Integration of Strategic Inventory and Monitoring Programs for the Forest Lands, Wood Lands, Range Lands and Agricultural Lands of the United States[1]

Raymond L. Czaplewski[2]

Abstract—The United States Department of Agriculture uses the Forest Inventory and Analysis (FIA) program to monitor the nation's forests and wood lands, and the National Resources Inventory (NRI) program to monitor the nation's agricultural and range lands. Although their measurement methods and sampling frames are very different, both programs are developing annual systems to better detect trends in land use and ecosystem health, evaluate effectiveness of public policies, guide sustainable development, and forecast alternative future conditions. Other federal programs use Landsat satellite data to map the nation's land cover, land use, and habitat diversity. I offer two proposals that could increase consistency and reduce cost among these federal monitoring programs. First, a national consortium would acquire Landsat data every two to five years for the entire USA, and rapidly detect abrupt changes in spectral reflectance associated with land clearing and major changes in land cover. This would provide spatial data to update existing maps of land cover and land use, and improve statistical monitoring. However, Landsat resolution is not sufficient to identify detailed categories of land use and forest cover; rather, higher-resolution sensors are necessary to significantly reduce the required amount of field data. Therefore, the second proposal is acquisition and interpretation of large-scale high-resolution aerial photography for hundreds of thousands of FIA and NRI sampling units. This ambitious enterprise might be feasible with collaboration between these two programs. They would integrate their separate photo-interpretation operations, and collocate 65-ha NRI sampling units with 1-ha FIA field plots. Each year, a 20% sub-sample of the collocated sampling units is photographed from low-elevation aircraft to detect rapid and obvious changes, while field data are gathered for a 10% sub-sample of field plots to detect slower and more subtle changes. Field data are paired with remotely sensed data, and empirical models statistically correct for measurement and classification errors in remotely sensed data. Implementation is a major enterprise that requires unprecedented partnerships among federal programs. I do not believe remote sensing will be an effective technological solution without such an enterprise. Most legislators and executive leaders are not aware of the magnitude of the logistical and institutional challenges. However, extensive coordination of remote sensing among existing federal programs could produce an efficient system to evaluate sustainability of the nation's forests and agricultural lands, and assess the health of the nation's ecosystems.

[1]Paper presented at the North American Science Symposium: Toward a Unified Framework for Inventorying and Monitoring Forest Ecosystem Resources, Guadalajara, Mexico, November 1-6, 1998.

[2]Raymond L. Czaplewski is Project Leader, Forest Inventory and Monitoring Environmentrics, USDA Forest Service, Rocky Mountain Research Station; 240 W. Prospect Road; Fort Collins, CO 80526, U.S.A. Telephone: (970)498-1292; e-mail: rczaplewski/rmrs@fs.fed.us

The Forest Inventory and Analysis[1] (FIA) program in the USDA[2] Forest Service produces a baseline and long-term set of scientifically sound resource data, technology, analysis tools, 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.[3]

FIA uses a two-phase probability sample of 1-ha plots, which are systematically distributed over 300 million hectares of forest land in the USA. FIA uses remote sensing (i.e., photo-interpretation of high-altitude small-scale aerial photographs) to measure 3 million plots on a 1-km grid at Phase 1, and 120,500 plots are measured on a 5-km grid in the field at Phase 2. Five regional FIA programs cover the USA. At any point in time, each FIA regional program is conducting a survey in one or two states, which are typically 5- to 25-million ha in size. When a state inventory is finished, the FIA inventory begins for the next state in that region. The inventory cycle begins anew after the last state in a region is surveyed. The cycle is 8-years in the southern USA, up to 15-years in the arid interior west, and longer in Alaska.

Demand for Annual Monitoring

Although the FIA national program is among the best in the world, FIA is in a state of crisis[4,1]. 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, but users of FIA data have little confidence in data that are more than 5 years old[5,1].

An Act of Congress recently directed the Forest Service to improve its FIA program[6,1]. FIA must convert its periodic system into an annual system, in which 20% of all FIA plots in each State are measured each year. The Act further envisions new technologies, such as remote sensing, models and statistical methods that integrate data from multiple sources.

