better how humans intervene in the process and how to account for these interventions.

Changes in Forest Carbon Stocks

Trees are composed of carbon that results from the photosynthesis process. Their growth results from the removal of carbon dioxide from the atmosphere (through respiration), justifying the label of forests as carbon sinks. Carbon from trees can also be emitted to the atmosphere through, for instance, the decomposition of wood, stumps, and leaves from deforestation. In this case, the trees are referred to as carbon sources. Trees stock carbon not only above ground (stem, branches, foliage, and understory vegetation) but also below ground (all living biomass of live roots). Carbon pools also include dead organic wood (nonliving woody biomass), litter, and soil organic matter (including organic carbon in mineral and organic soils). Anthropogenic changes in carbon stock normally result from changes in land use, such as conversion of natural ecosystems (such as forests) to cropland, grazing land, or pasture or abandonment of croplands; and activities such as harvesting of timber and establishment of tree plantations. Estimating forest carbon stocks and their changes is not a trivial task and the associated uncertainties are very high. Some changes cannot be reliably estimated in small intervals of time, as is the case with soil carbon. The estimation of carbon stock changes from the land use, land use change, and forestry sector is one of the components in the national greenhouse gas inventory that countries have to calculate annually. A very comprehensive report on methodologies for estimating changes in carbon stocks in all these pools has recently been published by the Institute for Global Environmental Strategies (IGES) for the Intergovernmental Panel on Climate Change (IPCC) and should be available in 2004.

See also: **Inventory**: Large-scale Forest Inventory and Scenario Modeling. **Resource Assessment**: Forest Resources; GIS and Remote Sensing; Regional and Global Forest Resource Assessments.

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GIS and Remote Sensing

M A Wulder, Canadian Forest Service, Victoria, BC, Canada

Introduction

Forest inventory data are the primary information source for forest management. Forest inventories are undertaken to provide a survey of the location, composition, and distribution of the forest resource and their relative amounts over a given area. Forest inventories are required to derive the information for resource evaluation enabling management decisions at a variety of levels, such as harvest plans through to the development of provincial or state level strategies. The production of a forest inventory data set follows a series of stages, the ultimate being the development of a digital spatial database. Forest inventory, stored and manipulated in a geographic information system (GIS), is a key information source for operational-level planning and strategic-level planning and management. Operational-level forest inventories are often calibrated with field-sampled measurements and are used to develop location-specific information required for harvest planning, road layout, and silvicultural activities. At the strategic level, forest inventories provide data for longer-term forest management, analysis, and decision-making. The general approaches to the development of information for operational- and management-level inventories are similar.

Remotely sensed data, excluding aerial photography, provide opportunities to update forest inventories, estimate inventory attributes, capture forest disturbances, and to estimate nontraditional forest characteristics such as habitat and biodiversity. Remotely sensed data are georeferenced and are therefore easily integrated with GIS databases. For example, forest disturbances related to insect damage or fire, that are captured in remotely sensed data, can be incorporated as unique attributes for individual polygons in an existing forest inventory database. These inputs aid in maintaining the currency of the forest inventory database, and, as a result, contribute to the informed management of remaining forest resources.

Forest Inventory GIS

A GIS has the capability to capture, store, integrate, analyze, and display spatially referenced data. In the case of forest inventory, a GIS facilitates initial database development through data capture; storage; integration of forest inventory information with other spatial data sets; analysis and modeling of the forest inventory attributes (spatially and aspatially); and graphical display of the spatial layers on screen or as hardcopy plots. The cartographic capabilities of a GIS provide the user with a wide range of options for portraying data and producing powerful thematic outputs.

