A STRATEGY FOR MONITORING AND MODELING VEGETATED ECOSYSTEMS WITH GEOMATIC TOOLS

Richard A. Fournier[1*], Joan E. Luther[2], and Marcelle Grenier[1]

[1] Centre d'Applications et de Recherche en Télédétection (CARTEL), Department of Applied Geomatics, Université de Sherbrooke, Sherbrooke, QC, Canada, J1K 2R1

[2] Natural Resources Canada, Canadian Forest Service, Corner Brook, NL, Canada, A2H 6J3

* Corresponding author: Richard.Fournier@USherbrooke.ca

ABSTRACT

We propose a strategy for understanding, modeling and monitoring natural ecosystems with geomatic tools that (i) enables assessment of the current status of natural ecosystems, (ii) provides a favourable context for spatially-explicit implementation of prediction models, and (iii) supports complex decision-making. The strategy is designed to progress from inventory to monitoring, then towards modelling and ultimately, as a base for decision support. The strategy requires a framework for the development of mapping methods for monitoring ecosystems based on Earth observation imagery and a multi-users perspective of sustainability.

Three phases compose our strategy whereby an inventory is a base of gradual expansion towards monitoring with the inclusion of models for additional predictive capabilities. The first phase aims at ***producing a baseline map***. The second phase focuses on assessing ***past or changing status*** of the landscape through either historical mapping or change detection. The third phase includes the ***implementation of models*** using an inventory or an updated map which relates to the desired attribute or indicator. The implementation of models can serve as a predictive tool for specific questions like carbon accounting, conservation or restoration of wetlands from anthropogenic influences. Moreover, since Earth observation programs are ultimately designed to support decision-making, a global framework is proposed for implementing effective decision-making tools based on the products of spatially-explicit monitoring.

Keywords: mapping methods, decision support, ecosystem modeling, vegetated ecosystems, geographic information systems, sustainable management of natural resources

1. INTRODUCTION

Monitoring ecosystems is a priority for effective management of vegetated ecosystems. Improvements in computers, software and mapping methods combined with the increasing availability of satellite images offers many possible solutions for the implementation of earth observation programs. The gradual expansion of data availability has resulted in the need for guidelines to support monitoring programs. Many professional groups have defined guidelines for best practices (Lawrence Berkeley National Laboratory. 2000). Similarly, the role of map makers is increasing in complexity, requiring the integration of data from many different sources, scales, and timeframes. Many research studies have focused on the impact of scale (Marceau and Hay 1999), sensor type (Ozesmi and Bauer 2002) or other specific aspects of monitoring (Groom et al. 2006). However, few studies step back from specific questions to assess the general requirements for effective monitoring of vegetated ecosystems.

In a conceptual form, ecosystem monitoring can be defined as the ability to map present, past and future states of the Earth surface. Therefore, ecosystem monitoring includes three distinct but interrelated timeframes and activities; (1) the present: establishing a common map baseline, (2) the past: producing a spatial history whereby changes are mapped according to specific time intervals or historical milestones, and (3) the future: developing predictive capabilities through spatial models driven by landscape-level variables. Typically, the three activities need to be completed chronologically from the first to the third. Each activity builds on one another although the methods for their completion may differ greatly.

Even if a good monitoring program is implemented, integration of several user-perspectives remains a difficult task to achieve. Sustainable development has acknowledged the complexity of multiple user-perspectives for the management of natural resources. It is widely accepted that sustainable development has three important components to consider: environment, social and economical values (Bruntland report, Gough et al. In press). Consequently, a monitoring program should be integrated with another set of formal procedures that include multiple user-perspectives to become an effective tool for decision-making (Bock et al. 2005).

We therefore propose two major objectives for this paper. The first objective proposes a framework for ecosystem monitoring that provides guidelines for the implementation of monitoring programs. It can also be seen as preliminary work towards best practices for monitoring vegetated ecosystems. The second objective is to propose a framework decision-making that incorporates monitoring products.

2. A FRAMEWORK FOR ECOSYSTEM MONITORING

Three phases form a framework containing the main steps common to most mapping projects (Figure 1): (A) establishing the ***project's basis***, (B) an iterative ***development loop*** on selected test areas, and (C) an ***operational loop*** on an extended area. These three phases can also be viewed as the preparation, development, and implementation of a mapping project.

