Toward an Annual National Inventory

Remote sensing can improve efficiency of statistical information. Landsat data can identify and map a few broad categories of forest cover and land use. However, more-detailed information requires a sample of higher-resolution imagery, which costs less than field data but considerably more than Landsat data. A national remote sensing program would be a major undertaking, requiring unprecedented partnerships between federal programs and stakeholders.

By Raymond L. Czaplewski

The Forest Inventory and Analysis (FIA) program of the USDA Forest Service produces a baseline and long-term set of scientifically sound resource statistics for the 748 million acres of forest and woodland ecosystems in the United States. These data are used to assess the extent, health, productivity, and sustainability of public and private forestlands. FIA information is critically important at many scales to effectively deal with conservation challenges; influence patterns of capital investment; and meet the needs of the forestry profession, resource managers, forest landowners, and the public.

FIA methods vary somewhat by region, but the following description is a valid generalization. The first phase uses a sample of 9.4 million plots, with one plot per 240 acres. Each plot is inexpensively classified into a few categories of land cover using high-altitude aerial photography. The second phase uses a subsample of 364,000 one-acre field plots, 120,500 of which are forested, with one plot per 6,200 acres. A two-person field crew can measure one forested field plot in one day. The Forest Health Monitoring (FHM) program measures more-expensive indicators on a subsample of 13,500 plots, 4,500 of which are forested, with one plot per 167,000 acres. Remote sensing at the first phase improves FIA estimates of forest area and population totals, but detailed information on forest composition and condition (table 1) primarily relies on expensive field data. Forest Service funding in 1999 was $37.2 million.

Although FIA is among the best programs of its kind in the world, more than half of all FIA information is out-of-date. Current FIA procedures and funding allow a 10- to 15-year remeasurement cycle, but data more than five years old are not reliable (American

Forest Council 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 and to better utilize remotely sensed data.

Rates of Change

Rapid changes in forest conditions, real or perceived, fuel the demand for annual FIA data. Rapid changes are driven by urbanization, implementation of public policies, and fluctuating economics in the forest products and agricultural sectors over large geographic regions (from 10 million to 50 million acres). Examples include clearing of forestland for agricultural or urban uses, conversion of agricultural lands into forestland, harvesting of wood, and regeneration of harvested forests. Other rapid changes are episodic, caused by hurricanes, wind, ice storms, floods, droughts, and insect epidemics. These processes cause changes in forest cover that can be detected with a variety of remote sensing technologies, the success of which depend on sensor resolution.

I assume that other indicators of forest conditions change more slowly among detailed categories of forest (table 1). An example is the average volume and number of trees per acre by tree species and two-inch diameter class. I make the same assumption for trends in down woody debris, nontree vegetation, and similar characteristics. Many other 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. These slow and ubiquitous processes are measured with field plots in the FIA and FHM programs.

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 remeasurement of field plots remains essential to monitor gradual changes in forest composition and calibrate for errors in remotely sensed measurements.

Remote Sensing Technologies

Remote sensing can improve efficiency if remotely sensed data are available when needed and if they are well correlated with important field measurements (table 1). For example, augmentation of field data with aerial photography can be six to 15 times more efficient in estimating total area of forest, and twice as efficient in estimating total wood volume (Aldrich 1979). A wide range of remote sensing technologies are used in forestry. Satellite data are correlated with some attributes in table 1, but information content increases with sensor resolution. Regardless, remotely sensed data contain various degrees of measurement errors that require statistical calibration with current FIA field data. My discussion of satellite data is based on reviews by Wynne and Carter (1997) and Holmgren and Thuresson (1998); my assessment of aerial photography is based on Aldrich (1979).

Low-resolution satellite data include AVHRR, MODIS, OrbView-2, ERS-2, and SPOT 4. These data are inexpensive and cover vast areas, having a 600- to 1,800-mile swath width. Spatial resolution is poor, with each pixel ranging between 160 and 320 acres in size. These data have proved successful for continental scale maps of forested landscapes, global change models, and detecting hot spots of severe deforestation within densely forested landscapes. These remotely sensed data do not have sufficient resolution to reliably measure and monitor most indicators of forest conditions in table 1.

