National Park Service
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Natural Resource Stewardship and Science

Landsat-based Monitoring of Landscape Dynamics at Apostle Islands National Lakeshore, 2004-2009

Natural Resource Technical Report NPS/GLKN/NRTR—2012/608

ON THE COVER
This photograph was taken at Apostle Islands NL during an outbreak of the saddled prominent caterpillar (*Heterocampa guttivitta*) in 2006. It affected just over 7% of the park and nine islands. As seen in this photo, the infestation can become quite prolific and rapidly defoliate deciduous trees.
Photograph by: NPS/Jim Nepstad

Landsat-based Monitoring of Landscape Dynamics at Apostle Islands National Lakeshore, 2004-2009

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This report received formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

This report is available from the Great Lakes Inventory and Monitoring Network website (http://science.nature.nps.gov/im/units/GLKN/monitor/landuse/landuse.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

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Abstract

Apostle Islands National Lakeshore (APIS) is composed of a group of 21 islands in western Lake Superior and part of the Bayfield Peninsula of northern Wisconsin. Disturbances, or distinct changes in vegetation cover, are an important part of how this ecosystem functions. Monitoring these disturbances through time will provide information regarding historic disturbance regimes compared to present and future conditions and trends. For this analysis, disturbances in and around APIS were delineated for six years, 2004-2009, using a combination of Landsat satellite imagery and high resolution aerial photos. We employed a set of computer algorithms, collectively known as LandTrendr, in conjunction with a dense time series of Landsat imagery (one set for each year) to track vegetation changes in and around the park. LandTrendr was used to identify apparent disturbances, after which high resolution imagery (airphotos) was used for photo interpretation to substantiate evidence of a disturbance, and hence, validate whether the disturbance occurred. For each validated disturbance, we identified the agent of change (fire, forest harvest, development, flooding due to beaver activity, and blowdowns) in addition to the year of occurrence, and starting and ending vegetation classes. Summary analyses showed that disturbances outside the park were dominated by forest harvest and development, while inside the park disturbances were caused primarily by beavers and forest pathogens, and to a lesser degree – development.

Acknowledgments

We would like to acknowledge staff at Apostle Islands National Lakeshore for assistance in aerial photo acquisition, providing on-the-ground knowledge of land cover changes, logistical support, and in helping to design the land cover monitoring program's scope and extent for the anlaysis.

The LARSE research group (http://www.fsl.orst.edu/larse/) at Oregon State University has been instrumental in the development of the Great Lakes Network's land use / land cover program, by providing assistance and guidance in development of the land cover monitoring protocol and in the implementation of the LandTrendr methods in land cover change detection.

We would also like to thank Natalya Antonova, Catharine Thompson, and Julie Van Stappen for reviewing and providing useful comments on this report.

List of Terms and Acronyms

APFO	Aerial Photography Field Office: a United States Department of Agriculture (USDA) Farm Service Agency (FSA) office located in Salt Lake City, UT.
APIS	Apostle Islands National Lakeshore
B&W	Black and white: airphoto type, commonly used prior to the 1990s.
CIR	Color infrared: the electromagnetic spectrum captured by a digital airphoto sensor (near-infrared, red, green).
DEM	Digital elevation model: a digital representation of ground surface topography or terrain.
Electromagnetic spectrum	The range of all possible frequencies of electromagnetic radiation. The electromagnetic spectrum of an object is the typical range of electromagnetic radiation emitted or absorbed by that particular object.
ETM+	Enhanced Thematic Mapper plus: one of the Earth observing sensors introduced into the Landsat program on 15 April 1999. http://landsat.usgs.gov/about_landsat7.php
GAP	Gap Analysis Program (http://gapanalysis.usgs.gov/)
GIS	Geospatial Information System: any system that captures, stores, analyzes, manages, and presents data that are linked to location.
ISRO	Isle Royale National Park
Landsat	The Landsat satellite family, and more specifically to either Landsat 5 (launched in 1984) or Landsat 7 (launched in 1999), both with 30 m pixels (resolution). http://landsat.gsfc.nasa.gov/about/
LTS	In this report it refers to a Landsat Time Series; more specifically it refers to a collection of images by scene.
NAIP	National Agriculture Imagery Program: acquires aerial imagery during the agricultural growing seasons in the continental U.S. Pixel resolution for this imagery typically ranges between 1 and 2 meters.
NGA	National Geospatial Agency
NLCD	National Land Cover Data: created by USGS to produce a consistent land cover map for the U.S using Landsat imagery. Currently there are three NLCD datasets; 1990, 2001 (versions 1 & 2), and 2006. http://www.mrlc.gov/

List of Terms and Acronyms (continued)

NVCS	National Vegetation Classification System: currently the National Standard for classifying the vegetation of the United States, maintained by NatureServe. http://biology.usgs.gov/npsveg/nvcs.html
Panchromatic	Incorporates all wavelengths of visible light.
RGB	Red, green, and blue: sometimes referred to as 'true color', it is the portion of the electromagnetic spectrum the film, or sensor, is quantifying.
SLC	Scan Line Corrector: device on-board the Landsat 7 (ETM+) satellite which compensates for the forward motion of the spacecraft so that the resulting scans are aligned parallel to each other.
SLC-off	Scan Line Corrector – off: this device failed in 2003, creating data gaps in each Landsat 7 (ETM+) image acquired after 31 May 2003.
TM	Thematic Mapper: one of the Earth observing sensors introduced into the Landsat program on March 1, 1984. http://landsat.usgs.gov/about_landsat5.php
VOYA	Voyageurs National Park

Introduction

Disturbance Monitoring Overview

Monitoring changes in land cover and land use has long been recognized as an important part of monitoring landscape processes (Cohen and Goward 2004). Data obtained from disturbance detection and monitoring have been used in ecosystem modeling of carbon (Law et al. 2004, Turner et al. 2006, Potapov et al. 2009, Powell et al. 2010); for mapping fire extent, severity, and recovery (Veraverbeke et al. 2010, Chen et al. 2011, Meigs et al. 2011); for evaluating policy effects on land use (Kennedy et al. 2012); and for modeling the effects of disturbances on watershed characteristics (Eshleman et al. 2009, Deel et al. 2012). Several techniques for detecting and delineating landscape change have emerged as remote sensing and GIS technologies have evolved (Cihlar 2000, Coppin et al. 2004, Lu et al. 2004, Radke et al. 2005, Wulder and Franklin 2007). A summary of the four most common types of change detection, including our opinions on the benefits and disadvantages and studies using these various techniques, is provided in Table 1.

Previous Landscape Dynamics Studies in the Upper Great Lakes Region

Previous landscape dynamics studies in the region have focused on large-scale changes in land cover and land use using moderate resolution imagery such as Landsat (30 m pixels). However, these studies have not focused specifically in the Chequamegon Bay region, nor have they provided consistent long-term data. Wolter et al. (2006) examined land use and land cover change in the U.S. Great Lakes basin for one time period (1992-2001) using two generations of the National Land Cover Dataset (NLCD) (Vogelmann et al. 1998). The study found that 2.5% of the watershed experienced change, with forest and agriculture categories experiencing the largest declines in area (approximately 2.3%). In addition, 49.3% of the changes were transitions from undeveloped to developed land with the greatest percentage of the overall watershed change occurring within 0-10 km of the shoreline.

In northeastern Minnesota, White and Host (2003, 2008) used General Land Office (GLO) survey data and aerial photography from the 1930s, 1970s, and 1990s to quantify forest disturbance frequency and spatial patterns. They found an increase in fire frequency from pre-settlement period (1860-1890) to the period between 1910 and 1940, followed by a decrease in fire frequency, which was replaced by increases in timber harvest rates. Wolter and White (2002) focused on forest cover type transitions and landscape structural changes in the same area using Landsat imagery from 1990 to 1995 and found that of the mature forested area, 4.2% was harvested, flooded, or burned five years later. Not surprisingly, forest harvests were highest on private lands (ca. 1.7% per year) and lowest on tribal land (ca. 0.55% per year), with the greatest rates of disturbance occurring on managed state forests (ca. 1.1% per year).

Lastly, Brown (2003) investigated the relationship and trends in land use and forest cover on private parcels in the Upper Midwest (the northern forested regions of Minnesota, Wisconsin, and Michigan) from 1970 to 1990 and found that land development increased in all 106 counties. In addition, the percentage of land in agriculture declined between the 1980s and 1990s, but held steady in some counties when observed over the entire time period (1970s to 1990s). This could reflect the conversion of previously-cleared forest lands for agriculture back to a forested cover type.

Table 1. Comparison of common methods used for change detection. The method used in this report is a type of spectral trajectory analysis.

Method	Description	Pros	Cons	Studies
Airphotos	Manual interpretation of available photos to delineate changes on the landscape. Also commonly used to classify land cover and land use.	Very detailed	Time intensive, very subjective based upon interpreter.	(Rutchey and Vilchek 1999, Lillesand and Kiefer 2000, Harvey and Hill 2001, Maheu-Giroux and de Blois 2005, Morgan et al. 2010)
Two date subtraction	Subtract the spectral values of one year of imagery from another year of imagery. A threshold is then developed to separate real change from 'false' change.	Simple, quick	Due to only two images being used, a large number of 'false' changes are detected due to sensor aberrations.	(Aldrich 1975, Coppin and Bauer 1995, Cohen et al. 1998, Healey et al. 2005, Kennedy et al. 2007a)
Spectral trajectory analysis	Detect temporal patterns or 'trajectories' in the sequence of imagery.	Largely removes year-to-year variation. Capture longer overall trends and more subtle disturbances.	Requires robust radiometric normalization. May involve complex statistical analysis to detect change.	(Kennedy et al. 2007b, Huang et al. 2009, Huang et al. 2010a, Kennedy et al. 2010b, Schroeder et al. 2011, Sonnenschein et al. 2011, Stueve et al. 2011, Kennedy et al. 2012)
Object orientated analysis	Relatively new technique incorporating spectral information (tone, color) as well as spatial arrangements (size, shape, texture, pattern, association with neighboring objects).	By including information from neighboring pixels (among others), it is beginning to approach human interpretation.	Works better with high resolution imagery and results vary depending on imagery used for analysis.	(Hay et al. 2003, Benz et al. 2004, Laliberte et al. 2004, Walter 2004, Wang et al. 2004, Yu et al. 2004, Desclee et al. 2006, Heurich et al. 2010, Lu et al. 2011)

Landscape perturbations produce ripple effects in multiple natural processes. Fitzpatrick et al. (1999) studied the effect of the major shift in land cover and land use since the late 1800s, seeing large changes in the sedimentation load and flow dynamics in northern Wisconsin watersheds. Verry (1983) studied the effect of forest composition within watersheds and how this affected the spring runoff events. He found that forested watersheds comprised of mixed age forests helped buffer the spring runoff events. Also, resulting effects of landscape disturbances such as fragmentation and land cover changes have been found to affect (both positive and negative) the abundance of rare and endangered species; biodiversity and habitat for birds, amphibians, and other animals; water quality; and in-stream habitat for fish (Ward 1998, With 2002, Fahrig 2003).

Because landscape disturbances can affect a broad range of natural resources, being cognizant of what is happening in the Chequamegon Bay region will help inform resource managers at the park about pressures affecting the areas under their jurisdiction. Although APIS is comprised largely of islands, it can still be affected by its surrounding environs (Hansen and Rotella 2002, Wiersma et al. 2004, DeFries et al. 2007). The loss of roadless areas and increased fragmentation along shoreline areas on the Bayfield Peninsula may affect the abundance and movement patterns of species of interest within the park, and may contribute to the spread of both aquatic and terrestrial exotic species. Forest harvests adjacent to the mainland portion of APIS may contribute to blowdown events, and abandoned logging roads may provide greater access to the park via motorized vehicles such as four-wheelers and snowmobiles.

Although many landscape dynamic studies have been performed in the upper Great Lakes region, there is a lack of this type of research in the Chequamegon Bay area. In addition, due to the culture of research conducted by many colleges and universities, many of these studies are supported by one-time funding ("soft money") from governments and organizations , thus, they are often limited to a duration of only two or three years. This is one of the many reasons the NPS Inventory and Monitoring program was developed: to provide consistent, long-term monitoring of ecologically significant parameters affecting national park lands.

GLKN Approach to Disturbance Monitoring at APIS

Given the choices in disturbance monitoring, the Network spent three years working with various collaborators to evaluate the advantages and disadvantages of various techniques. In addition to being accurate, the method chosen by GLKN needed to be cost-efficient to allow other Network programs to operate and to allow the possibility of monitoring additional vital signs in the future. One of the approaches considered during protocol development used direct airphoto interpretation of vegetation classes and land use. This method required extensive field validation for accuracy assessment and was deemed too subjective and field intensive for long-term monitoring. Another approach under consideration included the use of high resolution aerial photos with object-oriented software to delineate land cover classes which would then be monitored through time. This approach was not chosen due to the lack of a consistent source of high spatiotemporal resolution airphotos, and lack of repeatability. In the end, a consistent, unbiased approach was chosen that relies on freely available, moderate resolution (30m) satellite imagery (Landsat). The Landsat archive contains imagery from 1985 to present, the longest record of satellite imagery available today. To detect and delineate landscape changes we used a method called LandTrendr (Landsat-based detection trends in disturbance and recovery), which was developed by a group of research scientists at Oregon State University (Kennedy et al.

2010b). To briefly explain, LandTrendr is the process of capturing interesting features (disturbances) while removing the background, or noise. Sources of this noise include variation in atmospheric condition, changes in sun angle illumination, and small phenological changes. Details of the LandTrendr process can be found in Kennedy et al. (2010b). Lastly, this method also proved to be the most cost-efficient program for the Network in terms of cost per hectare. The cost of implementing the protocol at APIS was only 7¢ per hectare or 33¢ per hectare if $50,000 of airphotos purchased for park was included.

Following methods outlined in the landscape dynamics protocol (Kennedy et al. 2010a), changes in land cover and land use were summarized and categorized for the years 2004 through 2009. Disturbances were identified both within the park and in an area adjacent to the park to aid in placing the park in a larger landscape context. During the winter of 2010, the size and location of the area to be monitored outside park boundaries was determined during a meeting with park resource managers and representatives from Red Cliff and Bad River Reservations, Bureau of Indian Affairs, and the U.S. Forest Service (USFS). Together we decided to monitor a large portion of the Chequamegon Bay region, totaling ca. 170,000 hectares (Figure 1). The size of the analysis area was limited by the amount of time the Network could spend validating disturbances. It should be noted the ability to monitor large areas of land outside the park is due to the fact that Landsat imagery is being utilized as the foundation of the monitoring process.

Study Area

The study was conducted using two Landsat scenes (rows 27 and 28 in path 26), which included APIS and the adjacent shoreline of Bayfield, Ashland, and Iron counties in northwestern Wisconsin (Figure 1). The park is located in far northern Wisconsin on the south shore of Lake Superior. The park includes 21 of 22 islands of the Apostles archipelago and a 12 mile long, narrow strip of mainland shoreline. The islands range in size from as little as 1.2 ha (Gull) to over 4,000 ha (Stockton). In total, the park comprises an area of 28,074 ha, 40% (ca. 11,000 ha) of which is surface water. The total land area monitored in this study was approximately 188,000 ha (Table 2).

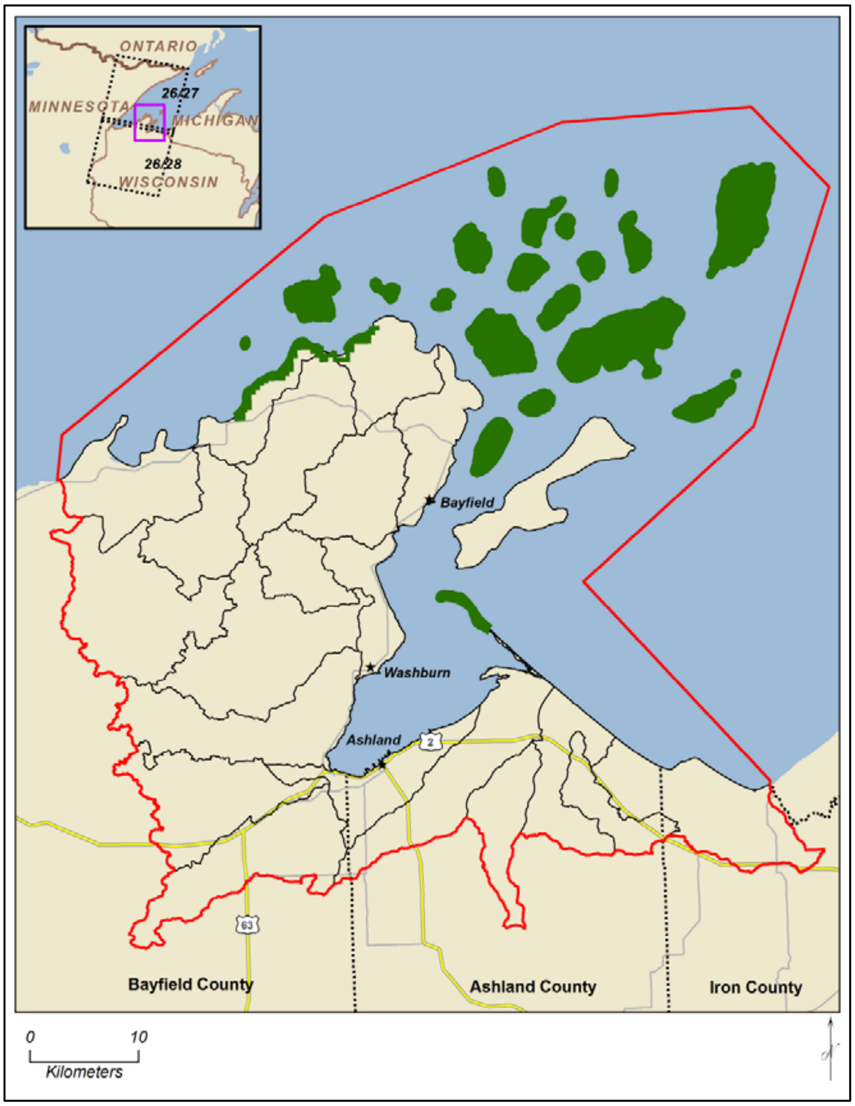

Figure 1. Study area for long-term monitoring of landscape-scale disturbances in and around Apostle Islands National Lakeshore, Wisconsin. The inset shows the extent (dotted black line) of the two Landsat scenes (26/27 and 26/28) processed and analyzed for this report. The larger map shows the extent of the analysis area (solid red), with 12-digit hydrologic units delineated (solid black), and solid green fill identifying the boundary of the park.

Table 2. Land area of each analysis region and the percent contribution of each analysis region to the overall analysis area.

Analysis area	Size (ha)	Percent of analysis area
APIS	17,047	9.1
Non-APIS	171,377	90.9
Total	188,424	100

Climate and Geology

Lake Superior has significant effects on the islands including moderating temperatures in all seasons and increasing the cloud cover and precipitation over and immediately downwind of the lake. The mean annual precipitation is approximately 78 cm (31 inches), with mean July and January temperatures approximately 19° C (66° F) and -11° C (12° F), respectively.

Soils in the area are relatively young, and of glacial origin. Glacial ice receded from the area roughly 8-10,000 years ago. Soils and landforms reveal processes of glacial ice sculpting, meltwater reworking of sediments, and inundation from ice margin lakes. Soils are commonly coarse till and glacial outwash sands in higher landscape positions, with clayey soils closer to the Lake Superior shoreline. Sandstone outcrops and shallow soils over bedrock are common along shorelines within the Apostle Islands (Miland 2006).

The Lake Superior basin has a long and complex geologic history. Some of the rocks in the area are greater than 2.5 billion years old. The majority of the Lake Superior shoreline consists of basalts formed from continental rifting roughly 1.1 billion years ago. The underlying bedrock and cliff exposures within the Apostle Islands National Lakeshore are primarily sandstone, also likely formed over 1 billion years ago, though some geologists date these formations at more around 600 million years ago (LeBerge 1994).

Vegetation

Prior to logging in the late 1800s and early 1900s, ca. 90% of the archipelago was comprised of upland mixed conifer and hardwood forest dominated by eastern hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*), sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and paper birch (*Betula papyrifera*) (Judziewicz and Koch 1993, Howk 2001). Currently the park is comprised mainly of second growth northern hardwood forest consisting of sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), aspen (*Populus* spp), birch (*Betula* spp.), basswood (*Tilia americana*), and northern red oak (*Quercus rubra*) (Hop et al. 2010, Sanders and Grochowski in press). According to the 2006 version of the National Land Cover Dataset (NLCD), the analysis area is comprised mainly of forest, with woody wetlands and agricultural comprising the next two largest classes (Figure 2).

