Remote sensing and GIS in forestry

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Remote sensing and GIS are complementary technologies that, when combined, enable improved monitoring, mapping, and management of forest resources (Franklin 2001).

The information that supports forest management is stored primarily in the form of forest inventory databases within a GIS environment. A forest inventory is a survey of the location, composition, and distribution of forest resources. As one of the principal sources of forest management information, these databases support a wide range of management decisions from harvest plans to the development of long-term strategies.

Historically, forest management inventories were primarily for timber management and focused on capturing area and volume by species. In the past decade, forest management responsibilities have broadened. As a result, inventory data requirements have expanded to include measures of non-harvest related characteristics such as forest structure, wildlife habitat, biodiversity, and forest hydrology.

The entire forest inventory production cycle, from planning to map generation, can take several years. Except for the photo interpretation component, forest inventory production is largely a digital process. *Operational level* inventories, based on both aerial photo interpretation and field-sampled measurements, provide location-specific information required for harvest planning. Forest *management level* inventories meet longer-term forest management planning objectives. Though these levels differ in detail, they both require information fundamentally based on forest inventory data.

A forest management inventory generalizes complex forest resource attributes into mapping units useful for forest management. The types of attributes attached to individual mapping units, or polygons, might include stand species composition, density, height, age, and, more recently, new attributes such as leaf area index (Waring and Running 1998).

Much of the information collected for forest inventory is generated by interpretation of aerial photographs at photo scales of 1:10,000 to 1:20,000, depending on the level of detail required. Other remote sensing sources such as airborne and satellite digital imagery have been valuable in updating forest attributes such as disturbance, habitat, and biodiversity. In providing more frequent information updates, remotely sensed data can improve the quality of forest inventory databases, thereby improving the resource management activities they support.

The quality of photointerpreted data depends on the experience of the interpreters and the use of quality assurance procedures such as interpreter calibration and field verification. Other factors can introduce inconsistencies that compromise the quality of forest inventory data. For example, there may be source data inconsistencies when aerial photography is acquired on different dates or in different weather conditions or inconsistencies in analysis when multiple contractors are used. The quality of the resulting data may vary significantly within a map area. For example, information about disturbances related to fire and insects may be inconsistent within a map area because the aerial photography from which it was interpreted was acquired in different years. Similarly, inconsistencies may occur at the edge of neighboring map sheets because data was collected in different years or was produced by different contractors.

Applications of remote sensing and GIS to forestry

The use of remote sensing by forest managers has steadily increased, promoted in large part by better integration of imagery with GIS technology and databases, as well as implementations of the technology that better suit the information needs of forest managers (Wulder and Franklin 2003). The most important forest information obtained from remotely sensed data can be broadly classified in the following categories:

- detailed forest inventory data (e.g., within-stand attributes)
- broad area monitoring of forest health and natural disturbances
- assessment of forest structure in support of sustainable forest management

Detailed forest inventory data

Forest inventory databases are based primarily on stand boundaries derived from the manual interpretation of aerial photographs. Stand boundaries are vector-based depictions of homogeneous units of forest characteristics. These stand polygons are described by a set of attributes that typically includes species composition, stand height, stand age, and crown closure. Digital remotely sensed data can be used to update the inventory database with change (e.g., harvest) information for quality control, audit, and bias detection. It can also add additional attribute information and identify biases in the forest inventory databases due to vintage, map sheet boundaries, or interpreter preferences.

The objective of managing forests sustainably for multiple timber and nontimber values has required the collection of more detailed tree and stand data, as well as additional data such as gap size and distribution. Detailed within-stand forest inventory information can be obtained from high-spatial-resolution remote sensing data such as large-scale aerial photography and airborne digital imagery. Two methods of obtaining this information are *polygon decomposition* (Wulder and Franklin 2001) and *individual tree crown recognition* (Hill and Leckie 1999).

Polygon decomposition analyzes the multiple pixels representing a forest polygon on a remotely sensed image to generate new information that is then added to the forest inventory database (see Wulder and Franklin 2001). For example, a change detection analysis of multidate Landsat Thematic Mapper satellite images can identify the areal extent and proportion of pixels where conditions have changed.

Individual tree crown recognition is based on analyzing high-spatial-resolution images from which characteristics such as crown area, stand density, and volume may be derived (Hill and Leckie 1999).

Forest health and natural disturbances

Fire, insects, and disease are among the major natural disturbances that alter forested landscapes. Timely update information ensures inventory databases are current enough to support forest management planning and monitoring objectives.

