MAPPING AND MODELLING FOREST CHANGE IN A BOREAL LANDSCAPE

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ABSTRACT

Timber harvesting is one of the major factors altering the species composition, age class distribution, and carbon fluxes over much of forested North America. Timber harvesting in Minnesota, the nation's largest paper producer, is expected to increase by approximately 25% in the next several decades to supply increased fiber demand for paper mill expansions. Similar expansions are also expected in adjacent northwestern Ontario. In contrast to these managed forested lands, the 2.0 million ha of the Boundary Waters Canoe Area (BWCA) and Voyageurs National Park (VNP) in Minnesota and adjacent Quetico Provincial Park in Ontario is the largest contiguous, forested wilderness area in North America. This wilderness landscape has its own disturbance regime generated mainly by large fires (Heinselman 1973) which is distinctly different from the anthropogenic disturbance regime imposed by timber harvesting immediately outside the BWCA-VNP-Quetico wilderness (Hall et al. 1991). Much of the forest is old-growth conifer, but there are large patches of early-mid successional forest as well.

There is no other place in the 48 contiguous states where there are large, matched, forested landscapes with contrasting natural and anthropogenic disturbance regimes. Therefore, Minnesota and adjacent northwestern Ontario is a natural "landscape laboratory" for determining the impact of extensive timber harvesting on landscape structure in comparison with an equivalent large landscape of uncut forest subject only to a natural disturbance regime.

We are using multitemporal data from Landsat Thematic Mapper (TM) 5 or 7 to classify forest cover to near species level (Wolter et al. 1995), then map the changes in the forest mosaic through time on a biannual basis to determine successional pathways under natural and managed disturbance regimes. Markov transition matrices are being developed from these data and analyzed using Markov theory (Pastor et al. 1993) to assess current trends in forest cover and steady state land cover distributions in order to help shape management policy at federal, state, and local levels.

Key Words
Research Fields: Forest Ecology, Forest Land Use Change
Geographic Area/Biomes: Boreal Forests
Remote Sensing: Landsat TM
Methods: Multitemporal imaging, Markov chains

QUESTIONS, GOALS, APPROACHES

Our activities fit several desired NASA goals as outlined in pp. 1-4 of NRA 99-OES-06 (July 29, 1999): (i) build a quantitative assessment of landscape and land use change using historical archives of satellite data; (ii) develop the scientific understanding and models necessary to simulate processes taking place and evaluate the consequences of observed and predicted changes; (iii) develop techniques, algorithms, models, and data sets needed for eventual operational monitoring of forest cover as part of the Global Observation of Forest Cover Project; (iv) address human induced and natural disturbance, incorporate the use of remotely sensed data, and provide an improved understanding of measurement techniques and requirements needed to improve current or future satellite based monitoring of disturbance. Our work is entirely under the GOFC theme.

We are documenting the *changes in land cover* by developing change matrices from overlays of georeferenced scenes taken at different dates. By comparing changes inside the Quetico-Superior Wilderness with those outside in manged forests, we will be able to *determine the extent of natural vs. anthropogenic causes of these changes*. Finally, by implementing the change matrices as Markov chains, we are able to *project the consequences of these rates of change forward in time*, both to the proximate future (next several decades) to steady state at some later time.

The study region encompasses approximately 137,000 km^2 or six Landsat Thematic Mapper (TM) footprints in northeast Minnesota and southern Ontario (Fig. 1). The Boundary Waters Canoe Area, Voyageurs National Park, Quetico Provincial Park, Superior National Forest, and the Chippewa National Forest are all located within the boundary of this study. The remaining area is largely managed state, county, or industrial forest. The ecology of this region, including disturbance regimes, has been previously described by Heinselmann (1973), Ohmann and Grigal (1979), Swain (1980), Baker (1989), Johnston and Naiman (1990a,b), Frelich and Reich (1995), Pastor and Mladenoff (1992), Pastor et al. (1993), and Mladenoff and Pastor (1993), among many others. Six TM data frames will be used corresponding to Worldwide Reference System (WRS) coordinates path 26-28 row 26-27; collectively centered at approximately $48^{o}26'N$, $92^{o}\ 20'W$

Although we are not formally involved in social science research, we have been and will continue to be in contact with policy makers within the State of Minnesota regarding the nature, causes, and consequences of these changes. These policy makers include resource managers of the Minnesota Dept. of Natural Resources and the U.S. Forest Service.

Our goals for this time period were to: (1) obtain scenes for northeastern Minnesota and adjacent Ontario for 1990, 1995, and 2000; (2) interpret and classify the scenes using multitemporal image analysis; (3) develop user and producer error matrices based on forest inventory analysis plot data; (4) clarify some mathematical problems in the use of Markov chains to analyze and project trends in land cover; (4) make preliminary projections of changes in land cover using Markov chains parameterized from the change matrices.

SIGNIFICANT NEW FINDINGS AND PROGRESS

Image classification and analysis

Classification of the Landsat TM data has been progressing well. Table 1 shows a breakdown of the TM footprints we are classifying, which scenes have been completed, and a tentative work schedule for the beginning of work for the remaining imagery. Apparently, allocation of funds into the LCLUC data account has been delayed somewhat, which has delayed the delivery of the data we requested for the northern tier of data from row 26.

