

The National Forest Inventory of the United States of America

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ABSTRACT : The mission of the Forest Inventory and Analysis (FIA) program of the Forest Service, U.S. Department of Agriculture, is to conduct the national forest inventory of the United States of America for purposes of estimating the area of forest land; the volume, growth, and removal of forest resources; and the health of the forest. Users of FIA data, estimates, and related products include land managers, policy and decision-makers, forest industry, environmental organizations, and university researchers. To accomplish its mission, the FIA program has established a sampling design with an intensity of approximately one permanent plot per 2,400 ha across the entire country. Depending on the region of the country, each plot is remeasured at intervals of five or 10 years. The program releases data annually and reports estimates at the county level for each state every five years. Due to budgetary constraints and natural variability among plot observations, sufficient numbers of plots cannot be measured to satisfy precision guidelines for the estimates of many variables unless the estimation process is enhanced using ancillary data. Classified satellite imagery has been demonstrated to be a source of ancillary data that can be used with stratified estimation techniques to increase the precision of estimates with little corresponding increase in costs. A crucial factor restricting the utility of FIA data is that the exact locations of inventory plots cannot be released to the public. Thus, users are generally not able to obtain estimates for small areas or for their own areas of interest if exact plot locations are required. To compensate, satellite imagery, inventory plot data, and the k-Nearest Neighbors technique are being used to construct Internet-based maps of forest attributes from which estimates for arbitrary user-defined areas of interest may be obtained.

Keywords : Stratification, Satellite imagery, Quality assurance, Model based inference

INTRODUCTION

The Forest Inventory and Analysis (FIA) program of the Forest Service, U.S. Department of Agriculture, conducts the national forest inventory of the United States of America (USA) to estimate the area of forest land; the volume, growth, and removal of forest resources; and the health of the forest. The FIA program uses the ends-ways-means strategic planning model to promote and facilitate national consistency. *Ends* are the criteria that must be satisfied for the program to be characterized as nationally consistent; *ways* are the procedures that lead to achieving the ends; and *means* are the resources that are committed to the effort. The program is defined in terms of six ends:

- End 1: A standard set of variables with nationally consistent meanings and measurements.
- End 2: Field inventories of all forested lands.
- End 3: Consistent estimation.
- End 4: Satisfaction of national precision guidelines.
- End 5: Consistent reporting and data distribution.
- End 6: Credibility with users and stakeholders.

These ends describe the major foci of the program and provide direction for methodological research. To facilitate achieving the ends, 10 ways have been prescribed:

- Way 1: A national set of core variables with a national field manual that prescribes measurement procedures and protocols for each variable.
- Way 2: A national plot configuration.

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Way 3: A national sampling design.

Way 4: Standardized formulae for probability-based (design-based) inference.

Way 5: A national database of FIA data with core standards and user-friendly public access.

Way 6: A national information management system.

Way 7: A nationally consistent set of tables of estimates of prescribed core variables.

Way 8: Publication of statewide tables of estimates for prescribed core variables at 5-year intervals.

Way 9: Documentation of the technical aspects of the program including procedures, protocols, and techniques.

Way 10: Peer review of and public access to the technical documentation.

The sections that follow provide more details on key aspects of the FIA program.

SAMPLING DESIGN AND PLOT CONFIGURATION

The FIA program has established permanent field plot locations using a sampling design that is assumed to produce a random, equal probability sample (McRoberts et al., 2005, Bechtold and Patterson, 2005). The sampling design is based on a tessellation of the USA into approxi-

mate 2,400-ha hexagons (Figure 1) with a permanent plot established at a randomly selected location in each hexagon. Some states contribute additional funding to double or triple the sample size, in which case the sampling intensity is approximately one plot per 1,200 ha or 800 ha, respectively.

The hexagonal array has been divided into five non-overlapping, interpenetrating panels, and measurement of all plots in one panel is completed before measurement of plots in the next panel is initiated. Panels are targeted for selection on a 5- or 10-year rotating basis, depending on the region of the country. With this approach a complete sample of each state is obtained every year.

