

The following manuscript was submitted to Journal of Forestry in February, 1999. It concisely describes a 3-stage sampling design for the Forest Inventory and Analysis (FIA) programs, in which traditional field data are supplemented with a sample of high-resolution aerial photography and wal-to-wall change detection with Landsat data. The purpose is more efficient implementation of annual FIA surveys, as mandated by PL 105-185, the Agricultural Research, Extension, and Education Reform Act of 1998, Section 253(c).

REMOTE SENSING FOR ANNUAL FOREST INVENTORY AND MONITORING

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Abstract

Remote sensing can improve timeliness and efficiency of national systems for forest statistics. Landsat satellite data can frequently detect major changes in land cover. A sample of high-resolution imagery can detect moderate changes and discriminate among detailed categories of forest cover and land use. A sample of field data measures the slow and more subtle changes and calibrates remotely sensed data. Implementation is a major undertaking that requires unprecedented partnerships among federal programs and stakeholders.

Introduction

The Forest Inventory and Analysis (FIA) program in the USDA Forest Service produces a baseline and long-term set of scientifically sound resource data and information to assess the extent, health, productivity, and sustainability of the forest and wood land ecosystems of the United States. FIA information is critically important at the national, regional and state scales to effectively deal with conservation challenges, influence patterns of capital investment, and meet needs of the forestry profession, resource managers, forest landowners, and the public.

FIA methods vary somewhat by region, but the following is a valid generalization of the FIA design. The first phase includes a sample of three million plots on a 1-km grid, each of which is inexpensively classified into a few categories of land cover with high-altitude aerial photography. The second phase uses 120,500 forested field plots, which are a sub-sample of the photo-interpreted plots and are on a 5-km grid. A two-person field crew can access and measure 1 forested field plot in one day. Some of the most important measurements are listed in Table 1. The Forest Service's Forest Health Monitoring Program measures more expensive indicators on 4,500 forested field plots, which are a subset of the FIA field plots and are on a 27-km grid. This sampling covers 300 million hectares of forest land across all ownerships in the United States. Remote sensing at the first phase improves FIA estimates of forest area and population totals, but the detailed data on forest composition and condition (Table 1) rely primarily on expensive field data.

Although FIA is among the best programs of its kind in the world, stakeholders feel that over half of all FIA information is out-of-date. Current FIA procedures and funding are sufficient for an 8- to 15-year re-measurement cycle, depending upon geographic region. However, users of FIA data have little confidence in data that are more than five years old (Blue Ribbon Panel, 1992). The Agricultural Research, Extension, and Education Reform Act of 1998 (PL 105-185, Section 253) directs the Forest Service to produce more timely FIA data, in which 20% of the FIA plots in every State are re-measured each year. The Act further envisions use of new technologies, especially remote sensing. My objective is to realistically portray an annual forest inventory and monitoring system that uses inexpensive remote sensing to reduce the required cost of field data.

Rates of Change

Rapid changes and trends in forest conditions, both real and perceived, drive the demand for annual FIA data. At a 5-year time scale over large geographic regions (*e.g.*, 5- to 25-million ha), rapid changes are driven by urbanization, implementation of public policies, and the regional, national and global economics of agriculture and forest products. Examples of these types of change include clearing forestland for agricultural or urban uses; conversion of agricultural lands into forestland; harvesting of wood; and regeneration of harvested forest areas. Other rapid changes are episodic, caused by hurricanes, ice storms, frost, hail, wind, lightning, floods, landslides, droughts and insect epidemics. These often cause changes in forest cover that can be detected with a variety of remote sensing technologies, the success of which depends on sensor resolution.

I assume other indicators of forest conditions change more slowly within detailed categories of forest (Table 1). An example is the average volume and number of trees per hectare by tree species and 5-cm diameter class, and their growth and mortality rates, for late-succession spruce-fir stands in protected areas of the interior-west of the USA. I make the same assumption for trends in down woody debris, non-tree vegetation, and similar characteristics. I further assume that many aspects of forest health are affected by gradual changes in forest demographics and anthropogenic stressors, such as air pollution, climate change, exotic species, and diseases. I assume these slow and ubiquitous processes are measured at regional scales (*e.g.*, 25- to 100-million ha) with FIA field plots.

