Effective and increased use of remote sensing data in forestry is likely to occur if appropriate procedures are developed to incorporate remote sensing data into operational systems. Central to this goal is the use of all available relevant information and resources: combining remote sensing with field measurements and ancillary information and, when appropriate, developing procedures that combine different types of remote sensing. When developing an integrated procedure, it is useful to combine data types so that their respective advantages and disadvantages complement one another and produce new information that is either unique or more cost-effective than the alternatives.

Using all available useful data and information and combining them in appropriate ways are the keys to obtaining accurate information about forests. This article describes three types of useful integration: (1) integrating different types of remote sensing data; (2) integrating remote sensing data with field measurements; and (3) integrating remote sensing, field measurements, and ancillary information. It also briefly considers the human dimensions of integration.

It is important to understand that the actual process of integration involves more than spatially merging the datasets within the framework of geographic information systems (GIS) and decision support systems (DSS), and their spatial and statistical analytical methods. Rather, integration is intended to produce information, and therefore it must be guided by expertise resident in forestry and remote sensing specialists.

Different Sensors

A growing suite of earth observation systems (both satellite and airborne) makes it possible to collect many potentially useful types of remote sensing data. When contemplating using remote sensing, it is best to be familiar with the spectral, temporal, spatial, and observational characteristics of the information, and whether it is in any way unique. This makes it possible to effectively evaluate the relative potential of individual sensors and various combinations of remote sensing systems.

Several types of spectral data are available. For example, optical sensors (air photo, multispectral, and digital multispectral cameras) are generally useful for identifying vegetation cover types and assessing vegetation condition. Optical hyperspectral sensors show promise for assessing the condition of forests based on the foliar chemistry of the canopy. Thermal sensors are useful for measuring the radiant temperature of the terrain. Radar sensors have shown promise for assessing the structure and biomass of forests. Lidar sensors provide an effective means of measuring tree and stand height and canopy structure.

Temporal data (i.e., data that are repetitively collected in a consistent way, typically by satellites) facilitate forest monitoring. This is usually done using repetitive data from a single satellite, but it can also be done using sensors with similar spectral bands (fig. 1, p. 62).

Remote sensing data from different sensors also varies significantly in spatial resolution (e.g., Landsat TM and aerial photographs) and therefore in area coverage, cost per area, availability, and so forth. Integrating such data appropriately can lead to cost-effective information. Accordingly, data collected at different spatial resolutions may be useful for inventories that employ multitap and multiphase sampling designs.

Observational differences in remote sensing data may also provide useful information. SPOT and some satellite radar systems can collect data at more than one view angle on different orbital passes. In general, differences in observation geometry are useful for assessing vertical structure and bidirectional reflectance characteristics.

This impressive array of capabilities collectively provided by a number of remote sensing instruments exists because no one sensor can do it all. By combining data from different sensors, foresters may capitalize on their respective strengths and obtain the best information.

Field Measurements

Measurements of the same parameter made by remote sensing will generally not be as accurate as measurements made on the ground, with the exception of certain spatial variables (e.g., crown cover). However, field measurements are time-consuming and expensive, and they usually require sampling. Remote sensing, on the other hand, may not be as accurate but often it can be used to inventory an entire area at an acceptable cost and so avoid sampling error. Because field measurements and remote sensing have these complementary advantages and disadvantages, it is often beneficial to combine them. Two useful ways of integrating remote sensing with field measurements are stratification and statistical estimation.

Stratification. Stratification involves...
subdividing a heterogeneous area into units (strata) that are internally more homogeneous than the entire area with respect to the parameters of interest. Stratification typically provides location, boundary, label, and area information.

Static stratification typically is based on current status (e.g., land cover). It is often used to increase the precision of estimates for specific geographic areas and is usually based on a single, recent acquisition of remote sensing data. Static stratification of satellite multispectral data is often accomplished by categorization (classification).