In general, locations of forested or previously forested plots are determined using global positioning system (GPS) receivers, while locations of non-forested plots are determined using aerial imagery and digitization methods. Each field plot consists of four 7.31-m (24-ft) radius circular subplots (Figure 1). The subplots are configured as a central subplot and three peripheral subplots with centers located at 36.58 m (120 ft) and azimuths of 0°, 120°, and 240° from the center of the central subplot. Each subplot includes a 2.08-m (6.8 ft) radius microplot on which seedlings and saplings are measured and a regionally optional 18.0-m (58.9-ft) radius annular macroplot on which additional large trees are measured.

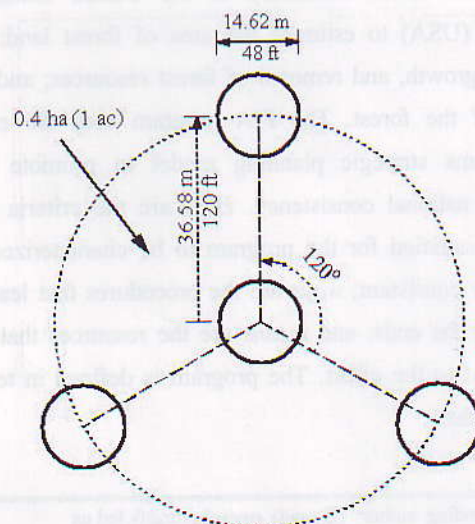
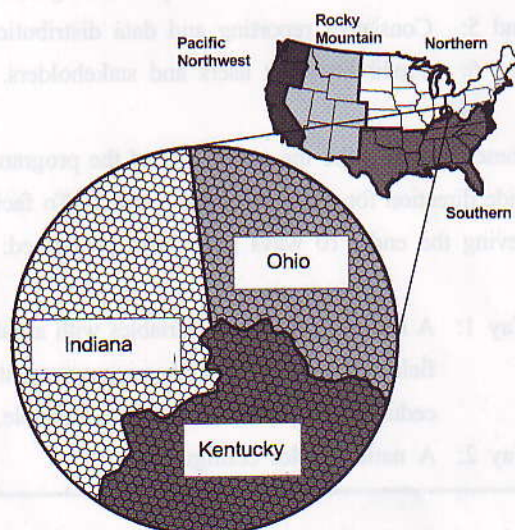


Fig. 1. FIA sampling hexagons and plot configuration.

THREE-PHASE PROGRAM

The FIA program conducts inventories in three phases. Phase 1 entails the use of remotely sensed data to obtain initial plot observations and to stratify land area in the population of interest. Phase 2 entails field crew visits to the physical locations of permanent field plots to obtain measurements of variables such as tree species, diameter, and height. Phase 3 entails field crew visits to a subset of the Phase 2 plots to obtain measurements for an additional suite of variables associated with forest and ecosystem health.

Phase 1. Remotely sensed data in the form of aerial photographs and satellite imagery are used to accomplish two Phase 1 tasks, initial plot land cover observation and stratification. In this phase, analysts determine a digitized geographic location for each field plot, and a human interpreter of aerial photography assigns the plot to a land cover/use category. Plot locations with forest land uses that are accessible to field crews are selected for further measurement via field crew visits in Phase 2. Despite the cost of photography and photo-interpretation, considerable savings are achieved with this approach because the expense of travel to and from plot locations is the greatest component of the total cost of measuring a plot.

The combination of natural variability among plot observations and budgetary constraints prohibits measurement of a sufficient number of plots to satisfy national precision standards for most inventory variables unless the estimation process is enhanced using ancillary data. Because FIA uses a systematic sampling design with permanent plots, stratified random sampling is not an option. Nevertheless, even with simple random or systematic sampling, stratified estimation may still yield increases in precision. Thus, the second Phase 1 task is to stratify the land area of interest using ancillary data. With stratified estimation, two tasks must be accomplished: first, each plot must be assigned to a stratum, and second, the proportion of the land area of interest in each

stratum must be determined. Although approaches to stratification vary by region to accommodate unique local forest features, the use of classified satellite imagery is emerging as the preferred source of ancillary data for this purpose (McRoberts et al. 2002, 2006). With this approach, image pixels are classified on the basis of predictions of land cover attributes into similarity classes that are used as strata. Strata weights are the proportions of pixels in strata, and plots are assigned to strata on the basis of the strata assignments of their associated pixels.