The creation of a forest inventory facilitates the generalization of complex forest resources into meaningful units. The units created are useful for forest management, as the attributes attached to a particular management unit, or polygon, were developed for this purpose. Recent developments in forest management have resulted in an expansion of the range of attributes attached to each polygon. Historically forest management inventories have focused on capturing information necessary to support harvesting and silviculture activities. These volume-based resource inventories have given way to vegetation resource inventories (VRI). A VRI captures a more diverse range of information required to support an increasingly broad range of management activities such as biodiversity conservation and habitat retention. Forest inventories are commonly the only data set capturing the forest structural characteristics over large areas. Information regarding forest structure is of interest to a large audience of practitioners engaged in every facet of natural resource management.

Traditionally forest inventory production was an analog process that culminated in the drafting of a paper map. The pervasiveness of GIS today has broadened the utility and importance of forest inventory data beyond the realm of its traditional users. Current forest management is based upon forest inventory databases which are both digital and spatially explicit. The general procedure for the map production component in the development of forest inventory databases is as follows:

1. Planning (e.g., sample design, creation of a data model, identification of attributes required).
2. Photo acquisition.
3. Photointerpretation (analog or digital-assisted).
    - Field reconnaissance
    - Calibration
    - Quality control
4. Digitization.
    - Capture of photo-interpreted polygons (including forest stand, lake, and swamp boundaries)
    - Attribute entry
    - Linkage of spatial and attribute data
    - Input of base map features (such as roads, rivers, utilities)
    - Inclusion of administrative boundaries
    - Edge matching at map boundaries of map sheets
    - Label placement
    - Quality control
    - Creation of final data set
    - Generation of outputs (hard-copy maps, reports).

The photo scale selected influences the information content, and subsequent detail of attributes that may be mapped. Typically, for forest inventory purposes, a photo scale in the range of 1 : 10 000 to 1 : 20 000 is used. Photointerpretation is the most important element of the inventory process, as the quality of the inventory is dependent on the quality of the photo interpretation. The use of experienced photo-interpreters is important. Quality control and interpreter calibration, with field data, are important elements of the photointerpretation process. The entire production cycle, from planning to generating final outputs, can take several years. Forest inventory production cycles may be shortened by using a process where the photointerpretation is done direct to digital (e.g., softcopy photogrammetry). Forest inventory databases can suffer from issues related to the length of time required to complete the inventory cycle. Forest disturbances, such as those due to fire and insects, may go undetected and not be captured in forest inventory databases. The inventory process may also be inconsistent over large areas due to operational constraints or issues of land tenure. As a result, inventory data for adjacent mapsheets may be collected at significantly different points in time. Remote sensing facilitates the continuous collection and updating of forest disturbances within the forest inventory cycle.

Remote Sensing

Air photos and digital images record energy properties at a point in time for a portion of the earth's surface. Using different combinations of film sensitivity and filters, air photos can selectively record certain wavelength ranges of the electromagnetic spectrum. Digital sensors can also be considered to use filters, but rather than using halide crystals in a film emulsion to record the image, energy detectors are used. Photographic film is generally limited in sensitivity to a narrow range of the electromagnetic spectrum (400–900 nm), while digital optical sensors can operate in a wider range of the electromagnetic spectrum (400–14 000 nm). Energy incident upon a detector, representing a wavelength range of electromagnetic energy, is typically converted to a digital number. The pattern of these digital numbers forms an image. Digital images can be considered a function of spectral, spatial, temporal, and radiometric resolution characteristics. Spectral resolution indicates range of wavelengths captured in the imagery. Spatial resolution is the pixel size or unit of area on the ground. Small pixels less than 1 m^2 in size, commonly referred to as high-spatial-resolution data, provide detailed images, conferring tree-level information. Larger pixels, such as those captured by Landsat sensors (30×30 m) capture stand or landscape-level characteristics. As a result, the types of attributes that can be estimated are closely linked to image spatial resolution. Temporal resolution indicates the frequency that a particular type of imagery is collected. A high temporal resolution (frequent acquisition) allows for capturing time-specific forest characteristics, and also allows for overcoming the presence of clouds. Radiometric resolution is generally interpreted as the number of intensity or quantization levels that a sensor can use to record a given signal. For example, 8-bits is a common quantization level, enabling a digital number range from 0 to 255. The radiometric resolution influences the precision with which attributes may be estimated and the categorical detail present. Greater radiometric resolution increases the level of attribute or categorical detail that may be attempted to be extracted from the imagery. These four image resolution characteristics (spatial, spectral, temporal, and radiometric) also combine to result in specific image characteristics. For instance, high spatial resolution imagery generally has a small spatial extent (i.e., covers a small area on the ground), is generally costly and collected infrequently, whereas lower spatial resolution data have a larger spatial extent and is collected frequently, often with data available at a lower cost.

