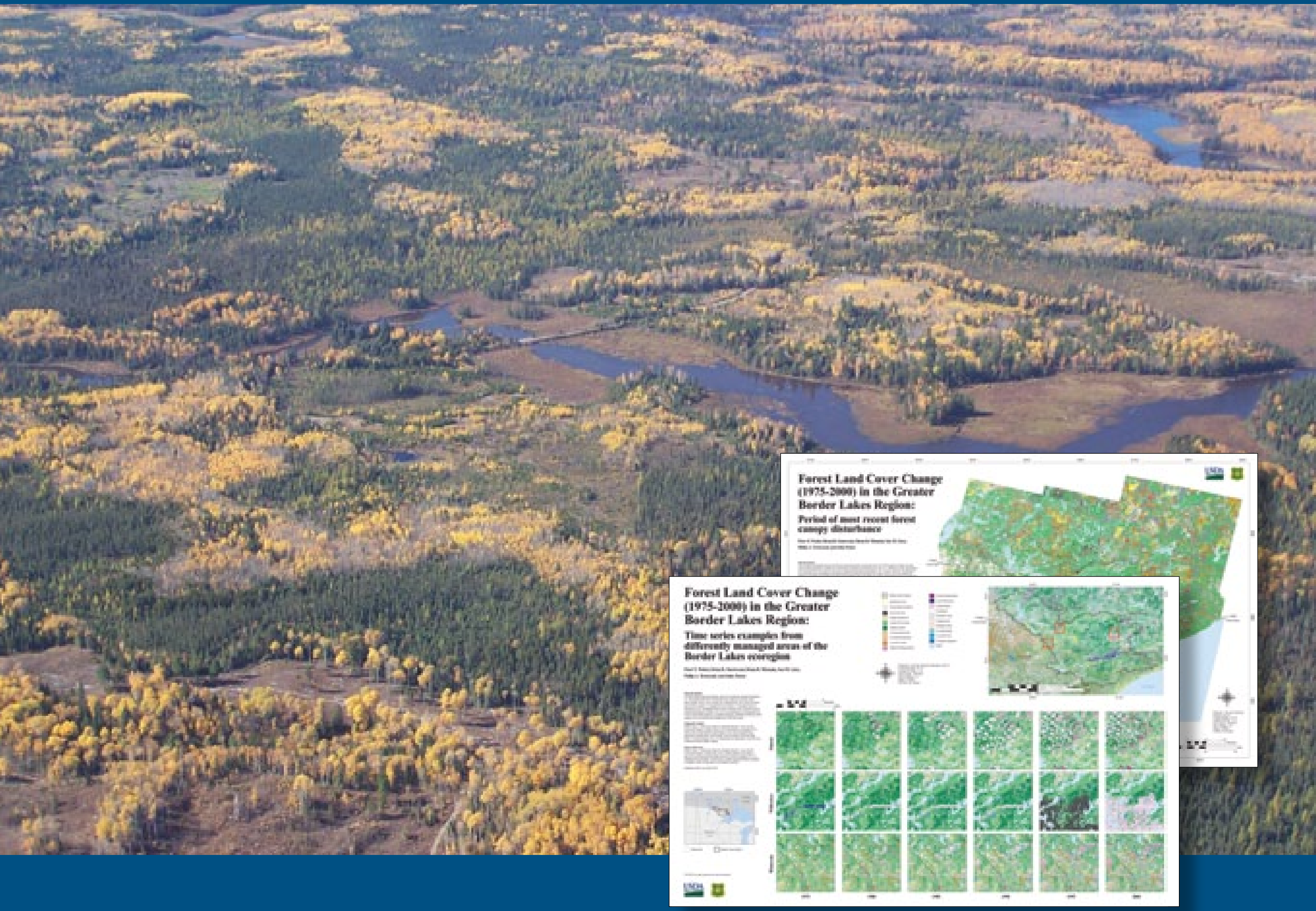
Forest Land Cover Change (1975-2000) in the Greater Border Lakes Region

Research Map NRS-3



United States Department of Agriculture

Forest Service

Abstract

This document and accompanying maps describe land cover classifications and change detection for a 13.8 million ha landscape straddling the border between Minnesota, and Ontario, Canada (greater Border Lakes Region). Land cover classifications focus on discerning Anderson Level II forest and nonforest cover to track spatiotemporal changes in forest cover. Multi-temporal Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Multi-Spectral Scanner (MSS) data from 1972 to 2000 were used to classify forest cover types and disturbances at 5-year intervals. A composite dataset depicting the period of forest disturbance was produced using the 1975-2000 sequence of land cover data. These land cover change data were produced to facilitate analysis of forest disturbance patterns, to support landscape simulation modeling, and to support cross-ownership land management within the region. A double-sided fold-out map shows A) forest land cover change across differently managed forests, and B) classified period of forest canopy disturbance for the entire study area. Digital versions of the map are available online, as are the datasets and code used to produce them.

Cover photograph: Landscape mosaic characteristic of the greater Border Lakes Region. Aerial image by Peter Wolter, Iowa State University, and Clayton Kingdon, University of Wisconsin-Madison; used with permission.