Phase 2. In the second phase, field crews visit plot locations determined in Phase 1 to include accessible forest land use. The field crews determine the location of the geographic center of the center subplot using GPS receivers. Phase 2 core variables are identified in the national FIA field manual and are measured on each plot in every state. Additional state and regional variables may be included, but no core variable may be deleted. Field crews record subplot-level observations of ownership, land cover, land use, land change, forest type, stand origin, stand age, stand size class, site productivity class, forest disturbance history, slope, aspect, physiographic class, and ground land use conditions. For each tree, field crews record observations and measurements that include species, live/dead status, lean, diameter, height, crown ratio (percent of tree height represented by crown), crown class (eg., dominant, co-dominant, suppressed), damage, and decay status. Field crew measurements and computer algorithms are used to calculate values for additional variables including individual tree volume and per unit area estimates of number of trees, volume, and biomass by subplot, by species groups, and by live/dead status. FIA field crews also identify distinct conditions defined by different classes of seven variables: land use, reserve status, owner group, regeneration status, tree density, forest type, and tree size class. If multiple conditions are identified on a plot, field crews assign allied trees to the condition class in which they occur and record information necessary for estimating the portion of the plot

area that is within each condition.

Phase 3. The third phase of the FIA program focuses on forest health. Phase 3 is administered cooperatively by the FIA program, the Forest Health Monitoring (FHM) program, other Forest Service programs, other federal agencies, state natural resource agencies, and universities. The FHM program consists of four interrelated and complementary activities: Detection Monitoring, Evaluation Monitoring, Intensive Site Ecosystem Monitoring, and Research on Monitoring Techniques. The ground survey portion of the FHM Detection Monitoring program is integrated with the FIA program as Phase 3.

The Phase 3 sample consists of a 1:16 subset of the Phase 2 plots with one Phase 3 plot for approximately every 38,450 ha. Because each Phase 3 plot is also a Phase 2 plot, all Phase 2 observations and measurements are acquired for all Phase 3 plots. Additional measurements on Phase 3 plots relate to forest ecosystem function, condition, and health; are generally acquired during summer months; and may be grouped into categories: (1) crown condition, (2) soil erosion potential, (3) soil fertility and/or toxicity, (4) lichens, (5) ozone bioindicators, (6) vegetation structure, and (7) down woody material. Each subplot on a Phase 3 plot includes a 36.6-m (120-ft) radius lichens plot, three 1.0-m² (10.76 ft²) vegetation plots, a 18.3-m (60-ft) down woody material transect, and a soil sampling area.

Phase 3 variables were selected to address specific criteria outlined by the Montréal Process working group for the conservation and sustainable management of temperate and boreal forests and is based on the concept of indicator variables. Observations of an indicator variable represent an index of ecosystem functions that can be monitored over time to assess trends. Indicator variables are used to address ecological issues such as vegetation diversity, fuel loading, regional air quality gradients, and carbon storage.

DATA ACCESS AND USES

1. The National Information Management System

The National Information Management System (NIMS) is crucial to the success of the FIA program and consists of two primary functions, data storage and data processing. NIMS is designed to accommodate in a nationally consistent manner Phase 1, Phase 2, Phase 3, and quality assurance data. The FIA database reflects the field data collection protocols documented in the national FIA field manual and contains nationwide, tree-level data that can be acquired by users for their own applications. NIMS simultaneously accommodates national requirements for processing core data and producing tables of forest resource statistics for both national and regional reporting requirements. NIMS is designed to be user-friendly and accessible. Input from users has been actively solicited as a means of engaging them in the development effort. In addition, NIMS provides a user-friendly interface to accommodate requests for data and data summaries and to facilitate use of a variety of software processing tools.

