



Landsat-based Monitoring of Landscape Dynamics at Pictured Rocks National Lakeshore, 2006–2011

Natural Resource Technical Report NPS/GLKN/NRTR—2014/866



ON THE COVER

An example of beech tree mortality due to beech bark disease within Pictured Rocks National Lakeshore.
Photograph by: Pictured Rocks National Lakeshore staff

Landsat-based Monitoring of Landscape Dynamics at Pictured Rocks National Lakeshore, 2006–2011

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Abstract

The Great Lakes Inventory and Monitoring Network (GLKN) implemented the long-term disturbance monitoring protocol at Pictured Rocks National Lakeshore (PIRO). Disturbances, or distinct changes in vegetation cover, are an important part of how this Great Lakes coastal system 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 PIRO were delineated for six years (2006–2011) 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 midsummer composite image, yearly since 1984) 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, forest pathogen, development, flooding due to beaver activity, and blowdown) in addition to the year of occurrence, and starting and ending vegetation classes. Summary analyses showed that disturbances inside the park “core” zone were dominated by forest pathogen and the remaining areas (park inland buffer zone and non-park) were dominated by forest harvests.

Acknowledgments

We would like to acknowledge staff at Pictured Rocks National Lakeshore for helping design the land cover monitoring program's scope and extent for the analysis.

The LandTrendr research group (<http://landtrendr.forestry.oregonstate.edu/>) at Oregon State University and Boston 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 the reviewers for 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.
HUC	Hydrologic unit code, an acronym used by the USGS in reference to their National Hydrography Dataset. In general, lower numerical values refer to larger subwatershed sizes. For instance, a HUC 8 is much larger than a HUC 12 subwatershed.
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.
MISS	Mississippi National River and Recreation Area

List of Terms and Acronyms (continued)

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.
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/
Panchromatic	Incorporates all wavelengths of visible light.
PIRO	Pictured Rocks National Lakeshore
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.
SACN	Saint Croix National Scenic Riverway
SLBE	Sleeping Bear Dunes National Lakeshore
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.
SWIR	Shortwave infrared band of information from the Landsat family of satellites (5, 7, and 8)
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
USGS	United States Geological Survey
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); mapping fire extent, severity, and recovery (Veraverbeke et al. 2010, Chen et al. 2011, Meigs et al. 2011); evaluating policy effects on land use (Kennedy et al. 2012); and 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, Wolter and Franklin 2007). A summary of the four most common types of change detection, including our opinions on the benefits and disadvantages of each and studies using these various techniques, is provided in Table 1.

Previous Landscape Dynamics Studies in the Western 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). 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). 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. More recently, Stueve et al. (2011a) investigated the amount of disturbance in the Lake Superior and Lake Michigan basins from 1985–2008 using Vegetation Change Tracker (VCT). They found that from 1985–1999, 4.0% of the land (0.26%/yr) was disturbed in the lower Lake Superior basin, and 2.9% of the land was disturbed from 2000–2008 (0.32%/yr). This study was performed on an extremely large scale, providing less information on smaller subunits of the Lake Superior watershed.

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% (0.79%/yr) was harvested, flooded, or burned five years later. When comparing disturbances among timber management status (managed vs. unmanaged) in each of the ownership types, the highest annual rates of mature forest area changing to early successional forests occurred within the private industrial unmanaged category (2.02%), with private industrial managed close behind at 1.66%. The lowest rates of conversion were found on federally unmanaged lands (0.17%) with county unmanaged the next least disturbed land type (0.22%).

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.	(Rutchev 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. 2010, Kennedy et al. 2010b, Schroeder et al. 2011, Sonnenschein et al. 2011, Stueve et al. 2011a, Zhu 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)

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 1990, but held steady in some counties when observed over the entire time period (1970s to 1990). This could reflect the conversion of previously-cleared forest lands for agriculture back to a forested cover type. In four national forests in northern Wisconsin and Michigan, a separate study (Stueve et al. 2011b) focused on studying “intermediate” wind disturbances, those not generally studied due partially to the fact that they are not easily detected with most remote sensing techniques. They found that these disturbances rivaled the amount of land disturbed by large, infrequent disturbances (e.g., fires, extreme wind events).