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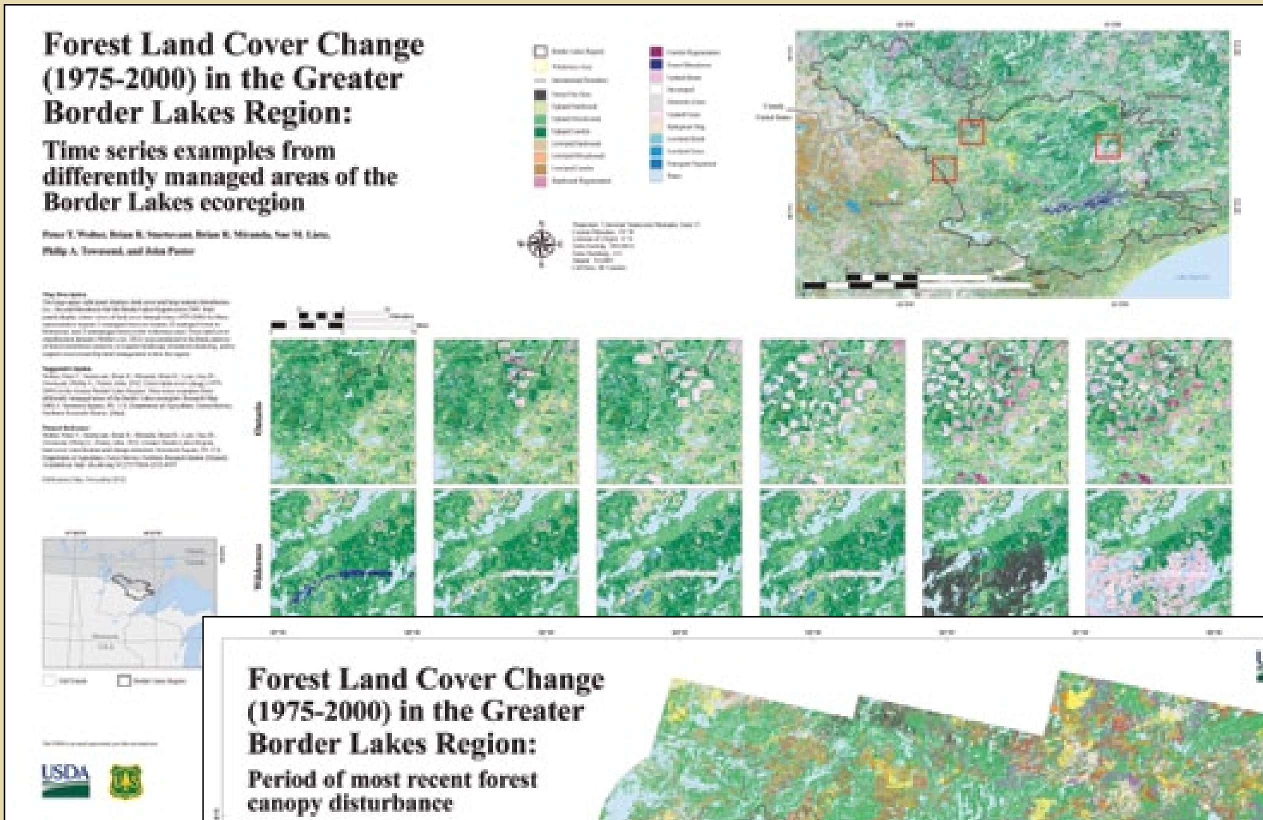

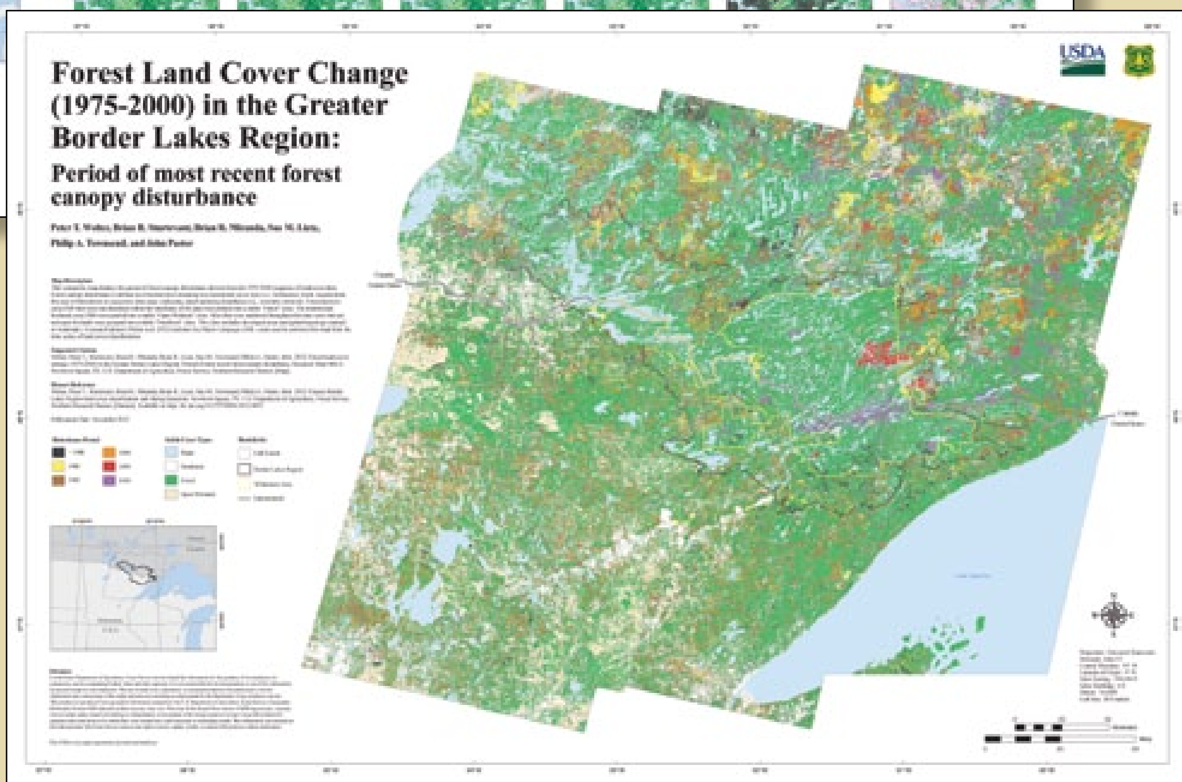

DESCRIPTION OF MAPS

The two-sided map is available in hardcopy format (22 inches x 36 inches) included with this publication. The map is also available in a digital printable PDF format available for download at http://nrs.fs.fed.us/pubs/42187. Spatial datasets used to construct the maps at the original 28.5 m resolution are also available online (Wolter et al. 2012).