Insect disturbance

Among the insects that cause the most damage to trees are defoliators and bark beetles (Armstrong and Ives 1995). Damage assessment for these insects is typically a two-step process that entails mapping the disturbed area followed by a quantitative assessment of the damage to the trees within the mapped areas.

Aerial sketch-mapping, where human observers manually annotate maps or aerial photographs, has been the most frequently used method for mapping areas damaged by insects (Ciesla 2000). This process is costly, subjective, and spatially imprecise. However, when augmented by ground survey methods and the integrated analysis of remote sensing and GIS, substantial benefits can be realized.

Insect damage causes changes in the morphological and physiological characteristics of trees, which affects their appearance on remote sensing imagery. Insect defoliation causes loss of foliage that results in predictable color alterations. For example, residual foliage after attack by spruce budworm will turn the tree a reddish color *(figure x13_Wulder1)*. The mountain pine beetle is a bark beetle that bores through the bark and creates a network of galleries that girdle the tree and cause the foliage to become a reddish-brown color. These foliage loss and color changes often occur during a short time period-this is the optimal time for detection by remote sensing. Knowing the characteristics of a particular damage agent, the most appropriate sensor characteristics and acquisition times can be selected (see example by Hall below).

Integrated remote sensing and GIS analyses that support insect damage monitoring and mitigation include:

- detecting and mapping insect outbreak and damage areas
- characterizing patterns of disturbance relative to mapped stand attributes
- modeling and predicting outbreak patterns through risk and hazard rating systems
- providing data to GIS-based pest management decision support systems

Fire

Fire is an ecological process that governs the composition, distribution, and successional dynamics of vegetation in the landscape (Johnson 1992). Knowledge of fire disturbance is necessary to do the following:

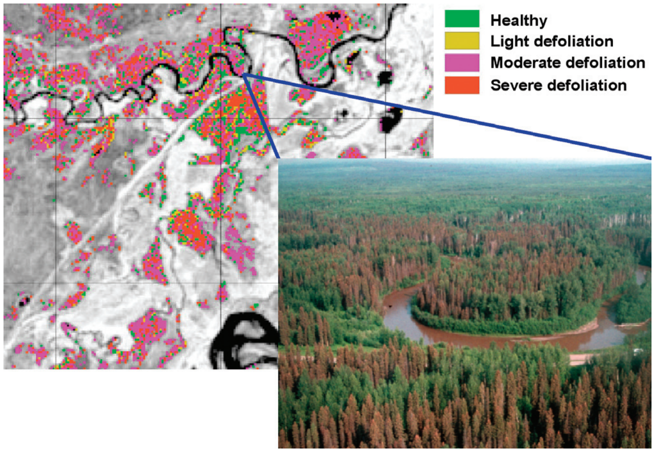

Figure x13_Wulder1 Landsat satellite classification for spruce budworm defoliation with field photograph depicting red-colored trees damaged by spruce budworm defoliation. (Location: Junction of Troy Lockhart Kledo Creek and Alaska Highway, Fort Nelson, B.C.).

Source: ©Her Majesty the Queen in the right of Canada, Natural Resources Canada.

- understand fire impacts on timber and nontimber values
- define salvage logging opportunities
- understand the effect of climate change and feedback processes on forest fire occurrence
- quantify the influence of fire on regional, national, and global carbon budgets (Kasischke and Stocks 2000).

To address this range of issues, foresters employ a multitude of field, global positioning system (GPS), and remote sensing (airborne and satellite) methods and data sources. Integrated remote sensing and GIS fire support systems are used in real-time, near real-time, and post-fire applications. For example, infrared and thermal-infrared cameras with integrated GPS/INS (inertial navigation system) technologies can observe fire hot-spots, active fires, and fire perimeters in real-time. Data on fire location and size is sent from the aircraft to field-based systems from which precise directions can be given to water-bombers and firefighting crews. Near real-time remote sensing and GIS systems are generally based on daily observations from coarse-resolution satellites such as the AVHRR (1 km pixel) and MODIS (250 m to 1 km pixel) satellites. Daily hot-spot information identifies the occurrence of fire activity over large areas and helps to target locations to collect more detailed information. Post-fire applications largely entail mapping the extent of burned areas from aerial photographs or satellite imagery and assessing fire damage to vegetation.

The Canadian Wildland Fire Information System (CWFIS) and the Fire Monitoring, Mapping, and Modeling System (Fire M3) are integrated remote-sensing- and GIS-based systems providing nationwide coverage to support fire management and global change research. NOAA AVHRR and SPOT VEGETATION remote sensing products can be used to monitor actively burning large fires in near real-time *(figure x13_Wulder 2)* to estimate burned areas and model fire behavior, biomass consumption, and carbon emissions (Fraser et al. 2000, Lee et al. 2002).