There has also been some research performed at Pictured Rocks National Lakeshore in regard to fire and vegetation history. By using fire scars, Loope (1991) found the average fire return interval across the park was 21.8 years, but that 84 years had passed since the creation of the last scar, indicating a current lack of fire in the system. In more recent years, there was a study that looked at historic building and road data from 1938, 1966, and 2005. They used these data to analyze the effects of roads and buildings on changes in landscape fragmentation and found that after park establishment, the increased development pressure outside the park boundary caused increased isolation and may actually have decreased the park’s effectiveness at protecting the land within its borders (Gimmi et al. 2009, Gimmi et al. 2011).

Landscape disturbances produce ripple effects in multiple natural processes. Fitzpatrick et al. (1999) studied the effect of the major shift in land cover and land use in a northern Wisconsin watershed since the late 1800s, and they found large changes in the sedimentation load and flow dynamics. 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 positively and negatively) 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 and around Pictured Rocks National Lakeshore can help inform resource managers at the park about pressures affecting the areas under their jurisdiction. However, despite many landscape dynamics studies having been performed in the upper Great Lakes region, there is a lack of this type of research in the Pictured Rocks National Lakeshore vicinity. 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 National Park Service Inventory and Monitoring program was developed: to provide consistent, long-term monitoring of ecologically significant parameters affecting national park lands.

Great Lakes Network Approach to Disturbance Monitoring at Pictured Rocks

Given the choices in disturbance monitoring, the Great Lakes Inventory and Monitoring Network (GLKN, or 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 (30 m) satellite imagery (Landsat). The Landsat archive contains imagery from 1984 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 Pictured Rocks was only 8¢ per hectare.

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 2006 through 2011. 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 2012, the size and location of the area to be monitored outside park boundaries was determined during a meeting with park resource managers. Together we decided to monitor the park administrative boundary plus a 20 km buffer, totaling ca. 230,000 hectares. The 20 km buffer outside the park boundary was chosen rather than watershed boundaries because the hydrologic contributing area to the park is almost entirely within the park boundary. The remaining watersheds all flow south into Lake Michigan, making these watersheds less relevant to the park. The total size of the analysis area was kept comparable to the sizes of analysis areas from other parks analyzed thus far. Our ability to monitor large landscapes stems from the fact that Landsat satellite data has been made freely available by the USGS.

Study Area

The analysis area included Pictured Rocks National Lakeshore (PIRO) and a 20 km buffer outside the park boundary (Figure 1). The park extends 62 kilometers between Munising on the west end to Grand Marais on the east end with the region dominated by northern hardwood and mixed conifer forests. Nearly 250,000 ha of land were included in this study, 12% of the land being located within the PIRO boundary (Table 2). The administrative boundary includes land identified as the “Inland Buffer Zone” (IBZ), created to permit sustained yield timber harvest and protect the watershed (Figure 1). This land is owned by the State of Michigan, private corporations, and private citizens, and comprises 58% of the land within the PIRO administrative boundary (Table 3). More information regarding the IBZ and its formation can be found in Gimmi and Radeloff (2013).