If these assumptions are approximately true, then remote sensing could be more efficient than field plots for frequent monitoring of rapid changes. However, less frequent re-measurement of field plots remains essential to measure more gradual changes in forest composition and health that can not be detected well with remote sensing. The issue is how to discover, tease apart, and understand the respective roles of rapid or episodic change events versus the slower trends observed across the landscape, and select different technologies to efficiently observe different types of change.

Remote Sensing Technologies

Remote sensing can reduce cost of forest inventory and monitoring if remotely sensed data are well correlated with important field measurements (Table 1), and remotely sensed data are available when

needed in the sampling design. For example, augmentation of field data with aerial photography can be 6 to 15 times more efficient in estimating total area of forest (MacLean 1963) and twice as efficient in estimating total wood volume (MacLean 1972). The following evaluates five broad categories of remotely sensed data for statistical inventory and monitoring of the Nation's forests each year.

Low-resolution, broad-swath satellite data include AVHRR, OrbView-2, SPOT 4 Vegetation Sensor, and MODIS Moderate Resolution Imaging Spectrometer. These data are very inexpensive and cover enormous areas (1000- to 3000-km in swath width). However, the spatial resolution is poor, with pixel sizes ranging between 0.25-km and 1.1-km wide. These data have proved successful for continental-scale maps of forested landscapes, global change models, and detecting hot spots of severe deforestation within dense forested landscapes. However, these remotely sensed data have insufficient resolution to reliably measure most indicators of forest conditions in Table 1.

Medium-resolution, medium-swath satellite data include Landsat 7, SPOT 4, the Indian Remote Sensing (IRS) satellite, Radarsat, and the Sovinform Sputnik Spin-2 TK-350 camera. These data have a reasonably small pixel size (10- to 30-m wide), and they are relatively inexpensive for large areas, having a 60- to 180-km swath width. For example, the conterminous USA is covered by 540 Landsat scenes. However, there is a limit to the quality of forest data measured by a satellite orbiting 700 km from the earth's surface; see Holmgren and Thuresson (1998) for a thorough review. With routine and standardized processing in a high-production environment, these data can separate forest from non-forest, and reasonably identify a few broad types of forest and several levels of forest density. Landsat data can distinguish somewhat more detailed categories of forest cover with proportionally more intensive effort and customized approaches (Wynne and Carter, 1997). These data can identify recent clearcuts, but they are less successful with partial cuts. These data can identify advanced regeneration of forests after land clearing. These data can identify urban centers, but they are less successful with sparse urbanization of forest lands. These synoptic data can measure size, shape and connectivity of forest patches, which are indicators of forest fragmentation and habitat suitability at landscape scales. High-quality, cloud-free data are available for temperate regions each year or two, which is sufficient for annual inventory and monitoring.

High-resolution, narrow-swath satellite data include Earlybird and Quickbird (EarthWatch), OrbView-3, Resource21, Lewis Hyperspectral Imager (TRW-NASA), Clark (CTA-NASA) and Carterra-1 (EOSAT). This type of remotely sensed data is very new in the civilian sector. The 4- to 10-km swath width and a small pixel size (1- to 3-m wide) are best suited for imaging small areas. Wynne and Carter (1997) provide a review. These satellite data have capabilities, limitations and cost similar to high-altitude, 230-mm, 1:40,000 small-scale aerial photographs from the USGS National Aerial Photography Program (NAPP). These satellite and photographic data can reliably distinguish a few broad types of forest in each region, several stages of stand development, clearcut and some partial cut areas, regeneration after land clearing, and concentrations of tree mortality (Aldrich, 1979). Photo-interpretation of these data can identify forest stands; distance to adjacent land uses, roads and non-forest cover types; many indices of forest fragmentation; and sparse urbanization in open areas or urbanization that disturbs broad areas of forest canopy. Depending on the sensor, it would take 200,000 to 1,000,000 images to cover the USA. The USDA National Agricultural Statistics Service and the USGS National Wetlands Inventory (NWI)

use NAPP photographs for national mapping applications on a 20-year time-frame, but this is not practical for annual monitoring. These photographic and satellite data are better suited to sampling. For example, FIA uses NAPP photographs and three million sample points to improve estimates of total forest area. The USDA Natural Resources Conservation Service's National Resources Inventory program uses NAPP and medium-scale aerial photography to interpret conditions and changes over five-year intervals on 65-ha sampling units. Segments of high-resolution satellite scenes could cover small sampling units. However, the NAPP schedule for acquiring aerial photography is not well suited to annual system, which requires a representative sample of current photography in each state for each year. However, the satellite data could be acquired whenever they are needed in the monitoring design.