FIA recently developed a strategy to accomplish this Congressional mandate[7,1]. Implementation requires $98,920,000 per year, which is a 4-fold increase in FIA funding. The strategy primarily relies on modifications to current FIA field procedures, and about half of the increased funding supports accelerated collection of field data. However, the strategy does not assume improved efficiencies through innovative applications of remote sensing.

Objectives And Outline

My objective is a realistic portrayal of a national monitoring system for forest lands that emphasizes remote sensing and reduces reliance on expensive field data. This portrait might help the FIA program decide if a expanded remote sensing component is desirable.

Many perceive remote sensing as an inexpensive solution to the growing demand for monitoring data. However, I attempt to demonstrate that substantive use of remote sensing requires a large institutional infrastructure, which can cost tens of millions of dollars per year. Other federal programs already conduct broad remote sensing activities and share some of the same objectives with FIA. I hope to show that sharing remote sensing operations with related federal programs is in the best interests of FIA. This could reduce costs. However, it would also produce strategic monitoring data across all types of land cover, ecosystems and land uses, thus serving the objectives of many institutions for sustainable development and healthy ecosystems.

I begin listing the primary indicators of forest conditions measured by FIA. An annual system is most valuable for monitoring rapid changes in forest conditions, which I assume are caused by changes in land use, timber harvesting and regeneration, and catastrophic disturbances. Remote sensing can detect these changes, and detection accuracy increases with sensor resolution. I describe the advantages and disadvantages of different types of remote sensing for monitoring land cover and land use across the entire nation. I recommend combination of periodic change detection with Landsat data, and manual interpretation of high-resolution aerial photography for an annual sub-sample of sites. I discuss opportunities for reducing costs and sharing resources and products among several federal agencies.

Indicators of Forest Conditions

FIA produces detailed statistical tables that describe the current amount of forest and trees, and rates of change by detailed categories of forest conditions (Table 1). Classification parameters include land use and ownership, forest type and origin, productivity and stage of development, and tree stocking. Indicator parameters include forest area, number of trees, wood volume, growth , mortality and removals. The indicator parameters are estimated for permutations of many detailed classification parameters (Table 1), resulting in thousands of estimates that characterize forest condition and health.

Value of Remotely Sensed Data for Monitoring Indicators

The value of remotely sensed data depends on their correlation with these parameters and changes over time. For example, certain satellite data are well correlated with presence or absence of forest cover, but they are not well correlated with detailed categories of different forest types. Such remotely sensed data would improve the estimate for area of all forest lands, which is among the most important indicators. However, the thousands of other parameters estimated by FIA would largely rely upon expensive field data. The value of remotely sensed data also depends on their capability to detect change, and their availability during the prescribed times in the monitoring schedule.

Rates of Change in Indicators of Forest Conditions

Rapid changes in forest conditions cause the demand for annual FIA data. I assume that the most rapid changes over large geographic regions (e.g., 5- to 25-million ha.) are driven by the regional, national and global economics of the agricultural and forest product sectors, urbanization, and changes in public policy. These cause changes in land use and land cover that affect sustainability and forest health. Examples include clearing forestland for agricultural or urban uses; afforestation of agricultural lands into forestland;

Table 1.—FIA field data used for primary statistical tables[1]

Forest conditions[1] (plot-level)	No. of classes	Tree-level conditions[1]	No. of classes
Land use[2,3]	5	Tree species[4]	331
Forest type,			
broad[2,4]	29	Tree size (DBH)	5-cm classes
detailed[4]	136	Tree damage	10
Stage of stand development[2]	4	Tree quality, value	5
Stand density[2,5]	5	Tree mortality (yes, no)	2
Stand origin[2] (natural, artificial)	2	Tree removal, harvest (yes, no)	2
Land ownership	10	Wood volume	continuous
Stand age	9	Growth in wood volume	continuous
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		

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

[2]Many or most of these categories could be reliably, although imperfectly, interpreted with large-scale aerial photography. 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 summarized by thousands of different combinations of tree and forest conditions.

land clearing, roads, utility corridors, and buildings associated with urbanization; harvesting of wood (i.e., clearcuts, partial cuts) and associated road construction; and regeneration of harvested forest areas (i.e., natural, planted). Other rapid changes at regional scales are caused by droughts, hurricanes, floods, landslides, ice storms and insect epidemics. These cause areal changes that can be detected, with varying degrees of success, by a variety of remote sensing technologies.