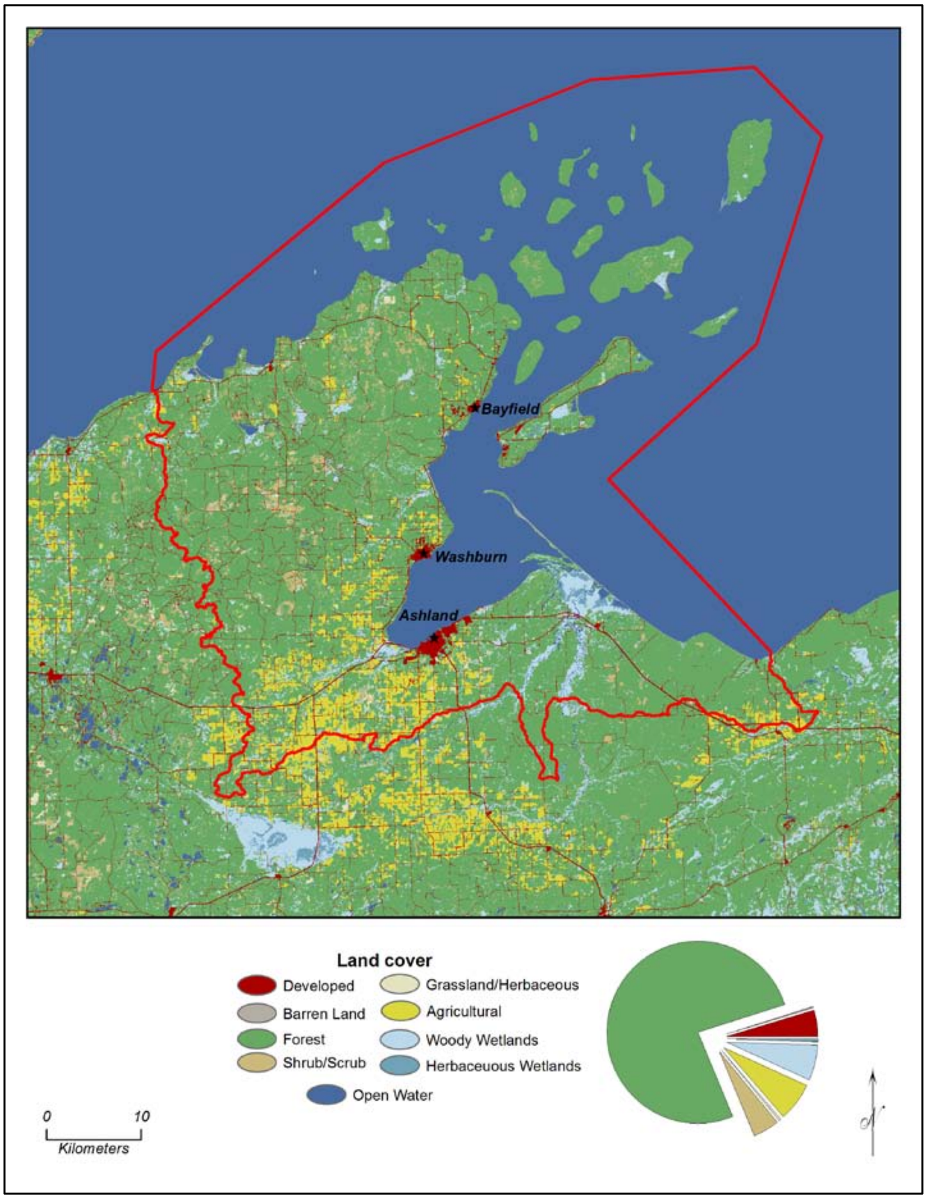

Figure 2. Land cover classes for the APIS analysis area (solid red line), circa 2006. Data from the 2006 version of the NLCD.

NPScape Metrics

NPScape is a Service-wide landscape dynamics monitoring project that provides landscape-level data, tools, and evaluations for natural resource management, planning, and implementation. Selected metrics (forest density, forest morphology, road density, population density, and conservation status) from this monitoring effort are summarized below as additional study area background for the analysis presented later in this report. More information regarding the NPScape project can be found online at: http://science.nature.nps.gov/im/monitor/npscape/index.cfm.

Forest Pattern

Forest pattern as evaluated by area density reveals the fragmentary effects of roads (‘developed’; Figure 2) in the study area (Figure 3). In brief, area density displays the percentage of forested 30 m pixels in a moving window of analysis (e.g., 7 x 7 pixels, or 4.41 ha). Results from four moving window sizes are presented in Figure 3, designed to reflect a range of landscape scales that are relevant to natural resource management. Raw percentages are then grouped into seven ecologically informative density categories (p): background (p=0%), rare (0<p<10%), patchy (10≤p<40%), transitional (40≤p<60), dominant (60≤p<90), interior (90≤p<100), and intact (p=100%). Intact forest patches are dramatically reduced both in number and in area when the scale exceeds 13 x 13 pixels (15.21 ha).

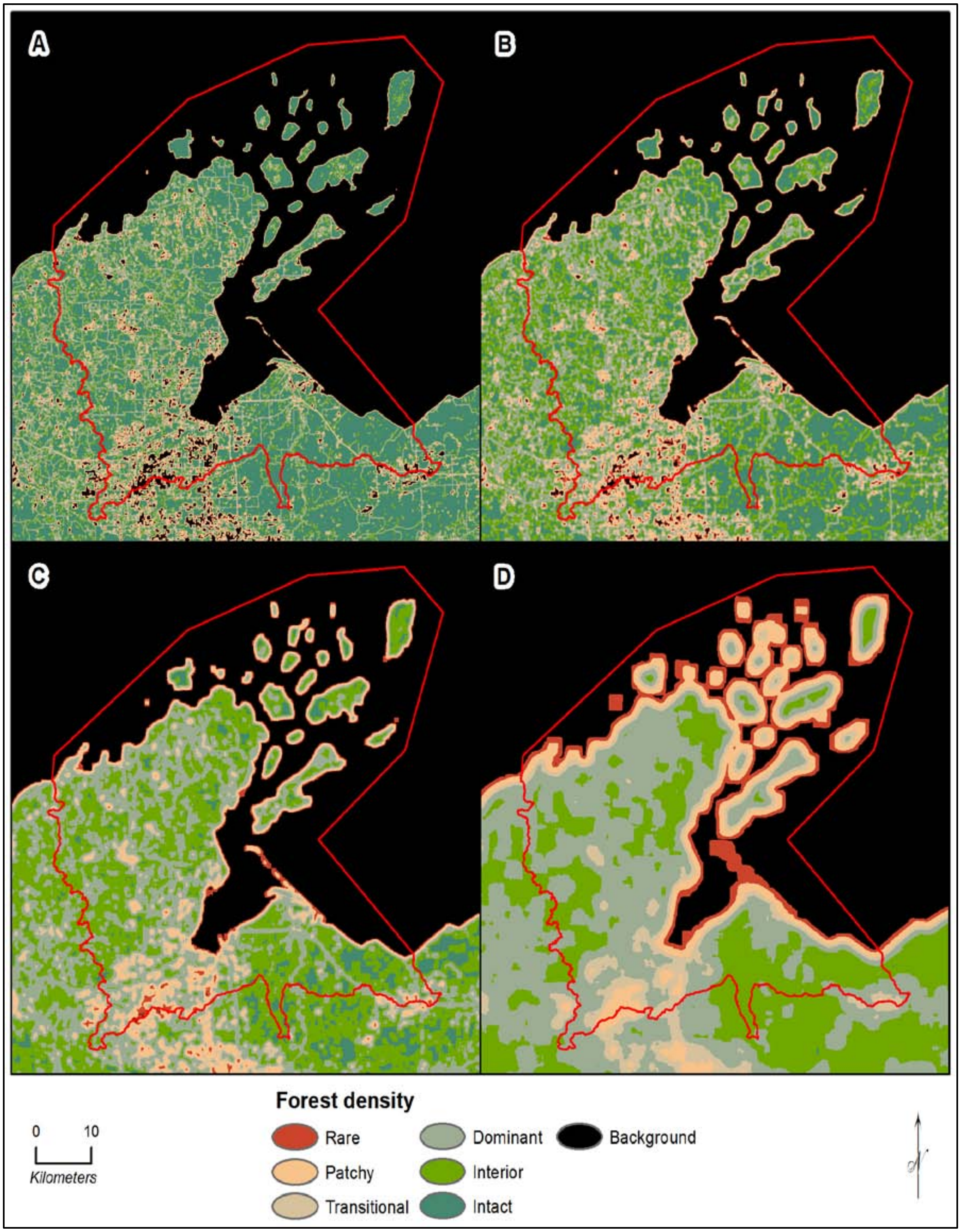

Figure 3. Forest density evaluated for four management-relevant landscape scales: (A) 7 x 7 pixels (4.41 ha), (B) 13 x 13 pixels (15.21 ha), (C) 27 x 27 pixels (65.61 ha), (D) 81 x 81 pixels (590.49 ha). Forested pixels considered in the analysis originated from NLCD 2006 (see Figure 2). Densities were calculated at the landscape (rather than sector) level. This causes forest density classes to grow in size beyond the original forest patches; such dynamics are important for resources that are influenced by proximity to forest. Forest density data from NPScape (National Park Service 2012a).

Roads as fragmentary features in the study region are further characterized by forest morphology (Figure 4). Forest morphology reports the structural classification of each forested 30 m pixel after "eroding" the edges of forest patches by two edge widths: 1 pixel, 30 m (Figure 4A); 5 pixels, 150 m (Figure 4B). The three most ecologically informative structural classifications are core, edge, and bridge. Core vs. edge describe two important types of forest habitat for species, while bridges constitute a form of structural connectivity. Core forest patches in the study region are highly sensitive to 30 vs. 150 m edge widths. The change in edge width dramatically increases forest edge, and interestingly also increases bridges on the mainland peninsula near Bayfield.

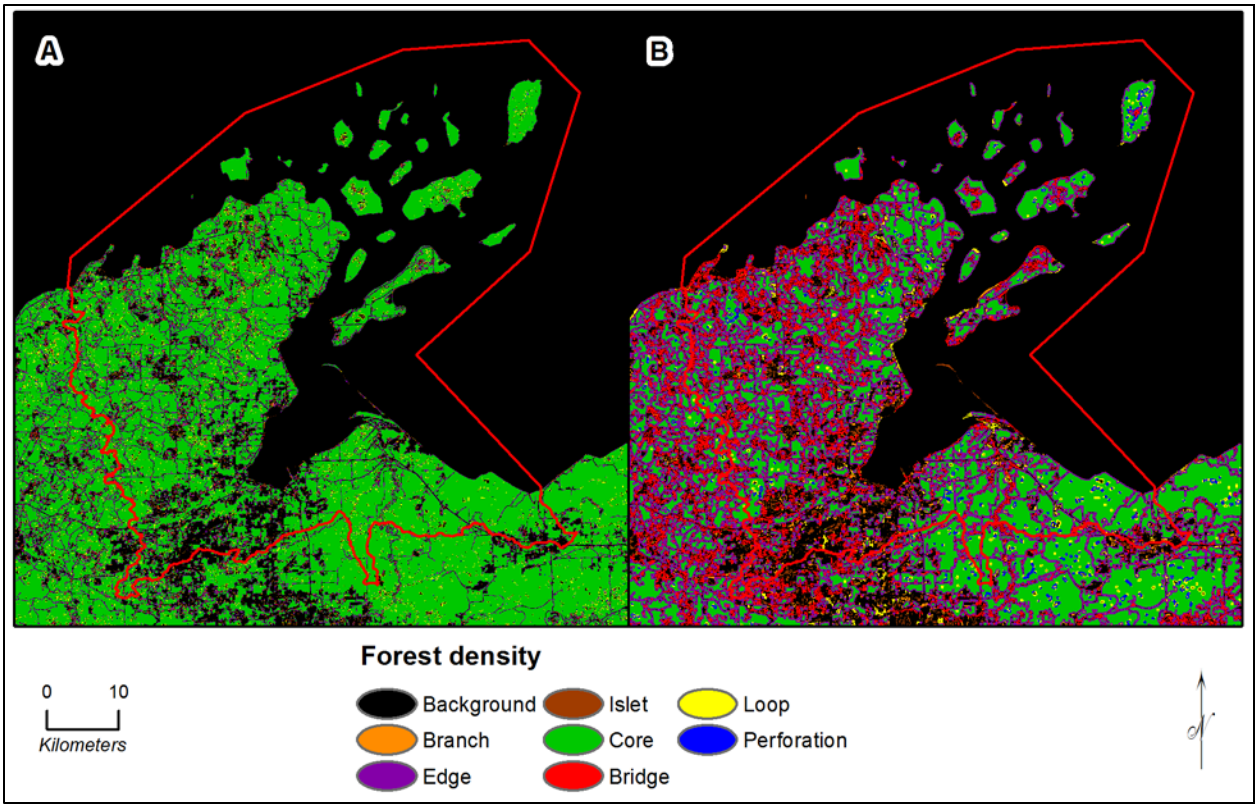

Figure 4. Forest morphology evaluated for two edge widths: (A) 1 pixel (30 m), (B) 5 pixels (150 m). Forested pixels considered in the analysis originated from NLCD 2006. Forest morphology data from NPScape (National Park Service 2012a).

Roads

The fragmentary effects of roads seen in Figures 3 and 4 are further described by patch size distributions of roadless area, calculated as areas >500 m from either major roads (interstates and highways; Figure 5A) or all roads (major roads and streets; Figure 5B). Comparing the two patch size distributions, it is apparent that most of the fragmentary effects of roads are due to the influence of streets and other minor roads (Figure 5B).

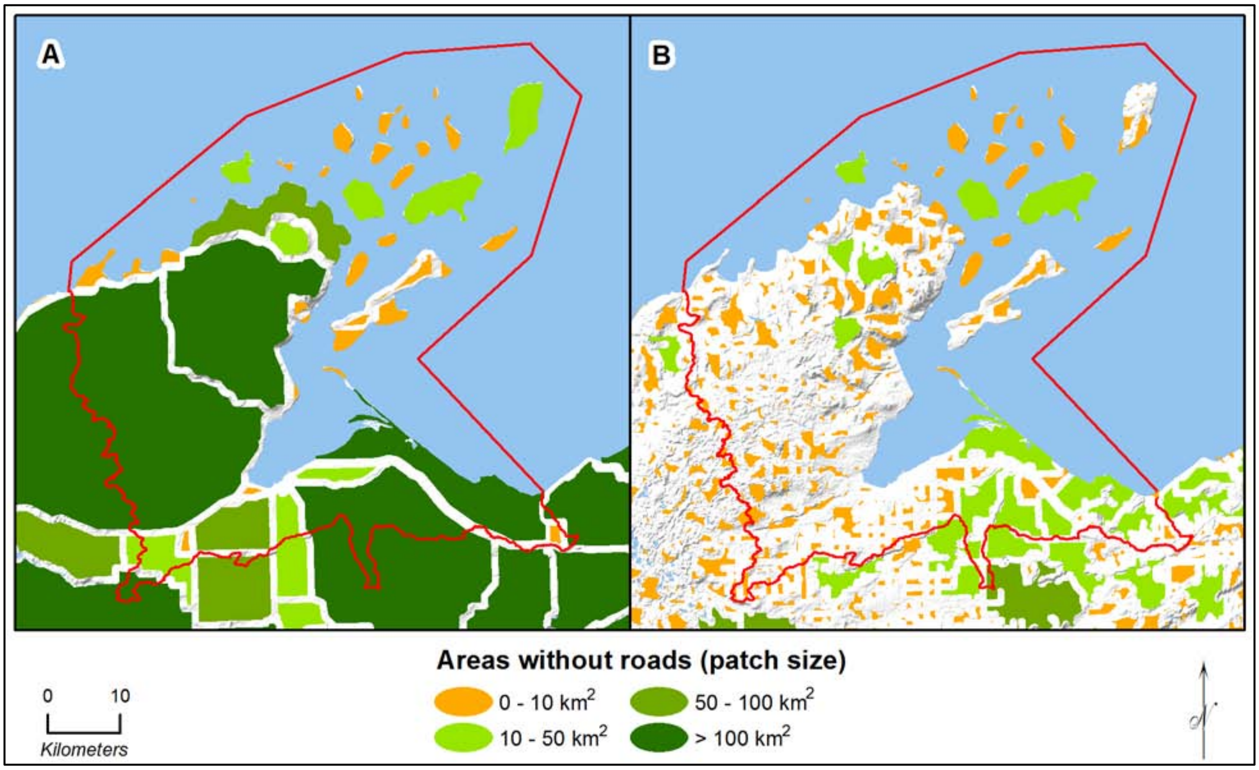

Figure 5. Patch size distributions of roadless areas calculated for two road classes: (A) major roads (interstates and highways), (B) all roads (major and minor roads). Roadless area data from NPScape (National Park Service 2012b).

Conservation Context

Most of the lands in the study area receive some formally designated level of protection (Figure 6). However, of these only about 25% receive the highest levels of protection, as seen in most national parks (GAP levels 1 and 2; Figure 6B). Lands that are classified as either GAP 3 or 4, or remain unclassified, are most susceptible to anthropogenic disturbance agents.

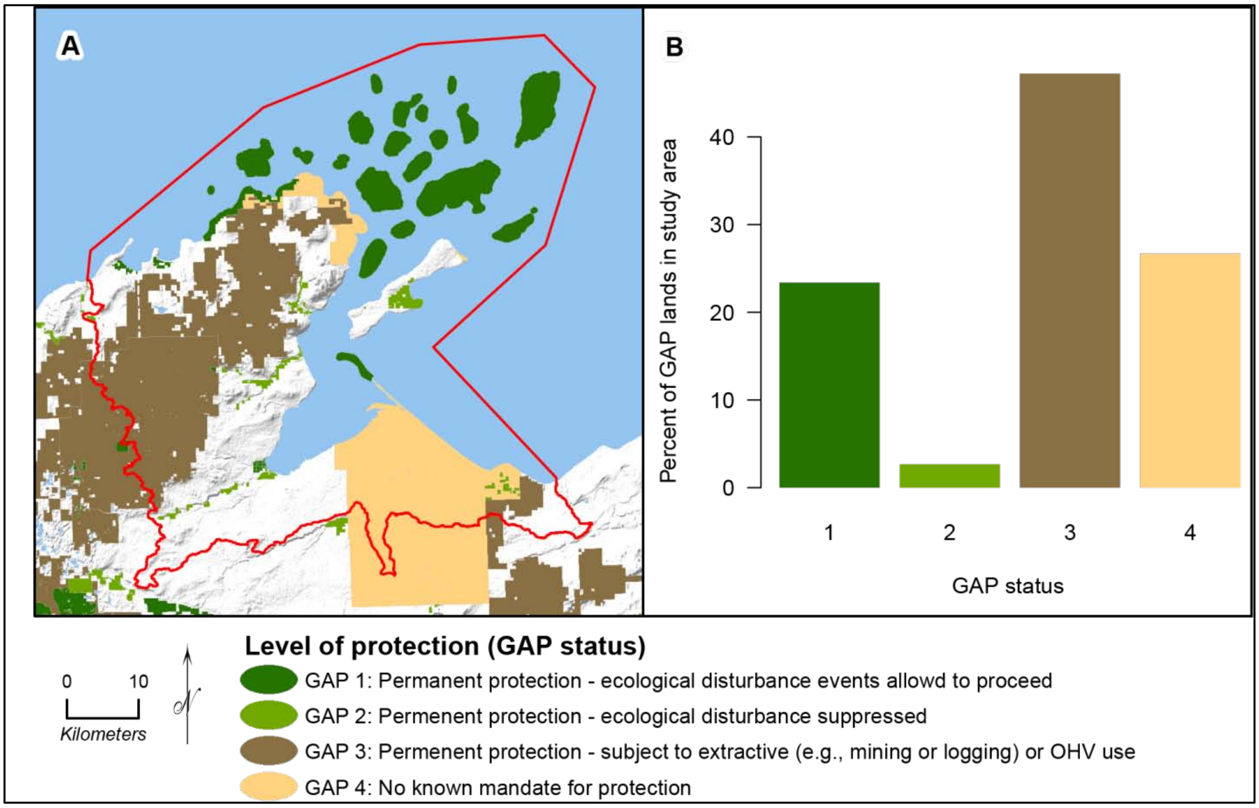

Figure 6. Conservation lands in the study region, reporting level and definition of protection (A), and a summary of the percentage of GAP lands in the study area by GAP status (B). GAP status codes from the Wisconsin Stewardship data of the USGS Gap Analysis program; summary statistics calculated by NPScape (National Park Service 2012c).

Methods

Image Data and Processing

Due to the location of Landsat scenes in reference to the park, two scenes (path 26 row 28 and path 26 row 27) were acquired for analysis (see Figure 1). *[NOTE: the word "scene" refers to the path/row address that is recorded every 16 days by the Landsat satellite; data recorded on a specific date is referred to as an "image"]* Landsat imagery was downloaded from the Landsat data archive via the U.S. Geological Survey's (USGS) GLOVIS website (http://glovis.usgs.gov/). To minimize the effect of phenology, imagery was selected in a two month window (July and August) during the peak growing season (Figure 7). For each year since 1984, the goal was to acquire enough imagery in the optimal phenological window such that one cloud-free composite of the entire study area could be used in the analysis. To aid in the production of the cloud-free composite, we also acquired a number of scan line corrector-off (SLC-off) images. These images include strips where there are no data due to a Landsat hardware malfunction, but nonetheless can be used to fill in critical gaps in the time series (http://landsat.usgs.gov/products_slcoffbackground.php). In total, 72 images (34 for scene 26/27, 38 for scene 26/28) were downloaded and processed for analysis. Each collection of images by scene will be referred to as a Landsat time-series (LTS).

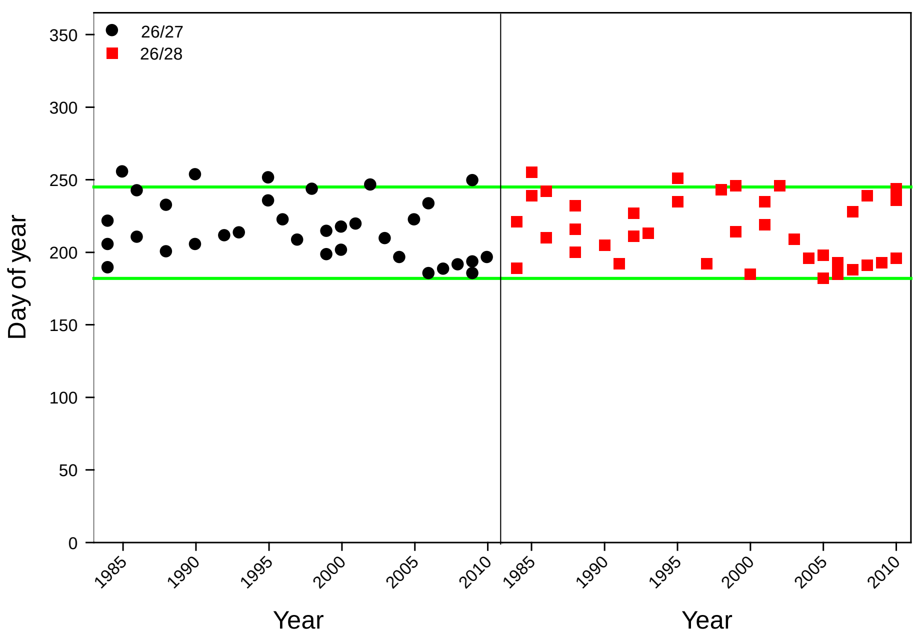

Figure 7. Day and year of Landsat images used for analysis for the two scenes (path 26 row 27 and path 26 row 28) with green lines denoting the time period between July 1st and August 31st.