Large-scale aerial photography is the highest resolution data considered here. This imagery ranges in scale from 1:500 to 1:12,000. Commercial aerial survey companies routinely acquire this type of imagery for specific sites. Photo-interpreters could reliably identify many of the forest cover conditions in Table 1 (Aldrich 1979). Measurements might include five to 10 broad types of forest; five stages of stand development; three stand density classes; clearcut and partial cut areas; regeneration success; stand origin (natural, artificial); three to five severity levels for tree mortality; wildland-urban interface; indicators of urbanization and fine-scale forest fragmentation; and stand size, shape and edge metrics. However, these photo-interpretations would include measurement errors that require statistical calibration with current field data. This type of imagery requires millions of images to completely cover the USA; therefore, this imagery is only practical over large areas when used for sampling specific sites. There are numerous implementation options, with a few being 70-mm 1:12,000-scale stereo-photography to cover a 50-ha primary sampling unit; 230-mm 1:8,000 stereo-photography to cover a 75-ha unit; or 1:2,500 stereo-photography to cover a 1-ha unit. Land use and forest stand boundaries could be mapped over an entire sampling unit. Depending on resolution and stereo capability of the data, mapped stands could be classified into many of the categorical variables in Table 1 (e.g., forest type), while other parameters (e.g., stand height and severity of tree mortality) might be photo-interpreted at random points within the primary sampling unit. Specifications for image acquisition could match the schedule required for annual inventory and monitoring.

The Minnesota Experience

The following recommendations are based on experience with the Annual Forest Inventory System (AFIS), which began in 1992 to improve timeliness of FIA data. AFIS was a joint effort between Minnesota Department of Natural Resources and USDA Forest Service Research and Development. Although remote sensing in AFIS emphasized detection of change with remote sensing, the experience with AFIS is relevant in a broader context.

Landsat data was the sole source of satellite data. AFIS did not use AVHRR data because of its limited resolution. In the beginning, AFIS avoided aerial photography because the cost of acquisition and interpretation is higher than cost of Landsat data.

Successful processing of Landsat for large geographic areas required rapid and automated techniques,

which was achieved in part by minimizing the number of land cover categories. AFIS used simple differentiation of hardwood, softwood and mixed forest types; high, medium and low densities of forest canopies; and several non-forest categories. A single technician could process a Landsat scene in five to 10 days. FIA divides Minnesota into four physiographic regions, and AFIS processed Landsat data for one region each year over a four-year re-measurement cycle. Registration of FIA field plots to Landsat imagery used softcopy interpretation, requiring an average of three minutes per plot. Over time, field crews used GPS techniques to improve registration.

Changes in spectral reflectance between Landsat images quickly identified many pixel-level changes in forest cover, which were primarily caused by landclearing and clearcuts. Vigorous regeneration of clearcuts over the four- year re-measurement cycle reduced the spectral differences in multi-temporal Landsat data, and this reduced success of change detection. However, Landsat data could be acquired at the same cost on a two-year cycle if the state were divided into zones that were aligned on the orbital paths of the Landsat satellite.

Landsat did not provide much useful data for forested plots soon after harvests and major disturbances. In addition, mis-registration and other errors with Landsat data caused incorrect classification of some FIA plots as having changed. If Landsat data suggested an FIA plot had drastically changed, then the plot was re-measured by a field crew. This consumed about half of the AFIS budget for field data. Much of this expensive field data simply verified whether or not these plots were cleared of trees. During the later stages of AFIS, large-scale aerial photography was re-considered to reduce cost of measuring such plots.