Medium-resolution satellite data include Landsat-5&7, Radarsat, SPOT-2&4, IRS-C&D and P2&5, Spin-2, EOS AM-1, and CBERS-1&2. These sensors have a reasonably small pixel size of 30 to 100 feet wide, and they are relatively inexpensive for large areas, having a 30- to 100-mile swath width. For example, the conterminous United States is covered by 540 Landsat scenes.

Table 1. Forest Inventory and Analysis field data used in primary statistical tables.

Forest conditions	Number of classes
Plot-level conditions[1]	
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
Number of trees[2,6], wood volume[2,6]	continuous
Growth[6], mortality[2,6], removals[2,6]	continuous
Tree-level conditions[1]	
Tree species[4]	331
Tree size (diameter at breast height)	2-inch classes
Tree damage	10
Tree quality, value	5
Wood volume	continuous
Growth in wood volume	continuous

[1] FIA measures many other indicators that describe landscapes, habitats, non-tree vegetation, etc.
[2] Photo interpretations and photogrammetric measurements with high-resolution imagery are well correlated with these field measurements (Aldrich 1979). The correlation is much lower with Landsat data and NAPP aerial photography.
[3] Includes timberland, other forestland, protected forest, nonforest land, and water.
[4] Any single geographic region has only 20 to 40 percent of these national categories.
[5] Includes overstocked, fully stocked, understocked, and nonstocked.
[6] Totals are produced for thousands of permutations of different tree and forest categories.

However, there is a limit to what can be measured by a satellite orbiting 500 miles from Earth. These data can separate forest from nonforest, and reasonably identify a few broad types of forest and several levels of forest density. Landsat data can distinguish more-detailed categories of forest cover with customized approaches (Wynne and Carter 1997). These data can identify recent clearcuts, but they are less successful with partial cuts. Landsat data can identify advanced regeneration of forests after land clearing. These data can identify urban centers, but they are less successful with sparse urbanization. They can measure size, shape, and connectivity of forest patches. High-quality, cloud-free data are available for most temperate regions each year or two, which is sufficient for annual inventory and monitoring.

High-resolution satellite data include Ikonos-2, OrbView-3&4, EROS-B1&2, and Quickbird-1&2, although none are operational yet. The two- to

six-mile swath width, and small pixel size of three to 10 feet wide, are best suited for imaging small sites. These satellite data have capabilities, limitations, and costs similar to high-altitude, nine-inch-square, 1:40,000 small-scale aerial photographs from the US Geological Survey (USGS) National Aerial Photography Program (NAPP). Each NAPP photograph covers an area five miles wide. These satellite and photographic data can reliably distinguish a few broad types of forest in each region, several stages of stand development, clearcuts and many partially cut areas, regeneration after land clearing, and concentrations of tree mortality. Photo interpreters can identify forest stands, land use, distance to adjacent roads and water, forest fragmentation, and many types of urbanization. Depending on scale, it would take 200,000 to 1 million images to cover the United States. The USDA National Agricultural Statistics Service and USGS National Wetlands Inventory use NAPP photographs for

national mapping on a 20-year time frame, but this is not practical for annual monitoring. The NAPP schedule for image acquisition is poorly suited to annual monitoring, but satellite data are expected to be available when needed.

Large-scale aerial photography ranges in scale from 1:2,500 to 1:12,000. Commercial aerial survey companies routinely acquire this type of custom imagery for small sites. Each photograph covers an area one-tenth to two miles wide depending on scale and format. Photo interpreters could reliably identify many of the forest cover conditions in *table 1*. 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; most indicators of urbanization and fine scale forest fragmentation; and stand size, shape, and edge metrics. This type of photography would require many millions of images to completely cover the nation, but sampling makes this imagery feasible on the national scale.

Using Remotely Sensed Data

Numerous land management agencies use remote sensing for portions of the country, but only a few programs consistently cover the whole country. Several of these programs use Landsat data to map the conterminous United States. Other programs use a sample of higher-resolution aerial photography to produce statistical estimates.