Preprocessing of images (atmospheric correction, cloud screening, relative normalization) within each LTS followed details given in Kennedy et al. (2010b), and are briefly summarized here. Atmospheric correction was performed for a single reference image within each LTS using the COST model (Chavez 1996). All remaining images in the LTS were normalized using the MADCAL (Canty et al. 2004) approach to match the radiometric properties of the reference image. No effort was made to normalize each LTS to one another. We used an automated cloud masking algorithm that incorporates the thermal band, a digital elevation model (DEM), a forest mask, and sun illumination geometry to automatically detect and remove clouds and associated shadows (Huang et al. 2010b). For images from the ETM+ sensor after the onset of scan line errors (2003 and later), missing pixel data were also masked. The normalized, cloud-screened images in the LTS served as the foundation for subsequent processing.

Next we applied the LandTrendr segmentation algorithms to every pixel in each scene's processing area. For details regarding any part of the LandTrendr process, see Kennedy et al. (2010b). LandTrendr algorithms operate on a single detection index; a detection index can be any single band of information. For this analysis we used the normalized burn ratio (NBR), which contrasts the short-wave infrared with the near-infrared bands (Key and Benson 2006). The segmentation process then proceeds as follows. First, image data from the LTS files were converted to NBR values and matched on a pixel-by-pixel basis with the cloud mask. If the pixel was pre-determined to be part of a cloud, this pixel was not used. When multiple images from a given year were available, the image closest to the median date of the LTS in that scene was preferred, but if the pixel was again masked (cloud, cloud-shadow, or missing data), the pixel value from the image next-closest to the median was used. This was repeated as necessary until an unmasked pixel was available or until no more images were available. The time-series of these source data was then sent to the segmentation algorithms, which are controlled by a number of parameters affecting the balance between over- and under-fitting (Table 3). The first phase of segmentation is to determine the vertex years that define the end points of segments, and the second phase is to determine the best straight-line trajectory fit through those vertices using a flexible mix of either point-to-point or regression lines. The values returned from the segmentation algorithm are: the yearly source data (representing the best unmasked NBR value for that pixel in each year), the years at which vertex years were found, the fitted NBR values for those vertices, and the yearly fitted NBR data (the NBR value of each point in the segments describing the trajectory). These data were written out as separate files to be used by subsequent mapping algorithms. A diagram providing an example of how the segmentation algorithm processes an individual pixel is provided below (Figure 8).

Table 3. Parameters used in the LandTrendr process.

Process	Parameter	Value
Segmentation	Spectral index	Normalized burn ratio
	Maximum number of trajectory segments	6
	Maximum p-value for fitting	0.05
	Recovery threshold	1
	Despiking threshold	0.9
	Best model proportion	0.75
Filtering	Percent loss threshold at 1 yr	10
	Percent loss threshold at 20 yr	5
	Pre-disturbance cover threshold	20
	Percent gain threshold for growth	5
Mapping	Minimum mapping unit	9 pixels (ca. 1 ha)

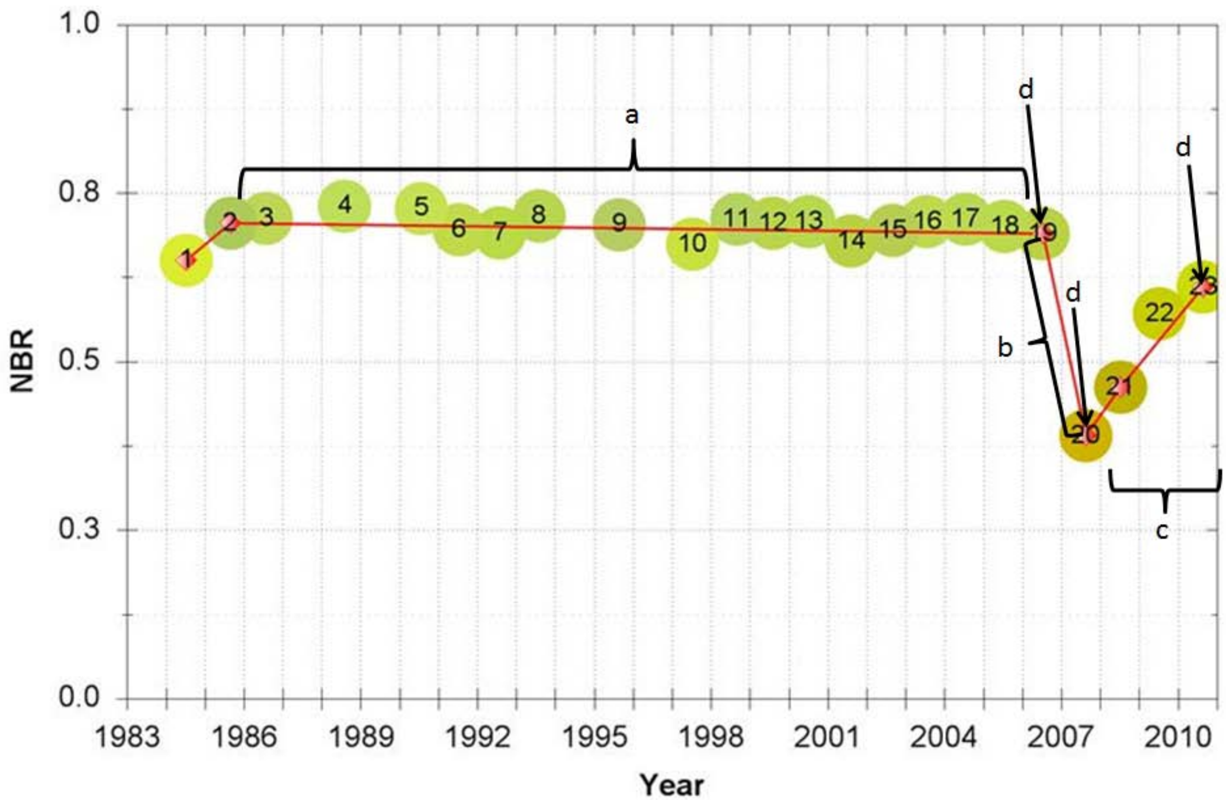

Figure 8. Diagram of how the LandTrendr segmentation algorithm processes a single pixel. The x-axis is the year of image acquisition and the y-axis is defined by the NBR value. Generally, NBR values range from low to high dependent on the amount of vegetation present. This graph shows a single pixel's NBR value from 1984 to 2011. We would interpret this graph as: stable vegetation cover from 1985 to 2006 (a), with subtle variation, or noise, each year, then a disturbance occurring in 2007 (b), causing a loss of vegetation, then recovering (c), to its original condition. This diagram also gives examples of vertices (d) connecting straight segments representing a smoothed pixel trajectory through time.

Disturbance polygons for the area were derived from the vertex files in several steps. For each pixel, disturbance segments were defined as those showing a decline in NBR value. A simple regression model was used to convert the NBR values to estimates of percent vegetative cover developed at 92 plots (Table 4 and Figure 9). The magnitude of disturbance for a segment was defined as the difference between the calculated vegetation cover values of the starting and ending vertices. This magnitude was divided by the pre-disturbance cover value to create a relative magnitude value truncated to ensure a range of 0 to 100%. Segments were accepted for further processing only if their relative magnitude value was greater than a threshold parameter (see Table 2 for parameters). This filtering is an effective means of reducing false changes from overfitting of anomalous or ephemeral spectral features in the times-series.

Table 4. Percent cover model parameters and summary statistics for each scene in analysis area.

Scene (path/row)	Model parameter	Value
26/27	NBR	123.119
	y intercept	10.613
	Degrees of freedom	49
	Adjusted R-squared	0.90
	Residual standard error	7.7
26/28	NBR	167.205
	y intercept	-22.491
	Degrees of freedom	41
	Adjusted R-squared	0.82
	Residual standard error	11.4

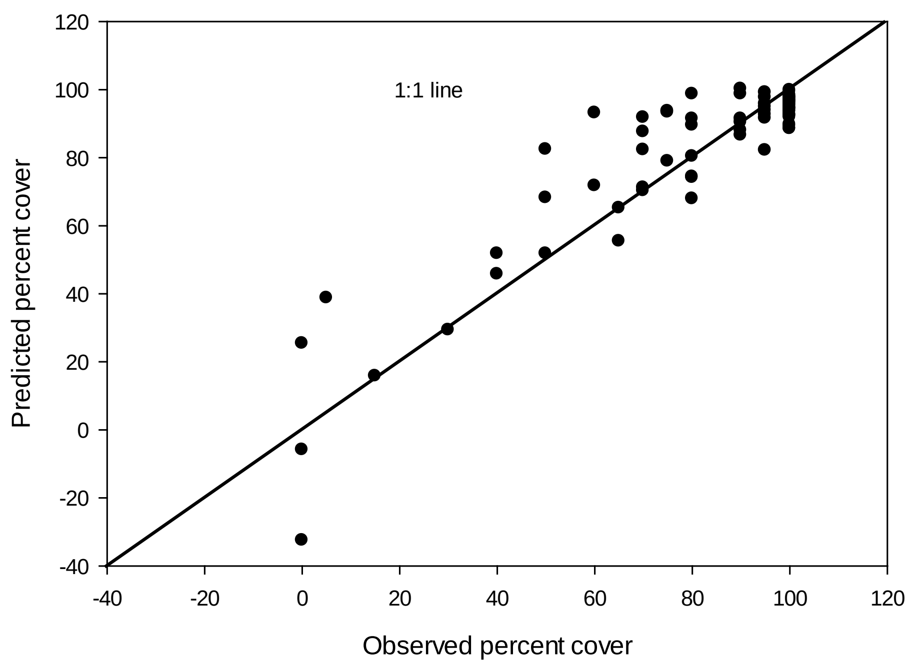

Figure 9. Predicted versus observed percent cover results from model predictions.

To create the final disturbance polygons, minimum mapping unit (mmu) rules were applied to ensure that patches of disturbance were at least nine pixels (0.81 ha) in size. The nine-pixel mmu captures most of the disturbances of interest to the Network (timber harvest, blowdown, fire, forest pathogen, beaver activity, development, and farmland conversion), while large enough to minimize the large numbers of small disturbances which would take us too long to validate. Adjacent pixels in a given year were grouped together into patches using an eight-neighbor rule, and each group was assigned a unique identifier. After group membership was determined for all pixels, any groups with fewer than 9 pixels were identified and removed. For remaining patches, gaps smaller than 9 pixels were filled if they were adjacent to three non-background pixels using a 4-neighbor rule. This gap filling was applied iteratively three times. In each iteration, the median of the surrounding pixels was used to assign values to the filled pixels; these were then added to patches.

Validation of Disturbances

Validation of possible disturbances followed details given in Kirschbaum and Gafvert (2010a), and is briefly summarized here. After disturbance polygons were created, the next step was to validate whether a change actually occurred in the polygon. In addition to validating whether changes occurred, additional information such as the change agent (Table 5) and the starting and ending vegetation classes were added during the validation process. Using high resolution imagery (Table 6), we were able to determine whether changes had indeed occurred, and by using contextual information we were able to determine the disturbance agent. In addition to using high resolution imagery, we also used an application called TimeSync (Cohen et al. 2010). This program allows the user to view composite image chips of the entire stack of Landsat imagery for pre-determined locations as well as the associated spectral trajectory of the pixel through time.

By viewing the high resolution aerial photos of the disturbance, its corresponding location on the series of Landsat image chips, and its spectral trajectory, we could make a well-informed decision regarding the validity and nature of change. To limit the potential for bias, two interpreters validated all disturbances. If a disturbance occurred within a polygon, additional attributes (fields) were populated within the feature class. These included most likely starting and ending class, using Version 1 of the 2001 National Land Cover Database (Homer et al. 2004), disturbance agent, post-timber harvest remaining percent cover, and whether the polygon was a candidate for field visit (Table 7).

We made field visits to 18 disturbance polygons to verify either the disturbance agent or the level of forest harvest. These visits occurred in the fall of 2011, and they confirmed that we had correctly estimated the amount forest harvest and identified disturbance agents. Details of the field validation, including photos and map of disturbances visited, are provided in Appendix E.

Table 5. Disturbance agents and definitions for each.

Disturbance agent	Definition
Agriculture	Disturbance caused by human activity by converting non-agricultural land to row crops.
Beaver	When beavers flood a previously wooded wetland, it usually kills trees, which then show up as a disturbance.
Blowdown	The uprooting and tipping over of trees by the wind. Strong wind events, sometimes termed 'straight-line winds,' can create varying patch sizes of downed trees. These blown down trees are evident in high resolution airphotos and are usually oriented in the direction of the wind event. If this event occurs on private lands and a salvage harvest occurs before it is seen, it is classified as a harvest.
Development	Permanent conversion of vegetated surface to non-vegetated surface such as mines, paved roads, parking lots, and buildings.
Fire	Detection is limited to instances where there is mortality in the overstory. Thus, areas in which fires only burn the understory are not delineated.
Harvest	Forest harvests, including clearcuts and thinnings, new logging roads, and post-harvest prescriptions such as herbicide application or scarification.
Forest pathogen	Disturbances (mortality) in the overstory due to insects (e.g., forest tent caterpillar, spruce budworm) or diseases (e.g., oak wilt).

Table 6. Aerial photos and high resolution satellite imagery used for validation. For explanation of acronyms used in this table, see list of acronyms on page xv and xvi.

Date	Resolution (meters)	Spectrum	Funding source	Type	Analysis area coverage
1992	1	B&W	APFO-NAPP	Airphoto	Entire
1998	1	B&W	APFO-NAPP	Airphoto	Bayfield county
Summer 2004	2	RGB	APFO-NAIP	Airphoto	Ashland county
Fall 2004	0.2	CIR	GLKN	Airphoto	APIS & part of peninsula
Spring 2005	0.3	RGB	GLKN	Airphoto	APIS
Summer 2005	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2006	2	RGB	APFO-NAIP	Airphoto	Entire
Summer 2008	1	RGB	APFO-NAIP	Airphoto	Entire
Fall 2008	0.3	RGB	NGA	Airphoto	APIS: entire, Non-APIS: partial
Spring 2009	0.15	RGB	Bayfield County	Airphoto	APIS: partial Non-APIS: partial
Spring 2009	0.3	RGB	Bayfield County	Airphoto	APIS: partial Non-APIS: partial
Spring 2010	0.2	RGB & CIR	GLKN	Airphoto	APIS
Summer 2010	1	RGB	APFO-NAIP	Airphoto	Entire

Table 7. Attributes filled in during the validation process at each polygon.

Field	Definition
Location	APIS or Non-APIS
High resolution airphoto	List (3) of the airphoto sets used to attribute polygon
Landsat imagery	List (3) of the years of Landsat imagery used to determine validity
Start class	Starting vegetation class(es), as noted in the 2001 NLCD (version 1). We indicate the three dominant (by area) vegetation classes present in the polygon.
Start class percent	Because the entire polygon is not always affected, this value is used to compute the actual area disturbed within the polygon.
End class	Ending vegetation class(es) present after the disturbance has occurred. These classes are determined using a decision tree as described in Kirschbaum and Gafvert (2010a).
End class percent	Same as start class percent, but for the ending vegetation class.
Disturbance agent	The interpreter uses all available contextual knowledge and available imagery to indicate the disturbance agent responsible for the change. For a list of possible agents, see Table 4.
Post-timber harvest remaining percent tree cover	In instances where there was not a clearcut (<20% tree cover remaining), the interpreter estimated the percent of tree cover remaining (±10%)
Field validation candidate	If the interpreter was not confident of the decision made by viewing available imagery and spectral trajectories, they would indicate that a field visit was necessary to confirm the polygon with a field visit.
Lab interpreter	Initials of interpreter who validated the polygon.

Land and Water Mask

To compare the amount of land disturbed in each analysis area, we summarized the total amount of land within them. We chose one cloud-free image from each Landsat scene (see Figure 1 inset) and developed a water index by dividing band 5 (shortwave infrared) by band 2 (green), used to distinguish water from land (Alesheikh et al. 2007, Ji et al. 2009). The resulting image was overlain on an airphoto from the same time period as the Landsat image used to compute the index, and a numerical threshold was chosen that eliminated persistent bodies of water, yet preserved low-lying areas subject to periodic flooding during times of high water levels. Thus, wetlands and seasonal bodies of water in this simple classification are considered to be ‘land.’

Results

See Appendix D for data tables used to create the graphs below.

Percent of Land Disturbed

APIS

During the six-year study period, a total of 7.48% of the land (1,276 ha) was disturbed inside the park. The only year with a significant amount of disturbance was 2006, in which multiple islands experienced a defoliation event by the saddled prominent caterpillar (*Heterocampa guttivitta*). In 2006 alone, 1,271 ha of land (7.45%) was disturbed, but this disturbance event did not result in tree mortality. There were small amounts of disturbance in years 2007 and 2008, representing a total 0.03% of land area in the park (Figure 10, Table D2).

Non-APIS

Collectively, 3.94% (0.66%/year) of the land (6,752 ha) outside the park was disturbed during the six-year period. The percent of land disturbed gradually increased to a peak in 2007 (0.97%) but was lower both before and after 2007 (Figure 10, Table D2).

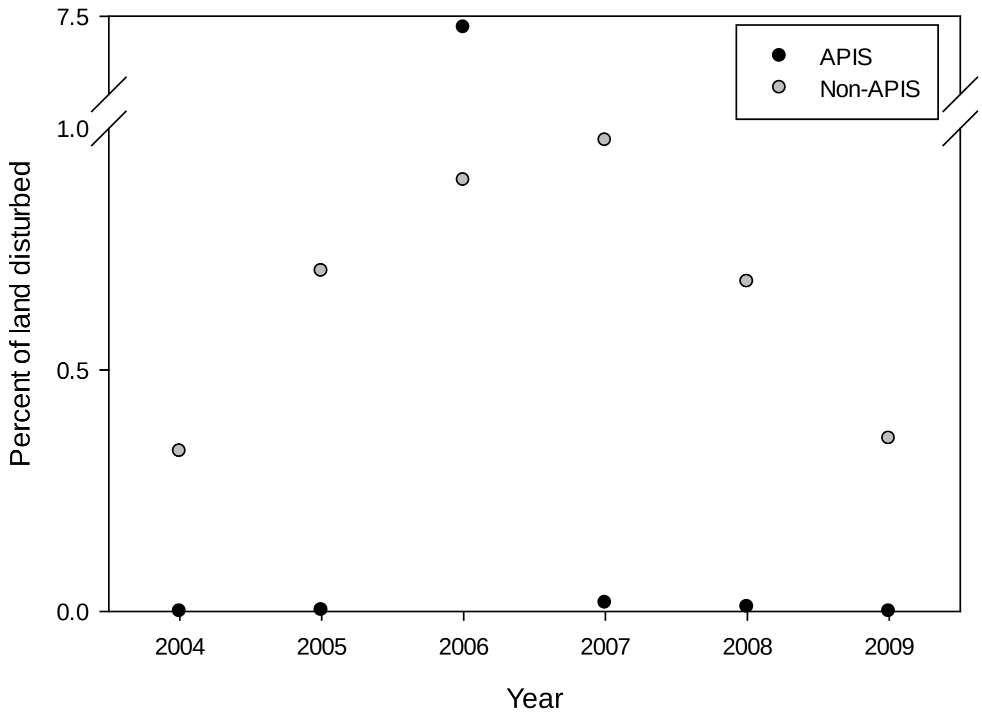

Figure 10. Percent of land disturbed by year and analysis area.

Disturbance Agents

See Table 5 for descriptions of these casual agents. Maps of the disturbance polygons are found in Appendices A (APIS) and B (Non-APIS).

APIS

During the six-year analysis period, there were three different disturbance agents detected inside the park boundaries: beaver, development, and forest pathogen. In 2005 there was a small development disturbance (ca. 0.5 ha) at Meyer's Beach due to enlarging the parking lot and adding a picnic area (Figure 11, Table D4). Following this disturbance, there were three consecutive years (2006-2008) of disturbances due to beaver activity, with the largest amount of area disturbed in 2008. Lastly, the park experienced a large defoliation event starting in 2006, affecting ca. 7.5% of the land inside the park (Figure 12, Table D4). The disturbance agent was a native caterpillar, the saddled prominent caterpillar, which preferentially defoliates hardwood species and was first recorded in the U.S. and Canada in the early 1900s (Rush and Allen 1987). The islands affected in 2006 included Rocky, South Twin, Otter, Cat, Outer, Ironwood, Manitou, and Stockton. In 2007, the insect only affected 1.7 ha. of land, all on Stockton Island (Figures 11 and A1, Table D4).

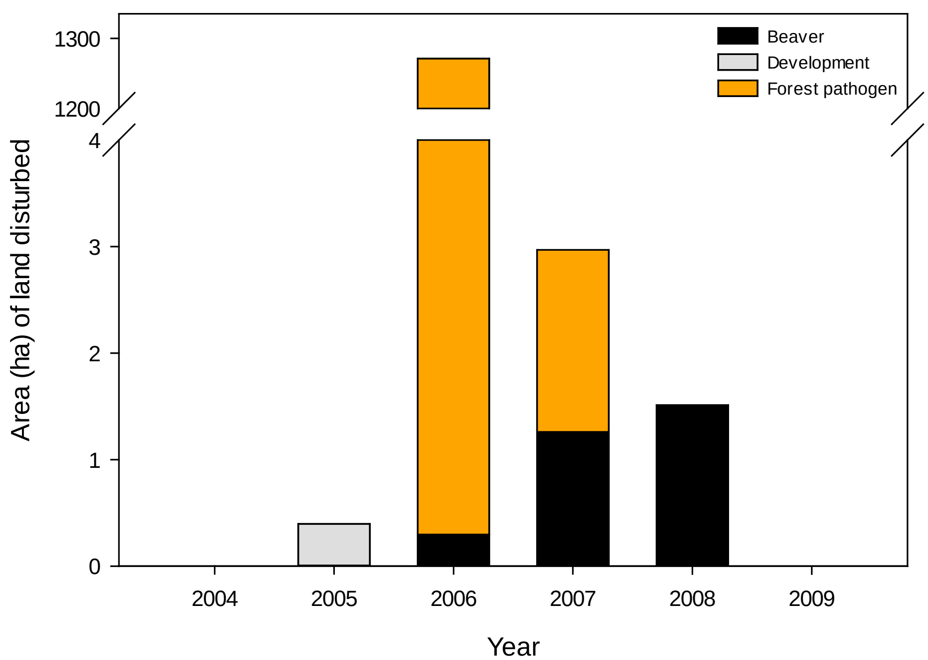

Figure 11. Area of land (hectares) disturbed by causal agent and year inside APIS during the analysis period.