2. Data uses

FIA data is the primary source of large area forest information for use by public land management and planning agencies, forest industry, environmental groups, and non-governmental organizations (NGO). Inventory data and estimates for each state are made available annually, and on a 5-year cycle each state receives a comprehensive analytical report that includes an assessment of the current status and trends of forest resources and ecosystem condition, analysis and discussion of probable factors influencing the status and trends, and 20-year predictions of likely trends in key resource attributes. The FIA program also reports national assessments on a 5-year cycle. In addition, the FIA program conducts special studies related to forest ownership patterns and trends, utilization of timber outputs, and non-timber resources such

as recreation, hydrology, and wildlife habitat.

FIA data is used by a wide array of public and private organizations. In response to extensive forest wildfires in the western USA, FIA data were the primary source of information for a biomass assessment for western states (Rummer et al. 2003). FIA is also the primary source of information for forest carbon reporting in the USA (Birdsey and Lewis 2003, O'Neill et al. 2006). In addition, FIA data were used for accuracy assessment of a national satellite image-based land cover product constructed by the U.S. Geologic Survey and for describing major vegetation cover types by the U.S. Fish and Wildlife Service. FIA data are used in assessments of the status of ecosystems in the USA by the Heinz Center (Heinz 2002), an NGO. At the international level, FIA provides data for sustainability reporting based on the Montréal Process criteria and indicators. Finally, the FIA program supports the Forest Resource Assessment (FRA) program of the United National Food and Agriculture Organization.

The Phase 3 component of the FIA program is the primary source of information for assessing the status of the biodiversity of American forests. Data from the down woody materials Phase 3 component of the program are used for estimating deadwood volume and fuels (Woodall 2003a, b). In addition, FIA data have been used for a variety of biodiversity research projects including national and multi-national assessments of tree species richness (McRoberts and Meneguzzo 2007, Magnussen et al. 2007), local and regional species and diameter diversity assessments (McRoberts et al. 2008), naturalness assessments (McRoberts et al. in press), and a conifer/deciduous diversity assessment (McRoberts 2009).

ESTIMATION

The FIA program uses probability-based (design-based) inferential techniques to calculate population estimates for medium to large geographic areas such as counties, National Forests, and States. Using strata constructed from satellite imagery in Phase 1, post-stratification

estimation techniques are used to increase the precision of estimates with little corresponding increase in costs (McRoberts et al. 2002, 2006). Stratified estimates for FIA variables are calculated using methods described in Cochran (1977):

$$\bar{Y}_{Str} = \sum_{h=1}^H w_h \bar{Y}_h,$$

and

$$\text{Var}(\bar{Y}_{Str}) = \sum_{j=1}^H w_j^2 \frac{\hat{\sigma}_j^2}{n_j},$$

where

$$\bar{Y}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} Y_{hi},$$

$$\hat{\sigma}_h^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} (Y_{hi} - \bar{Y}_h)^2,$$

and Y_{hi} is the i^{th} observation in the h^{th} stratum of the variable of interest; $h=1, \dots, H$ denotes strata; w_h is the weight for the h^{th} stratum, calculated as the proportion of pixels assigned to the stratum; n_h is the number of plots assigned to the h^{th} stratum; $\bar{Y}_h$ is the sample mean for the h^{th} stratum, and $\hat{\sigma}_h^2$ is the sample estimate for the stratum variance. For estimation purposes, at least five plots per stratum are considered necessary to obtain reliable stratified estimates. If fewer than five plots are assigned to a stratum, then similar strata are combined or the estimation area is increased so that it includes sufficient numbers of plots per stratum.