The USGS Multi-Resolution Land Characteristics (MRLC) program uses Landsat data to map three forest categories, three urban categories, three woodland categories, three agricultural categories, and 21 other categories of land use and cover (Volgelmann et al. 1998). The USGS Gap Analysis Program (GAP) maps critical habitats to help conserve biological diversity. GAP uses 18 categories of forest, although not all occur in every region. Both programs use sophisticated remote sensing techniques that require considerable analytical input. MRLC began in 1995 with an annual budget of $10 million, and GAP began in 1994 with an annual budget of $3.6 million. Neither program has yet covered the entire country. These programs plan to update their maps to compensate for changes in land cover, perhaps on a 10-year cycle.

Three programs use a sample of aerial photography to cover the United States. The FIA program uses small-scale NAPP photography for 9.4 million photo-interpreted plots. The USDA Natural Resources Conservation Service's National Resources Inventory (NRI) uses NAPP and small-format aerial photography for 300,000 primary sampling units. Most sampling units are 160 acres, with a sampling intensity of 1 to 4 percent of the total land area. Accuracy of NRI data is limited by quality and scheduling of aerial photography. NRI has been conducted once every five years, but is changing to an annual system, much like FIA. The annual budget for NRI is $8.5 million. Finally, USGS National Wetlands Inventory uses a sparse sample of small-scale NAPP photography for its estimates of status and trends, but this is a minor part of its overall mapping program.

The Minnesota Experience

The Annual Forest Inventory System (AFIS) began in 1991 as a joint effort between the Minnesota Department of Natural Resources and the USDA Forest Service. Lessons learned in AFIS are relevant to the mandate in Public Law 105-185. AFIS successfully used numerous Landsat scenes to classify land cover into a few broad categories and detect abrupt changes over
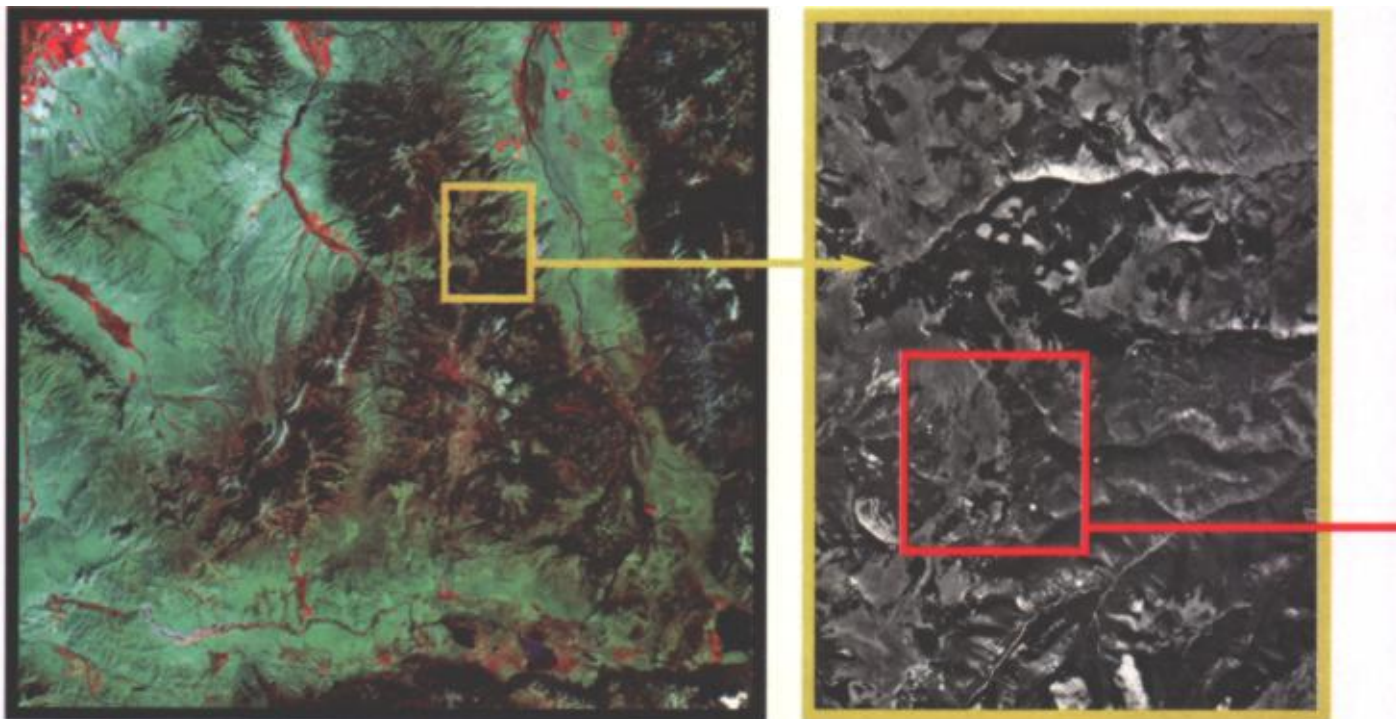
time. AFIS processed Landsat data that was re-imaged over four-year intervals, but vigorous regeneration of clearcuts reduced the accuracy of change detection. Had Landsat data been purchased along orbital paths rather than physiographic regions, change detection could have been conducted every two years at little extra cost. A single technician could process a Landsat scene in five to 10 days because changes in land cover were detected with simple digital methods. AFIS classifications of land cover with Landsat replaced NAPP photography for the first phase in the FIA statistical design, and image acquisition dates for Landsat were more compatible than NAPP for an annual system. In addition, Landsat provided maps of land cover and change that are not feasible for large regions with aerial photography or field sampling.