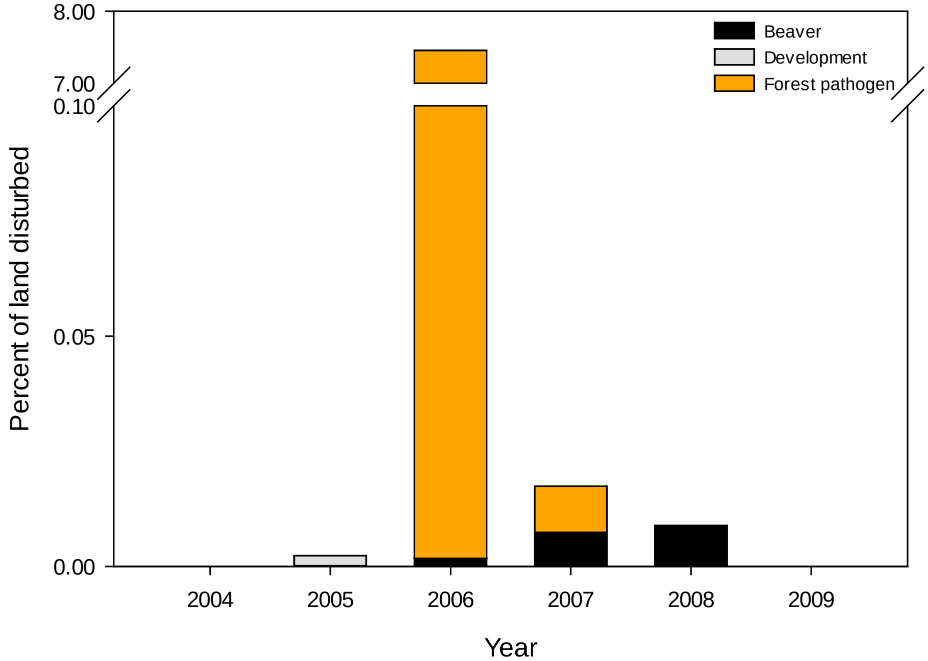

Figure 12. Percent of land disturbed by causal agent and year inside APIS during the analysis period.

Non-APIS

Forest harvest was the dominant disturbance agent outside the park. Harvest occurred in each year of the analysis period, and peaked in 2007 with nearly 1% of the land outside the park experiencing some level of this harvest. In addition to forest harvest, development was one of the most consistent, albeit minor, disturbance agents, occurring in each of the analysis years (Figure 13, Table D4). There was also some beaver activity outside the park, with disturbances in each of the years, although when totaled over the analysis period, they affected <0.1% of the land. The final two disturbance agents present were fire (2007 and 2008) and conversion of land to agricultural (2006-2009) (Figure 13 and Table D4).

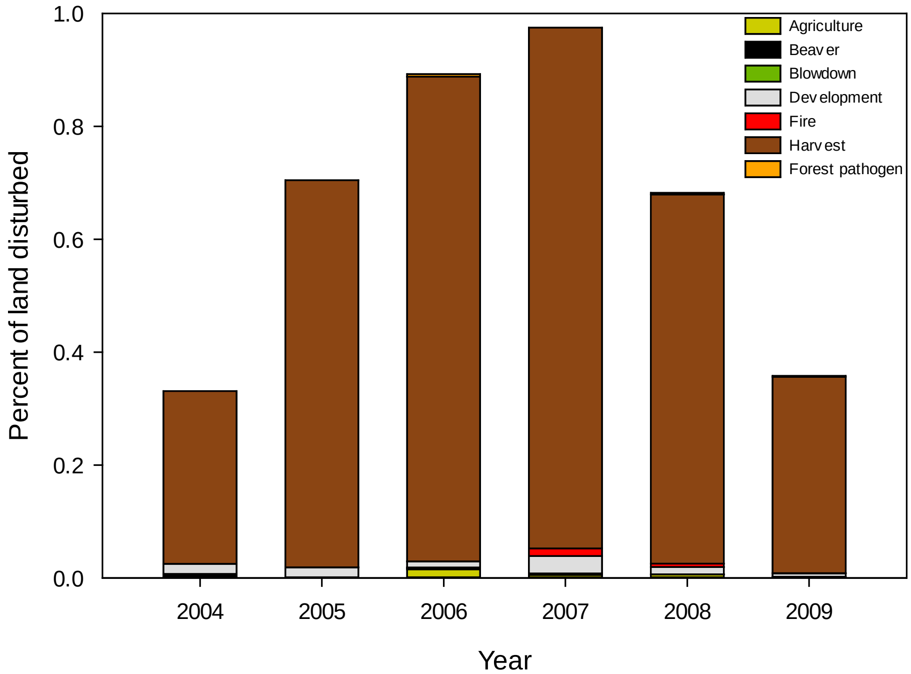

Figure 13. Percent of land disturbed by causal agent and year outside the park boundary (Non-APIS) during the analysis period.

Land Cover Dynamics

It is possible to identify up to three distinct starting and ending classes for polygons that encompass multiple cover types. For more details on how starting and ending classes are defined and chosen, see Kirschbaum and Gafvert (2010a). To facilitate displaying data in this report, starting and ending classes have been combined into generalized groupings (Table 8).

Table 8. Generalized starting and ending vegetation classes used to describe disturbance polygons, with the composition of each generalized class.

Generalized class	Groups in this general class
Upland forest	Upland evergreen forest, upland deciduous forest, upland mixed forest
Upland woodland	Upland evergreen woodland, upland deciduous woodland, upland mixed woodland
Upland shrub/herb	Upland shrub, upland herbaceous
Lowland forest	Lowland evergreen forest, lowland deciduous forest, lowland mixed forest
Lowland shrub/herb	Lowland shrub, lowland herbaceous
Development	Development
Agricultural	Agriculture
Road	Impervious road, pervious road, unknown road
Water	Water
Bare ground	Beaches, rock, rocky outcrop, gravel, bare ground, impervious surface, pervious surface

APIS

The large forest pathogen outbreak in 2006 did not result in a change of cover type within the park (Figure 14). This was due to the disturbance event only being defoliation and not mortality. In 2005, upland forest was converted to the development class, and in 2007 a beaver disturbance converted water to the lowland shrub/herb class. Lastly, in 2008 a beaver disturbance converted lowland shrub to lowland herbaceous and standing water (Figure 14).

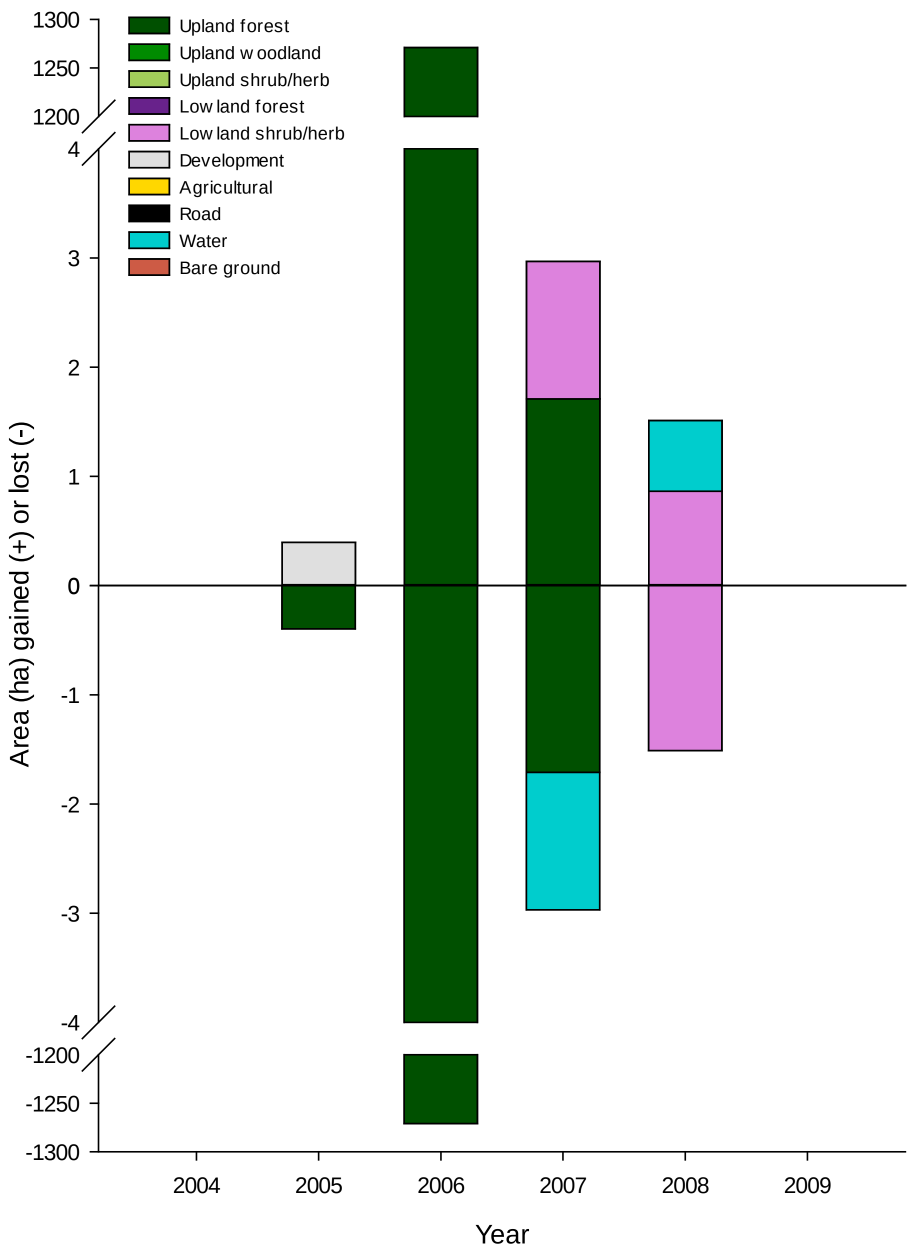

Figure 14. Area (in ha) of vegetation cover type lost (-) and gained (+) at APIS during the analysis period (2004-2009). In some cases (year 2006) the vegetation lost is the same amount and type as vegetation gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to shift the vegetation type.

Non-APIS

Outside the park, the majority of the disturbances occurred in upland forest, which was most often converted to upland woodland and upland shrub/herb (Figure 15). In instances where the forest harvest was a thinning and >50% of the canopy cover remained, it remained in the forest vegetation class as described in Kirschbaum and Gafvert (2010a). The remaining classes that gained area (in order of greatest to least) were development, road, bare ground, agriculture and water. Specific values can be found in Table D9.

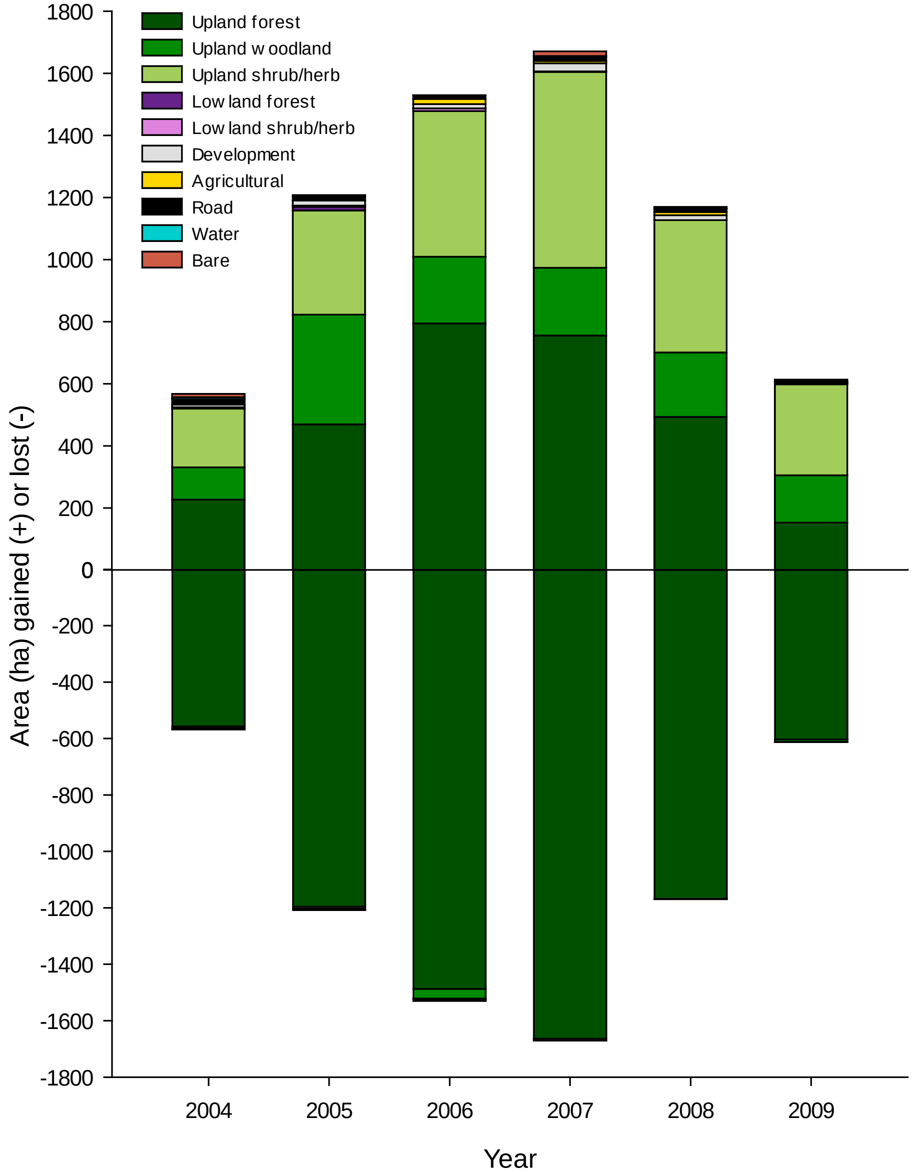

Figure 15. Area (in ha) of vegetation cover type lost (-) and gained (+) outside APIS during the analysis period (2004-2009). In most years the vegetation lost is also represented in the vegetation gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to shift the vegetation type. One such example is a forest thinning which removes a portion of the tree cover, but is still classified as forest because it did not meet the lower percent cover threshold for woodland.

Disturbance Agents by Ownership Type

The bulk of the analysis area falls into private ownership, with the next largest landowner within the area being Bayfield County, which owns a large portion of the peninsula. In the southern portion of the analysis area, the Bad River Band of Lake Superior Chippewa owns the majority of the land and a large portion of the Bad River watershed (Figure 16 and Table D5). We used the Wisconsin Stewardship data of the USGS Gap Analysis Program to attribute each disturbance to a particular land owner, allowing the summarization of disturbances by land owner.

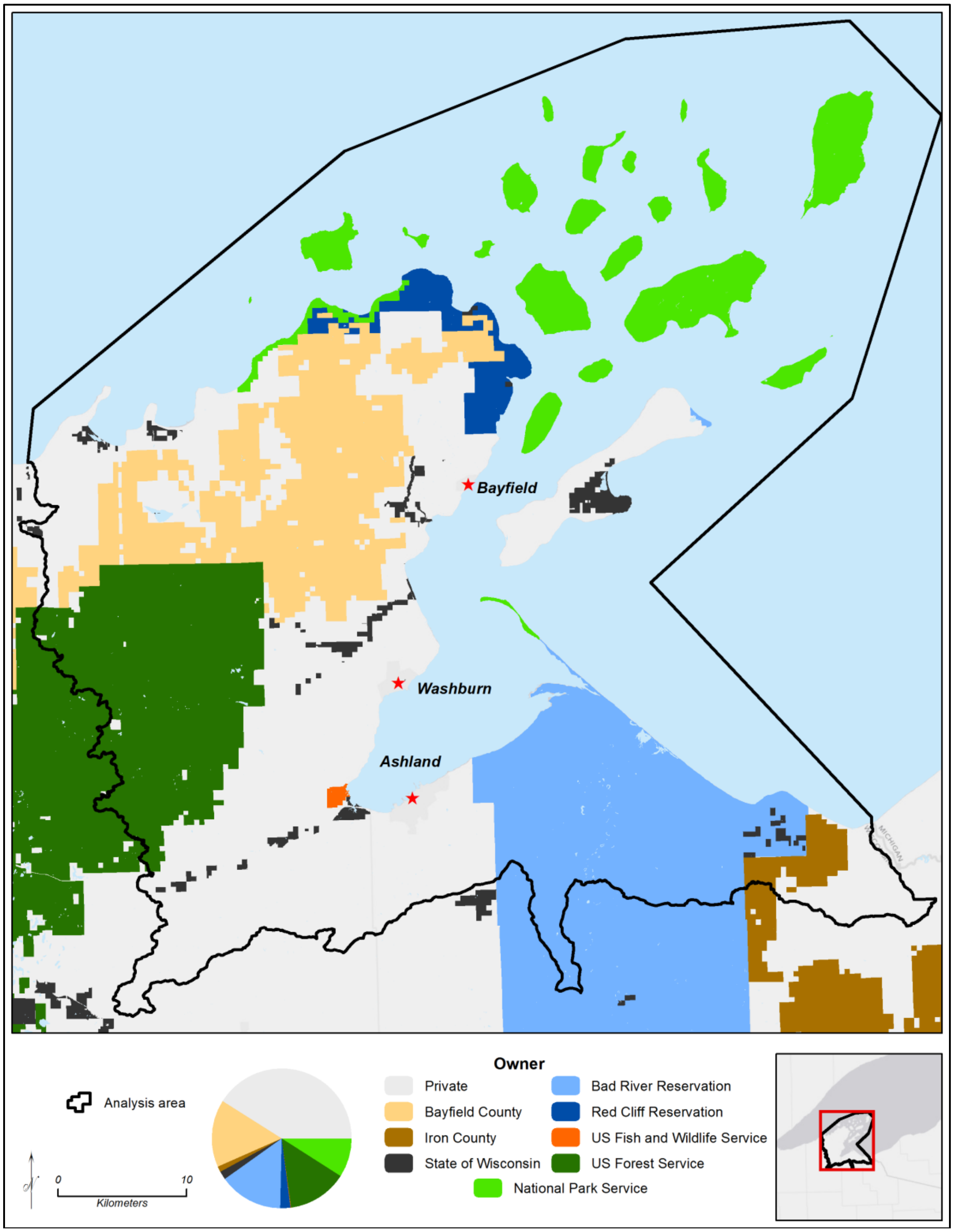

Figure 16. Map with pie graph of ownership types within the analysis area (solid black line).

The total amount of disturbed land was summed for the analysis period to provide information regarding the amount and type of disturbance by land ownership (Figure 17). The U.S. Forest Service (USFS) disturbed the largest percent of land (8.92%) among the ownership types in the analysis area. Forest harvest represented the majority of disturbances for the USFS, with fire and beaver being the only other disturbance agents within this ownership. The National Park Service had a large amount of disturbance as well, although the majority of this disturbance was from the outbreak of the saddled prominent caterpillar in 2006. In contrast, the Bad River Reservation experienced the least amount of disturbance among ownership types, with disturbances occurring largely due to forest harvests, along with some minor disturbance by beaver. The Red Cliff Reservation and private lands were the only two land owners with >0.1% disturbance due to development. Lastly, Bayfield and Iron counties were largely dominated by forest harvests, with insignificant (<0.01%) amounts of other disturbances (Figure 17 and Table D6).

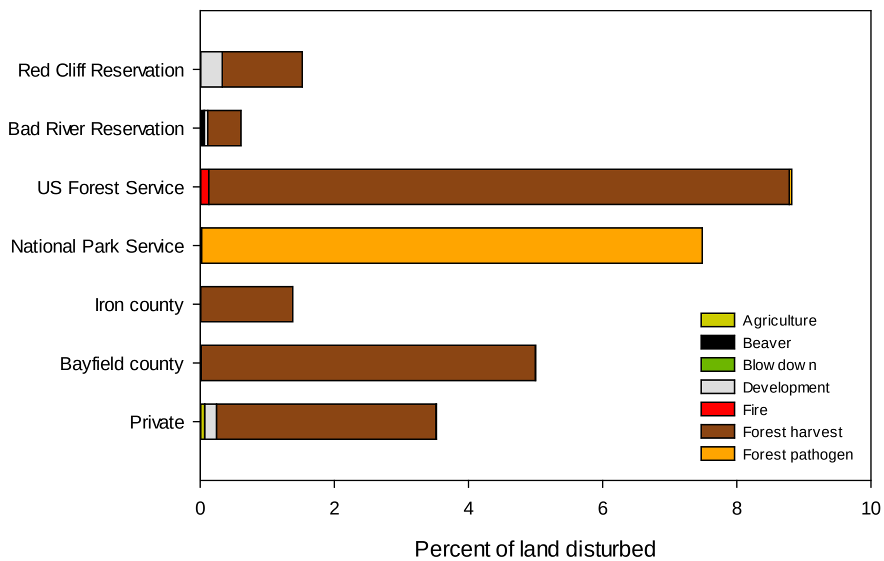

Figure 17. Percent of land disturbed by land owner and disturbance agent, totaled for the analysis period (2004-2009).

During the validation process, each forest harvest is attributed by percent cover remaining, and 95% of forest harvest disturbance on USFS lands showed a degree of thinning rather than clearcut (Figure 18). Iron County forest lands showed the second highest percentage of thinning, but they had a very small percentage of total land harvested (ca. 1.5%). The landowner utilizing the lowest amount of thinning (compared to clearcuts) was Bayfield County, which still had 51% of their harvests experience some level of thinning (Figure 18 and Table D7).