The rapid fire detection and response system implemented by the U.S. Forest Service Remote Sensing Applications Center, in cooperation with NASA and the University of Maryland, uses MODIS satellite imagery to identify hot spots throughout the United States. MODIS Active Fire Map products are compiled daily at 3:00 A.M. and 3:00 P.M. mountain time and are available over the Internet approximately two hours later. In addition to forest fire detection, the center provides image data from several different sensor sources in support of fire response and post-fire assessment activities (Quayle et al. 2002, Orlemann et al. 2002). An example of MODIS data for forest fire detection is shown in figure x7-6 in chapter 7.

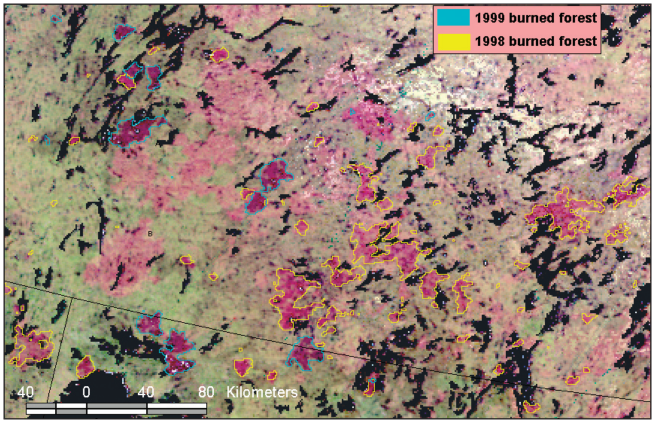

Figure x13_Wulder2 Sample of Canada-wide burn area mapping from Fire M3 depicting an area in the Northwest Territories.

Source: ©Natural Resources Canada.

Landscape ecology, habitat, and biodiversity

Sustainable forest management requires that landscape ecological characteristics related to habitat and biodiversity be included in forest inventory and certification procedures (Vogt et al. 1999). The characteristics of interest are (1) spatial patterns within the landscape, (2) specific habitat-related forest conditions, and (3) the ecological processes that link spatial pattern, habitat, and ecosystem functioning.

Land-cover information is one example of spatial patterns readily obtainable by classifying remotely sensed data. Other useful datasets include forest canopy information (e.g., crown closure or leaf area estimates), understory information (Hall et al. 2000), and measures of the distribution and boundaries of landscape units such as forest fragmentation (Debinski et al. 1999). Remote sensing can provide repeatable and consistent methods to develop these data layers such that changes over time can be monitored and habitat models can be developed and validated for individual species.

Habitat assessment is typically GIS-based; it involves selecting data layers likely to be of value in developing predictive models for the occurrence and distribution of individual species or species assemblages, as well as the identification of species useful as indicators of ecological condition (see example by Franklin below). The use of remotely sensed data together with other spatial datasets integrated within a GIS environment has greatly enhanced the habitat assessment process.

Improvements in forest management also depend on increased understanding of ecological processes within the carbon, nutrient, and hydrological cycles. Remotely sensed data provides key inputs to models of carbon flux, nutrient uptake and the influence of fertilization, and drought and water stress indicators (Lucas and Curran 1999).

Future directions of remote sensing in forestry

A key development in remote sensing has been the increased availability of high-spatial- and high-spectral-resolution remotely sensed data from a wide range of sensors and platforms including photographic and digital cameras, video capture, and airborne and spaceborne multispectral sensors. Hyperspectral imagery promises to provide improved discrimination of forest cover and physiological attributes. Radar applications are being developed that penetrate the forest canopy to reveal characteristics of the forest floor (discussed in chapter 8). New technologies such as LIDAR can provide estimates of forest biomass, height, and the vertical distribution of forest structure with unprecedented accuracy (Lim et al. 2003). The use of advanced digital analysis methods and selective use of complementary data have provided more detailed information about forest structure, function, and ecosystem processes than ever before (Culvenor 2003, Hill and Leckie 1999).

As the availability of multiresolution remotely sensed imagery and multisource data increases, so will the capability to generate timely and accurate maps of forest composition and structure. Operational capabilities continue to improve forest attribute mapping with a precision commensurate with forest management scales. This, in turn, will contribute to efforts aimed at assessing the sustainability of our forests through better forest practices and improved decision-making in forest management.