I further assume that other indicators within detailed categories of forest (Table 1) change more slowly. An example is the average volume and number of trees per ha 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 changes in non-tree vegetation, down woody debris, and other indicators. I further assume that many aspects of forest health is affected by the slowly changing demographics of forest populations, annual variations in weather patterns and anthropogenic stressors, such as air pollution, climate change and exotic pests. I assume these slow and ubiquitous processes are measured at regional scales (e.g., 25- to 100-million ha) through probability samples of field plots across the USA; these include the Forest Health Monitoring Program[10,3,8], which supports detailed field measurements of 4,500 forested plots on a 25-km grid, and the FIA program, which supports basic field measurements of 120,500 forested plots on a 5-km grid.

If these assumptions are approximately true, then remote sensing is better suited for frequent monitoring (e.g., 20% of plots each year) of rapid areal changes, and less frequent re-measurement of field plots (e.g., 10% of plots each year) is better suited for monitoring the slower changes in tree composition and rates of change per unit area. Remote sensing is generally less expensive than field measurements, and this strategy could reduce costs.

Remote Sensing

Remote sensing can improve annual strategic monitoring if remotely sensed data are well correlated with high-priority field data; remotely sensed data are available when needed for the monitoring design; and remotely sensed data cost less than field data or sufficiently increase statistical efficiency. For example, augmentation of field data with remote sensing can be 6 to 15 times more efficient in estimating forest area (MacLean 1963) and twice as efficient in estimating wood volume (MacLean 1972). I evaluate 5 types of remotely sensed data[11] relative to these criteria for annual monitoring at the national scale.

Low-Resolution, Broad-Swath Satellite Data

These remotely sensed data are very inexpensive and cover enormous areas (1000- to 3000-km in swath width) with a large pixel[12] size (0.25- to 1.1-km wide).[11] Sensors include AVHRR, OrbView-2[13], SPOT 4 Vegetation Sensor, and MODIS Moderate Resolution Imaging Spectrometer.

These data are suitable for continental-scale maps of forested landscapes[14], global change models and monitoring acute deforestation in dense forests[15]. These data are available nearly daily, and might replace the FIA Phase 1 aerial photography to improve statistical efficiency. However, these data have insufficient resolution to monitor most indicators of forest conditions. For example, AVHRR data can not detect presence of forest in a pixel if the proportion of forest is less than 20%.

Medium-Resolution, Medium-Swath Satellite Data

When lay-people discuss remote sensing, they frequently refer to these sorts of data. Sensors include Landsat 7, SPOT 4, the Indian Remote Sensing[17] (IRS) satellite, Radarsat, and the Sovinform Sputnik Spin-2 TK-350 camera. These data are relatively inexpensive for large areas, having a 60- to 180-km swath width, and they have a reasonably small pixel size (10 to 30-m wide)[11]. Because of its broad swath width and spectral resolution, Landsat is the most efficient for synoptic mapping of forests over very large areas, such as the entire USA.

Holmgren and Thuresson (1998) throughly review these types of satellite data for forests. With routine and standardized processing in a high-production enterprise, these data can accurately separate forest from non-forest, 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 proportionally more intensive effort and customized approaches, including: masking forest from non-forest cover; specialized application to each homogeneous region; multiple dates of Landsat imagery; state-of-the-art classification algorithms; and extensive use of ancillary data in national-scale geographic information systems (Wynne and Carter, 1997; Zhiliang Zhu, personal communications). These data can identify recent clearcuts, but 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 for identification of sparse urbanization. These synoptic data can measure size, shape and connectivity of forest patches, which are indicators of forest fragmentation and habitat suitability at landscape scales. Theses data can map broad landscape patterns and changes over time; for example, Wickham and Norton (1994) developed landscape classification system that include urbanized, residential, wetland, water, forest, clearcut and agriculture, which exist as continuous expanses, mosaics or patches. High-quality, cloud-free data are available for temperate regions each year or two. Cloud-free data are not available for much of Alaska, but Radarsat might solve this problem. Therefore, data availability is satisfactory for annual inventory and monitoring. However, there is a limit to the quality of data measured by satellites 700 km from the earth's surface.