Despite the potential and demonstrated abilities of remotely sensed data, the practical use by forest managers has been limited to date. Key to increasing the use of remote sensing in forestry are its integration with GIS technology and databases, as well as an understanding of the information need relative to the capabilities of the technology. In the following sections we present successful and nascent application areas where the integration of remotely sensed and GIS data enables the generation of unique data for forest characterization.

Forest Inventory Information from Remotely Sensed Data

The demands for current inventory information at increasingly finer levels of detail are resulting in opportunities to incorporate inventory derivatives from remotely sensed data in at least two ways: polygon decomposition and individual tree crown recognition. Polygon decomposition is a process whereby attributes generated from remotely sensed data may be integrated with existing forest inventory databases. When the spatial resolution of a given remotely sensed data source is finer than the inventory polygon size, multiple pixels may be generalized and a new forest inventory attribute developed. Even at a Landsat Thematic Mapper satellite resolution of 30 m, there are over 20 pixels within a minimum mapped forest stand polygon size of 2 ha. For instance, new forest inventory attributes indicative of forest change may be developed following a polygon decomposition approach. To achieve this result, a change detection procedure can be applied to multiple dates of satellite imagery to create a pixel-based change map. The pixel-based change may then be generalized to create new forest inventory attributes for each polygon, such as area and proportion changed. These new attributes may in turn be analyzed in conjunction with existing forest inventory attributes or viewed alone to provide for a landscape-level representation of forest disturbances. Given that the development of forest inventory databases is primarily from the manual interpretation of aerial photographs, remotely sensed data can be used to update the inventory database with harvest information for quality control and audit purposes. Biases in forest inventory databases (due to vintage, map sheet boundaries, or interpreter preferences) may also be detected using landscape-level remotely sensed land cover information.

Individual tree crown recognition is based on high spatial resolution images from which individual tree characteristics such as crown area, stand density, and volume may be derived and integrated with the forest inventory database. There are growing demands for these tree and stand attributes to be collected at increasingly finer levels of detail, and to collect others such as gap size and distribution to ensure forests are being managed sustainably for a multitude of timber and nontimber values. Information needs such as these can only be provided through the seamless integration of remote sensing and GIS technologies.

Fire, insects, and disease are among the major natural disturbances that alter our forested landscapes and their impacts need to be determined on a timely basis to ensure inventory databases are continuously maintained and updated in support of forest management planning and monitoring of sustainability. Remote sensing and its integration with GIS are technological tools that provide the capability to monitor the health of our forests. The roles that integrated remote sensing and GIS systems may serve when addressing forest pests, including:

1. Mapping and detecting insect outbreak areas.
2. Characterizing patterns of disturbance (by determining spatial relationships to mapped stand attributes).
3. Modeling and predicting outbreak patterns (such as through hazard rating).
4. Provision of data to GIS-based pest management decision support systems.

These roles result in information products that are intended for management planning, supporting impact studies, and contributing to regional or national reporting on the status of forests.

Fire is an ecological process that governs the composition, distribution, and successional dynamics of vegetation on the landscape. As a result, knowledge of fire disturbance is useful in:

1. Understanding fire impacts on timber and nontimber values.
2. Definition of salvage logging opportunities.
3. Understanding climate change effects on forest fire occurrence.
4. Quantification of the influence of fire on regional, national, and global carbon budgets.