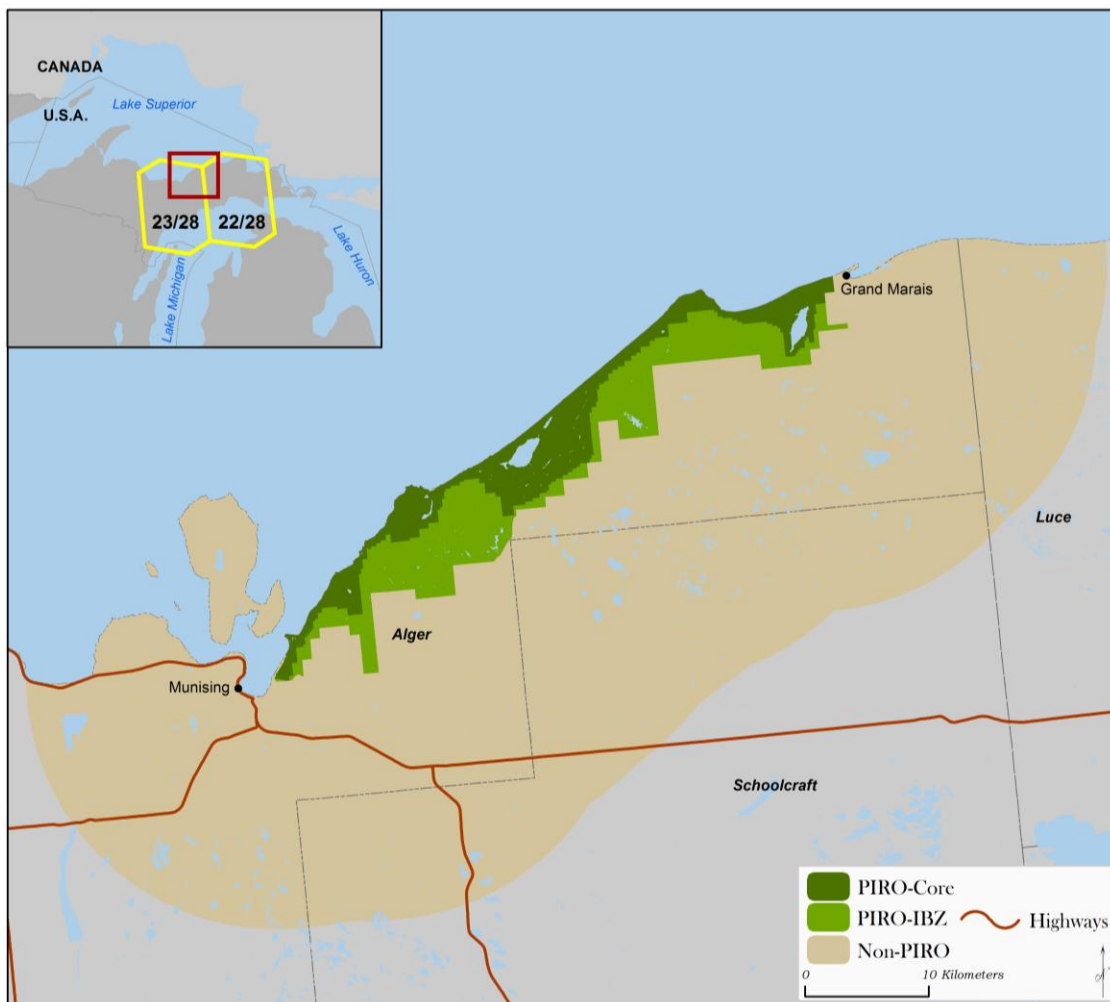


Figure 1. Study area for long-term monitoring of landscape-scale disturbances in and around Pictured Rocks National Lakeshore, Michigan. The inset shows the extent (yellow lines) of the two Landsat scenes (23/28 and 22/28) processed and analyzed for this report. The larger map shows the two zones within PIRO (dark and light green) and the extended analysis area (light brown) outside the park.

Table 2. Land area of each analysis region and the percent contribution of each region to the overall analysis area. “PIRO” is all land within the administrative boundary and “Non-PIRO” refers to all land outside the administrative boundary.

Analysis area	Size (ha)	Percent of analysis area
PIRO	26,416	12
Non-PIRO	203,668	88
Total	230,084	100

Table 3. Land area of each PIRO zone and percent contribution to PIRO.

PIRO zone	Size (ha)	Percent of PIRO
Core	11,148	42
IBZ	15,258	58
Total	26,406	100

Vegetation

Overall, forest (deciduous, evergreen, and mixed) comprises 61% of the analysis area, with woody wetlands contributing an additional 23% (Figure 2). The remaining land cover classes collectively contribute the balance of 16%.