Table 1. Landsat Image Processing Schedule 2002-2003

	Path 28		***Path 27***		***Path 26***	
Row 26	1984	start 8/02	1984	start 9/02	1984	start 10/02
	1990	start 11/02	1990	start 12/02	1990	start 1/03
	1995	start 2/03	1995	start 3/03	1995	start 4/03
	2000	start 5/03	2000	start 6/03	2000	start 7/03
Row 27	1984	done	1984	done	1984	done
	1990	done	1990	done	1990	done
	1995	done	1995	done	1995	done
	2000	start 5/02	2000	start 6/02	2000	start 7/02

Recently, we have been spending time correcting misregistration errors among the dates of imagery in row 27. It is essential that these errors be dealt with early to insure the integrity of the change detection and ultimately the transition probabilities. Once this is complete we will be able to begin the 2000 layer of the change detection in row 27.

Markov models

One of the mathematical problems we discovered involved adjusting the transition probability (Markov) matrices to account for user and producer error, as originally proposed by Hall et al. (1991). The elements of the user and producer error matrix are thought to be conditional probabilities of correspondence between the classified scene and that actually observed on the ground during forest inventory surveys. However, we have found that this is strictly true only if the ground survey was completed in the same period and the satellite image was taken. If the ground survey was completed over an extended period of time, then the conditional probabilities in the error matrix represent the sum of a conditional misclassification probability (true error) and a transition that took place on the ground between the time when the satellite image was acquired and the survey team visited the site. Thus, the conditional probabilities in the error matrix overestimate the actual misclassification error. If the error matrix is then used to adjust the transition probabilities by the method specified by Hall et al. (1991), then the transitions for a given class sum to more than 1.0 (we have a mathematical proof of this).

Therefore, without knowing the actual transitions on the ground (since they occur during the time of the survey itself) we cannot adjust the transition matrix to account for conditional misclassification error. Our best approach is then to minimize the probability of misclassification by decreasing user and producer error. We have done this by aggregating cover classes into six high-level classes: closed canopy forests, regeneration, water, development, wetlands, and upland grass (include agriculture). The user and producer errors for these are < 10%. Since this includes both true misclassification error and unknown transitions, the misclassification errors are therefore very small. We have completed a Markov analysis of this high level classification with adjustment of the transition matrices by the method of Hall et al. (1991). This analysis constitutes the Ms. Thesis (Mathematics) of Ms. Bingbing Li, who successfully defended her thesis in August 2001. Ms. Li is now a Ph.D student in Statistics at the University of Minnesota, Minneapolis.

Ms. Li has shown that, should transition probabilities for the period 1990-1995 determined from the image analyses (above) remain constant, then mature forest cover will decline from the current 60% of the landscape to less than 40% in the next 60 years because of conversion to regenerating aspen after clearcutting. Regenerating aspen will climb correspondingly from slightly less than 10% of the landscape to greater than 33%. This is an enormously rapid rate of change, probably far greater than what is expected with climate warming alone.

One assumption of these transition probabilities is that they apply to all ages of forest within a given cover type. However, the probability of transition to another covertype is also a function of age as well as covertype. For example, 30 year old aspen has a lower probability of being cut and converted to regeneration or of succeeding to late stage conifers than a 60 year old aspen stand. Yet both 30 and 60 year old stands will register very similarly on a Landsat image. We are beginning to explore how to incorporate age classes into the Markov transition matrix. We make the probability of a given stand being converted to regeneration a logistic function of age, with maximum probability occurring at the rotation age and declining thereafter. The transition probabilities for succeeding to the next age class or successional stage are then constrained so that the sum of all these time-dependent probabilities equals 1.

We now have a flexible model to examine the effects of changes in rotation age and harvest intensity on landscape dynamics. The resulting transition probability matrix is a hybrid between Markov and Leslie (age-dependendent; Leslie 1945) matrices. As far as we are aware, this is a new mathematical object. We are investigating the mathematical properties of this new matrix in comparison with the first order Markov chains previously investigated by Ms. Li to determine if relaxing the assumption of homogeneity of transition probability within a covertype alters the long-term predictions of the models. We are parameterizing the age distribution with data from the Minnesota Dept. of Natural Resources.

New Products

The scenes for which we have completed classification and ground truthing are indicated above in Table 1.

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CONCLUSIONS

Based on wall-to-wall coverage and classification of rates of forest cover change in northern Minnesota's managed forests, we anticipate a significant decline in mature forest cover and a corresponding increase in regenerating aspen in clearcuts in the next 60 decades unless forest policies change to alter these transition probabilities.

PUBLICATIONS AND PRESENTATIONS

Preliminary results of this work have been presented at:

3rd North American Forest Ecology Workshop
Issues of Scale: From Theory to Practice
June 24-27, 2001
Duluth, Minnesota

86th Annual Meeting of the Ecological Society of America
August 5-10, 2001
Madison, Wisconsin

Also, a manuscript of our preliminary results is *in press* in Landscape Ecology:

Wolter, P.T. and M.A. White, 2001. Recent forest cover type transitions and structural changes in northeast Minnesota, Landscape Ecology, *in press*.