About the Dataset

The land cover classifications for the Greater Border Lakes Region described herein for each 5-year interval from 1975 through 2000 are available online as a U.S. Forest Service Research dataset (Wolter et al. 2012). The spatial extent of the dataset is defined by the combined extents of the six imagery scenes used for the classifications. Arc Macro Language (AML) code used to map forest disturbances by date (as shown here) from the land-cover inputs is also included. The dataset will be updated with more recent classifications (i.e., 2005, 2010, etc.) as time and resources permit.

INTRODUCTION

The greater Border Lakes Region comprises about 13.8 million ha straddling the international boundary between Minnesota and Ontario, Canada (Fig. 1). The region is an expansion of the approximately 2.1 million ha Border Lakes ecoregion defined by Bauer et al. (2009) and Shinneman et al. (2010). The greater Border Lakes Region includes the combined wilderness areas of the Boundary Waters Canoe Area Wilderness (BWCAW), Quetico Provincial Park, and Voyageurs National Park, as well as managed forests across multiple land ownerships in Minnesota and managed crown lands of Ontario. The region is an ideal context for evaluating forest disturbance because of the disparate forest management in the managed forests on both sides of the border and within the wilderness areas. Historical forest disturbance has been studied and mapped within portions of this region (Heinselman 1996), and different land management agencies and private industry maintain harvest and fire records, but recent disturbance history has not been mapped consistently across this region.

Land cover change studies are becoming increasingly prevalent in the scientific literature—particularly given the recent accessibility of Landsat-based imagery (Cohen et al. 2010). While production of land cover classifications from Landsat imagery has become somewhat routine, specialized methods are still required to produce land cover maps that are both consistent across Landsat scenes and reliable in terms of the accuracy of the classification. Research has shown the fundamental importance of land use and disturbance history as it impacts future vegetation states and landscape recovery patterns (Schoennagel et al. 2008, Spies et al. 1994)—suggesting that knowledge of past land cover and disturbance patterns can help guide land management within the current landscape. Unfortunately many peer-reviewed land cover classifications remain within the research institutions from which they were created with limited capacity to distribute the mapped information essential for effective land management. Such mapped information—both past and present—can supplement larger-scale mapping efforts (e.g., National Land Cover Database, see Homer et al. 2004) and ownership-specific resource inventories to support both subsequent research efforts and the coordination of management activities across land ownerships (Lytle et al. 2006).

This document describes land cover classification and change detection methods used to produce a series of Anderson Level II (Anderson et al. 1976) land cover classifications as spatial datasets (Wolter et al. 2012) at 5-year intervals between 1975 and 2000 across the greater Border Lakes Region. The spatial extent of the datasets is the combined extents of the six imagery scenes used for the classifications. Land cover changes across the 25-year time series were used to produce a continuous, consistent mapping of recent (1975-2000) forest disturbance across the entire region. Land cover changes are focused primarily on stand-replacing forest disturbances. Maps included in this publication provide examples of land cover changes from three differently managed areas (Minnesota managed, Ontario managed, and wilderness), and the composite forest "period of disturbance" map for the full extent of the dataset. Digital versions of land cover from each of the six dates, and Arc Macro Language (AML) code used to produce forest disturbances by date from the land cover inputs are available online (Wolter et al. 2012). The dataset will be updated with more recent classifications (i.e., 2005, 2010, etc.) as time and resources permit.

Figure 1.—Location of the Border Lakes ecoregion (dark gray outline) within the full extent of the classified Landsat scenes that define the greater Border Lakes Region (dotted black line).

METHODS

Imagery and Image Processing

Six Landsat footprints (hereafter referred to as scenes) were required to cover the greater Border Lakes Region. These scenes correspond to the Landsat Worldwide Reference System (WRS-2) path (P) and row (R) combinations: P28 R26, P28 R27, P27 R26, P26 R26, P27 R27, and P26 R27. To capture changes as precisely as possible using Landsat imagery, we (as well as Wolter and White 2002) targeted images collected during stable growing season conditions, free of clouds, and as close to calendar matches from one year to the next (Table 1). In a number of cases such precise pairing was not possible. Thus, substitute images were acquired either before or after peak growing season from the same year or selected growing season images from the year immediately before or after the target years (i.e., 1975, 1980, 1985, 1990, 1995, and 2000). In the case of fire disturbance that occurred between time-steps, off time-step images were subsequently selected, after the Wolter and White (2002) analyses, to assist identification of these spectrally unique, but ephemeral, disturbance signatures.

Original work by Wolter and White (2002) used Landsat TM and ETM+ data acquired from the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center (EROS) prior to open access to the archive. Those image data were acquired in raw, unrectified format at 28.5 m nominal resolution and geometrically rectified (see Wolter and White 2002 for details on image pre-processing).

All additional Landsat images (off-step MSS, TM, and ETM+ imagery) used in this recent effort were downloaded from the EROS web site (http://glovis.usgs.gov/). These Landsat images are convenient as they are precision-orthorectified and geo-corrected using Global Land Cover Facility GeoCover data (www.landcover.org). The format of these images is unsigned 8-bit, in Universal Transverse Mercator (UTM) zone 15 coordinates with World Geodetic System (WGS) 84 ellipsoid

Table 1. Landsat images used for this research map series, organized by footprint (i.e., Landsat Worldwide Reference System [WRS-2] path [P] and row [R] combinations).