Proportionally, the vegetation within the park varies from that found outside. In the non-PIRO area, woody wetlands comprise nearly twice as much of total land area, with increases in herbaceous wetlands as well (Figure 3). The increases in wetlands outside the park are offset by a large decline in the percentage of open water.

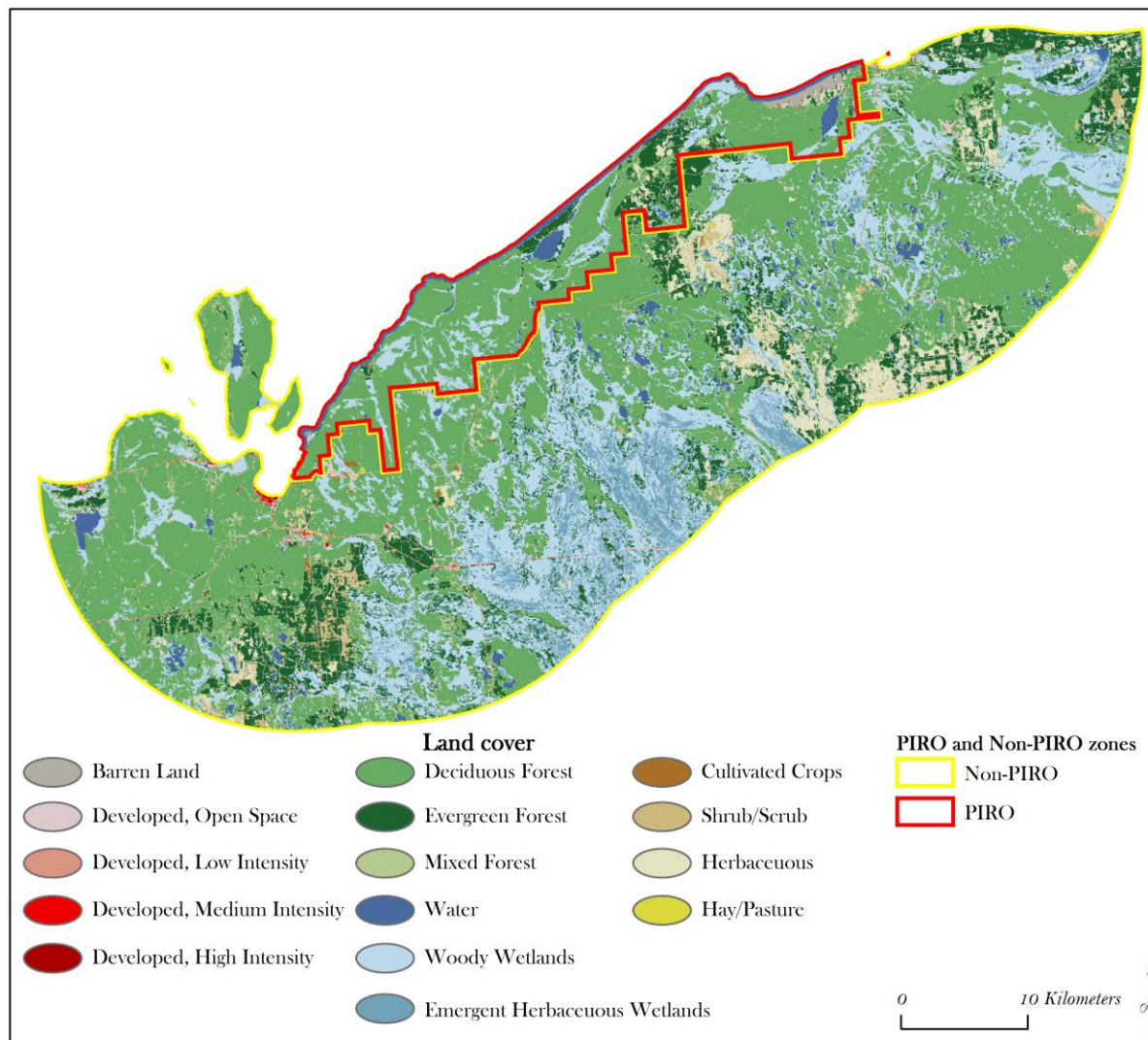


Figure 2. Vegetation classes within the analysis areas (PIRO and Non-PIRO). Data from 2006 National Land Cover Database.