High-Resolution, Narrow-Swath Satellite Data

These remotely sensed data are very new in the civilian sector. Their 4- to 10-km swath width and a very small pixel size (1- to 3-m wide)[11] are best suited for small areas. Sensors include Earlybird and Quickbird (EarthWatch), OrbView-3[13], Resource21, Lewis Hyperspectral Imager (TRW-NASA), Clark (CTA-NASA) and Carterra-1 (EOSAT). Depending on the sensor, 200,000 to 1,000,000 images are required to cover the entire USA. Each image requires 95 megabytes of storage, and the expected cost is $200 (Wilford, 1998).

Wynne and Carter (1997) review these types of satellite data for forests. These data have resolution, coverage and cost that are similar to high-altitude aerial photography, which are discussed in the next section. These data can[11] distinguish about 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. 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. These satellite data could be acquired whenever they are needed for an annual inventory and monitoring system.

Given the cost and volume of these data, these data are not practical for wall-to-wall mapping of the entire USA. However, these data could monitor thousands of sample areas, each of which are 1-ha to 4,000-ha in size.

Small-Scale Aerial Photography

Aldrich (1979) reviews this traditional type of remote sensing. High-altitude large format (230-mm) images have resolution, coverage and cost similar to high-resolution, narrow-swath satellite data, which are described above[11]. The USGS National Aerial Photography Program[18] (NAPP) acquires 1:40,000 small-scale photography for most of the USA on roughly a 5-year cycle.

Small-scale aerial photography is widely used in many environmental monitoring programs. FIA uses NAPP photographs to improve its estimates of forest area and navigate to its field plots. The USDA Natural Resources Conservation Service uses NAPP and other small-scale imagery to photo-interpret conditions and changes on 65-ha sampling units in their National Resources Inventory[19,8] (NRI). The USGS National Wetlands Inventory[20,8] (NWI) uses NAPP photographs to map 10 categories of wetlands at 1:24,000 scale. NWI also uses NAPP images for a small sample of 1000-ha sampling units every 10 years; the purpose is regional statistics for status and trends of wetlands in the USA. The USDA National Agricultural Statistics Service[21] (NASS) uses NAPP photographs to delineate 250-ha primary sampling units and classify each unit as cultivated crop land, land used for livestock production, urban land, or other land uses. NASS then uses interviews with farmers and land managers to collect information about crops, operator households, animals, environmental factors, etc.

NAPP photography has several shortcomings for annual inventory and monitoring. The volume of 230-mm photographs is immense, requiring 350,000 images to cover the USA. The NWI[20] and NASS[21] programs require 20 years to map the entire USA with NAPP imagery. Sampling of NAPP imagery can speed this process for statistical estimation, and sampling is used by the FIA[1], NRI[19] and NWI programs. Annual monitoring requires a representative sample of photographs each year for each state; however, image acquisition[18] covers each state once every 5 years. High-resolution, narrow-swath satellite data, which were discussed in the previous section, could overcome his latter problem.

Custom 1:40,000 small-scale 35-mm aerial photography could be acquired for sampling units up to 100-ha in size. The schedule for image acquisition could match specifications for annual inventory and monitoring. However, higher-resolution 1:12,000 scale 70-mm aerial photography could be acquired at approximately the same cost for 100-ha sampling units.