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References

Armstrong, J. A., and W. G. H. Ives, eds. 1995. Forest insect pests in Canada. Natural Resources Canada, Canadian Forest Service, Science and Sustainable Development Directorate, Ottawa, Ont.

Ciesla, W. M. 2000. Remote sensing in forest health protection. United States Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, Remote Sensing Applications Center, Salt Lake City, Utah. Report, No. 00–03.

Culvenor, D. 2003. Extracting individual tree information: A survey of techniques for high spatial resolution imagery. In *Remote Sensing of Forest Environments: Concepts and Case Studies*, ed. M. Wulder, and S. Franklin, 255–277. Dordrecht, Boston, London: Kluwer Academic Publishers.

Debinski, D. M., K. Kindscher, and M. E. Jakubauskas. 1999. A remote sensing and GIS based model of habitat and biodiversity in the Greater Yellowstone Ecosystem. *International Journal of Remote Sensing* 20: 3281–3291.

Franklin, S. E. 2001. Remote sensing for sustainable forest management. Boca Raton, Florida: CRC Press.

Fraser, R. H., Z. Li, and J. Cihlar. 2000. Hotspot and NDVI differencing synergy (HANDS): A new technique for burned area mapping over boreal forest. *Remote Sensing of Environment* 74: 362–376.

Hall, R. J., D. R. Peddle, D. L. and Klita. 2000. Mapping conifer under story within boreal mixed woods from Landsat TM satellite imagery and forest inventory information. *The Forestry Chronicle* 76: 887–902.

Hill, D. A., and Leckie, D. G., eds. 1999. International forum: Automated interpretation of high spatial resolution digital imagery for forestry. Proceedings of a workshop held February 10–12, 1998. Natural Resources Canada, Canadian Forest Service, Victoria, B.C.

Johnson, E. A. 1992. *Fire and vegetation dynamics: Studies from the North American Boreal forest.* Cambridge, United Kingdom: Cambridge University Press.

Kasischke, E. S., and B. J. Stocks, eds. 2000. *Fire, climate change, and carbon cycling in the boreal forest.* New York: Springer-Verlag.

Lee, B. S., M. E. Alexander, B. C. Hawkes, T. J. Lynham, B. J. Stocks, and P. Englefield. 2002. Information systems in support of wildland fire management decision making in Canada. *Computers and Electronics in Agriculture* 37: 185–198.

Lim, K., P. Treitz, M. Wulder, B. St-Onge, and M. Flood. 2003. LiDAR remote sensing of forest structure. *Progress in Physical Geography* 27(1): 88–106.

Lucas, N. S., and P. J. Curran. 1999. Forest ecosystem simulation models: The role of remote sensing. *Progress in Physical Geography* 23: 391–423.

Orlemann, A., M. Saurer, A. Parsons, and B. Jarvis. 2002. Rapid delivery of satellite imagery for burned area emergency response (Baer). In *Proceedings of the 9th Biennial Forest Service Remote Sensing Applications Conference*, ed. J. D. Greer. Bethesda, Md.: American Society of Photogrammetry and Remote Sensing.

Parsons, A., and A. Orlemann. 2002. Mapping post-wildfire burn severity using remote sensing and GIS. Annette Parsons, Andrew In Proceedings 2002 ESRI User Conference. ESRI. Redlands, Calif. gis.esri.com/library/userconf/proc02/pap0431/p0431.htm

Quayle, B., M. Finco, K. Lannom, R. Sohlberg, J. Descloitres, M. Carroll, J. Norton, and D. Kostyuchenko. 2002. USDA Forest Service MODIS active fire mapping and delivery. Proceedings of RS2002: Ninth Biennial Forest Service Remote Sensing Applications Conference, San Diego.

Vogt, K. A., B. C. Larson, J. C. Gordon, D. J. Vogy, and A. Fanzeres. 1999. *Forest certification: Roots, issues, challenges, benefits.* Boca Raton, Florida: CRC Press.

Waring, R., and S. Running. 1998. *Forest ecosystems: Analysis at multiple scales.* 2nd ed. Academic Press.

Wulder, M., and S. E. Franklin. 2001. Polygon decomposition with remotely sensed data: Rationale, methods, and applications. *Geomatica* 55(1):11–21.

Wulder, M., and S. Franklin, eds. 2003. *Remote sensing of forest environments: Concepts and case studies.* Dordrecht, Boston, London: Kluwer Academic Publishers.

Web sites

Canadian Wildland Fire Information System
cwfis.cfs.nrcan.gc.ca/en/index_e.php

U.S. Forest Service Remote Sensing Applications Center Rapid Response Web site
www.fs.fed.us/eng/rsac/fire_maps.html