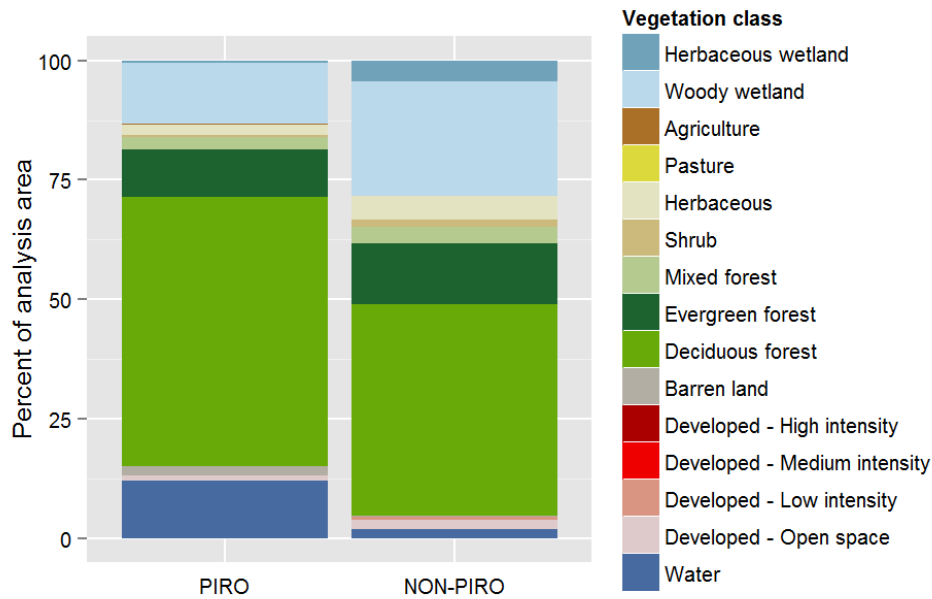


Figure 3. Relative abundance of vegetation classes within each of the analysis areas.

Ownership

We summarized disturbances by ownership description and owner name as denoted by the Michigan Gap Analysis Program (GAP) ownership layers. We realize the ownership layer contains mistakes, but for this landscape study we accepted the minor errors. Ownership is broken into two tiers, where owner 01 (owner name) is more detailed and owner 02 (owner description) is less detailed. The main difference is that state lands are grouped together in owner 02.

The analysis area is largely held in private ownership, accounting for nearly 40% of the ownership (Figure 4). Other large land owners were State Forest and National Forest, with ca. 30% and 20% of the total, respectively. Spatially, the National Forest lands were largely on the west side of the analysis area, State Forest lands were located from the central to east part of the analysis areas, and private land was distributed equally from east to west within the analysis area (Figure 5).