Medium- and Large-scale Aerial Photography And Videography

Aldrich (1979) reviews this type of aerial photography. Photo-interpreters could reliably identify[11] most of the forest cover conditions in Table 1. Measurements might include 5 to 10 broad types of forest; 5 stages of stand development; 3 stand density classes; clearcut and partial cut areas; regeneration success; stand origin (natural, artificial); 3 to 5 severity levels for tree mortality; wildland-urban interface; indicators of forest fragmentation and urbanization; and stand size, shape and edge metrics. However, these photo-interpretations would include measurement error that requires statistical calibration with accurate field data.

70-mm 1:15,000-scale stereo photography could cover 100-ha primary sampling units, and 230-mm 1:8,000 photography could cover units up to 400-ha in size. Land use and forest stand boundaries could be mapped over the entire primary sampling unit. 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) could be photo-interpreted at random points within the primary sampling unit. The schedule for image acquisition could match specifications for annual inventory and monitoring.

Multi-stage Monitoring Design

Based on cost, resolution, coverage and scheduling, I propose a combination of two types of remotely sensed data to augment field data in annual monitoring. First, a time-series of Landsat data would cover the entire USA. The Landsat data would replace the current FIA Phase 1 photo-interpretation of low-resolution NAPP[18] aerial photography. Second, I propose a sample of medium- or high-resolution aerial photography, which would provide considerable information at a fraction of the cost of FIA field data. I describe programs to implement these two types of remote sensing for annual monitoring in the next sections. This would create a multi-stage design, with a census of Landsat pixel data at Stage 1, the sample of high-resolution aerial photography at Stage 2, and traditional FIA field plots at Stage 3.

A National Program to Map Changes in Land Cover

Multi-temporal Landsat satellite data can detect abrupt changes in spectral reflectance at the scale of a few adjacent 30-m pixels. These changes are often caused by clearcutting, land clearing and catastrophic disturbances to forest cover. These changes are rare across most landscapes, and general sample surveys, like FIA, are not well suited to monitor rarities. In addition, satellite data provide detailed spatial data that are important to land managers but missing from statistical surveys like FIA.

Numerous National Forests and state governments use Landsat data to map land cover for large sub-regions of the USA. However, only two federal programs map land cover for the entire USA. The USGS[22] Multi-Resolution Land Characteristics (MRLC) Program[23,24] maps 3 forest categories, 3 urban categories, 3 wood land categories, 3 agricultural categories, and 21 other categories of land use and cover. The USGS GAP Analysis Program[25] maps critical habitats to help conserve biological diversity. The minimum map unit is 100-ha, and the classification system uses 18 categories[26] of forest for the entire USA. The MRLC program began in 1995 with an annual budget[8] of $10,000,000. The GAP program began in 1994 with an annual budget[8] of $3,600,000. These programs use sophisticated methods that stretch the limits of satellite data for immense regions. Success requires considerable input of energy, and neither program has completed mapping the entire USA. These programs plan to update maps for changes in land cover, but updates are not funded.

I propose[27] an additional national program that uses Landsat data on a 2- to 5-year cycle to map abrupt changes in land and forest cover. This program would fully utilize all 540 Landsat scenes[8] that cover the USA. The intent is a relatively inexpensive process to update costly maps of land cover and land use. MRLC, GAP, NWI[20], National Forests and state agencies could use the maps of change to modify their older thematic maps. The proposal provides a time-series of Landsat data to these programs for their additional use, such as major revisions to land cover maps on a 10-year cycle. FIA could use updated MRLC and GAP maps to replace photo-interpretation of its 3 million Phase 1 photo-plots to improve statistical estimates for current extent of forest land. FIA could further improve statistical estimates of changes in forest cover with these maps of change. Similarly, NRI could use updated Landsat data as ancillary measurements to improve its estimates of changes in land use and extent of agricultural and range lands. Photo-interpretation of Landsat images could identify changes in extent and distribution of broad types of landscapes patterns, such as urban, residential, wetland, water, forest, clearcut and agriculture (Wickham and Norton 1994).