If Landsat data suggested that an FIA plot might have been affected by timber harvest or change in land use, then the plot was remeasured by a field crew. Remeasuring consumed about half the budget for field data. Misregistration and other errors with Landsat data caused incorrect classification of some FIA plots as having changed.

Much of the expensive field data merely verified whether or not these plots were cleared of trees. In the beginning, AFIS did not use aerial photography because Landsat is less expensive for large regions. During later stages of AFIS, a sample of aerial photography was reconsidered because high-resolution imagery could reduce the cost of field data to verify change detection from Landsat data.

Multistage Sampling

AFIS demonstrated that Landsat data can improve FIA products. However, Landsat data alone do not greatly reduce the required amount of field data. Landsat provides only broad information about forest conditions, and the detailed information in *table 1* requires field measurement. However, high-resolution imagery provides much more detailed data that are bet-
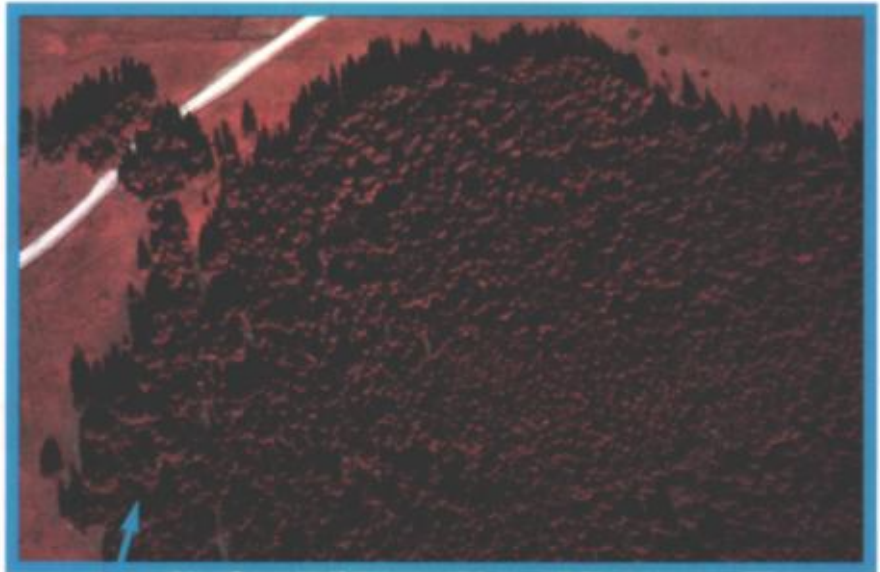
Real or perceived rapid changes in forest cover and conditions fuel the demand for annual FIA data. The causes of such changes can be detected with a variety of remote sensing technologies and data types. Levels of sensor resolution are key to successful detection; some of those levels are illustrated in this sequence of photographs of the Beaverhead-Deerlodge National Forest in Dillon, Montana.
Left to right: **A Landsat Thematic Mapper (TM) satellite image; a higher-resolution digital ortho quad image; a high-altitude aerial photograph; a digital infrared camera image (above). The latter was taken five years after the TM image, closer to the time when the change in forest cover was investigated. To assess conditions at the forest, plot, and tree levels costs less than field data but more than Landsat data.**