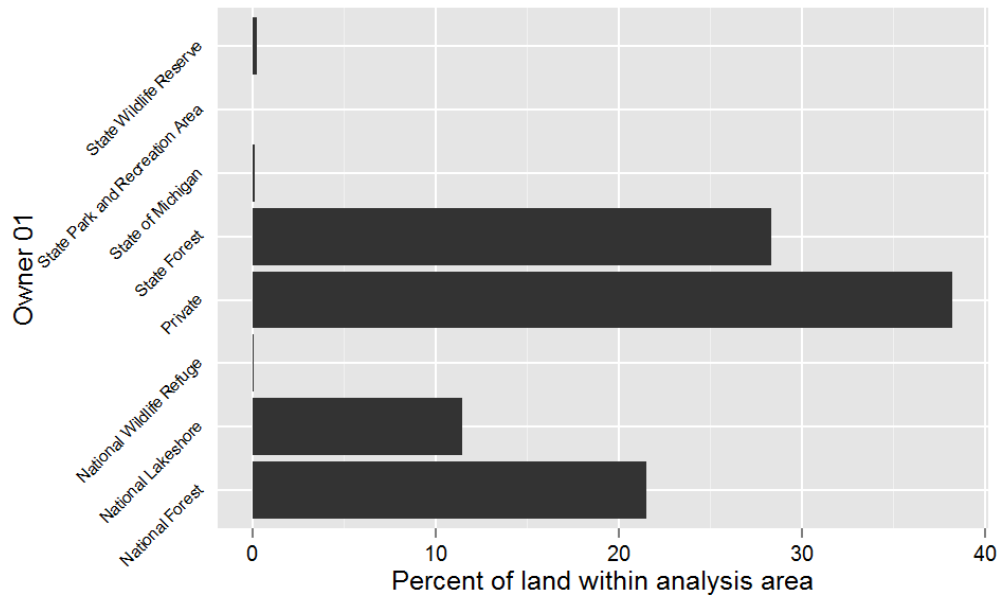


Figure 4. Percent of land within the analysis area, summarized by owner 01, the more detailed ownership type. Data from the Michigan GAP analysis dataset.

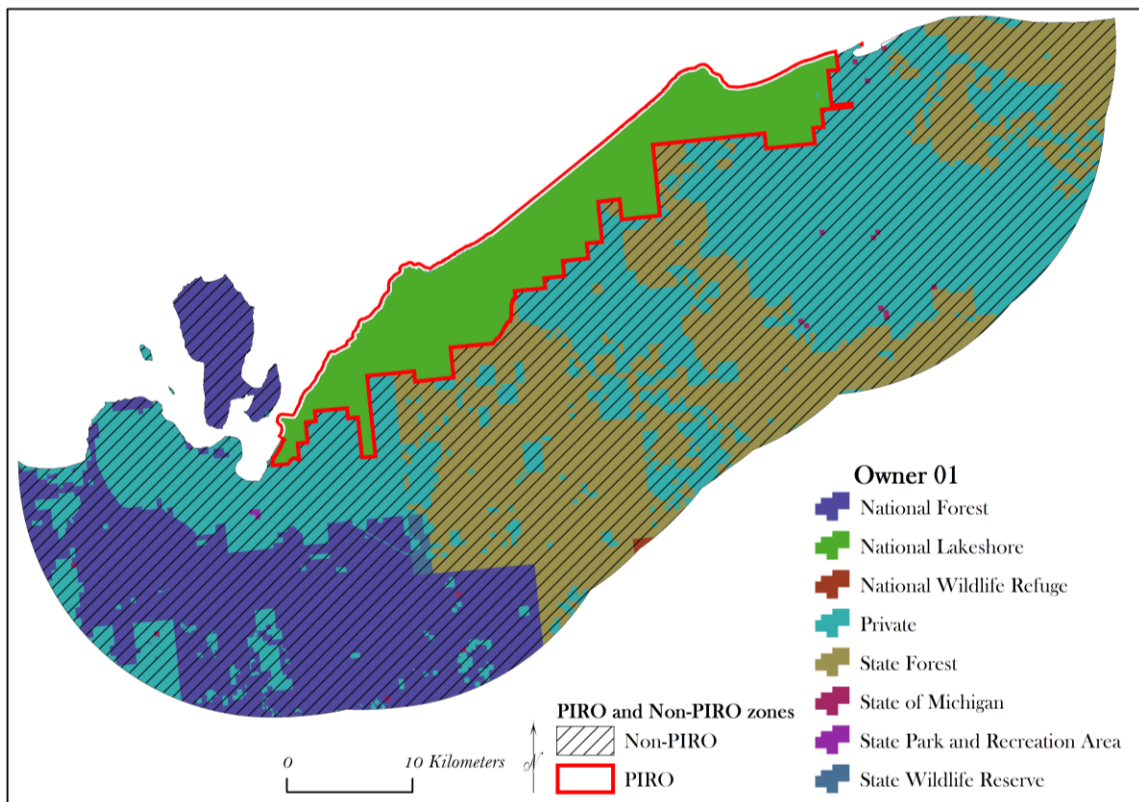


Figure 5. Spatial distribution of land ownership within the analysis area. Data from the Michigan GAP analysis dataset.