Having an explicit understanding of the project's basis is essential before starting method development. This involves initially stating the context in which the mapping project exists leading to explicit general and specific objectives for the project. However obvious as this step may sound, it is far from easy to reach a compromise when the project involves many partners. Central to setting objectives are a common set of definitions usually associated with the surface classes that are mapped. Surprisingly, major discrepancies can exist between definitions from one jurisdiction to another or from one field to another. It is the case for classes like forest and wetland for which various definitions make map comparison erroneous if the definitions used are not validated. A common set of definitions and objectives prepares the project well but the criteria for success of the project remains to be defined. Establishing quantitative and potentially qualitative criteria that will determine if the map is satisfactory must be considered in the project's objectives. Once the project basis is agreed upon, the development loop can be initiated.

The iterative development loop has eight steps to define the best options for the development of a method adapted to the projects' objective. The ***first step*** addresses the essential working elements at the base of the mapping framework. For instance, it is important to define the technical considerations according to the objectives of the study (Fournier et al 2007). Then, other choices are required on the output format (raster or vector), and their resolution/scale. The minimum mapping unit is also a critical element to define. In cases where remote sensing images are used, one must choose suitable imagery for the application. For example, there are cases where a combination of optical and radar satellite images are best suited to map wetlands (Fournier et al. 2007). Another element at the base of a successful mapping method is the selection of suitable test areas. Test areas need to be representative of the overall spatial extent for which the mapping method will be applied. The ***second step*** is the selection of a realistic evaluation or validation strategy which will impact on the choice of the data input. Careful care must be given to the evaluation strategy to make sure it supports, as much as possible, quantitative criteria for success. The ***third step*** involves the selection of the most suited input data for the mapping method and its evaluation. Data selection is often a compromise from the range of available datasets. The development of a method favoring multi-layer inputs also imposes compatibility between spatial layers which can be available in raster, vector or in point format. In the ***fourth step*** the mapping method and its evaluation are implemented through the most suited software. Image processing software and GIS are most often used to implement an efficient workflow. In the ***fifth step***, the resulting maps are produced along with statistics required to analyze the outputs. This analysis is applied in the ***sixth step*** where the results from the method are confronted with the evaluation dataset. Success criteria are tested in the ***seventh step***. When at least one criterion is not met, the work is pursued in the iterative loop. However, as an ***eight step***, changes or improvements are assessed through one of the steps before looping again into the development loop. Passes through the iteration loop will be necessary until all criteria for success have been met or if the criteria are changed to meet realistic limitations.

When the criteria for success are met, the work moves to the implementation loop, whereby it is possible to expand method implementation to extended areas. Similar to the development loop, this phase can generate significant changes in the mapping methods. However, these changes can be reduced to a minimum if method development was made on test areas representative of the extended area. Interestingly, numerous mapping methods that are published often deal with a limited spatial extent and their expansion to other areas or on much larger area, requires many adjustments. For those mapping methods planned to be applied over large areas, it is important to test applicability of the selected methods to an extensive set of representative areas before a full implementation. Large scale or multi-scale implementation can also lead to important limitations if the data flow is important (Hyde et al. 2006). For instance, mapping Canada with Landsat scenes requires processing over 700 images. In addition, the work flow must take into consideration areas masked by clouds, bad atmospheric conditions, image acquisition outside of the selected temporal window, and other potential problems that need to be overcome. Therefore, addressing the limitations for operational implementation is far from trivial and requires a separate and significant effort.

The framework in Fig. 1 was proposed for the development of a mapping method but it can also be adapted to the two other components of a complete monitoring program, namely a spatial historic of changes and development of a predicting model. It is however understood that some steps need to be adapted if another component is treated. For instance, the mapping framework for producing a series of historical map of change includes a common spatial resolution for all maps, and also a minimum and maximum interval of time between images. These considerations alter greatly the choice and preparation of input data in step 4. Similarly, implementation of a model needs a complete reassessment of the project's basis as it is likely to differ greatly from those of the mapping project. Implementation of these three components leads to a full monitoring program with the ability to map current status, changes with time and predicted or planned future status.