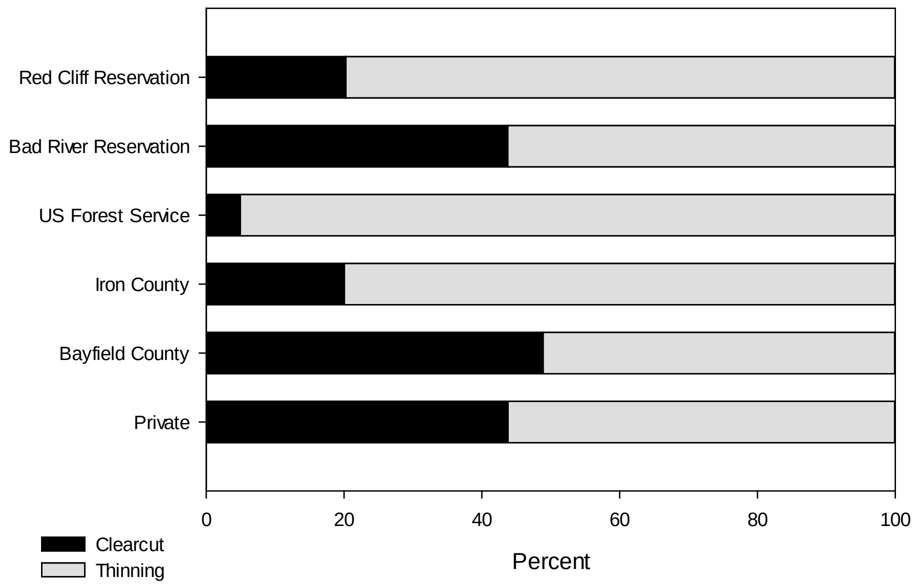

Figure 18. Percent of forest harvests in each of two categories, clearcut and thinning by land owner.

In addition to generating the ratio of clearcut:thinnings, we summed the total number of thinnings and normalized this number to compare across land owners by calculating the number of thinnings per 1,000 ha of land. To determine the mean level of thinning across ownership types the mean percent of tree cover remaining after the thinning activity was also calculated. Of the land owners experiencing >2% disturbance due to forest harvest (Bayfield County, private, USFS), USFS had the greatest number of thinnings/1,000 ha (11.61), followed by Bayfield County (3.57) and private ownership (3.12). Alternatively, the USFS had the lowest mean percent of tree cover remaining after thinnings (39%), while Bayfield County and private lands had the same percent remaining cover (47%) (Figure 19 and Table D7). The spatial distribution of clearcuts and thinning is displayed in Appendix C.

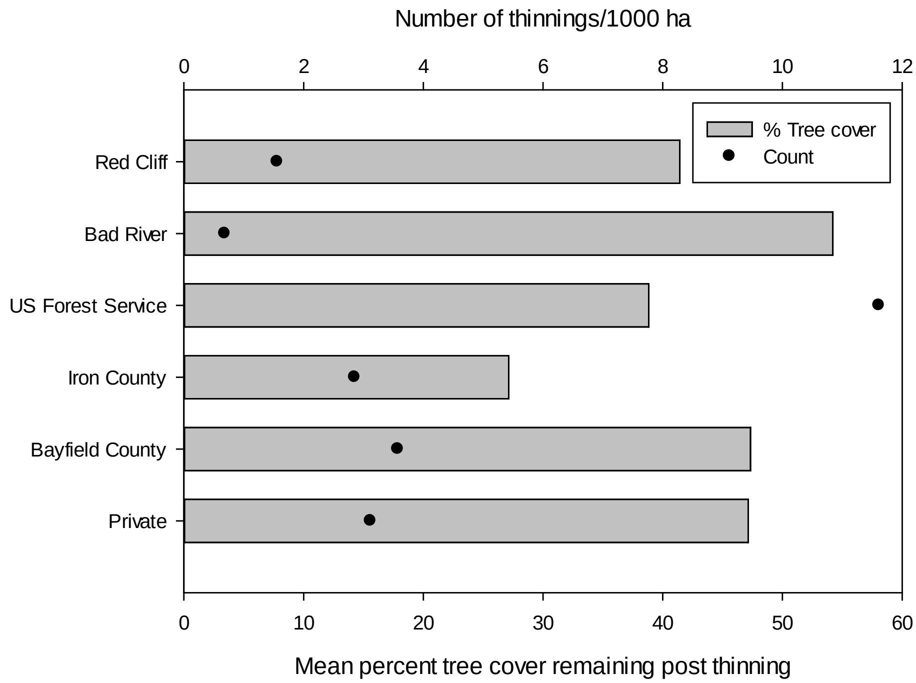

Figure 19. Mean percent of tree cover remaining post thinning (bars) and the count of thinnings per 1,000 ha of land by land owner (dots).

Discussion

APIS

There was much less disturbed area inside the park than outside of it. This difference was expected due to the very different management strategies used by the NPS compared to landowners throughout the rest of the analysis area. The goal of the National Park Service, as defined in the Organic Act, is "…to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations" (16 U.S. Code, Subch. 1). As such, management inside national parks differs greatly from the strategy of private landowners and even other agencies such as the USFS. This variation is well summarized by the conservation status of lands in the region, which is a reflection of the levels of protection (see Figure 7).

While the near absence of human-caused disturbance at APIS in all years but 2006 was expected, a healthy ecosystem must have enough natural disturbances to maintain a diversity of habitats for native plants and wildlife. Certainly, there have been large scale disturbances in the past; with logging occurring on most of the islands, starting in the 1840s, with the most recent logging occurring in 1974 on Outer Island (Busch 2008). Following these disturbances, various islands were inhabited and used for multiple purposes including farming, fishing, logging, and residence (both primary and secondary) (Busch 2008). However, since these events, the amount and type of disturbances has been largely undocumented, thus leaving a void in the disturbance regime history. The rates and types of disturbances considered "normal" for an area the size of APIS is a question that needs further consideration. Fortunately, this program can help provide important insights into such questions over time.

Non-APIS

By monitoring a substantial amount of land outside the park boundary, we were able to gain an ecologically relevant landscape perspective and evaluate the dominant disturbance agents by land ownership, something not normally done by agencies focused on their boundaries. The results from the analysis showed that the USFS had harvested nearly 9% of their lands, although the majority (95%) of the harvests was some level of forest thinning, with an average of 40% tree cover remaining, post-harvest. Among landowners, USFS harvested the largest percentage of their lands, followed by Bayfield County, with nearly 5% of their land being harvested. After USFS and Bayfield County, the next largest timber harvester was private land owners (3%). We expected private land owners as the most likely group to take advantage of their forested land by harvesting merchantable timber to either help pay mortgages or property taxes. However, this is not the case within the analysis area, with only 3% of private lands showing some level of harvest. However, we have only analyzed the most recent six years and these patterns may change in the future. If it does, we will be in the position to see how land ownership and disturbance regimes change, and how patterns of forest harvest affect forest pattern (see Figures 3 and 4).

Comparison Across Park Units

Landscape disturbance detection has been completed at two other park units within the GLKN: Voyageurs (VOYA, Kirschbaum and Gafvert 2010b) and Isle Royale (ISRO, Kirschbaum and Gafvert 2012) national parks. At both parks, the analysis area was expanded to regions outside the park boundary, allowing us to evaluate landscape change in the park within the context of the surrounding environs. The years summarized were 2002-2007 and 2003-2008 for VOYA and ISRO, respectively. At VOYA the analysis area included a large area north of the park and an area south of the park boundary (Figure 20). Ownership north of the park was largely comprised of provincial Crown lands rented for timber production, while the area to the south was a mix of ownership types, including federal (USFS), state (Department of Natural Resources), and private. At ISRO, the extended analysis area included the mainland shoreline north and south of Thunder Bay, Ontario, Canada, including the Sibley Peninsula (Figure 20). This analysis area was largely dominated by Crown lands, with more private ownership occurring in and around the city limits of Thunder Bay, and a large provincial park on the southern half of the Sibley Peninsula.

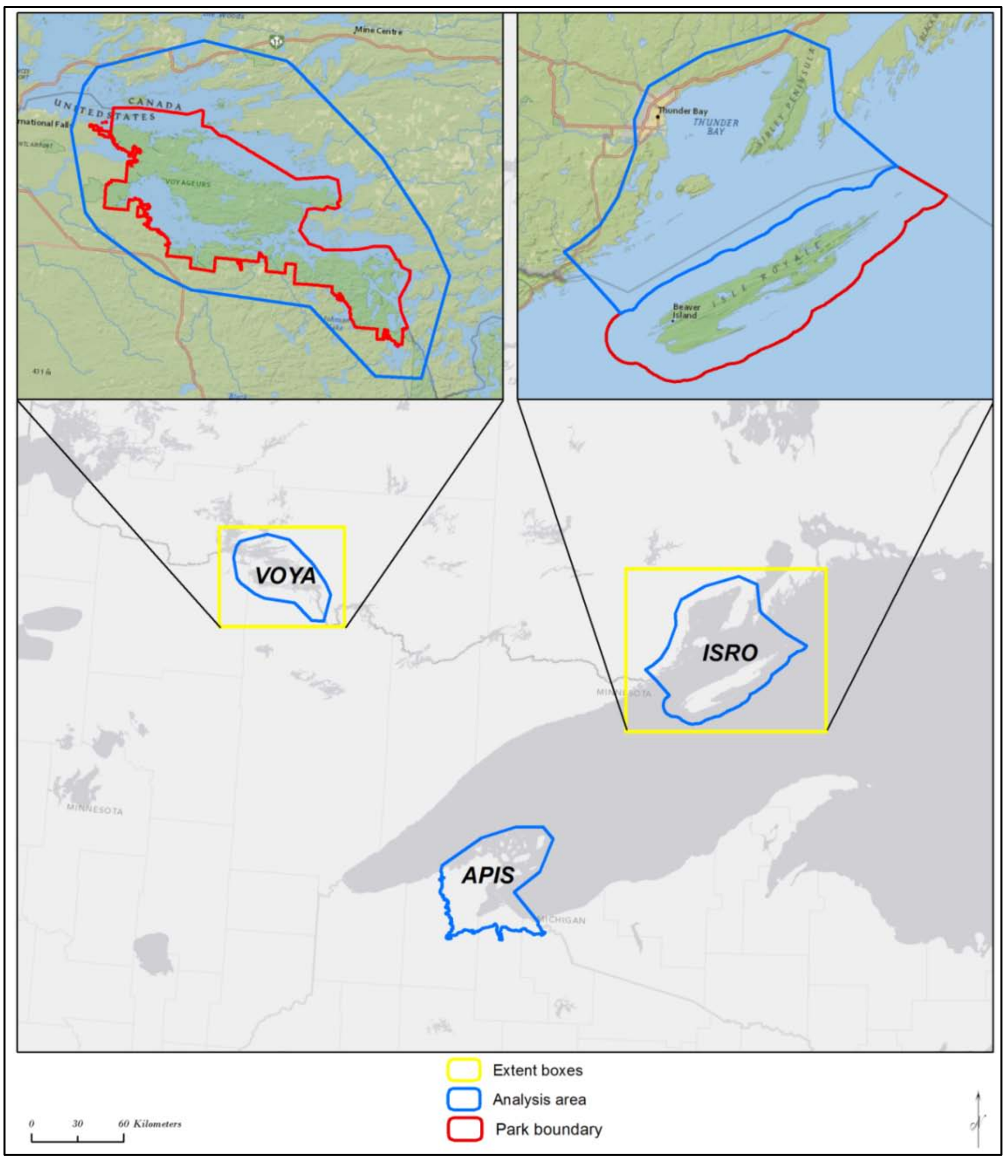

Figure 20. Map of the VOYA, ISRO, and APIS analysis areas. Inset maps: the park (red outline) and area outside the park (blue outline).

Among the three parks, APIS had the greatest percentage of land disturbed, followed by VOYA, then ISRO. However, if the large single event of defoliation is removed, APIS more closely resembles ISRO in terms of land disturbed (Figure 21). Because this large single disturbance did not include tree mortality, it has a smaller effect on the landscape, and thus, could be treated separately. Interestingly, APIS and ISRO had similar disturbance agents and amount of land disturbed despite their differing proximity to the mainland.

When the disturbance regimes outside the parks are compared, VOYA has nearly three times more disturbance outside the boundary than do APIS and ISRO, which were nearly the same (Figure 21).

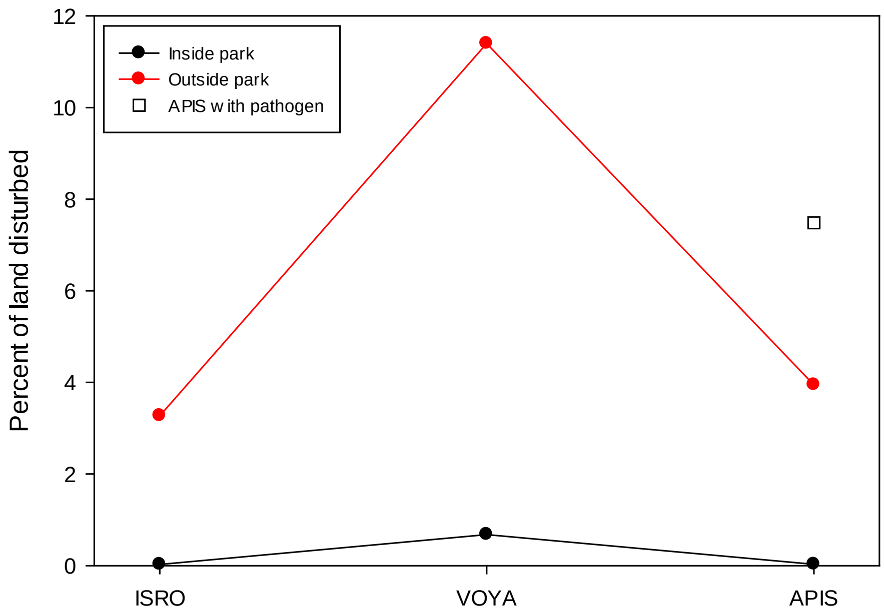

Figure 21. Percent of land disturbed inside the park (black line and circle) versus outside the parks (red line and circle). The hollow square symbol includes the forest pathogen event inside APIS, while the black circle does not incorporate this disturbance.

Disturbance agents

There were two disturbance agents present in all three parks during the analysis periods. These agents were forest pathogen and beaver, with APIS experiencing much more forest pathogen disturbance (7.5%) than the other two parks. APIS also experienced approximately the same level of disturbance by beaver (0.01%) as ISRO (0.01%), although VOYA had much more disturbance by beaver (0.18%). Disturbances by blowdown and fire were also prevalent at VOYA (0.15% and 0.33%, respectively; Figure 22).

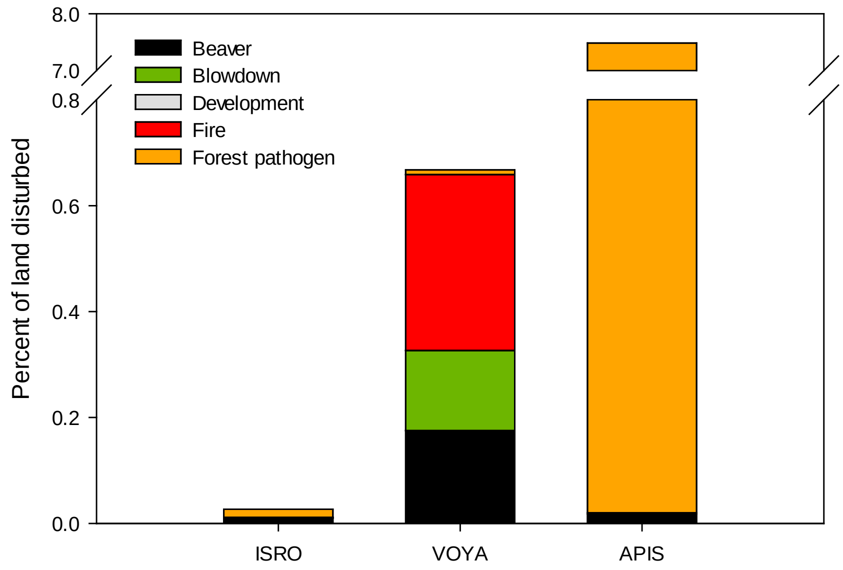

Figure 22. Percent of disturbed land at ISRO, VOYA, and APIS by causal agent.

Outside the parks, forest harvest remained the most frequent disturbance type, followed by development and beaver (Figure 23). The largest amount of forest harvest occurred outside VOYA (10.85%), followed by APIS (3.78%), then ISRO (2.41%); Figure 23). Interestingly, the analysis area outside ISRO had the largest amount of disturbance by development, likely because of the proximity to Thunder Bay, Ontario, with a population just over 100,000.

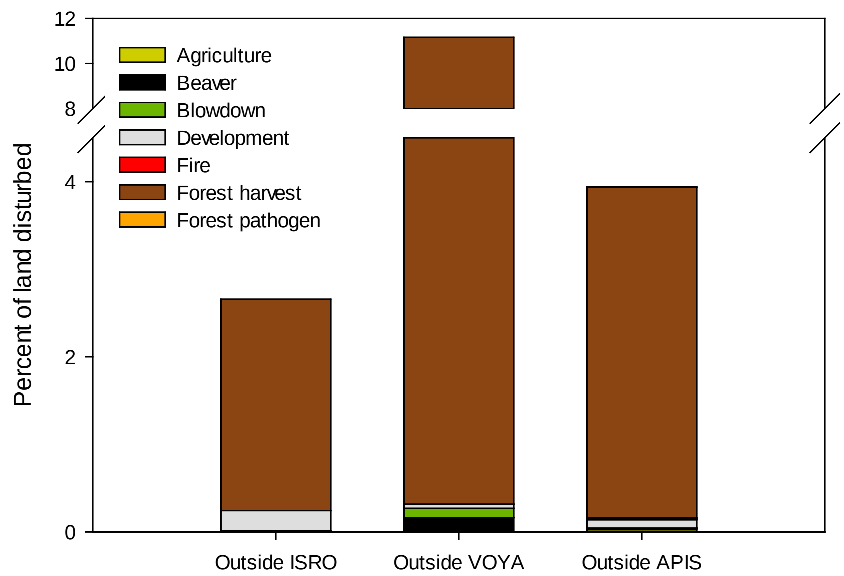

Figure 23. Percent of land disturbed by disturbance agent outside each of the respective parks.

Conclusions

We have summarized the first period of disturbance analysis at APIS into five points:

1) APIS experienced one large disturbance event during the analysis period, with no resulting mortality. This event was centered over Ironwood Island and affected the surrounding islands, totaling 1,272.57 ha (7.47% of the total land area).

2) If the forest pathogen outbreak is not included, a total of 3.47 ha (0.03% of the total area) inside the park were disturbed during the analysis period. The causal agents of these disturbances were beaver and development.

3) USFS logged the largest percentage of land by ownership within the study area. It also employed partial harvest (thinning) at the highest rate among landowners.

4) Of parks previously studied, APIS's disturbance regime more closely resembles that of ISRO.

5) Forest harvest and development are the disturbance agents occurring outside the park that have the greatest potential to affect park natural resources.

In this report we have documented six years of disturbance activity, which is too short of a time period to draw any sweeping conclusions or provide trend analyses of the disturbance regimes at work in the park and the neighboring area. Instead, this report represents a foundation on which we will continue to monitor the same types of activities and develop a long-term record of disturbance. Over a longer term, this program may help reveal a change in the disturbance regime (size, location, frequency) due to climate change, with increased high intensity storm events, or outbreaks of insect or disease due to higher mean annual temperatures. As time progresses, the information able to be gleaned from these reports will become more apparent.

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Appendix A. Spatial Distribution of Disturbances at APIS.

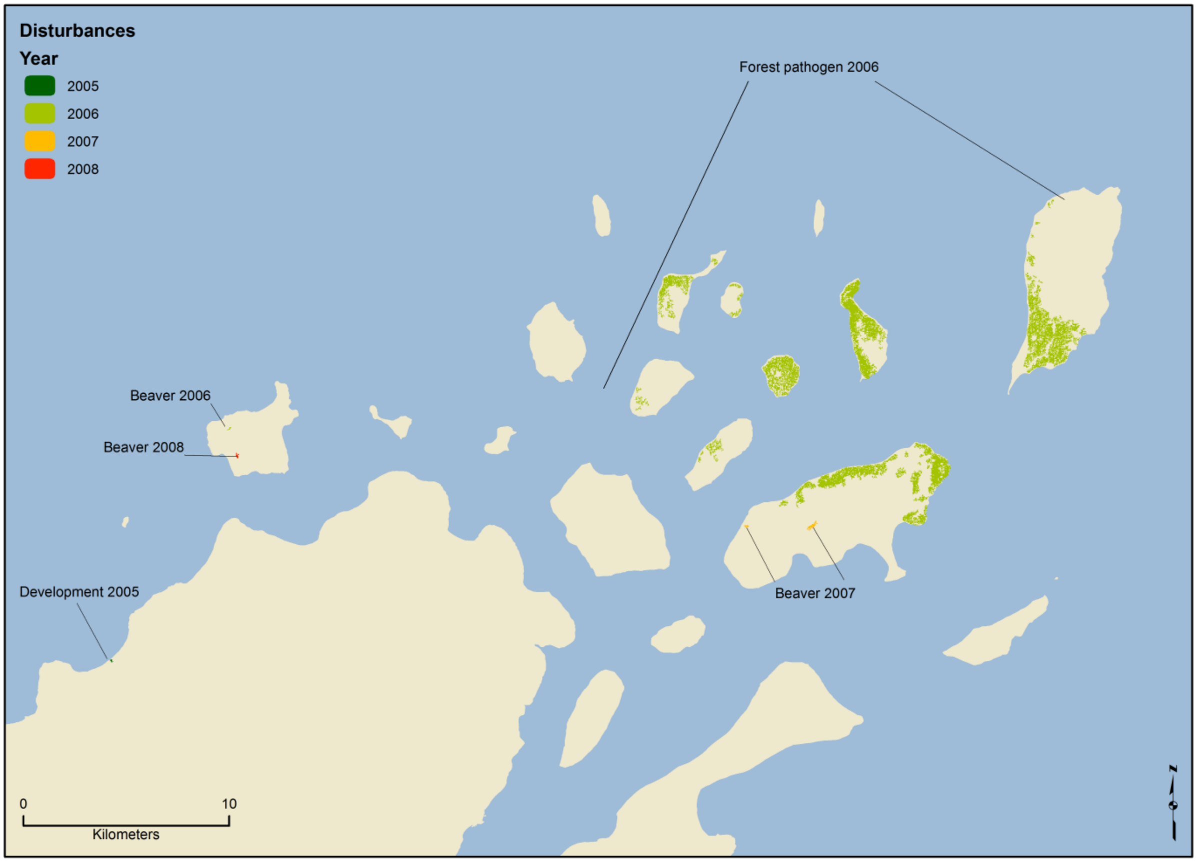

Figure A1. Spatial extent and year of disturbances within the APIS boundary.