Unfortunately, Landsat data might not significantly reduce the need for frequent field measurements in an annual FIA system. Landsat satellite data cannot accurately discriminate the detailed composition of forests. If forest composition changes through moderate disturbances and land management (e.g., drought, tree diseases, partial cutting, or shifts in land ownership and management objectives), then FIA must have sufficient field data to measure the new conditions. Also, some abrupt spectral changes in Landsat are caused by artifacts that are not changes in forest condition, and the characterization of changed areas requires new FIA field data. I believe that satellite data alone are not sufficient to fundamentally improve efficiency of an annual FIA system, and higher-resolution remotely sensed data are also necessary to improve the efficiency of field data.

A National Sampling Program With High-resolution Imagery

Photo-interpretation of high-resolution aerial images can accurately distinguish among many detailed forest conditions. Since these images contain substantially more information than Landsat data, high-resolution aerial images have greater potential to reduce expense of an annual FIA system. The measurement cost of an FIA plot by a 2-person field crew is 4 times greater than the cost for acquisition of custom high-resolution aerial images and photo-interpretation[11].

Only two federal programs[28] monitor changes in land cover over the entire USA with a sample of aerial imagery. The National Resources Inventory[19] (NRI) makes extensive use of available NAPP[18] and small-format aerial photography for 300,000 primary sampling units (PSUs) 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, all of which originate with other federal programs. The NRI has been conducted once every 5 years, but NRI is changing to an annual system, much like FIA. The annual budget for NRI is $8,500,000[8]. The National Wetlands[20] Inventory employs a sparse sample of small-scale NAPP photography for their status and trends estimates. This is a small part of their overall mapping program, which has an annual budget of $7,750,000 per year[8].

I propose a national program that specifically acquires an annual sample of high-resolution aerial images to monitor land use, land cover and change. This national program could be a cost-sharing partnership between FIA and NRI. The sample sites would include 300,000 65-ha NRI PSUs, and another 320,000 new 65-ha PSUs would be established to cover existing 1-ha FIA field plots[29]. To reduce cost, new 65-ha plots might be established over 1-ha FIA field plots in forest and woodland landscapes, while new 1-ha FIA field plots would be established within existing 65-ha NRI PSUs in agricultural and range landscapes.

Each year, the proposed national program would procure 1:8,000 230-mm photography or similar high-resolution remotely sensed data for 20% of the 65-ha PSUs. An interpreter would delineate and classify different land uses, land cover and forest stands in each PSU. Points within the PSU would be interpreted for more detailed measurements of forest composition. As each PSU is re-imaged over time, photo-interpreters would measure changes between dates.

One point within the 65-ha PSU would be a 1-ha FIA field plot, while other points could be measured in the field by NRI crews. Goebel et al. 1998 report results from a pilot study in Oregon that tested integration of NRI and FIA field procedures. This partnership would expand monitoring well beyond forest and wood lands to cover all land uses and land cover in the USA.

Technical and Institutional Considerations—Acquisition and interpretation of custom aerial photography for 300,000 NRI PSUs and 320,000 FIA PSUs requires a large infrastructure and budget. Even if 20% of these PSUs were sampled each year with aerial photography, this infrastructure would dwarf that required for interpretation of 540 Landsat scenes every 2- to 5-years. We need strategies that would incrementally build this infrastructure, reduce the number of PSUs, and reduce cost of other components of the NRI and FIA programs.

Separate NRI and FIA sampling frames could converge into a single sampling frame through sampling with partial replacement. Some existing NRI PSUs would be abandoned and replaced with new 65-ha PSUs that cover existing 1-ha FIA field plots. This strategy is most appealing in landscapes dominated by forest lands. Likewise, new FIA field plots could be established within existing NRI PSUs, and old FIA field plots abandoned, in agricultural landscapes. This process might span 5 to 10 years. A sub-sample the FIA plots might be photographed during early years. For example, 12,000 Forest Health Monitoring[10] plots[29] are a 4% sub-sample of the FIA sampling frame. Additional PSUs could be added each year thereafter.