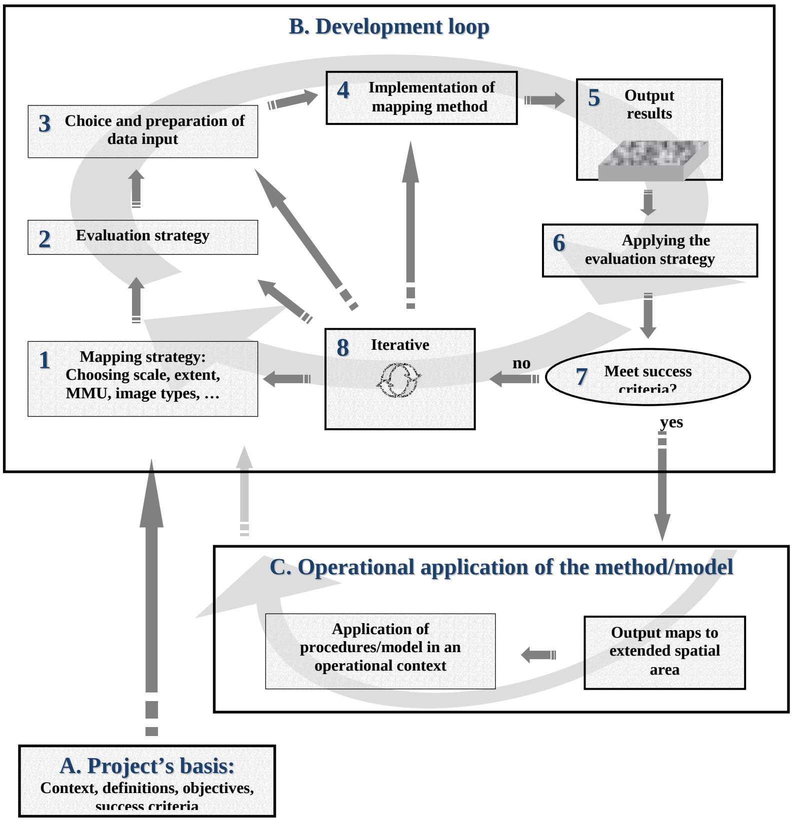

Figure 1. Flow diagram of a framework for mapping and monitoring of vegetated ecosystems.

Several monitoring programs can serve as practical cases to assess the relevance of the framework. Known examples include the GAP program in the U.S.A. (Jennings 2000) or CORINE in Europe (Bronge and Näslund-Landenmark 2002). The ability to implement monitoring programs is facilitated by the availability of extensive coverage with satellite images. These images are useful to produce a history of spatial change on the landscape. Continuity in the spatial coverage is also an important consideration to make sure present and future conditions can be mapped. Extensive image collection programs like the Global Land Cover using Landsat images (Latifovic and Pouliot 2005) and the MODIS program (Hodges et al. 2001), contribute to global and regional monitoring. New sensors are constantly improving the monitoring abilities by augmenting the range of spatial resolutions from the meter to the km (Groom et al. 2006). Consequently, these datasets also raise the importance of selecting the relevant scale for a monitoring program.

Two Canadian monitoring programs can also be used to illustrate the framework. The first example, the Earth Observation for Sustainable Development (EOSD; Wood et al. 2002) combined with the Carbon Budget Model of the Canadian Forest Sector (CFS-CBM; Kurz and Apps, 2006) of the Canadian government include all components of the framework for monitoring Canadian forests. The EOSD mapping program concentrated on three related activities: (i) mapping landcover to provide a national coverage on forest/vegetation type and stand density (Wulder et al. 2003), (ii) monitoring changes in the landscape with the reference year 1990 to be consistent with the Kyoto protocol, and (iii) producing a national map of aboveground tree biomass (http://eosd.cfs.nrcan.gc.ca/biomass/). EOSD therefore included components representing current status and change history. Moreover, vegetation biomass is a critical input of the modeling component, CFS-CBM, which is a tool for carbon budget accounting in the context of the Kyoto protocol. EOSD landcover products are available on-line for those wishing to address other issues through a predictive model.

The second example is the Canadian Wetland Inventory (CWI) which uses a uniform approach to produce a reference map of wetlands for national reporting (Fournier et al. 2007). Wetlands are complex entities to map as they require fine resolution to resolve complex spatial patterns. They also tend to vary greatly with time (within the year and yearly) and across the varied ecological regions of Canada. The CWI deals with compromises required for national monitoring program, namely the use of multi-sensors (optical – radar), selection of the most suitable time frames, and a minimum mapping unit of 1 ha. The CWI is the first step of a monitoring program that would include the other components of spatial history and modeling. A similar monitoring program, the National Wetland Inventory of the U.S.A. (FWS 2004; Dahl and Watmough 2007) included a base inventory at a reference time followed by map production at regular intervals from the reference date. In both of these programs, the proposed framework can help to find the best compromise for the implementation of a monitoring program adapted to the project's objectives.