Appendix B. Spatial Distribution of Disturbances Outside the APIS Boundary.

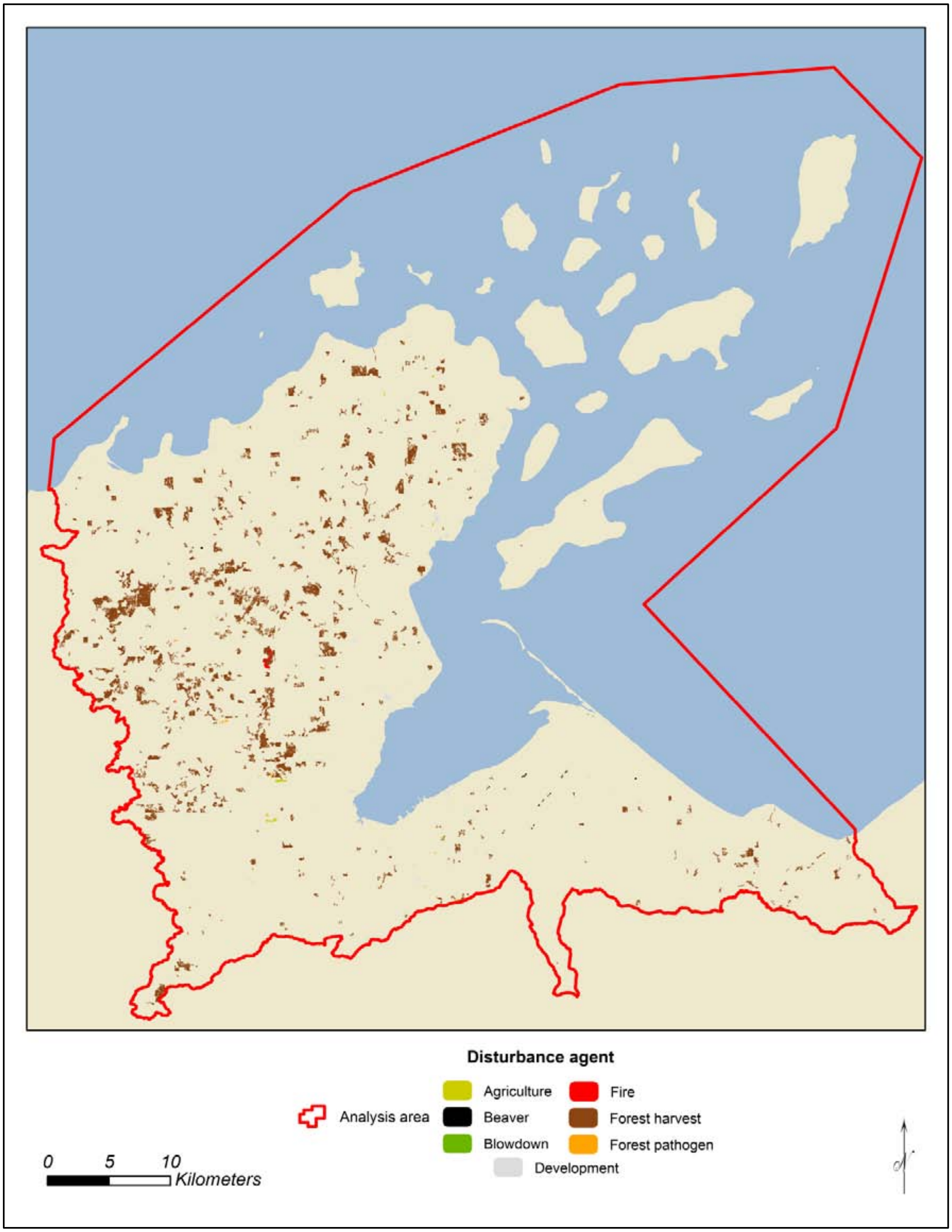

Figure B1. Overview of disturbances outside APIS for the analysis period .

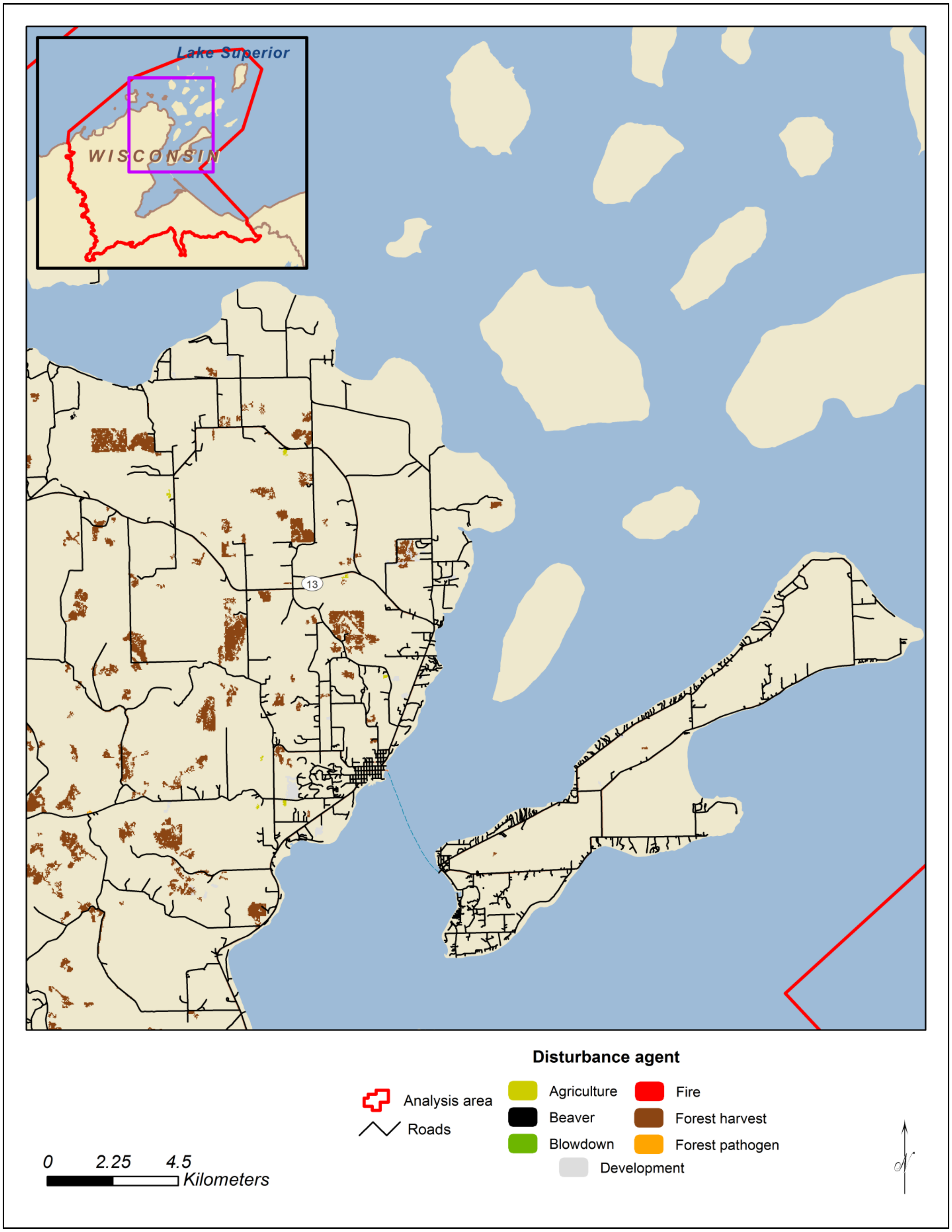

Figure B2. Close-up of disturbances outside APIS (northeast Bayfield Peninsula) for the analysis period .

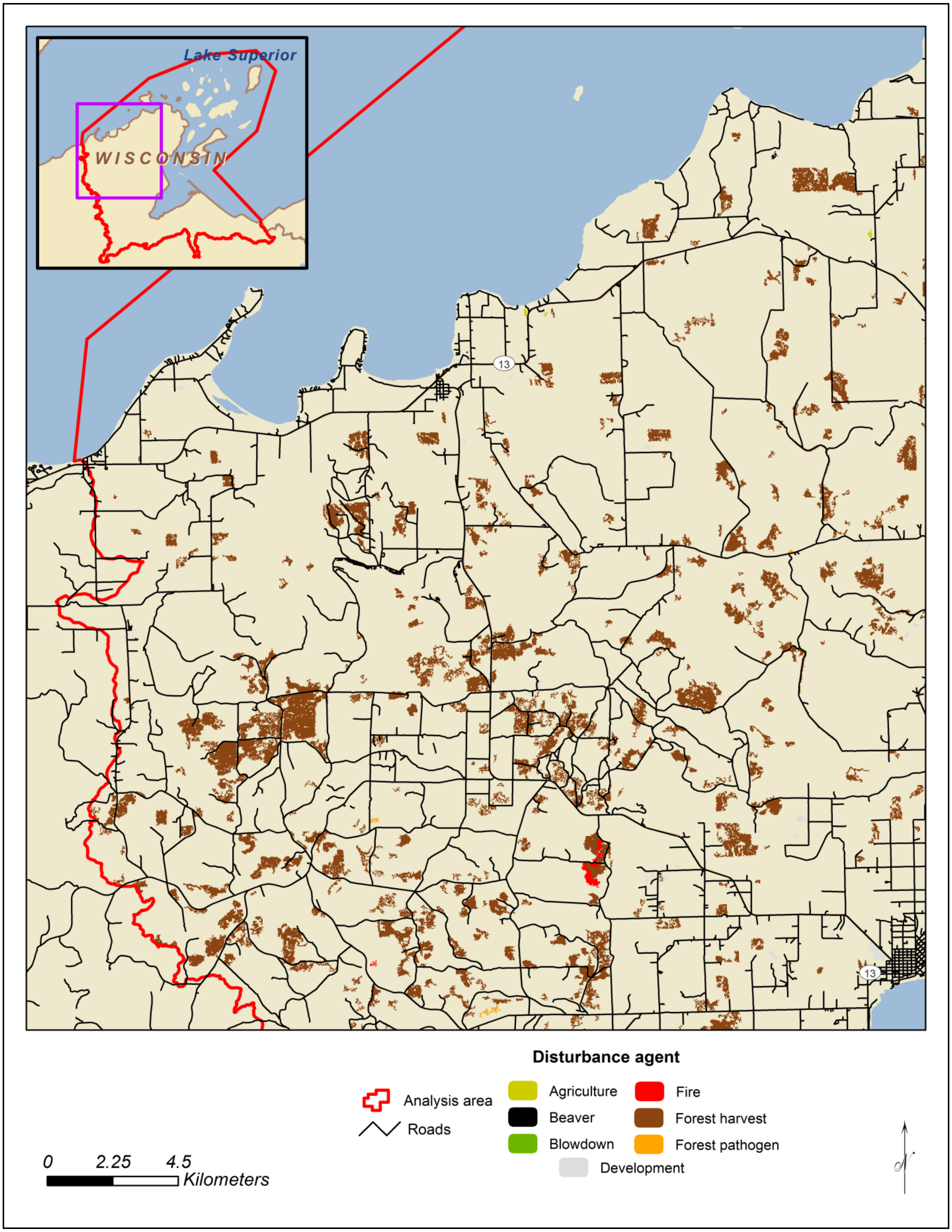

Figure B3. Close-up of disturbances outside APIS (northwest Bayfield Peninsula) for the analysis period .

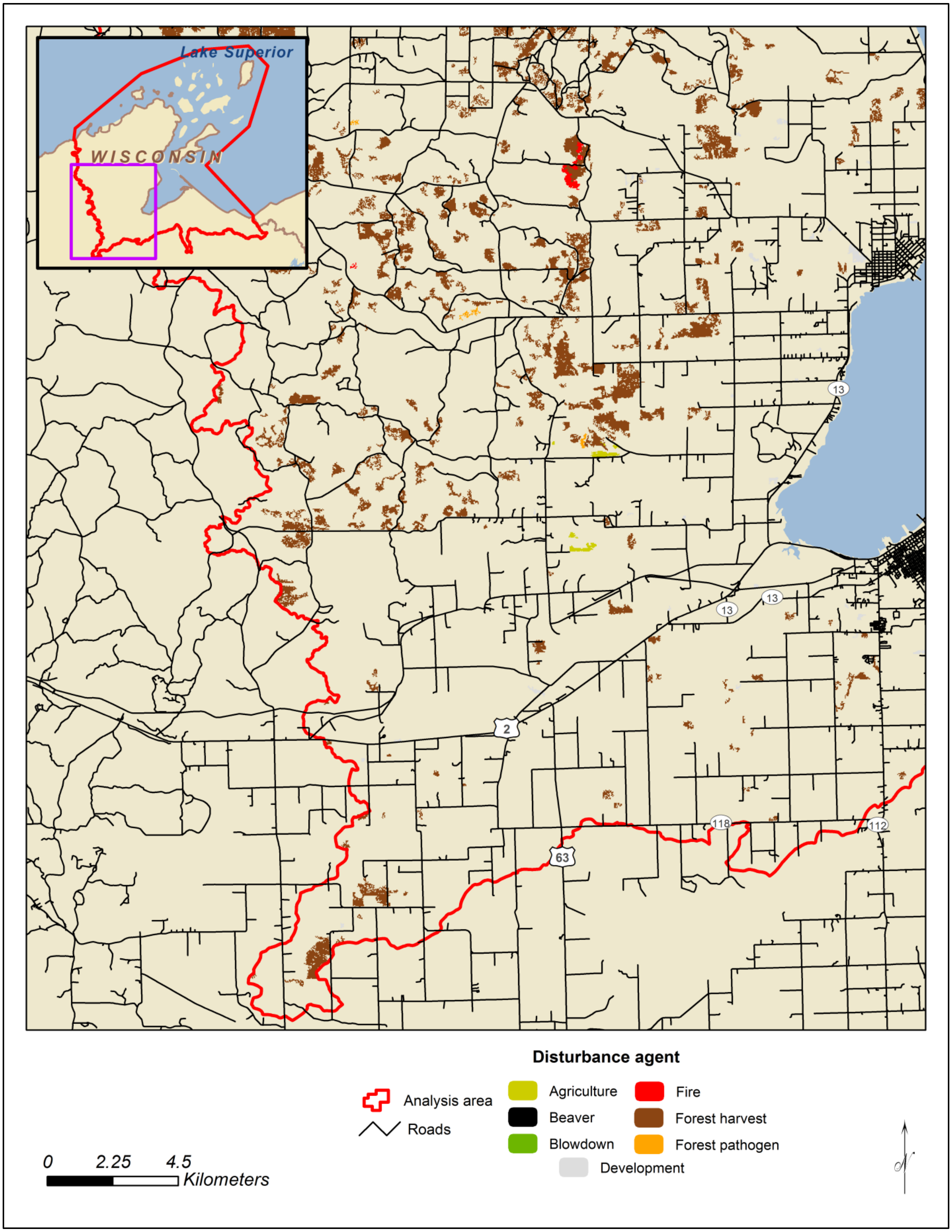

Figure B4. Close-up of disturbances outside APIS (southern Bayfield Peninsula) for the analysis period .

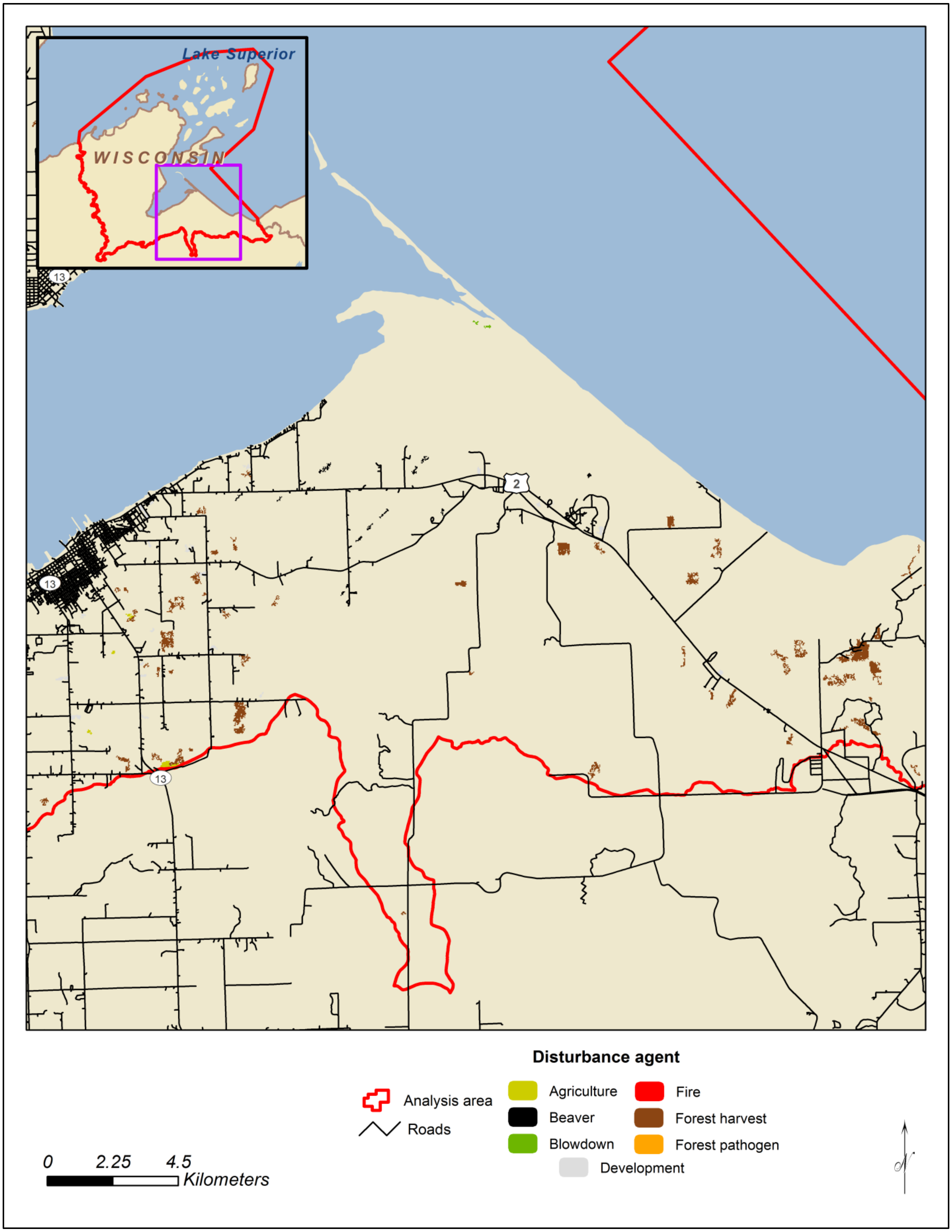

Figure B5. Close-up of disturbances outside APIS (Ashland County/Bad River) for the analysis period .

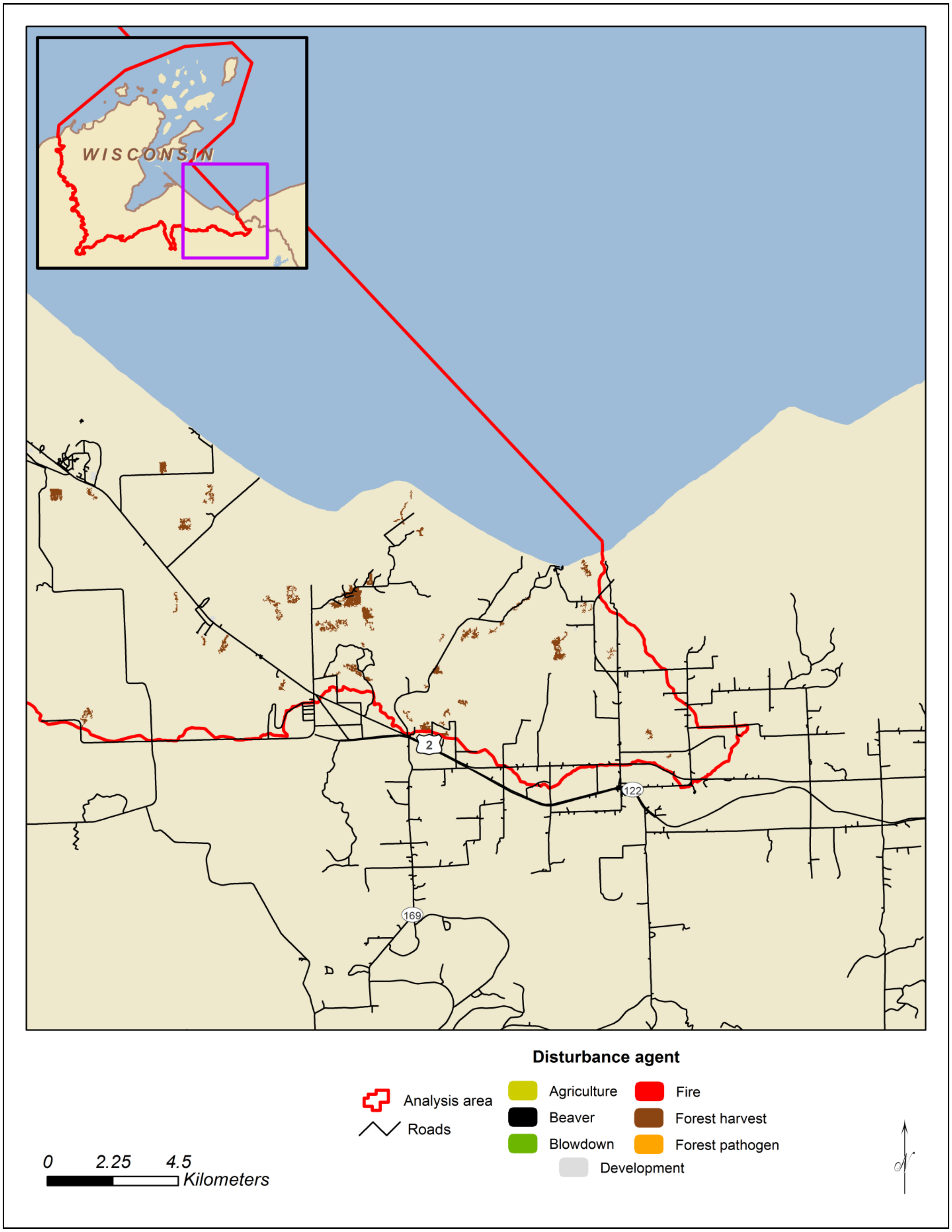

Figure B6. Close-up of disturbances outside APIS (Iron County) for the analysis period .