The effectiveness of stratified estimation is often evaluated using relative efficiency (RE) calculated as,

$$\text{RE} = \frac{\text{Var}(\bar{Y}_{SRS})}{\text{Var}(\bar{Y}_{Str})},$$

where $\text{Var}(\cdot)$ is estimated variance, $\bar{Y}_{SRS}$ is the estimate of the mean obtained under the simple random sampling (SRS) assumption, and $\bar{Y}_{Str}$ is the estimate of the mean obtained using stratified estimation. $\text{RE} > 1.0$ indicates that

the strata and stratified estimation have the desired effect of reducing variance and increasing precision, while $RE \approx 1.0$ indicates the strata are having little beneficial effect. RE may be interpreted as the factor by which the sample size would have to be increased to achieve the same precision under the SRS assumption as is achieved with stratified estimation. McRoberts et al. (2002) obtained RE estimates for forest area as great as 2.65.

1. Area Estimation

Area estimation is based on the known areas of the strata used for variance reduction and the plot observations. The stratum estimate of total area by condition class is the product of the known stratum area and the mean of the proportion area by condition class over all plots in the stratum. Specific details, particularly for unique situations, are documented in Bechtold and Patterson (2005).

2. Volume estimation

Stem volume of individual trees with $dbh \geq 12.7$ cm (5 in) is estimated using statistical models as the volume of the central stem above a 30.48 cm (1 ft) stump and to a minimum top diameter of 10.16 cm (4 in). The models are constructed regionally and are based on combinations of observations or measurements for species, diameter, and height. All live volume includes stem volumes for all trees, while growing stock volume excludes volume for the cull portions of trees and all volume for cull trees.

3. Components of change

FIA inventories are designed to produce data to estimate the components of change (growth, removals, mortality) that are aggregated to estimate net change over time. Calculation of most components of change are based on the observed changes in condition and tree measurements between inventory cycles. In addition, the FIA program

produces a non-sample based estimate of timber removals using data obtained from surveys of the consumption of roundwood by timber-using industries and import/export information.

4. Ratio estimation

Per unit area estimates by condition class (e.g., volume by forest type) are calculated using a ratio estimator of the general form,

$$\bar{y} = \frac{\sum_{i=1}^{n_h} y_i}{\sum_{i=1}^{n_h} a_i},$$

where y_i is the observation or measurement of the variable of interest on the i^{th} plot and a_i is the area of the condition on the same plot. The general form of the variance estimator is as documented by Särndal et al. (1992).

5. Error estimation

Sampling errors are calculated as the product of 100 and the ratio of the standard error of the estimate and the estimate itself. The FIA program also calculates precision using a technique that permits comparisons across areas of different sizes. With this approach, precision (PREC) is defined as,

$$PREC = \frac{\sqrt{\text{Var}(\hat{Y})}}{\hat{Y}} \sqrt{\frac{\hat{Y}}{S}},$$

where,

$$S = \begin{cases} 40,469 \text{ ha} & \text{for area} \\ 28,316,980 \text{ m}^3 & \text{for volume} \end{cases}$$

The program has established precision guidelines of

$$\text{PREC} = \begin{cases} 0.03 & \text{for area estimates} \\ 0.05 & \text{for volume estimates in the eastern USA} \\ 0.10 & \text{for volume estimates in the western USA} \end{cases}$$

QUALITY ASSURANCE

The primary features of the quality assurance/quality control (QA/QC) component of the FIA program are nationally consistent measurement protocols and procedures, extensive crew training and independent checks. Each new field crew receives several weeks of training after which they are tested and certified for their ability to satisfy national measurement quality objectives. Experienced crew members assist in the initial training of new field crews and are paired with new crew members to provide additional on-the-job training during the field season. Field crews use portable data recorders (PDR) that are programmed with data checks to provide alerts if data are illogical or outside of established norms. Plot measurements are reviewed by field crews for attributes that the PDRs do not check and are edited before being transmitted to the office. Data are checked further for errors during office processing. Each variable has an associated tolerance level and performance objective. For example, for dbh the tolerance level is ± 0.25 cm per 50 cm and the performance objective is 95%; thus, 95% of measurements of trees with dbh=50 cm should be within 0.25 cm of the true dbh.