Methods

Image Data and Processing

Due to the location of Landsat scenes in reference to the PIRO analysis area, two scenes (22/28 and 23/28) were acquired for analysis (see Figure 1). 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 acquired from the U.S. Geological Survey (USGS). To minimize the effect of phenology, imagery was selected in a two-month window (July and August) during the peak growing season (Figure 6). 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 analysis area could be analyzed. 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_slcbackground.php). In total, 171 images were downloaded and processed for analysis. Each collection of images by scene will be referred to as a Landsat time-series (LTS).

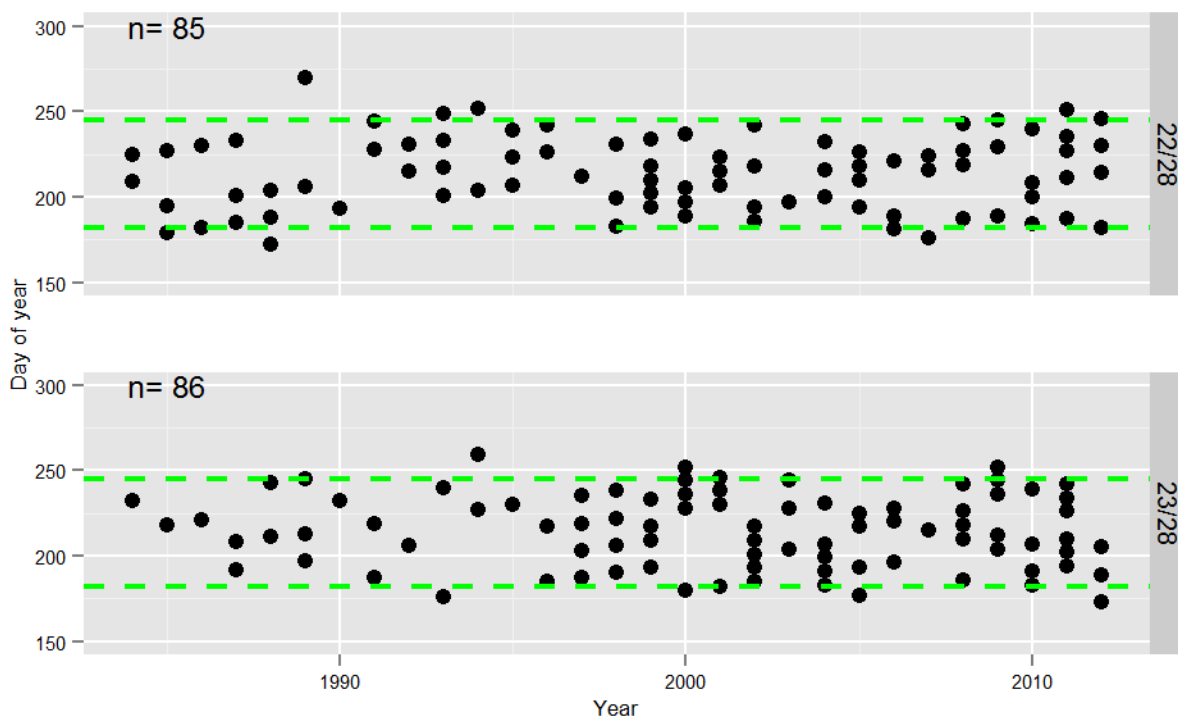


Figure 6. Day and year of Landsat images used for analysis for scenes 22/28 (top) and 23/28 (bottom), with green dotted lines delineating the time period between 1 July and 31 August.