Appendix C. Spatial Distribution of Thinnings and Clearcuts Outside the APIS Boundary.

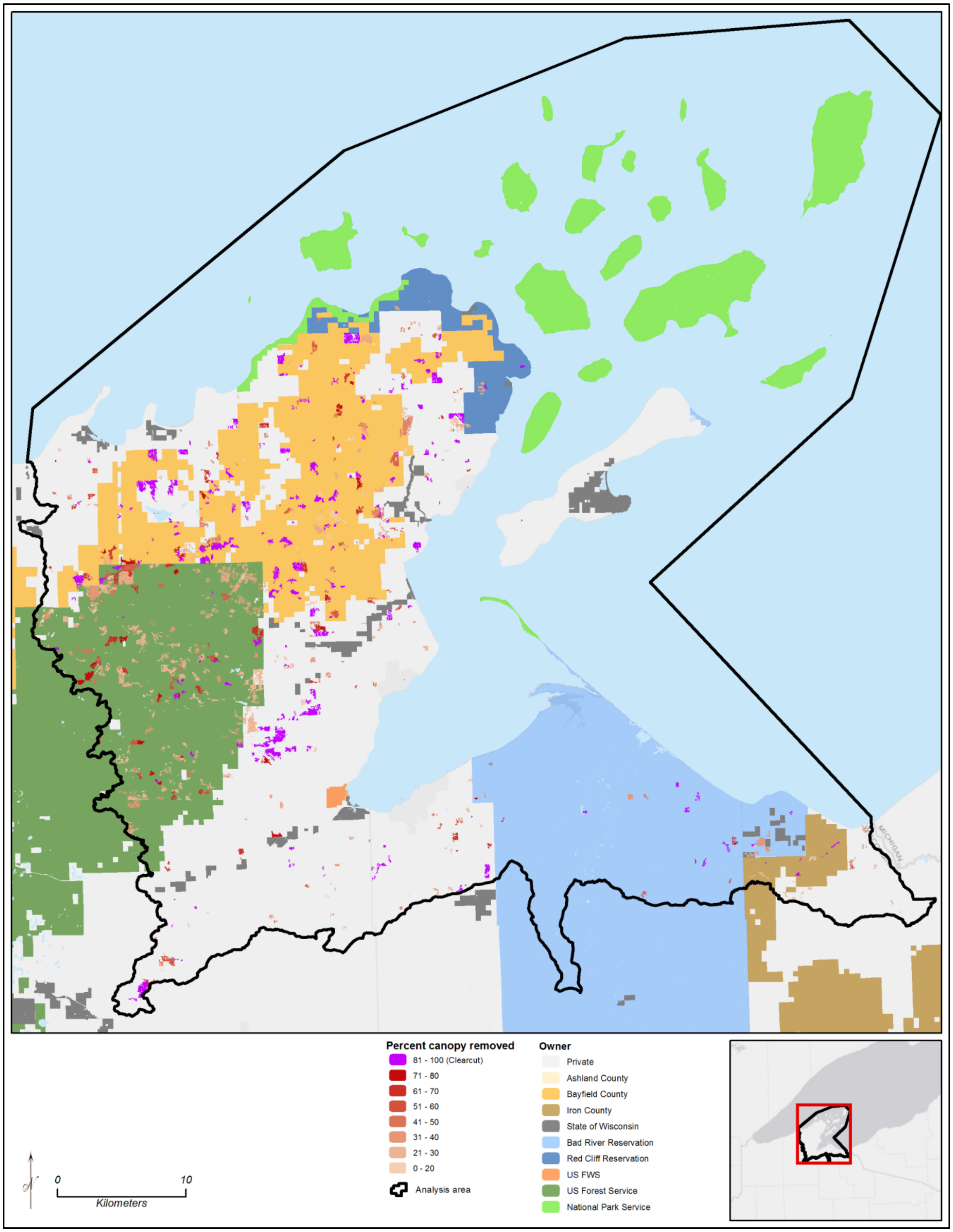

Figure C1. Overview of forest harvest intensity (non-APIS) overlain on ownership type.

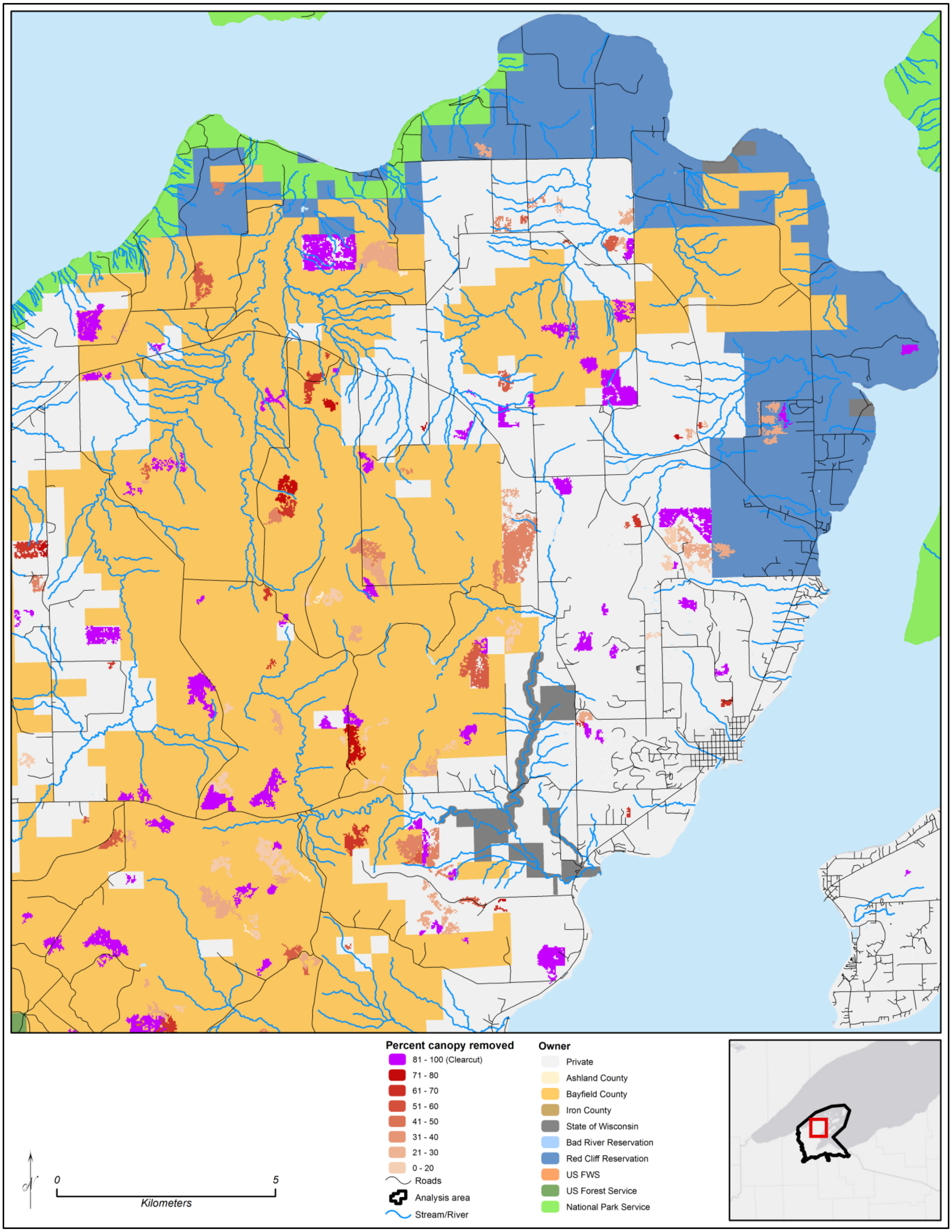

Figure C2. Close-up (1 of 6) of thinning intensity and clearcuts (non-APIS) overlain on ownership and hydrology.

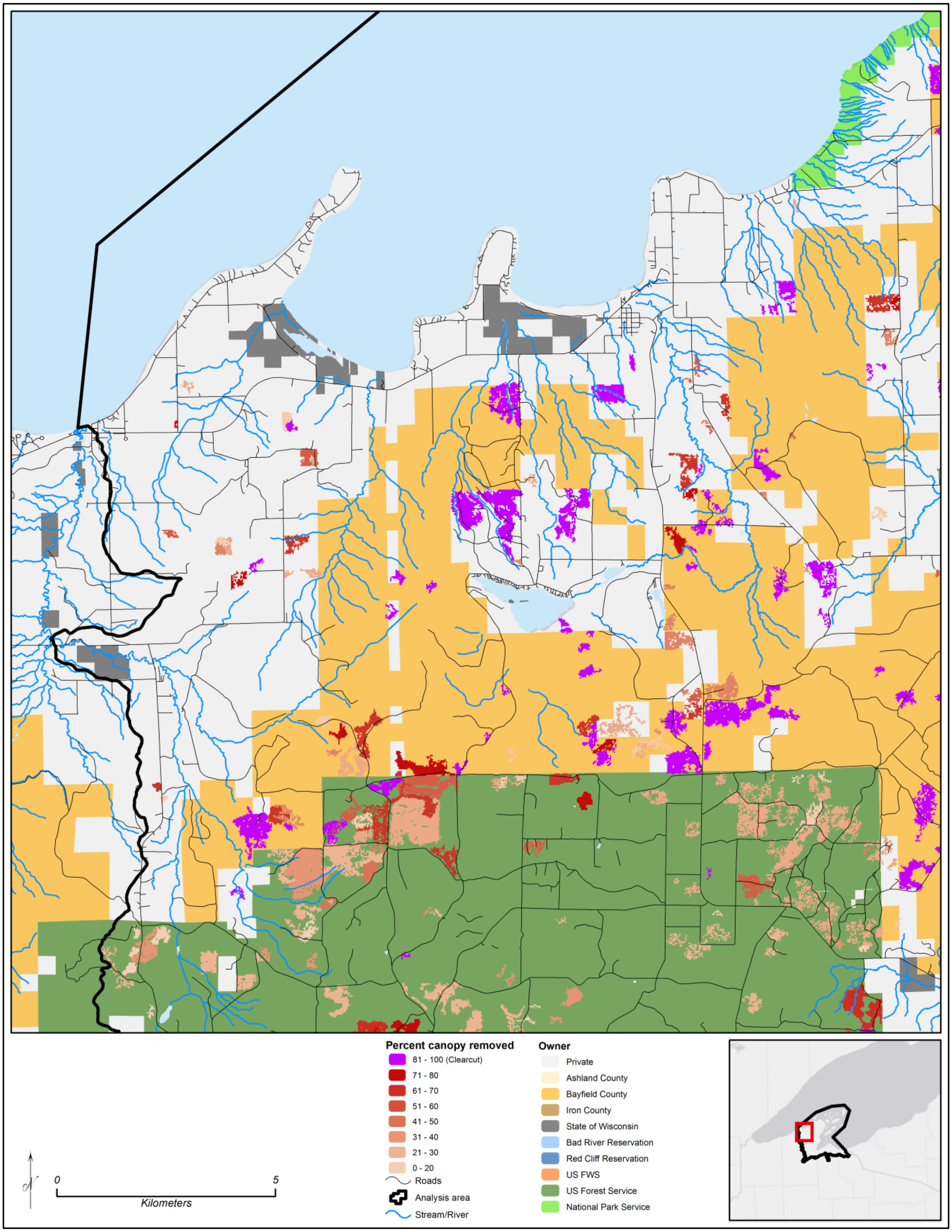

Figure C3. Close-up (2 of 6) of thinning intensity and clearcuts (non-APIS) overlain on ownership and hydrology.

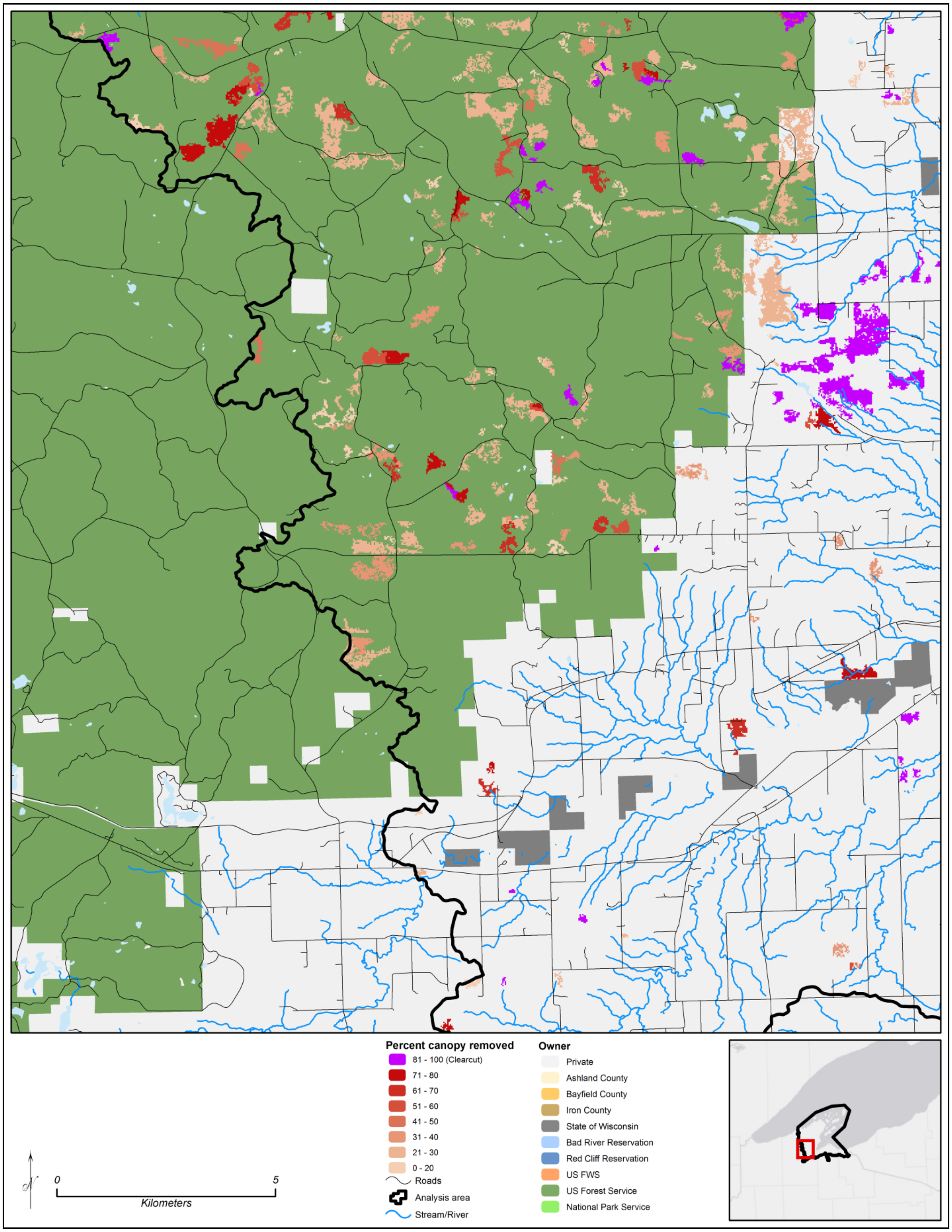

Figure C4. Close-up (3 of 6) of thinning intensity and clearcuts (non-APIS) overlain on ownership and hydrology.

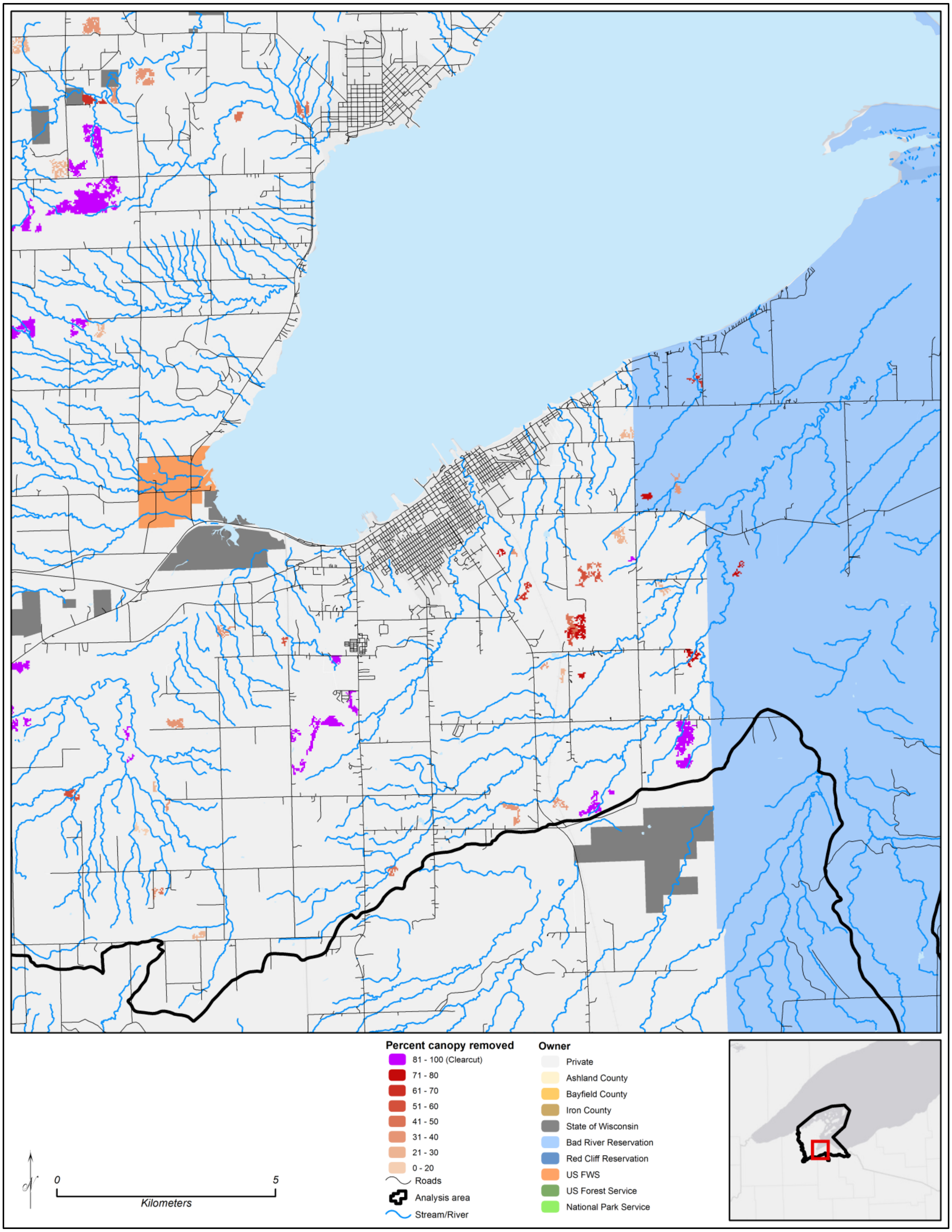

Figure C5. Close-up (4 of 6) of thinning intensity and clearcuts (non-APIS) overlain on ownership and hydrology.

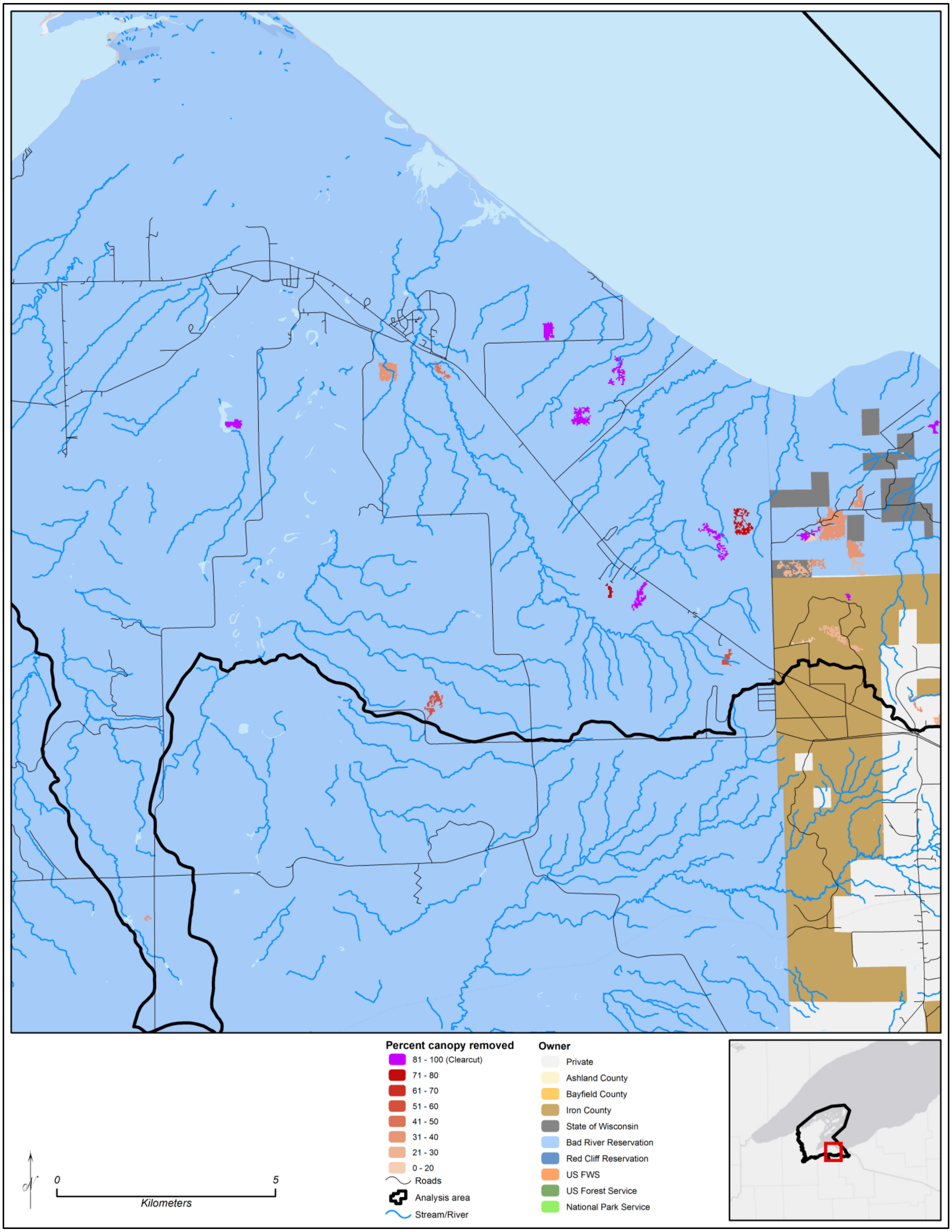

Figure C6. Close-up (5 of 6) of thinning intensity and clearcuts (non-APIS) overlain on ownership and hydrology.