3. FROM MONITORING TO DECISION-MAKING

Monitoring provides important spatially-explicit products but how can they be used for decision-making? Implementation of a monitoring program, in particular the reference maps, the spatial history, and the tools to map spatial changes, provide the status of the landcover. The products are spatially-explicit documents from which decisions can be taken, however, another framework is required to ensure that all important user-perspectives are taken into consideration for decision-making.

Models are practical tools to predict the condition of an ecosystem, but they can also integrate several user-perspectives. We suggest a decision-making framework that supports the requirements of ecosystem-based management wherein mapping methods using satellite remote sensing are used as inputs in the application of ecosystem models. This framework of ecosystem-based management is under development by the Canadian Forest Service and its partners (CFS-EBM) and is currently applied to forest management (Luther et al. 2007). CFS-EBM represents a common approach to holistic management as it enables the development and evaluation of forest management plans with respect to multiple forest values in an ecosystem-based approach. Management scenarios can be evaluated through collaborative decision-making by land managers and stakeholders seeking trade-offs among social, economic, and ecological values. CFS-EBM identifies four interrelated groups of activities needed for a useful framework: (i) predicting future landscapes as a result of various ***agents of change*** (i.e., natural succession, natural disturbances, climate change, and ecosystem management), (ii) assessing impacts of agents of change on ***ecosystem values*** with models of economic, social, and ecological indicators, (iii) conducting ***trade-off analyses*** of multiple values on a common land base, and (iv) recommending management ***adaptations***. Implementation of the monitoring framework is a base for the production of important map inputs. However, selection of the appropriate ecosystem models for monitoring and forecasting sustainability indicators over time is key for this adaptive management process.

Integration of information and knowledge is essential to advance ecosystem modeling and further support decision-making. However decision-making goes one step beyond the model results by introducing indicators linked to multiple values that are considered important to the decision. CFS-EBM, proposes a structure of increasing complexity for remote sensing applications development that involves three general areas: (i) mapping attributes, (ii) parameterizing existing ecosystem models, and (iii) developing new ecosystem models adapted to decision-making (Fig. 2). The models can represent agents of change required simulating future forest landscapes or values representing indicators of sustainable forest management that are agreed upon among stakeholders.

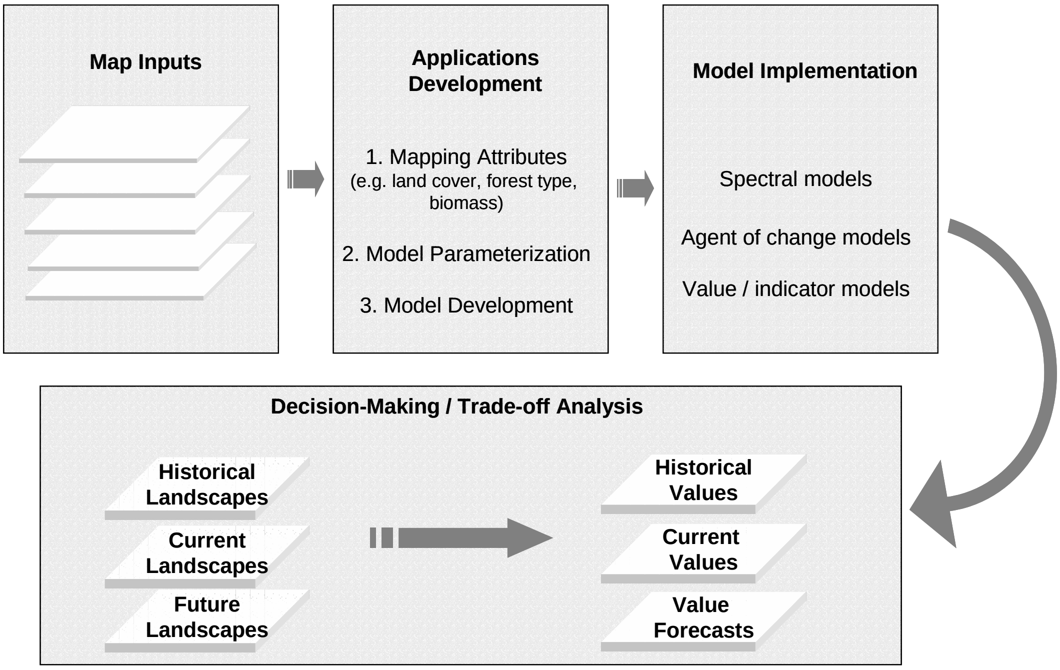

Figure 2. Geomatics applications development supporting decision-making (adapted from Luther et al., 2007).