Landsat TM, ETM+			Landsat MSS		
P: 28 R: 26	**P: 27 R: 26**	**P: 26 R: 26**	**P: 28 R: 26**	**P: 27 R: 26**	**P: 26 R: 26**
8/26/2000	7/18/2000	12/10/2000	7/7/1981	2/12/1981	2/11/1981
8/21/1995	7/31/1996	5/16/2000	7/12/1980	7/29/1980	10/8/1980
8/7/1990	7/29/1995	2/4/1998	7/3/1980	7/11/1980	12/16/1979
9/26/1985	7/31/1990	6/9/1997	1/23/1980	7/2/1980	9/17/1979
5/21/1985	10/21/1985	5/19/1995	2/24/1979	6/11/1979	1/9/1977
6/3/1984	4/28/1985	6/1/1994	9/7/1976	7/5/1976	7/4/1974
4/16/1984	5/27/1984	5/10/1992	7/30/1975	5/9/1975	2/11/1976
		12/18/1991	3/8/1975	9/26/1974	9/2/1975
		8/28/1991	2/29/1974	5/28/1973	5/8/1975
		9/26/1990	5/29/1973	2/9/1973	12/16/1972
		10/14/1985		9/18/1972	
P: 28 R: 27	**P: 27 R: 27**	**P: 26 R: 27**	**P: 28 R: 27**	**P: 27 R: 27**	**P: 26 R: 27**
7/9/2000	9/12/2000	12/10/2000	7/3/1980	2/12/1981	5/12/1981
8/21/1995	8/19/2000	5/16/2000	7/17/1974	5/27/1980	2/11/1981
8/7/1990	8/14/1995	2/4/1998		6/11/1976	10/8/1980
9/26/1985	7/31/1990	6/9/1997		9/24/1976	12/16/1979
	6/2/1986	5/19/1995		2/21/1976	9/17/1979
	4/28/1985	6/1/1994		6/23/1975	1/9/1977
	6/28/1984	12/20/1992		9/26/1974	7/4/1976
	5/27/1984	5/10/1992		2/22/1974	2/11/1976
		8/28/1991		7/3/1973	8/6/1975
		8/12/1991		9/18/1972	
		9/26/1990			

and datum. We transformed (nearest neighbor) all newly acquired images to UTM15 coordinates, with North American Datum (NAD) 83 and Geodetic Reference System (GRS) 1980 ellipsoid, to 28.5 m to match the older 2002 analyses.

Since it was difficult to find cloud-free images for two pairs of scenes (e.g., R26 and R27) along a particular path (e.g., P: 26 or P: 27) for the same date across six time-steps, we chose to process imagery for change detection on a scene-by-scene basis rather than mosaic imagery by path or study region (Wolter and White 2002). This allowed more freedom to select optimal imagery, rather than having to ignore perfect, cloud free images because the date-compliment scene to the north or south was compromised by clouds. We further accepted images with clouds within about 60 km of either the west or east edges of scenes (i.e., 32.4 percent of a 185 km wide image), but never in the middle 60 km, and then used neighboring images from the same time-step to cover gaps due to cloud cover (Landsat path side lap is ~37.5 percent or 69.3 km at 47.5° north latitude).

A consequence of this method is that the 5-year time-steps between classifications were nominal as precise dates varied by scene (Table 1).

Land Cover Classification and Change Detection Techniques

The land cover classification and change detection methods presented here are extensions of earlier work by Wolter and White (2002) and Pastor et al. (2005), and were completed in four distinct stages (Fig. 2). In Stage 1, we simplified Wolter and White's initial classification for 1990, initially classified to genus- and/or species-level detail, to Anderson Level II classes (Table 2). Upland and lowland vegetation classes were differentiated based on intersections with U.S. National Wetlands Inventory (Wilen 1990), and the Canadian National-Scale Ontario Land Cover (OLC) wetland classes (see Wulder et al. 2003). The 1990 land cover classification served as the "base" year for the time series across the whole region (Wolter and White 2002).

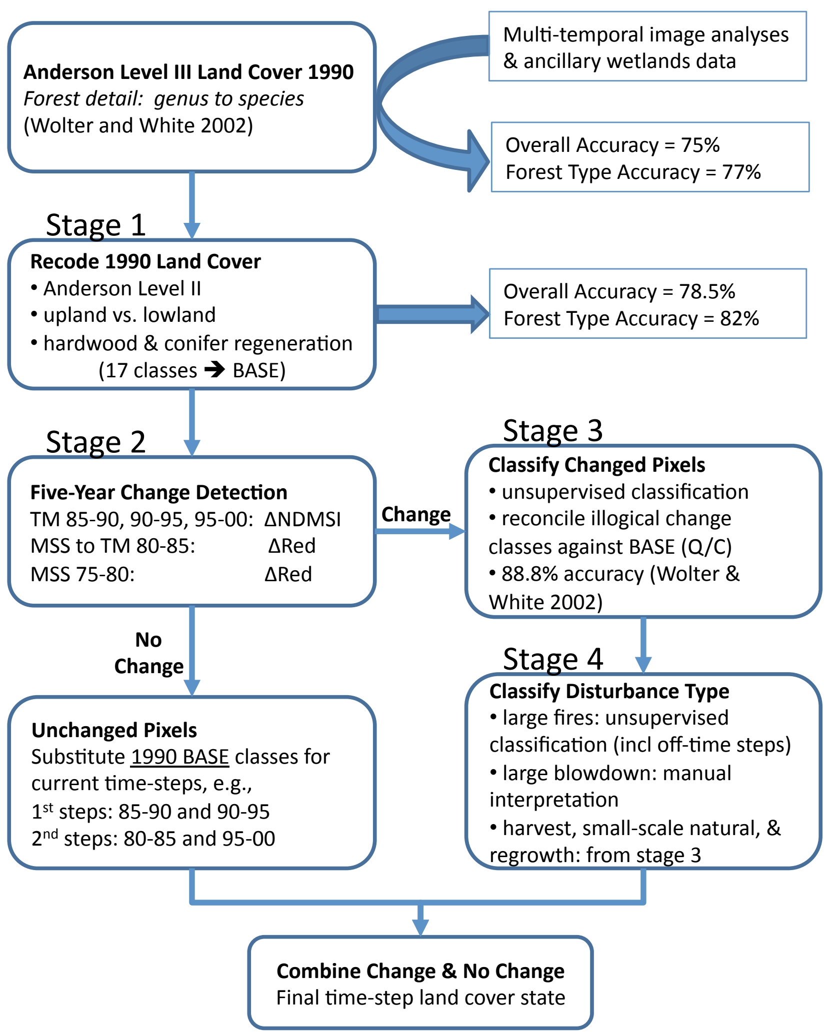

Figure 2.—Flowchart describing the land cover classification and change detection process used to produce the land cover maps from 1975-2000.