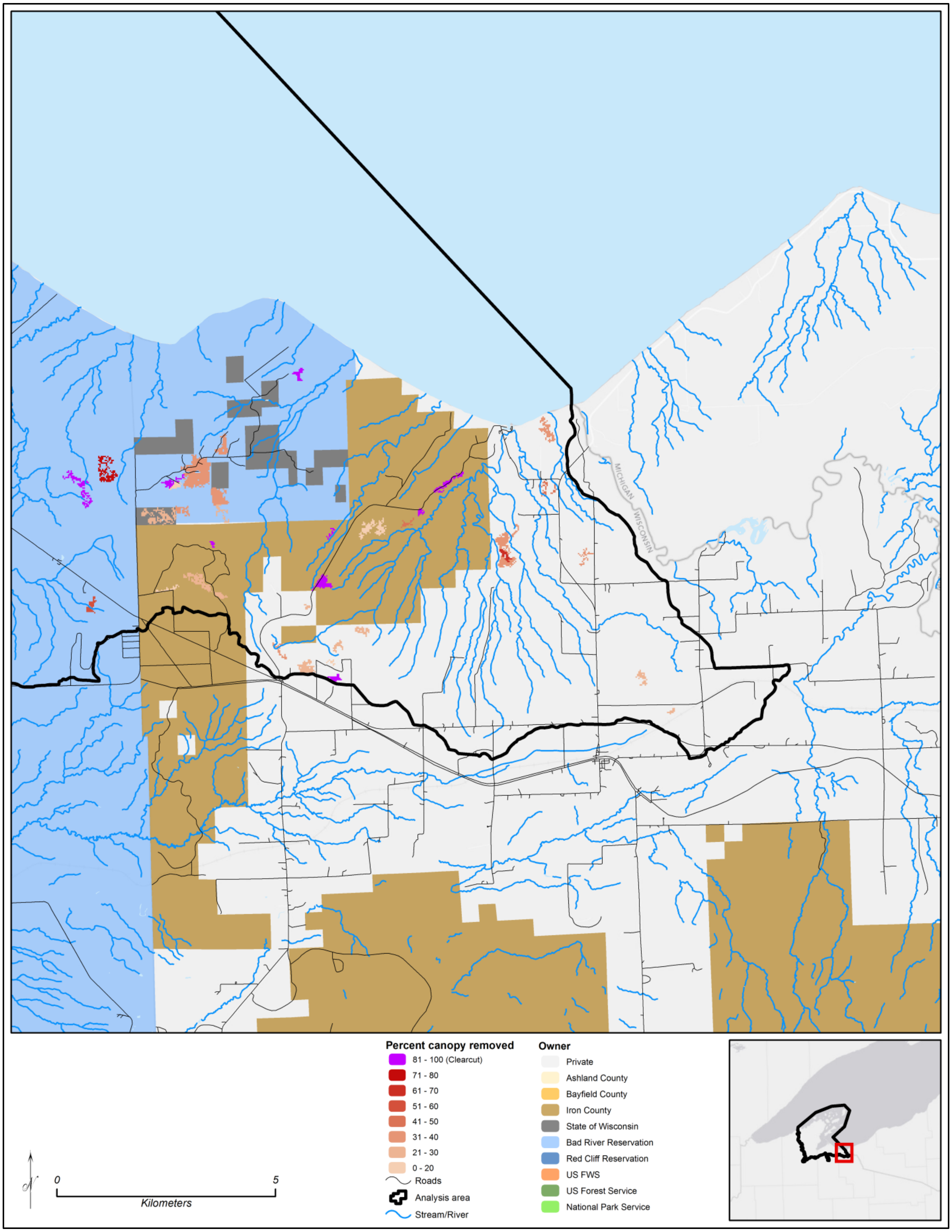

Figure C7. Close-up (6 of 6) of thinning intensity and clearcuts (non-APIS) overlain on ownership and hydrology.

Appendix D. Supplemental Tables.

Table D1. Area (ha) and percent of each vegetation class within the analysis area. Data summarized from the 2006 National Land Cover Dataset.

Class name	Area (ha)	Percent of analysis area
Developed	8696.88	4.68
Barren Land	436.05	0.23
Forest	141989.94	76.33
Shrub/Scrub	8713.62	4.68
Grassland/Herbaceous	743.04	0.40
Agricultural	12769.11	6.86
Woody Wetlands	11673.54	6.28
Emergent Herbaceous Wetlands	988.47	0.53

Table D2. Percent and area (ha) of land disturbed by year and analysis area.

Year	APIS (ha)	APIS (%)	Non-APIS (ha)	Non-APIS (%)
2004	0	0	567.37	0.33
2005	0.40	<0.01	1207.92	0.70
2006	1271.16	7.46	1529.98	0.89
2007	2.97	0.02	1670.99	0.98
2008	1.51	0.01	1169.70	0.68
2009	0.00	0.00	613.09	0.36
Total	**1276.04**	**7.49**	**6759.05**	**3.94**

Table D3. Hectares disturbed by disturbance agent and year for each analysis area.

		Hectares of disturbances							
Analysis area	Year	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen	Total
APIS	2004	0	0	0	0	0	0	0	**0**
	2005	0	0	0	0.40	0	0	0	**0.40**
	2006	0	0.30	0	0	0	0	1270.86	**1271.16**
	2007	0	1.26	0	0	0	0	1.71	**2.97**
	2008	0	1.51	0	0	0	0	0	**1.51**
	2009	0	0	0	0	0	0	0	**0**
	Total	**0**	**3.07**	**0**	**0.40**	**0**	**0**	**1272.57**	**1276.04**
Non-APIS	2004	2.84	9.14	0	31.07	0	524.32	0	**567.37**
	2005	0	0.70	0	31.32	0	1175.90	0	**1207.92**
	2006	26.41	2.78	2.23	18.59	0	1471.99	7.98	**1529.98**
	2007	9.07	4.43	0	52.81	23.17	1581.52	0	**1670.99**
	2008	9.93	0.99	0	22.35	9.90	1121.32	5.22	**1169.70**
	2009	1.44	2.34	0	10.20	0.40	595.84	2.88	**613.09**
	Total	**49.68**	**20.39**	**2.23**	**166.34**	**33.46**	**6470.87**	**16.08**	**6759.05**

Table D4. Percent of land disturbed by disturbance agent and year for each analysis area.

Analysis area	Year	Percent of land disturbed							
		Agriculture	**Beaver**	**Blowdown**	**Development**	**Fire**	**Forest harvest**	**Forest pathogen**	**Total**
APIS	2004	0	0	0	0	0	0	0	**0**
	2005	0	0	0	<0.01	0	0	0	**0**
	2006	0	<0.01	0	0	0	0	7.46	**7.46**
	2007	0	0.01	0	0	0	0	0.01	**0.02**
	2008	0	0.01	0	0	0	0	0	**0.01**
	2009	0	0	0	0	0	0	0	**0**
	Total	**0**	**0.02**	**0**	**0**	**0**	**0**	**7.47**	**7.49**
Non-APIS	2004	<0.01	0.01	0	0.02	0	0.31	0	**0.34**
	2005	0	<0.01	0	0.02	0	0.69	0	**0.71**
	2006	0.02	<0.01	<0.01	0.01	0	0.86	<0.01	**0.89**
	2007	0.01	<0.01	0	0.03	0.01	0.92	0	**0.97**
	2008	0.01	<0.01	0	0.01	0.01	0.65	<0.01	**0.68**
	2009	<0.01	<0.01	0	0.01	<0.01	0.35	<0.01	**0.36**
	Total	**0.03**	**0.01**	**<0.01**	**0.1**	**0.02**	**3.78**	**0.01**	**3.95**

Table D5. Area and percent of each ownership type within the analysis area.

Owner	Area (ha)	Percent of analysis area
Bad River Reservation	27848.64	14.78
Bayfield County	29380.18	15.60
Iron County	2454.30	1.30
National Park Service	17047.10	9.05
Private	77292.04	41.03
Red Cliff Reservation	4491.90	2.38
State of Wisconsin	3638.70	1.93
US Fish & Wildlife	232.65	0.12
US Forest Service	26005.51	13.80

Table D6. Percent of disturbed land by ownership type and disturbance agent for analysis period. USFWS did not have any disturbances.

Owner	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen	Total
Bad River Reservation	0	0.06	0.01	0.05	0	0.49	0	**0.61**
Bayfield County	0	0	0	0.01	0	4.99	0	**5.00**
Iron County	0	0	0	0	0	1.38	0	**1.38**
National Park Service	0	0.02	0	<0.01	0	0	7.47	**7.49**
Private	0.06	0.01	0	0.17	0	3.27	0.01	**3.52**
Red Cliff Reservation	0	0	0	0.33	0	1.19	0	**1.52**
State of Wisconsin	0	0	0	0	0	0.06	0	**0.06**
US Forest Service	0	0	0	0	0.13	8.65	0.04	**8.82**

Table D7. Characterization of forest harvest disturbances by land owner within the analysis area.

Owner	% Clearcut	% Thinning	Average % remaining cover	#/1000 ha
Bad River Reservation	43.77	56.23	54.21	0.68
Bayfield County	48.90	51.10	47.33	3.57
Iron County	20.04	79.96	27.14	2.85
Private	43.80	56.20	47.14	3.12
Red Cliff Reservation	20.25	79.75	41.43	1.56
US Forest Service	4.92	95.08	38.84	11.61

Table D8. Percent of land disturbed by agent for three analysis areas.

Owner	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen	Total
ISRO	0	0.01	<0.01	0	0	0	0.02	**0.03**
VOYA	0	0.18	0.15	0	0.33	0	0.01	**0.67**
APIS	0	0.02	0	<0.01	0	0	7.47	**7.49**
Outside ISRO	0	0.02	0	0.23	0	2.41	0	**2.66**
Outside VOYA	0	0.16	0.10	0.05	0	10.85	<0.01	**11.17**
Outside APIS	0.03	0.01	<0.01	0.10	0.02	3.78	0.01	**3.94**

Table D9. Hectares of land lost in each of the cover types by year and analysis area.

Analysis area	Year	Upland forest	Upland woodland	Upland shrub / herbaceous	Lowland forest	Lowland shrub / herbaceous	Development	Agriculture	Road	Water	Bare ground
APIS	2004	0	0	0	0	0	0	0	0	0	0
	2005	0.40	0	0	0	0	0	0	0	0	0
	2005	1271.16	0	0	0	0	0	0	0	0	0
	2007	1.71	0	0	0	0	0	0	0	1.26	0
	2008	0	0	0	0	1.51	0	0	0	0	0
	2008	0	0	0	0	0	0	0	0	0	0
	Total	**1273.27**	**0**	**0**	**0**	**1.51**	**0**	**0**	**0**	**1.26**	**0**
Non-APIS	2003	557.19	0	5.25	3.01	1.49	0	0.43	0	0	0
	2004	1196.21	0	6.48	3.11	0.90	0	1.22	0	0	0
	2005	1487.51	34.42	1.93	5.91	0	0	0.22	0	0	0
	2006	1663.92	0.86	6.21	0	0	0	0	0	0	0
	2007	1168.28	0	1.07	0	0.35	0	0	0	0	0
	2008	603.34	8.37	1.38	0	0	0	0	0	0	0
	Total	**6676.45**	**43.65**	**22.31**	**12.03**	**2.75**	**0**	**1.86**	**0**	**0**	**0**

Table D10. Hectares of land gained in each cover type by year and analysis area.

Analysis area	Year	Upland forest	Upland woodland	Upland shrub / herbaceous	Lowland forest	Lowland shrub / herbaceous	Development	Agriculture	Road	Water	Bare ground
APIS	2004	0	0	0	0	0	0	0	0	0	0
	2005	0	0	0	0	0	0.40	0	0	0	0
	2005	1271.06	0	0	0	0.10	0	0	0	0	0
	2007	1.71	0	0	0	1.26	0	0	0	0	0
	2008	0	0	0	0	0.86	0	0	0	0.65	0
	2008	0	0	0	0	0	0	0	0	0	0
	Total	**1272.77**	**0**	**0**	**0**	**2.22**	**0.40**	**0**	**0**	**0.65**	**0**
Non-APIS	2003	226.49	104.42	189.03	0	4.48	8.60	1.16	16.20	6.17	10.81
	2004	469.21	353.43	336.01	11.57	3.82	17.01	0	11.57	0	5.31
	2005	794.44	215.02	468.66	0	9.56	13.11	17.32	9.77	2.12	0
	2006	755.00	219.05	630.68	0	1.80	26.14	7.77	12.52	2.63	15.42
	2007	493.12	207.42	426.49	0	0	16.07	9.93	11.06	0.99	4.62
	2008	152.27	153.08	293.25	0	0	2.08	1.44	4.04	2.34	4.59
	Total	**2890.53**	**1252.42**	**2344.10**	**11.57**	**19.66**	**83.02**	**37.61**	**65.16**	**14.25**	**40.74**

Appendix E. Field Validation Polygons.

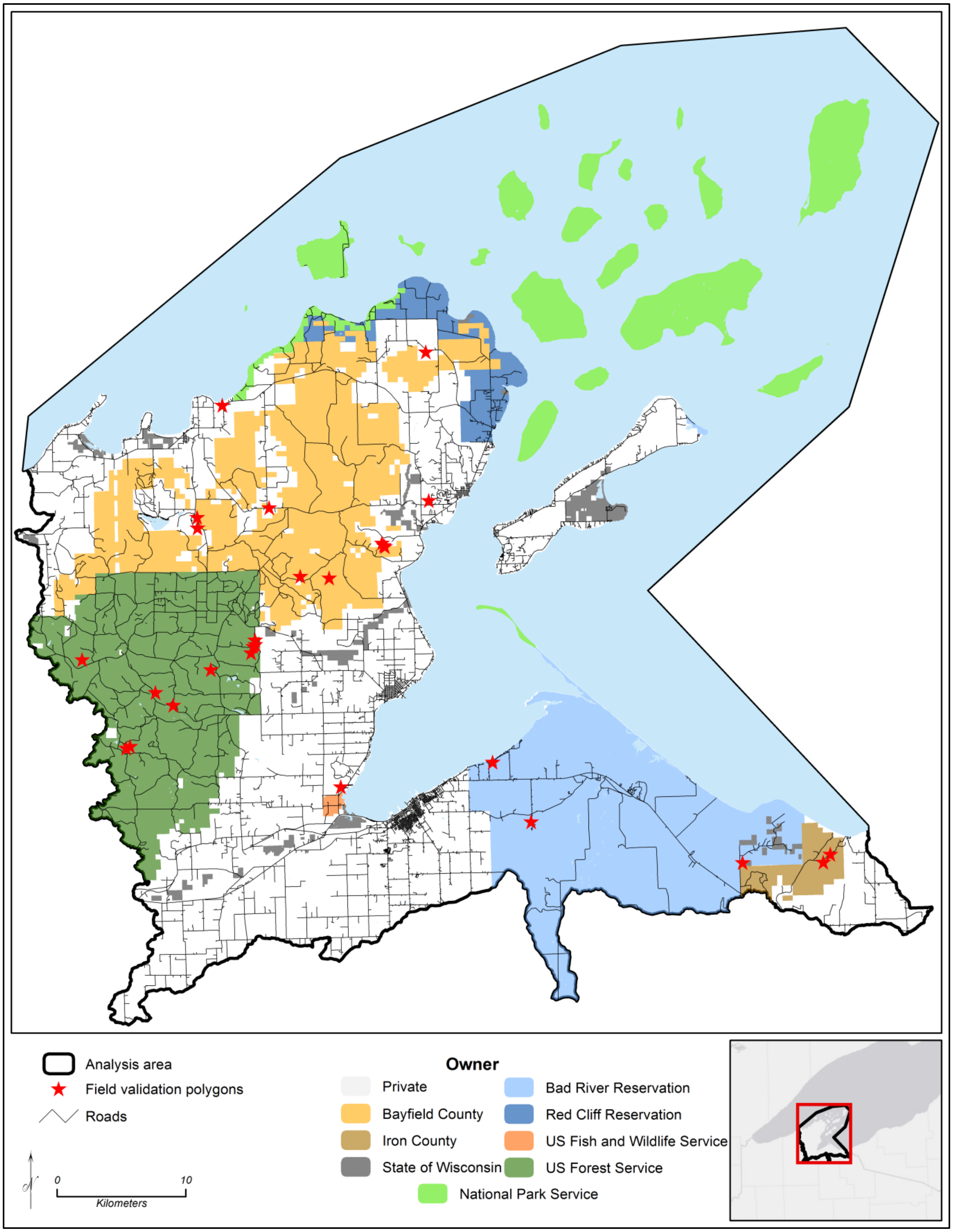

Figure E1. In the fall of 2011, GLKN staff visited 20 disturbance polygons (red stars) to validate the disturbance agent and/or percent of canopy remaining.

Figure E2. Polygon ID: 912009. Description: Partial timber harvest off of County Trunk C on Bayfield County land. The office interpreter predicted 50% remaining tree cover, and our field visit estimated 40% remaining canopy.

Figure E3. Polygon ID: 842009. Description: Partial timber harvest in a red pine plantation off of County Highway C on Bayfield County land. The office interpreter predicted 50% remaining tree cover, and our field visit estimated 40% remaining canopy.

Figure E4. Polygon ID: 462008. Description: Small land clearing on private land off of Star Route Rd. Office prediction was land use development, and this was confirmed in the field.

Figure E5. Polygon ID: 862006. Description: Disturbance polygon located off of Highway 13. Office prediction of disturbance agent was agriculture, and the prediction was correct, as there was a row crop planted at the time of the field visit.

Figure E6. Polygon ID: 822007. Description: Located off of Old County Highway K. The office decision for disturbance agent was agriculture, as it was believed to be a Christmas tree farm. The field visit validated this correct assumption.

Figure E7. Polygon ID: 582007. Description: A large disturbance occurring on private land off of County Highway J. The field visit confirmed the causal agent was development. There were multiple house lots for sale, but no houses were being built at the time of visitation.

Figure E8. Polygon ID: 992009. Description: A partial timber harvest occurred on Bayfield County land near Mt. Ashwabay. The office estimate of canopy removed was 40%, and our in-the-field estimate was 50% remaining.

Figure E9. Polygon ID: 642008. Description: A large depression located on Bayfield County land near Mt. Ashwabay. This large depression was a 'borrow' pit, where the subsoil was used as fill somewhere nearby. The disturbance agent was confirmed in the field.

Figure E10. Polygon ID: 222008. Description: This patch was part of a complex of disturbance polygons on the Chequamegon-Nicolet National Forest, off of Forest Road 694. In the office this polygon was difficult to attribute. In the field we found significant evidence of fire, thus confirming one of the assumed disturbance agents.

Figure E11. Polygon ID: 142007. Description: This patch was part of a complex of disturbance polygons on the Chequamegon-Nicolet National Forest, off of Forest Road 694. In the office this polygon was difficult to attribute. In the field we found standing dead snags with fire scars.

Figure E12. Polygon ID: 232009. Description: Timber harvest polygon on the Chequamegon-Nicolet National Forest off of Forest Road 252. Only a few trees remained, most likely a seed tree retention prescription. In the field the estimated percent cover remaining was <20%, thus confirming the decision in the office to classify this event as a clearcut.

Figure E13. Polygon ID: 282009. Description: This disturbance occurred on U.S. Forest Service land off of Forest Road 251. In the office the prediction was a post-harvest prescription which was confirmed in the field. There was evidence of site preparation and new red pine seedlings planted.

Figure E14. Polygon ID: 272009. Description: This disturbance, located on U.S. Forest Service land off of Forest Road 251, was an understory fire which also killed some overstory trees.

Figure E15. Polygon ID: 162009. Description: Located on U.S. Forest Service, land off of Forest Road 262, this polygon experienced a timber harvest. In the office the interpreter estimated 30% remaining forest cover, and in the field we estimated 30% remaining tree cover.

Figure E16. Polygon ID: 492009. Description: Additional land was cleared for this quarry expansion. This confirmed the office interpretation made during the validation process. The quarry is located off of Highway 13 south of the City of Washburn.

Figure E17. Polygon ID: 522008. Description: This polygon experienced a disturbance in the form of a driveway expansion. The field visit confirmed the ‘development’ disturbance agent predicted in the office.

Figure E18. Polygon ID: 3222006. Description: Beaver activity resulted in flooding and eventual tree mortality in this area. The field visit confirmed this disturbance agent.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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