Development of models specifically adapted to environmental assessment, agents of change and indicators of values is therefore central to the implementation of a decision-making framework. These models formalize metrics of values, that are important to the stakeholders involved in the decision-making process. Testing a complete scenario requires adressing an extensive set of values associated with priorities of the stakeholders for the area of interest. These questions should be as mutually exclusive as possible to avoid overemphasizing one aspect over another. A chart can be produced on the relative values of these indicators according to different scenarios (Fig. 3). Analysis of such a chart combined with the spatial-explicit map outputs produced under a series of potential scenarios provides important information to support compromises among the various user-perspectives**.**

4. DISCUSSION AND CONCLUSIONS

The number of tools and approaches available to support decisions on the management of vegetated ecosystems is increasing constantly. This can create a feeling of confusion as the interpretation of information may not be consistent from one approach to another, or from one stakeholder to another. If no effort for integration is applied, the resulting interpretation from one perspective at a time may exacerbate the divergence of conclusions regarding management options. Moreover, management questions of ecosystems are extremely varied as they deal with conservation of habitat or for ecosystem biodiversity (Leyequien et al. 2007), management of invading insects (Royer et al. submitted), overall forest management (Mowrer 1997; Lachowski et al. 2000), to name a few. Monitoring is a first component of a full process of decision-making providing reliable spatial products. Such products are convenient for the integration of information and knowledge in a functional framework for decision-making. Placing these products in the context of the various user-perspectives from stakeholders is an important second component. Although each component varies according to the objectives, the main steps required to accomplish a full exercise of monitoring and decision-making can be formalized. We suggest that formalization of this process could be accomplished in a guide of best practices for decision-making for vegetated ecosystems. Preparation of this guide would be the next logical step to increase the relevance of maps for decision-making supporting ecosystem-based management.

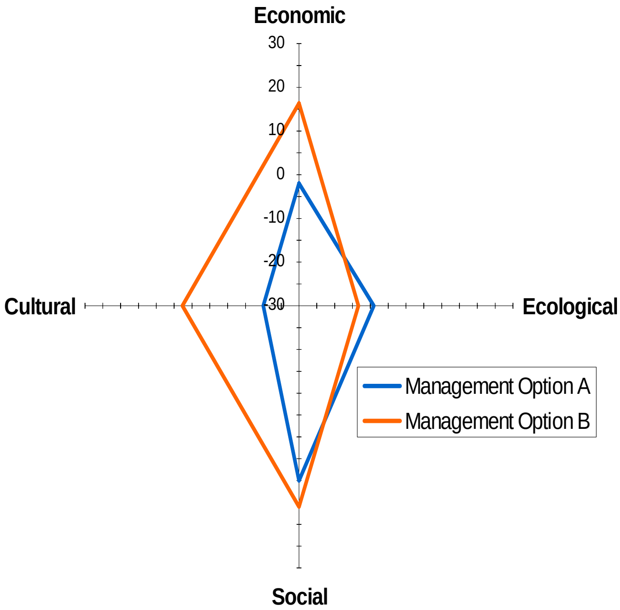

Figure 3. Conceptual diagram indicating trade-offs among social, economic and ecological values according to management options (adapted from Luther et al. 2007).

5. REFERENCES

Bock, M., Rossner, G., Wssen, M., Remm, K., Langanke T., Lang, S., Klug H., Blaschke, T., and Vrscaj, B. 2005. Spatial indicator for nature conservation from European to scale. *Ecological Indicators*, 5: 322-338.

Bronge, L.B., and Näslund-Landenmark, B. 2002. Wetland classification for Swedish CORINE land cover adopting a semi-automatic interactive approach. *Canadian journal of remote sensing*, 28(2): 139-155.

Dahl, T.E. and Watmough, M.D. 2007 Current approaches to wetland monitoring in prairie Canada and the continental United Sates of America. *Canadian Journal of Remote Sensing*, 33: S17-S27.

Fournier, R.A., Grenier, M., Lavoie, A. and Hélie, R. 2007 Towards a strategy to implement the Canadian Wetland Inventory using satellite remote sensing. *Canadian Journal of Remote Sensing*, 33: S1-S16.