ter correlated with attributes in *table 1*. A multistage statistical design can combine wall-to-wall Landsat data at the first stage, a sample of high-resolution imagery at the second stage, and traditional FIA and FHM field plots at the third stage. The National Academy of Sciences recommended a similar approach 25 years ago (Aldrich, 1979). I describe two enterprises that would implement a multistage design.

The first enterprise would acquire all Landsat scenes that cover the conterminous United States. Multi-date Landsat data would rapidly identify abrupt changes in spectral reflectance that are often associated with clearcuts, landclearing, and reforestation. Change detection allows relatively inexpensive updates to existing MRLC and GAP maps. FIA would use updated maps to replace its photo interpretation of 9.4 million first-phase plots. Direct annual cost is estimated at $1.5 million to $2 million.

The second enterprise would acquire a national sample of large-scale aerial photography or high-resolution satellite imagery. The resulting data would detect changes in land use, partial cuts, forest management, and severe episodic events. Sample imagery would include 364,000 primary sampling units, each covering an existing FIA field plot. Each sampling unit could range from 40 to 640 acres in size, and the collection of sampling units would encompass 1 to 10 percent of the total land area. The large sampling units would better capture rare features than one-acre FIA field plots, which encompass only 0.016 percent of the landscape. Each year, 20 percent of the large sampling units would be remeasured with new high-resolution imagery. Photo interpreters would delineate and classify land uses, land cover, and forest stands within each sampling unit. Photogrammetry would produce more-detailed measurements of forest characteristics at secondary sampling points within each 40- to 640-acre sampling unit, and one of these points would be a one-acre FIA field plot. These measurements would be well correlated with many field observations in *table 1*. Photo interpreters would measure

changes over the five-year interval between acquisition of new imagery for each permanent sampling unit. High-resolution imagery could improve statistical efficiency, allowing a reduction in the required number of FIA sampling units. Calibrated measurements from the high-resolution images might even replace field data for inaccessible areas. The large sampling units better match the scale of Landsat images than one-acre FIA plots, thus improving the linkage between Landsat data and more accurate measurements of sampling units. This enterprise could cost $15 million to $25 million each year.

The latter enterprise is similar to the National Resources Inventory (NRI). The cost of new imagery and interpretation might be shared between FIA and NRI, which would make the enterprise more feasible and efficient. This partnership poses considerable technical challenges, such as: incremental alignment of separate FIA and NRI sampling frames; complex statistical techniques for calibration and composites of multiple time-series of multivariate sample data; a sophisticated information management system; capacity-building in the aerial survey industry to deliver large quantities of photography; and adjustments for cloud cover and missing data (Czaplewski 1999). Bureaucratic challenges would be equally formidable (USDA Forest Service Inventory and Monitoring Institute 1998). Robust solutions to these challenges are untested, cost-effectiveness must be evaluated, and risks must be reduced through simulations and realistic pilot tests.

Conclusion

Congress has emphasized the need for more-current statistical information about the nation's forests. Traditional FIA field procedures would satisfy this need at an estimated annual cost of $82 million. Multistage remote sensing might save $20 million each year and produce valuable new products. Implementation requires an unprecedented infrastructure that can acquire and process hundreds of Landsat scenes and tens of thousands of high-

resolution images each year. Expectations must be kept realistic, numerous details await analysis, and formidable problems remain unsolved. Multistage sampling with remote sensing was envisioned by the National Academy of Sciences in 1974, but the vision has never been implemented. However, if these challenges can be overcome, a partnership among existing federal programs could produce the world's premier system to estimate national trends in land cover and land use, detect changes in health of wildlands and agricultural landscapes, evaluate effectiveness of public policies, and guide sustainable use of the nation's natural resources.

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Raymond L. Czaplewski (e-mail: czap@ lamar.colostate.edu) is project leader and mathematical statistician, Forest Inventory and Monitoring Environmetrics, USDA Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80526.