AFIS demonstrated that Landsat data do serve a useful role for annual forest inventory and monitoring. Landsat data could replace high-altitude NAPP photography in the statistical design. The acquisition dates for Landsat are more compatible than NAPP dates for an annual system. In addition, Landsat data provide useful wall-to-wall spatial coverage that does not exist with FIA sampling. However, Landsat data alone do not greatly reduce the required amount of field data. Although Landsat data can accurately differentiate forest from non-forest, Landsat data cannot accurately measure the detailed composition of forests in Table 1. Detailed information requires measurements with more complete and accurate techniques, which are more expensive than Landsat data.

In order for remote sensing to reduce cost of annual inventory and monitoring, I believe that medium-resolution Landsat data should be coupled to sampling with high-resolution aerial photography or satellite data. Such imagery produces observations that are reasonably correlated with many of the detailed field data gathered by FIA (Table 1). The following sections describe two remote sensing enterprises that could reduce the cost of annual monitoring with field data. These enterprises would create a multi-stage design, with a wall-to-wall coverage of Landsat data at the first stage, a sample of high-resolution imagery at the second stage, and traditional FIA field plots at the third stage.

National Mapping of Changes

Numerous National Forests, land management agencies and state governments use Landsat data to map

large sub-regions of the USA. However, only two federal programs cover the entire USA. The USGS Multi-Resolution Land Characteristics (MRLC) Program maps three forest categories, three urban categories, three wood land categories, three agricultural categories, and 21 other categories of land use and cover. In addition, the USGS Gap Analysis Program (GAP) maps critical habitats to help conserve biological diversity. The minimum map unit is 100-ha. The GAP classification system uses 18 categories of forest for the entire USA, although a subset of these categories occur in any single region. The MRLC program began in 1995 with an annual budget of \$10,000,000; the GAP program began in 1994 with an annual budget of \$3,600,000. Neither program has completed the entire USA. These programs use sophisticated methods that stretch the limits of Landsat data for immense regions, and success requires considerable analytical inputs. These programs plan to update their maps to capture changes in land cover, perhaps on a 10-year cycle, but updates are not currently funded.

An annual forest inventory and monitoring enterprise could efficiently build upon the MRLC and GAP programs. The new enterprise would acquire Landsat data on a 2- to 5-year cycle to rapidly identify abrupt changes in land and forest cover. This enterprise would fully utilize all 540 Landsat scenes that cover the USA. The intent is relatively inexpensive updates to costly maps of land cover and land use produced by MRLC and GAP. FIA would use this updated information to further improve statistical estimates. State agencies, National Forests, MRLC and GAP could use the new Landsat data to modify their older land cover maps. FIA could use revised MRLC and GAP maps to replace photo-interpretation of its three million first-phase plots.

National Sampling With High-resolution Imagery

High-resolution aerial photographs and satellite imagery contain substantially more information than Landsat data, and such imagery has greater potential to reduce expense of an annual FIA system. The measurement cost of a forested FIA plot by a 2-person field crew is 4 times greater than cost for acquisition and photo-interpretation of sample imagery.

Only two federal programs monitor changes in land cover over the entire USA with a sample of aerial photography. The USDA Natural Resources Conservation Service's National Resources Inventory (NRI) makes extensive use of available small-scale NAPP and small-format aerial photography for 300,000 primary sampling units in the USA. Most sampling units are 65-ha in size, with a sampling intensity of 1% to 4% of the land area. However, the quality of NRI data is limited by the quality and scheduling of aerial photography, most of which originates with other federal programs. The NRI has been conducted once every five years, but NRI is changing to an annual system, much like FIA. The annual budget for NRI is \$8,500,000. In addition, the USGS National Wetlands Inventory (NWI) employs a sparse sample of small-scale NAPP photography for their estimates of status and trends. This is a small part of their overall mapping program, which has an annual budget of \$7,750,000 per year.

An annual forest inventory and monitoring program could develop a new national enterprise that specifically acquires an sample of high-resolution imagery each year. The primary incentive is improved statistical estimates of rapid changes caused by shifts in land use, forest management and episodic

events. In addition, interpretation of high-resolution imagery provides measurements that are well correlated with many field observations, which can improve the accuracy of all FIA statistics. The sample sites would include 320,000 Primary Sampling Units (PSUs) which cover existing 1-ha FIA field plots, of which 120,500 are forested FIA plots. Each PSU would range in size from 10 to 500 hectares in size.