Table 2. Land cover classification scheme

CLASSIFICATION	CODE	DESCRIPTION
Water	W	Surface water including lakes, ponds, rivers, streams, and some wetland areas.
Emergent vegetation	EM	Wetland areas dominated by *Carex* spp., *Typa* spp., *Scirpus* spp., or similar vegetation growing above the surface of wet soil or water.
Lowland grass	LG	Graminoid-dominated low-lying areas with saturated soils commonly found near streams, lakes, and marshes.
Lowland brush	LB	Areas dominated by short woody vegetation over wet or saturated soil. Examples: Ericaceous vegetation, *Alnus* spp., *Salix* spp., and *Cornus* spp.
Sphagnum bog	BOG	Wetlands dominated by *Sphagnum* spp. that are commonly associated with very sparse, small diameter, stagnant woody vegetation including Ericaceous brush, *Picea mariana*, and *Larix laricina*.
Upland grass	UG	Areas dominated by graminoid vegetation and forbs that do not intersect with any of the National Wetlands Inventory's (NWI) moisture modifier data.
Domestic grass	DG	Areas covered by cultivated or noncultivated herbaceous vegetation dominated by short manicured graminoids and/or forbs. Examples: agricultural fields and pastures, golf courses, and miscellaneous lawns.
Upland brush	UB	Areas dominated by short woody vegetation over relatively dry soil that do not intersect with NWI moisture modifiers. Examples: *Corylus* spp., *Viburnum* spp., *Rubus* spp., and very early successional hardwood regeneration.
Conifer regeneration	CREG	Early successional coniferous forest that is spectrally distinct from mature forest classes, brush classes, and early successional hardwood regeneration.
Hardwood regeneration	HREG	Early successional hardwood forest that is spectrally distinct from mature forest classes, brush classes, and early successional conifer regeneration.
Lowland conifer	LC	Forested areas composed primarily of wetland conifer species (e.g., *Picea mariana*, *Larix laricina, Thuja occidentalis*) that intersected with NWI moisture modifier data.
Lowland hardwood	LH	Areas dominated by hardwood tree species commonly associated with wetlands (e.g., *Fraxinus nigra*, *Acer rubrum*, *Salix* spp., *Ulmus* spp.) that intersected with NWI moisture modifier data.
Lowland mixedwood	LM	Forest areas consisting of lowland mixtures of hardwood and conifer species, as specified above, that intersect with NWI moisture modifier data.
Upland conifer	UC	Forest dominated by upland conifer species (e.g., *Picea glauca*, *Abies balsamea*, and *Pinus* spp.) that do not overlap with NWI moisture modifier classes.
Upland hardwood	UH	Forests dominated by upland hardwood species (e.g., *Populus* spp., *Betula papyrifera*, *Acer saccharum*, and *Fraxinus Americana*) that are not coincident with NWI moisture modifier.
Upland mixedwood	UM	Forest areas consisting of upland mixtures of hardwood and conifer species, as specified above, that do not intersect with NWI moisture modifier data.
Forest blowdown*	BLOW	Stand-replacing forest disturbance due to extreme wind events, such as the July 4, 1999 blowdown event in northeast Minnesota.
Forest fire scars*	FIRE	Stand-replacing forest disturbance due exclusively to wildfire events.
Developed	DEV	Lands dominated by residential housing structures, commercial industrial development, and/or copious areas of pavement.

* Identified in the final stage of the classification and change detection process.

Right: Recreational use characteristic of the wilderness area. Photo by Sue Lietz, U.S. Forest Service.
Below: Landscape mosaic characteristic of the greater Border Lakes Region. Aerial image by Peter Wolter, Iowa State University, and Clayton Kingdon, University of Wisconsin-Madison; used with permission.

In Stage 2, vegetation change between time periods (e.g., 1985 and 1990) was quantified using the normalized difference moisture stress index (NDMSI; see Hunt and Rock 1989, Wilson and Sader 2002, Wolter and White 2002) applied to leaf-on imagery from the respective time periods. Pixels that showed differences in this index >1.5 standard deviations (+/-) between time periods were designated as changed pixels; all others were considered unchanged. Change analysis between dates involving MSS (1975-1980) or MSS and TM (1980-1985) imagery followed different protocols since the MSS sensor did not have a shortwave infrared band required to calculate NDMSI. Prior to change analysis, 60 m MSS pixels were rescaled (nearest neighbor) to 28.5 m to match TM/ETM+ spatial resolution. Differences in visible red reflectance between image dates were used as a surrogate tool to identify change pixels (Desclée et al. 2007).