High-resolution imagery could reduce the total number of field plots needed to achieve data quality standards. For example, the proposed sample imagery captures considerable information about forest composition and changes over the entire 65-ha PSU. The area within the 65-ha PSUs is about 2.00% of the landscape, while only 0.03% of the landscape is within the same number of 1-ha FIA plots. Also, the larger PSUs would be more efficient for rare types of land cover and change, and linear features, such as riparian areas, roads, utility corridors, and windbreaks.

High-resolution imagery could reduce the frequency that FIA plots must be re-measured by field crews. Remote sensing could accurately identify field plots that are undisturbed, and models could predict the current conditions on these plots based on old field measurements. Photogrammetric methods at Stage 3 sampling points could measure tree mortality and changes in individual tree heights and crown sizes on FIA plots as correlates to wood growth and indicators of model accuracy.

Photo-interpretation of high-resolution imagery might replace field measurements of remote or inaccessible plots, and compensate for missing data from FIA plots that are too hazardous for field measurement or to which access is denied by private landowners[30]. High-resolution imagery could accurately monitor FIA field plots that were non-forest but could change into forest; this is very important for monitoring afforestation. High-resolution imagery could identify FIA plots with small slivers of forest, which is very important to accurately estimate forest extent as FIA converts to mapped plots.

High-resolution aerial imagery of 65-ha sampling units might provide opportunities to measure other indicators of forest condition. For example, the spatial scale of a 1-ha FIA field plot might be too confined to measure many components of habitat, but the 65-ha size might be sufficient. Photo-interpretations of 65-ha units would provide training and labeling sites, which are essential for processing satellite data.

Soft-copy digital techniques could improve efficiency of capturing photo-interpreted data. This includes registration of field plots to imagery, digitization of polygon boundaries and planimetry, photogrammetric measurements of tree heights and crown diameters, and entry of resulting measurements into the FIA data base. Digital images could be filed and managed with modern information management software.

Statistical Estimation—Although remotely sensed data could reduce cost of data acquisition in an annual monitoring system, statistical combination of diverse types of monitoring data is complex. The multivariate composite estimator could combine time-series of field data, model predictions, and multiple types of remotely sensed data, while models for measurement and prediction errors help quantify the quality of the resulting information. Statistical calibration models for each photo-interpreter could be developed with historical imagery and field data. Results of complex statistical estimators might be stored as expansion factors to simplify analyses. Diagnostic statistics would detect biased calibration and prediction models. The statistical simplicity of the remote sensing component could be protected from fluctuations in budgets by changing the pace of field data collection.

Summary

The demand for more current monitoring data is clear and compelling. Acceleration of traditional FIA field procedures would satisfy this demand, but this requires an unprecedented increase in funding[7,1]. Remote sensing could reduce costs by augmenting field data with synoptic satellite data and sampling with higher-resolution aerial photography. The National Academy of Sciences (1974, cited in Aldrich 1979) recommended this exact same approach 25 years ago.

However, effective use of remote sensing requires an unprecedented institutional infrastructure that can acquire and process hundreds of Landsat scenes and tens of thousands of aerial photographs each year. Legislators and administrators need to understand the scope of this infrastructure when comparing remote sensing to historical technologies. Unless the information needed from inventory and monitoring is dramatically reduced, remote sensing is not a cheap solution to expensive monitoring requirements. However, a strong partnership among the Forest Inventory and Analysis Program[1], the National Resources Inventory Program[19] and mapping programs in the US Geological Survey[20,23,25,22] could produce more cost-effective results with remote sensing. This partnership could produce the world's premier system to monitor trends in forest lands, agricultural lands, range lands, wood lands and land use to evaluate effectiveness of public policies and guide sustainable development.

Acknowledgments

Ideas expressed in this paper originated during my association with the Annual Forest Inventory System, which was a research and development project conducted jointly with the Minnesota Department of Natural Resources and the Forest Inventory and Analysis Programs at the USDA Forest Service North Central Research Station and Rocky Mountain Research Station. Mark Hansen, Bill Befort, Hans Schreuder, Dave Heinzen, Allan Ek, Jeff Goebel, and Wayne Fuller were particularly influential during development of the concepts presented in this paper. I thank the following reviewers: Zhiliang Zhu, Victor Rudis, Jeff Goebel, Steen Magnussen, Bill Befort, George Deegan, Jim Rack, and Henry Lachowski. Any errors remain my responsibility.

