (1993). Similarly the variance for $\hat{Y}$ can be obtained by summing the variances of the $\hat{Y}_s$ included in the summation in (2) and adding the necessary covariance estimates that can be obtained by suitably modifying eq (5.12) in Schreuder and others (1993).

Based on the discussion in the review of literature, we decided that it was generally better to develop bootstrap-based variance estimates. These yield more reliable confidence intervals for the parameters of interest and can be computed easily even though they are more computer-intensive than traditional variance estimates.

Although there are several more efficient bootstrap variance estimation techniques we will concentrate on the straightforward method at this time since the method should work over a wide range of situations and is likely to be implemented by numerous users.

To implement the bootstrapping we select n plots at random with replacement from the n plots available. This sample is used to generate bootstrap estimates using equation (1) for the information collected on the one-hectare plot. From each of the n plots selected, four subplots of the four in each plot are selected with replacement. This sample of n plots and 4 subplots is then used to generate estimates for the information collected at these subplots using equation (1) and using equation (2) for linear combinations of information requiring information from various subplots. This constitutes one bootstrap sample. We select such bootstrap. We then generate the following estimates:

$$\bar{Y}(B) = \sum_{i=1}^{n_B} \hat{Y}_i(B) / n_B \quad (3)$$

with bootstrap variance estimator:

$$v\{(B)\} = \sum_{i=1}^{n_B} \left\{ \hat{Y}_i(B) - \bar{Y}(B)^2 \right\} / (n_B - 1) \quad (4)$$

Generating n_B estimates $\hat{Y}_i(B)$, also generate lower bound $LB_{\alpha/2}\{\hat{Y}(B)\}$ and upper bound $UB_{\alpha/2}\{\hat{Y}(B)\}$, which are those sorted values of $\hat{Y}_i(B), i = 1....,n_B$ such that there are $n_B * \alpha/2$ below LB and an equal number above UB. We use $\alpha = 0.05$.

Organization and Recommendations

It is clear that there is considerable overlap in the above missions for FIA and NFS-R1, and those need to be worked out in close collaboration between the interested parties involved. The various organizations within the agency involved in inventory and monitoring need to work together to develop a comprehensive, legally and scientifically defensible survey system that is also as cost effective as possible.

It is clear that major organizational changes will have to be made in Region 1. For example: change future remote sensing and GIS roles of local universities to emphasize research, applications assistance and technology transfer to Region, planning zones, and National Forests, rather than production work. Reach out to include other universities, the Remote Sensing Applications Center, and the Regional Remote Sensing Service Team.

The Regional Office role in GIS and remote sensing map development will concentrate on coordination, training, and accountability. The Regional Remote Sensing Service Team should conduct GIS and remote sensing data development at zone centers, especially if the results are expected to serve resource management as well as general planning purposes. Such data should be developed to Regional standards to facilitate Region wide summarization and reporting, and assessment.

Retain flexibility on plot design when possible. For example the Region 1 approach of using a plot that collapses into the FIA plot both in area and transect sampling has considerable promise. But the Region 6 plot design should not be rejected simply because it does not.

Evaluate the gain and losses using the Region 1 potential plot design and the Region 6 plot relative to the FIA plot. Do this in a scientific publication prior to making the decision to drop those in favor of the FIA plot.

Clearly identify what the FIA grid can and cannot do for NFS management and project planning surveys. This will be addressed too in the Region 1 pilot study.

Remember that the main FIA product is a database and reports based on that for general consumption, whereas NFS needs a database for decisionmaking and long-term assessment. Hence the users and uses of the data are quite different.

Develop statistically valid yet practical project planning surveys if feasible. This may require time and analyses of management survey data before this can be done.

Hire statistical analysts to analyze the strategic and management databases for NFS purposes. That capability is in short supply in NFS currently and is desperately needed. In line with that, identify promising Bayesian methods for decision making for management and project planning in NFS.

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