FWS, 2004. Technical procedures for wetlands status and trends. U.S. Fish and Wildlife Service, Branch of Habitat Assessment. December 2004. 62 p.

Gough, A.D., Innes, J.L., and Allen, S.D. In press. Development of common indicators of sustainable forest management. Ecological Indicators.

Groom, G., Mucher, C., Ihse, M., and Wrbka, T. 2006. Remote sensing in landscape ecology: experiences and perspectives in a European context. Landscape Ecology 21(3): 391–408.

Hodges, J.C.F., Friedl, M.A., and Strahler, A.H. 2001. The MODIS global land cover product: New data sets for global land surface parameterization. In *Proceedings of the Global Change Open Science Conference*, Amsterdam.

Hyde, P., Dubayah, R., Walker, W., Blair, J.B., Hofton, M., and Hunsaker, C. 2006. Mapping forest structure for wildlife habitat analysis using multi-sensor (LiDAR, SAR/InSAR,ETM+, Quickbird) synergy, *Remote Sensing of the Environment*, 102: 63-73.

Jennings, M.D. 2000. Gap analysis: concepts, methods, and recent results. *Landscape ecology*, 15: 5-20.

Kurz W.A. and M.J. Apps 2006 Developing Canada's national forest carbon monitoring, accounting and reporting system to meet the requirements of the Kyoto protocol. *Mitigation and Adaptation Strategies for Global Change*, 11: 33–43

Lachowski, H., Maus, P., and Roller, N. 2000. From pixels to decisions: digital remote sensing technologies for public land managers. *Journal of Forestry*, 98(6): 13–15.

Latifovic, R., and Pouliot, D. 2005. Multitemporal land cover mapping for Canada: methodology and products. *Canadian journal of remote sensing*, 31(5): 347-363.

Lawrence Berkeley National Laboratory. 2000. *Best practices guide: Monitoring, evaluation, reporting, verification, and certification of climate change mitigation projects*. Lawrence Berkeley National Laboratory, Berkeley, California, 55 p. (http://www.iie.org/programs/energy/)

Leyequien, E., Verrelst, J., Slot, M., Schaepman-Strub, G., Hetkonig, I.M.A., and Skidmore, A. 2007. Capturing the fugitive: applying remote sensing to terrestrial animal distribution and diversity. *International Journal of Applied Earth Observation and Geoinformation*, 9: 1–20.

Luther, J. E., Fournier, R. A., Hearn, B., Piercey, D., Royer, L., and Strickland, G. 2007. Remote sensing within an ecosystem-based management framework for sustainable forests. Proceedings FORESTSAT 2007: Forests and Remote Sensing: Methods and Operational Tools, 31 Nov 5 – 7, 2007, Montpellier, France.

Marceau, D.J. and Hay, G.J. 1999. Remote sensing contributions to the scale issue. *Canadian Journal of Remote Sensing*, 25(4): 357-366.

Mowrer, H.T. 1997. *Decision support systems for ecosystem management: an evaluation of existing systems*, Gen. Tech. Rep. RM-GTR-296. Fort Collins, CO. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 154 p.

Ozesmi, S.L., and Bauer, M.E. 2002. Satellite remote sensing of wetlands. *Wetlands ecology and management*, 10: 381-402.

Royer, L., Luther, J.E., Piercey, D., and Crummey, H. Submitted. Improved detection of incipient insect outbreaks using a purposely biased sampling method within the zone of risk predicted by an initial susceptibility model, *Canadian Journal of Forest Research*.

Wood, J.E., Gillis, M., Goodenough, D., Hall, R., Leckie, D., Luther, J. E., and Wulder M. 2002. Earth Observation for Sustainable Development of Forests: Project Overview. Page not available in IGARSS 2002, Proceedings: IEEE International Geoscience and Remote Sensing Symposium and the 24th Canadian Symposium on Remote Sensing (CD-ROM). June 24-28, 2002, Toronto, ON. IEEE, Piscataway, New Jersey.

Wulder, M. A., Dechka, J. A., Gillis, M. A., Luther, J. E., Hall, R. J., Beaudoin, A., and Franklin, S. E. 2003. Operational mapping of the land cover of the forested area of Canada with Landsat data: EOSD land cover program. *The Forestry Chronicle*, 79(6): 1075–1083.