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Footnotes

[1]FIA, Forest Inventory and Analysis Program, http://www.srsfia.usfa.msstate.edu/wo/wofia.htm

[2]USDA, United States Department of Agriculture, http://www.usda.gov/

[3]Citation from National Association of State Foresters, which regularly acknowledges FIA as its highest priority for USDA Forest Service research. http://www.stateforesters.org/

[4]Second Blue Ribbon Pannel on Forest Inventory and Analysis, 1998, which included national leaders from the full forestry community in the USA, including federal and state agencies, industry, academia, environmental organizations, and other user groups.

[5]Conclusion from the First Blue Ribbon Panel on FIA, 1993.

[6]PL 105-185, Agricultural Research, Extension, and Education Reform Act of 1998, 253(c), http://frwebgate.access.gpo.gov/cgi-bin/useftp.cgi?IPaddress=waisback,access.gpo.gov&filename=publ185.105&directory=/diskb/wais/data/105_cong_public_laws

[7]Draft Strategic Plan for PL 105-185, Section 253(c), August, 1998.

[8]National Environmental Monitoring Initiative, http://www.epa.gov/cludygxb/sites.html

[9]FIA Database Retrieval System, http://www.srsfia.usfs.msstate.edu/scripts/ew.htm

[10]FHM, Forest Health Monitoring Program, http://willow.ncfes.umn.edu/fhm/fhm_hp.htm

[11]Remote sensing for annual forest monitoring, http://www.fs.fed.us/ne/rsb/farm4.html

[12]Pixel stands for "picture element." It is the smallest spatial unit in a digital image, and is an indicator of resolution to be resolved, most features require a cluster of similar pixels.

[13]Orbital Imaging Corporation, http://www.orbimage.com/

[14]AVHRR map of forest types in USA, http://www.srsfia.usfs.msstate.edu/rpa/rpa93.htm

[15]NASA, http://www.mtpe.hq.nasa.gov/EC, Joint Research Centre http://www.mtv.sai.jrc.it/USGS, http://edcwww.cr.usgs.gov/landdaac/1KM/1kmhomepage.html

[16]FIA Remote Sensing Band, http://www.fs.fed.us/ne/rsb/remote.html

[17]IRS, Indian Space Research Organization, http://www.isro.org/

[18]NAPP, National Aerial Photography Program, http://edcwww.cr.usgs.gov/Webglis/glisbin/guide.pl/glis/hyper/guide/napp/

[19]NRI, National Resources Inventory, http://www.nhq.nrcs.usda.gov/NRI/intro.html

[20]NWI, National Wetlands Inventory, http://www.nwi.fws.gov/

[21]NASS, National Agricultural Statistics Service, http://www2.hqnet.usda.gov/nass/

[22]USGS, Geological Survey, US Department of Interior, http://www.usgs.gov/

[23]NAPP, Multi-Resolution Land Characteristics Interagency Consortium, http://www.epa.gov/mrlcpage/index.html

[24]NALC, North American Landscape Characterization project provides early 1990's Landsat data, http://edcwww.cr.usgs.gov/landdaac/pathfinder/pathpage.html

[25]GAP, USGS Geographic Approach to Planning for Biological Diversity program, http://www.gap.uidaho.edu/gap/

[26]Only a fraction of the national forest types exist in each region within the USA.

[27]Dr. William Befort, Minnesota Department of Natural Resources originally suggested a national Landsat program to identify changes in land cover.

[28]In addition, FIA uses 3-million Phase 1 photo-plots over the entire USA to improve statistical accuracy. However. FIA photo-plots are not permanent, and are not directly used to monitor changes in land cover.

[29]Includes both forested and non-forest FIA or FHM plots.

[30]For decades, FIA and NRI have gained access to field plots through voluntary consent from private landowners. However, this is a sensitive public issue. Aerial photography of the same plots is less sensitive, but is not immune from similar controversy.