In Stage 3, pixels identified as changed were classified using an iterative, self-organizing, maximum likelihood classifier into one of 17 cover classes (i.e., Table 2), deferring the identification of specific disturbance types until the final stage (Fig. 1). Leaf-off winter Landsat images were used to identify conifers below hardwood overstory to more accurately discern the hardwood, conifer, and mixed-wood forest classes (Wolter et al. 2008). Logical cover-type transition checks were performed to correct unlikely change or illogical change classes. In the first 5-year time-steps (backward and forward in time: 1985-1990 and 1990-1995, respectively), change classes were compared to the 1990 base classification to ensure the transition class made sense: a 5-year transition from upland grass (UG) to mature upland mixed forest (UM), or water to upland conifer are examples of unlikely and illogical transitions, respectively. In the second set of time-steps from the base year (i.e., 1980-1985 and 1995-2000), resulting change classes were checked against base and the first time-step classifications for illogical transitions. For pixels that did not change between the 1990 base year and the first time-steps (backward and forward from 1990), the associated land cover classification value from of the 1990 base classification was transferred to the respective time-step year (1985 and 1995). Pixels that did not change from time-step 1 to 2 (i.e., 1980-1985 and 1995-2000) adopted pixel values from the step 1 classifications, and so forth.

In Stage 4, large-scale (>100 ha) natural disturbances (i.e., fire and blowdown) were identified and used to distinguish these forest-cover changes from all other disturbances. Recent burn scar spectral signatures were readily distinguished from other forest disturbance classes using both Landsat TM/ETM+ (dark purple-maroon in the 5, 4, 3 band combination) and MSS (blackish in 4, 3, 2 band combination) imagery. However, this unique spectral signature fades after a few years. Therefore, the entire Landsat archive (1972-2000 by each scene) was examined to detect evidence of large scale (>100 ha) fire activity between 5-year time periods to better capture these ephemeral

Disturbances in the greater Border Lakes Region. Above: Pagami Creek Fire, Sept 4, 2011. Photo by Kari Greer, U.S. Forest Service, Superior National Forest. Right: Clearcut example from Minnesota. Aerial image by Peter Wolter, Iowa State University, and Clayton Kingdon, University of Wisconsin-Madison; used with permission.

signatures (Fig. 1). Once an off-time-step image (with recent fire activity) was discovered, all no-change areas for the time-step containing the fire event were masked out. Then, recent fire scars were distinguished from other disturbance types using the unsupervised classification methods described for Stage 3 above. Large-scale (>100 ha) tree blowdowns were then separated from remaining forest disturbances by manual image inspection (shape and pattern assessment) and digital recoding, rather than by unsupervised image classification. Changed pixels were then merged with the unchanged pixels to complete the final maps for each time step (Fig. 2).

Harvest disturbances represent the most prevalent form of canopy-replacing disturbance within the managed areas of the Border Lakes Region (Sturtevant et al.[1]). While most of the harvest operations were qualitatively distinguishable from other disturbance types (i.e., large fires and blowdowns), cutting operations range in size from very large to very small, and the size distributions differ on each side of the international border (Sturtevant et al.[1]). Given that the cause of disturbance was more difficult to distinguish at the finer spatial scales, we did not attempt to classify other disturbance types apart from major fire and blowdown events. Other forest disturbances include insect disturbance (primarily defoliation), small-scale fire and wind disturbances, flooding by beaver impoundment, and anthropogenic linear features such as road and utility development. Future analysis of the classified maps (Wolter et al. 2012) could allow greater separation by disturbance type.

Notably, the canopy openings caused by the major insect defoliators in the region range from ephemeral changes in leaf area (e.g., forest tent caterpillar [*Malacosoma disstria*]) to widespread mortality (e.g., spruce budworm [*Choristoneura fumiferana*]), where impacts range widely within a given defoliator species. Yet even widespread defoliation mortality is patchy in space and time (Kneeshaw and Bergeron 1998), and is limited to the specific host tree species within the mixed forests of the greater Border Lakes Region (James et al. 2011). Hence, methods alternative to those presented here are necessary to properly map and quantify the partial canopy disturbances caused by defoliation damage (Townsend et al. 2012).

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[1] Sturtevant, B.R., et al. 2012 manuscript in preparation. Processes underlying divergent forest disturbance legacies in the Border Lakes Region of Minnesota (USA) and Ontario (Canada).

Land Cover and Disturbance Class Evaluation

Overall accuracy of the full 1990 forest classification (six Landsat scenes at near tree species level detail), that served as the "base" year for our change analyses, was 75.0 percent (Kappa [$\hat{k}$] = 0.74) (Wolter and White 2002). Average accuracy among the full complement of forest classes was 78.5 percent (commission/inclusion) and 74.7 percent (omission/exclusion). After aggregation to Anderson Level II classes, the new overall accuracy was 78.5 percent ($\hat{k}$ = 0.77), with an average accuracy among aggregated forest classes of 82.4 percent (commission/inclusion) and 80.9 percent (omission/exclusion) (see Appendix). Accuracy of 1990 to 1995 change classification results reported by Wolter and White (2002) was 88.8 percent ($\hat{k}$ = 0.87). More details on accuracy assessment can be found within Wolter et al. (2012). Because we extended Wolter and White (2002) methods of change detection (MSS protocol differed slightly as noted above) and unsupervised reclassification of change types for other time-steps before 1990 and after 1995, it is reasonable to expect similar change class accuracies for the remaining time-step land cover classifications.

Burn scar identification was independently evaluated using available fire perimeter records from the Canadian large fire database (LFD; Stocks et al. 2002), the Superior National Forest, and fire point locations assembled by the Minnesota Department of Natural Resources and the Superior and Chippewa National Forests (Cardille and Ventura 2001). The LFD is a national-scale product with recognized spatial inaccuracies—however the dates of fire events are accurate. Polygons representing fire perimeters were overlaid with each classified image for the time step prior to and immediately after the year of each fire. The proportions of land cover types within the fire perimeters were tabulated for both time periods to determine if fire scars or other disturbances were mapped within the perimeter. Validation focused on stand-replacing forest fires, defined as those fire polygons that affected primarily forested land cover and contained at least 10 percent of its area where forest was converted to a transitional cover type. A forest fire event was tallied as correctly classified if cells identified as "fire scar" were represented within the polygon. For fire records for which there were no available perimeter data, the public land survey (PLS) section that included the ignition location was used as the analysis window instead of a perimeter. For those large fire (>200 ha) observations meeting the above criteria (n=66), approximately 74 percent contained mapped fire scars. The fact that some large fires were not mapped as fire scars suggests that rapid revegetation following those fires, potentially in combination with understory burning that did not impact the canopy, may have masked the fire scar signature. In addition, some portions of the burned area (as indicated by fire polygons) were classified as some transitional type rather than fire scar, indicating regeneration following the burn affected the fire scar classification. However 30 additional fire scars were mapped that did not correspond to any of the available fire records, including fires smaller than the 200 ha threshold for the LFD (Ontario), fires in Minnesota that occurred prior to the state records, and a subset (less than 10) that were apparently missed by the recording agencies.