Each year, the enterprise would procure high-resolution imagery for 20% of these PSUs. An interpreter would delineate and classify different land uses, land cover and forest stands over each 10- to 500-ha PSU. Points within the PSU could be interpreted for more detailed measurements of forest composition, and one of these points would be a 1-ha FIA field plot. As each PSU is re-imaged over time, photo-interpreters would measure changes between dates.

An important issue is the capacity of commercial satellites or aerial survey firms to deliver imagery each year for tens of thousands of small sample sites that are separated kilometers apart and spread across the entire USA. However, improvements in remote sensing technologies and a stable market for large amounts of imagery should stimulate increased capacity.

This enterprise is similar to the existing National Resources Inventory (NRI), which is conducted by the USDA Natural Resource Conservation Service. NRI emphasizes agricultural and range lands, but NRI also covers forest and woodlands. The cost of imagery and interpretation could be shared between FIA and the NRI, which would make the enterprise more feasible. This partnership poses considerable technical and bureaucratic challenges (Goebel *et al.* 1998; Czaplewski, 1999), such as incremental alignment of separate FIA and NRI sampling frames. However, this partnership would efficiently produce consistent and compatible application of remote sensing methods to all types of land cover in the USA.

Conclusion

The U.S. Congress clearly identified the need for more current strategic information on the Nation's forests. Acceleration and redirection of traditional FIA field procedures would satisfy this demand. However, the annual inventory and monitoring program specified by Congress would cost \$82,089,000 using traditional FIA procedures, while the funding available in 1999 is \$37,185,000. Increased use of remote sensing could improve efficiency and produce valuable new products, such as frequently updated maps of changes in land cover with Landsat data. The sample of high-resolution imagery could improve efficiency and monitor more moderate changes. Although field data remain essential to calibrate remotely sensed data and measure the slow and more subtle changes in forest health and composition, remote sensing could reduce the frequency and amount of required field data. The National Academy of Sciences (1974) recommended a similar approach 25 years ago for reasons that remain valid today.

Effective use of remote sensing requires an unprecedented public investment in an institutional infrastructure that can acquire and process hundreds of Landsat scenes and tens of thousands of high-resolution images each year. The annual cost would likely exceed the \$8,500,000 budget for the USDA

National Resources Inventory and the \$3,600,000 budget of the GAP program, both of which rely on remote sensing.

Unless the information needed from inventory and monitoring is dramatically reduced, remote sensing is not an inexpensive substitute for field data. However, remote sensing could improve the efficiency of field data in production of statistical estimates. The cost of remotely sensed data could be shared among the Forest Inventory and Analysis Program and similar programs in other government agencies. This partnership could produce the world's premier statistical system to efficiently estimate trends in land cover and land use, evaluate effectiveness of public policies, and guide sustainable use of the Nation's natural resources.

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Table 1.-- FIA Field Data Used for Primary Statistical Tables¹

No. of classes

Forest Conditions¹ (Plot-level)

Land use ^{2,3}		5
Forest type	broad ^{2,4}	29
	detailed ⁴	136
Stage of stand development ²		4
Stand density ^{2,5}		5
Stand origin ² (natural, artificial)		2
Land ownership		10
Stand age		9
Stand productivity		7
Area by forest condition classes		continuous
Number of trees ^{2,6} , wood volume ⁶		continuous
Growth ⁶ , mortality ^{2,6} , removals ^{2,6}		continuous
Tree-level Conditions ¹		
Tree species ⁴		331
Tree size (DBH)		5-cm classes
Tree damage		10
Tree quality, value		5
Tree mortality (yes, no)		2
Tree removal, harvest (yes, no)		2
Wood volume		continuous
Growth in wood volume		continuous

¹ FIA measures many other indicators that describe landscapes, habitats, non-tree vegetation, etc.

² Many or most of these categories could be reliably, although imperfectly, interpreted with high-resolution imagery. Photo-interpretation could also identify categorical degrees of tree density, volume, mortality and removals.

³ Includes timberland, other forest land, protected forest, nonforest land, and water.

⁴ Any single geographic region of USA has only 20 to 40% of these national categories.

⁵ Includes overstocked, fully stocked, understocked, and non-stocked.

⁶ Totals are produced for thousands of permutations of different tree and forest categories.

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