Field checks of data quality are also conducted. *Hot checks* are inspections conducted as part of the training process by QA/QC staff, provide immediate feedback about a crew's performance, and are conducted on both training and field plots. Errors discovered during hot checks are corrected. *Cold checks* are remeasurements of field plots by QA/QC staff without the original crew present. The QA/QC crew compares its measurements to the measurements of the original crew and corrects errors. *Blind checks* are remeasurements of field plots by QA/QC crews without the original crew present and without access to the original crew data. No corrections are made

as a result of blind checks; rather two data sets are maintained separately as a means of assessing uncertainty in measurements.

MODEL-BASED INFERENCE

Frequently, the tabular estimates of forest inventory variables are not adequate to satisfy user requirements; for example, areas of interest (AOI) based on ecological rather than political boundaries, fragmented AOIs, and small AOIs for which the number of plots is insufficient to produce acceptably precise estimates. The first two examples may generate requests for direct access to inventory data so that users can conduct their own analyses. When the requests do not require exact plot locations, there are few constraints on data access. However, if exact locations are required, then several issues must be considered. First, revealing exact locations may entice users to visit the plots to obtain additional information, thus artificially disturbing the sampling location and contributing to bias in inventory estimates. Second, plots may be located on private land, and while land owners usually permit access by inventory field crews, they are generally less receptive to access by non-inventory personnel. For FIA, which must obtain owner permission to access plots on private land, user visits to plot locations may jeopardize future access by inventory field crews. In addition, the program is prohibited by public law from revealing the exact locations of plots on private land. Thus, if exact plot locations are required for a user's analysis, policy constraints may prohibit the inventory program from accommodating the user's data request. An alternative, which also addresses the requirement for estimates for small AOIs, is to construct maps of forest resources that are sufficiently unbiased and precise that users may obtain estimates for small areas that are as precise as those obtained using dense field plot data alone, and more precise than those obtained using sparse field plot data. A current popular approach is to construct such maps using satellite imagery, inventory plot data, and any

of several modeling techniques of which the non-parametric, multivariate k-Nearest Neighbors (k-NN) technique has become extremely popular (McRoberts et al. 2007, Tomppo et al. 2008).

The approach to estimating forest resources from pixel predictions is fundamentally different than the approach based on plot observations. The plot-based approach is characterized as probability-based (design-based) inference and is based on the assumption that each plot observation is constant and fixed, apart from measurement error. The pixel-based approach is characterized as model-based inference and is based on the assumption that each observation for a plot associated with a pixel is a random realization from a distribution of possible values. The differences in these underlying assumptions require fundamentally different techniques for assessing bias and for estimating precision. In addition, a complex component of model-based inference is dealing with spatial correlation among pixel predictions and residuals. Variance estimators for model-based inference accommodate this correlation as,

$$\text{Var}(\bar{Y}) = \frac{1}{N^2} \text{Var}\left(\sum_{i=1}^N \hat{y}_i\right) = \frac{1}{N^2} \sum_{i=1}^N \sum_{j=1}^N [\text{Cov}(\hat{y}_i, \hat{y}_j) + \text{Cov}(\varepsilon_i, \varepsilon_j)]$$

where N is the number of pixels in the AOI, $\hat{y}_i$ is the prediction for the i^{th} pixel, and $\varepsilon_i = y_i - \hat{y}_i$ is the residual error (McRoberts and Tomppo 2007). Both covariance expressions may be complex, and for $i \neq j$, it is not possible to assume that $\text{Cov}(\hat{y}_i, \hat{y}_j) = 0$ or that $\text{Cov}(\varepsilon_i, \varepsilon_j) = 0$. Model-based techniques for regression model predictions have been reported by McRoberts (2006) and for the k-NN technique by McRoberts et al. (2007).

SUMMARY

In summary, the FIA program of the U.S. Forest Service conducts inventories of approximately 3 million km² of forest land using nationally consistent and standardized methods. Data are made available via a publicly accessible

database and are used by variety of government, non-government, university, and public users. Inventory data are combined with data from other sources such as satellite imagery to accommodate user requests for maps and small area estimates.

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