The accuracy of the forest blowdown class was assessed through comparison with an independently derived map of wind disturbance severity (Rich et al. 2010). The severity map corresponds to a small portion of the full classification extent, but overlaps a portion of the area mapped as blowdown in the 2000 classification year. Only upland areas were included in the severity map, and we further masked out obvious image edge artifacts as well as all areas mapped as the forest fire scar class in either 1995 or 2000 to avoid confusion across disturbances. After applying these masks, we quantified the relative frequency of wind disturbance severity within the blowdown class and across all other classes (Fig. 3). The distribution demonstrates that most of the blowdown pixels correspond to mapped high severity levels. For a direct comparison between maps, we reclassed the severity map to four discreet severity classes with thresholds of 10, 34, and 67 percent severity (Rich et al. 2010). We then rescaled the severity class map to match the 28.5 m resolution of our classification using majority class assignment. We assessed accuracy of the blowdown class through direct comparison with the highest severity (67-100 percent) class. We calculated an overall accuracy of 74.6 percent ($\hat{k}$ = 0.74), with an average accuracy of 67.4 percent (user's) and 34.8 percent (producer's) (See Appendix). These results indicate that we can be confident that areas mapped in our blowdown class do represent very severe wind disturbance. The blowdown class likely does not represent all areas impacted by wind disturbance, especially areas with low to moderate disturbance.

Period of Most Recent Forest Canopy Disturbance

A composite map depicting the period of forest canopy disturbance was produced using the 1975-2000 sequence of land cover data. First, a map of forest disturbance was created for each consecutive time period (e.g., 1980-1985). Forest canopy disturbance was defined as a forested pixel changing to a transitional cover type (i.e., herbaceous, brush, regeneration, fire scar, or blowdown) in successive time steps, indicating stand-replacing disturbance (i.e., overstory removal). To extend

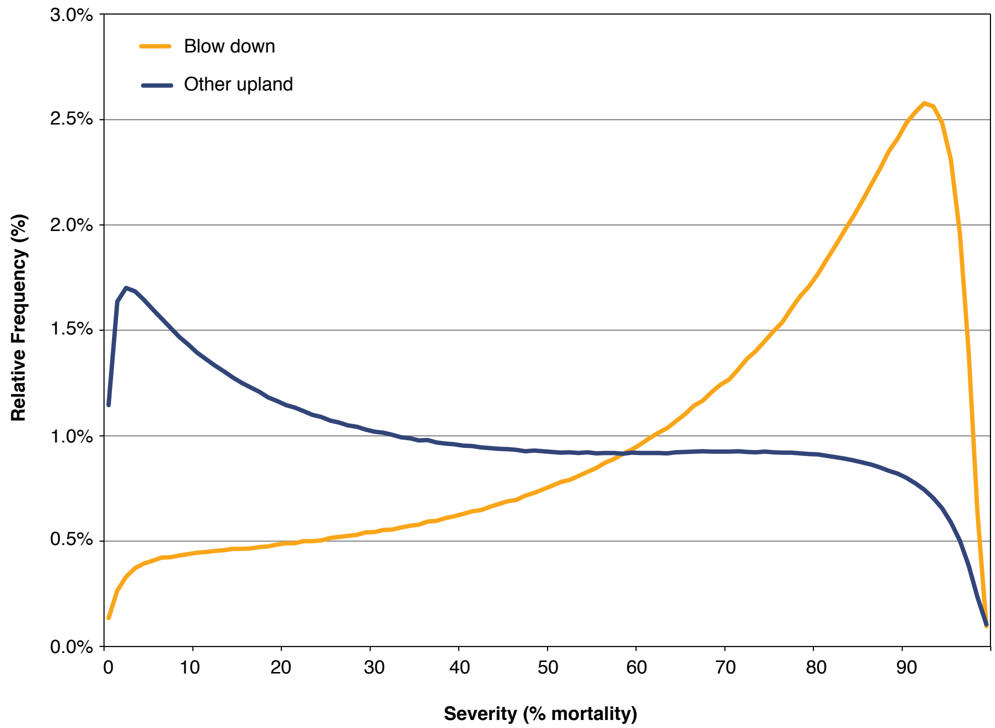

Figure 3.—Relative frequency of wind disturbance severity values (Rich et al. 2010) among cells classified as forest blowdown and all other upland classes, for a subset of the greater Border Lakes Region classification for the year 2000.

the forest disturbance series earlier in time, pixels that were classified as a transitional cover type in 1975 were considered disturbed forest if the pixel changed to a forest type later in the time series. Because the actual timing of disturbance is unknown for the 1975 disturbed pixels, these were assumed to be disturbed prior to 1975 and assigned to a single class. Relative density of pre-1975 disturbance pixels within a given "patch" may be interpreted as the relative recovery of forest there, with the caveat that the original land cover type (i.e., forest or nonforest) for "nonrecovered" pixels in the patch cannot be determined. The six individual disturbance maps from each time period were then merged, with the latest dates given priority in case of overlap, to produce a composite map of the period of disturbance. To complete the map, undisturbed areas were pooled into three stable classes. Forested pixels circa 2000 that were not disturbed within the timeframe of the data were pooled into a stable "forest" class. The nonforested lowlands (EM, LG, LB, BOG) circa 2000 were pooled into a stable "open wetlands" class. Sites that were nonforest throughout the time series but are not open lowlands were grouped into a stable "nonforest" class. This class includes developed areas and upland openings (natural or manmade). Note that while nonforest classes do experience change over the course of the land cover time series, the major changes occurring on this landscape are linked to natural and human forest conversion factors (Sturtevant et al.[1]). The research dataset (Wolter et al. 2012) includes Arc Macro Language (AML) code used to construct the period of most recent disturbance map from the time series of land cover classifications, and will be updated to include more recent classification dates.