To address this range of issues, current methods employ a range of data sources, including field observation and measurement, global positioning system (GPS) occurrence locations, forest inventory, and from remote sensing (including airborne and satellite). A similarly wide range of methods is applied to address unique forest conditions, characteristics, and fire information needs. Applications have been developed to capture a unique temporal domain to address differing management needs. Airborne infrared and thermal remote sensing systems enable real-time applications, where active fires and fire hot spots are detected. Data telemetry systems will transmit observations about fire location and size from the aircraft to field-based systems from which precise directions can be given to water-bombers and fire-fighting crews. Near real-time remote sensing GIS systems have also been developed to identify where fire activity is occurring over large areas and to aid in targeting locations for collecting finer precision information. Near real-time systems are generally based on daily satellite observations from the coarse-resolution (1 km pixel size) National Oceanic and Atmospheric Administration (NOAA) Advanced High Resolution Radiometer (AVHRR) data. Postfire applications are undertaken to map burned areas, from aerial photographs or satellite imagery, to aid in assessing fire damage.

Future Directions

High spatial resolution remotely sensed data are available from a wide range of sensor/platform configurations, including aerial photography, digital aerial photographs, video and digital cameras, and multispectral airborne and space-borne sensor systems. The multitude of possible high spatial resolution image data sources are increasing the possibilities to extract detailed information about forest structure, function, and ecosystem processes. The extraction of forest structure and biophysical information from high spatial detail imagery requires nontraditional digital analysis approaches and, often, the careful use of complementary data. Lidar is an example of a complementary data source for combination with high spatial resolution optical data. Lidar provides unprecedented accuracy in estimates of forest biomass, height, and the vertical distribution of forest structure. Samples of high spatial resolution remotely sensed data may be combined with more spatially extensive, yet less detailed information sources such as Landsat or existing GIS inventory database, to provide for landscape-level characterizations. Hyperspectral sensors collect data over many narrow spectral bands, rather than the few broad bands represented by most optical sensors. The ability to purposely select specific bandwidths of spectral information is intended to allow for improved discrimination of cover and physiological attributes. Additional research is ongoing to determine the utility of hyperspectral data in a forest management context. High spatial resolution, lidar, and hyperspectral data are examples of information sources poised to impact forest management operations. As the availability of these alternate data sources improves, as their associated costs decline, and as optimal methods to extract information from these data become better understood, data integration opportunities, and subsequent management options, are expected to increase. Landsat, and Landsat-type, sensors are also envisioned to play a continuing role in map update, broad area characterization, and change detection applications.

Conclusions

Remote sensing and GIS are complementary technologies that combine to enable improved mapping, monitoring, analysis, modeling, and management of forest resources. Forest inventory, as a cornerstone of forest management activity, has benefited from developments in GIS and may be further improved through the judicious integration of remotely sensed data. Additional information on forest inventory attributes, insect and fire damage, habitat, and biodiversity can be developed through the integration of remotely sensed and GIS data. As the availability of multiresolution, multisource data increases, so should the capability to generate timely and accurate maps of forest composition and structure. In turn, the future should see operational capabilities improved for routine mapping of a range of attributes as well as improvements in the extraction of characteristics at a precision commensurate with strategic-level forest management scales, which will contribute to efforts aimed at assessing the sustainability of our forests. The combination of remotely sensed attribute estimates with the analytical utility of geographic information systems and advanced forest process models is a powerful means to generate information that describe forests and contributes to a better understanding of the influence of disturbances, management practices, and a changing climate on the sustainability of forest ecosystems.

See also: **Ecology**: Natural Disturbance in Forest Environments. **Inventory**: Forest Inventory and Monitoring. **Landscape and Planning**: Spatial Information. **Resource Assessment**: Forest Change.

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