Pre- and post-stratification are effective ways to use static stratification for improving the precision of plot-based statistical estimates. Pre-stratification is useful for determining optimal sample size and allocation for collecting new plot data. Post-stratification consists of grouping existing field data on the basis of strata defined using the remote sensing data, calculating a mean and variance for each stratum, and weighting the stratum values proportional to its area. Useful information for these tasks, such as strata boundaries and sizes, are obtainable from remote sensing. The goal of stratification is to get equal precision with fewer field samples, or greater precision with the same number of samples originally planned.

Dynamic stratification can be used to obtain information on trends or the location of changes. It is typically based on the results of remote sensing–based change detection. Dynamic stratification of satellite multispectral data often is effectively accomplished by detecting changes in two different, phenologically equivalent acquisitions. Several techniques are available for change detection based on satellite remote sensing data, including categorical classification, radiometric, and hybrid procedures.

Statistical estimation. Useful integration of remote sensing data and field data can be performed statistically. Multiphase sampling is a very effective way to combine different sources of information because of the way it produces an improved estimate by combining a large sample of relatively inexpensive and easy-to-make but perhaps biased measurements (e.g., remote sensing) with a smaller sample of accurate measurements (e.g., field plots) that are subject to sampling error.

In contrast, multistage sampling is used when it is not possible to interpret all of the data for the entire study site from any of the data sources, and different variables are measured at each stage. For example, large sample units might be selected at the first stage (e.g., on moderate spatial resolution multispectral satellite images) and forest cover interpreted and delineated on it. At the next stage, smaller sample units can be established inside the primary units and density or forest cover type mapped (e.g., from aerial photographs). At the final stage, field plots are established within each forest cover type and timber volume is measured on the ground. The field measurements are then expanded through the multiple stages to get timber volume for the forested area.

Ancillary Information

The use of data and information produced by previous studies is likely to increase the cost-effectiveness of any information-producing procedure. Drawbacks to using existing information are that the data and information may not be exactly what you are looking for, or may not be current. The following applications illustrate the effective integration of remote sensing data with both field and ancillary data into procedures developed in response to specific information needs at the regional and stand level.

Regional level. The benefits of using remote sensing for regional-level tasks are:

- It can provide an instantaneous portrait of an entire region or forest, regardless of ownership.
- It can reduce the need to visit each stand or collect and interpret a large amount of aerial photography.
- It may provide more precise and consistent assessment of cover type variability within stands than many current field methods.

Assessing the forest management
practices of different organizations may be accomplished by merging ancillary information on land ownership boundaries with forest harvesting information based on the temporal analysis of satellite remote sensing data. This integration of information makes it possible to track the size, shape, and location of harvested areas by ownership per time interval.

**Stand level.** At a more local scale, many forest organizations maintain GIS databases. The following applications are concerned with validating and updating the information in GIS-based forest information management databases.

Detecting errors in stand boundaries may be accomplished by merging ancillary information from a GIS stand attribute database and categorized Landsat TM data. The TM data is spectrally categorized to indicate current land cover. The area of the stand is “cut out” of the Landsat data using a polygon from a GIS database representing the stand’s boundary. The homogeneity of the land cover inside the stand polygon is then checked, and if a significant proportion of the polygon is not occupied by the forest cover type indicated by the attribute data in the stand database, the boundary of the stand is considered to be in error (fig. 2a).

Identifying inadequately or mislabeled stand attribute data may be performed by merging and comparing categorized forest cover type information derived from Landsat TM data with the forest cover type attribute in the GIS stand data base. A spatial analysis is performed on the categorized Landsat data to assess the homogeneity of the forest cover types within the polygon occupied by the stand according to the database. If a stand is found not to be homogeneous, then it could be subdivided, if possible, to improve homogeneity. If a stand cannot be easily subdivided, then the attribute data should be modified so that it indicates that the stand contains more than one forest cover type in certain proportions (fig. 2b).

**Human Dimensions**

Resource management issues are becoming increasingly complex, requiring involvement of many people and organizations with an interest in the outcome of decisions. Effective strategies for dealing with these issues will only result from the collaborative efforts of these different individuals and organizations. At a technical level this will require combining the skills of foresters, remote sensing experts, statisticians, and GIS experts. At the decisionmaking level it will involve agency resource managers, public and private stakeholders, nongovernmental organizations, and research scientists. Such situations create opportunities for additional integration.

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