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FOREST TYPE MOSAIC

Figure 4.—Forest types characteristic of the study area.
Upper left: Upland conifer example; mixed pine stand in the BWCAW. Photo by Sue Lietz, U.S. Forest Service.
Middle left: Lowland conifer example; tamarack forest in northeast Minnesota. Photo by Sue Lietz, U.S. Forest Service.
Lower left: Lowland conifer example; lowland spruce forest in northeast Minnesota. Photo by Peter Wolter, Iowa State University; used with permission.
Upper Right: Upland mixedwood example; white pine and paper birch forest in northeast Minnesota. Photo by Peter Wolter, Iowa State University; used with permission.
Middle Right: Upland conifer example; jack pine mix in BWCAW. Photo by Brian Sturtevant U.S. Forest Service.
Lower Right: Upland deciduous example; aspen stand with balsam fir understory in the BWCAW. Photo by Brian Sturtevant, U.S. Forest Service.

APPENDIX

Table A1. Accuracy of the greater Border Lakes Region recoded land cover images.

Land Cover	User's Accuracy	Producer's Accuracy	Overall Accuracy
1 [W]	0.885	0.975	
2 [EM]	0.938	0.565	
3 [LG]	0.500	0.778	
4 [LB]	0.663	0.663	
5 [BOG]	0.752	0.666	
6 [UG]	0.654	0.845	
7 [DG]	0.939	0.756	
8 [DEV]	0.966	0.887	
9 [UB]	0.415	0.672	
10 [BLOW]	0.674	0.348	0.746
11 [CREG]	0.852	0.821	
12 [HREG]	0.853	0.848	
13 [LC]	0.828	0.830	
14 [LM]	0.735	0.807	
15 [LH]	0.915	0.821	
16 [UC]	0.788	0.772	
17 [UM]	0.883	0.713	
18 [UH]	0.740	0.861	
19 [FIRE]	0.881	0.743	
			(3820/4869) = 0.785

Table A2. Accuracy of the greater Border Lakes Region 1990 land cover image (Wolter and White 2002).

Land Cover	User's Accuracy	Producer's Accuracy	Overall Accuracy
JP	0.733	0.787	
JP-H	0.757	0.963	
RP	0.741	0.776	
RP-H	0.554	0.891	
SF	0.662	0.633	
SF-H	0.735	0.771	
C	0.707	0.630	
C-H	0.565	0.795	
T	0.815	0.677	
BS	0.785	0.878	
ABC	0.638	0.744	
CREG	0.821	0.852	
BA	0.810	0.860	
BA-LC	0.874	0.765	
BA-UC	0.688	0.855	
AB	0.820	0.669	
AB-LC	0.785	0.646	
AB-UC	0.653	0.845	
NH	0.808	0.724	
NH-Con	0.826	0.905	
NH-UC	0.833	0.714	
H-trn	0.733	0.846	
HREG	0.838	0.820	
BARE	0.748	0.773	
W	0.975	0.885	
E-aq	0.552	0.941	
EM	0.576	0.919	
SPHAG	0.793	0.902	
UG	0.755	0.346	
LG	0.778	0.510	
AGRIC	0.756	0.939	
UB	0.672	0.415	
LB	0.639	0.670	
ERIC	0.806	0.509	
DEV	0.817	0.946	
ROAD	0.927	0.916	
lh	0.479	0.897	
C-lowBA	0.667	0.848	
			(3653/4869) = 0.750

Table A3. Accuracy of the greater Border Lakes Region 1990 to 1995 change classification.

Land Cover	User's Accuracy	Producer's Accuracy	Overall Accuracy
11 [CREG]	0.770	0.960	
12 [HREG]	0.870	0.900	
1 [W]	1.000	0.960	
2 [EM]	0.920	1.000	
6 [UG]	0.890	0.750	
7 [DG]	0.870	0.930	
3 [LG]	0.890	0.850	
9 [UB]	0.920	0.920	
4 [LB]	0.950	0.910	
8 [DEV]	0.920	1.000	
[FLD]	1.000	1.000	
19 [FIRE]	1.000	1.000	
			(310/349) = 0.888

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This document and accompanying maps describe land cover classifications and change detection for a 13.8 million ha landscape straddling the border between Minnesota, and Ontario, Canada (greater Border Lakes Region). Land cover classifications focus on discerning Anderson Level II forest and nonforest cover to track spatiotemporal changes in forest cover. Multi-temporal Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Multi-Spectral Scanner (MSS) data from 1972 to 2000 were used to classify forest cover types and disturbances at 5-year intervals. A composite dataset depicting the period of forest disturbance was produced using the 1975-2000 sequence of land cover data. These land cover change data were produced to facilitate analysis of forest disturbance patterns, to support landscape simulation modeling, and to support cross-ownership land management within the region. A double-sided fold-out map shows A) forest land cover change across differently managed forests, and B) classified period of forest canopy disturbance for the entire study area. Digital versions of the map are available online, as are the datasets and code used to produce them.

KEY WORDS: Land cover classification, land cover change, forest disturbance, land cover change map

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