Preprocessing of images (geometric registration, atmospheric correction, and cloud screening) within each LTS followed details given in Zhu et al. (2012), and are briefly summarized here. We have assumed that the level of Landsat images used (L1T) are already precisely registered and that sub-pixel misregistration will not influence our analysis. All images were atmospherically corrected with

the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS), using the 6S radiative transfer approach (Vermote et al. 1997, Masek et al. 2006). Missing pixel data were also masked for images from the ETM+ sensor after the onset of scan line errors (2003 and later). We used the cloud masking algorithm (Fmask) defined in Zhu and Woodcock (2012), which identifies clouds, cloud shadow, and snow based on a time-series of Top of Atmosphere reflectances of each pixel. The registered, atmospherically-corrected, 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. See Kennedy et al. (2010b) for details regarding any part of the LandTrendr process. LandTrendr algorithms operate on a single detection index; a detection index can be any single band of information. Although the algorithm itself can only be run on single detection index, LandTrendr can be run multiple times, using different indices. These results are then combined into one disturbance layer. For this analysis we used the normalized burn ratio (NBR) and the short-wave infrared (SWIR) band. In our experience in northern hardwood forests, the SWIR band does better at delineating clearcuts, while NBR is more sensitive to the more subtle disturbances such as forest thinning. For the remainder of the report, we will refer to these indices collectively as disturbance indices (DI). A diagram providing an example of how the segmentation algorithm processes an individual pixel is provided below (Figure 7).

First, image data from the LTS files were converted to DI 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. 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 DI value for that pixel in each year), the years at which vertex years were found, the fitted DI values for those vertices, and the yearly fitted DI data (the DI 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.

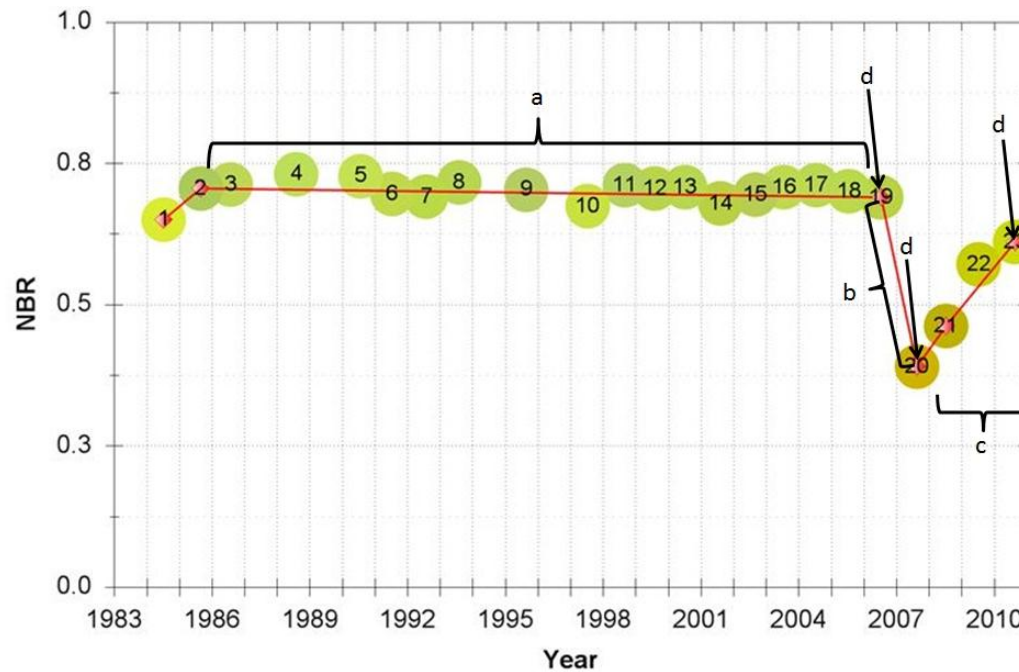


Figure 7. Diagram of how the LandTrendr segmentation algorithm processes a single pixel. The x-axis is the year of image acquisition and the y-axis is defined by the NBR value. Generally, NBR values range from low to high dependent on the amount of vegetation present. This graph shows a single pixel's NBR value from 1984 to 2011. We would interpret this graph as: stable vegetation cover from 1985 to 2006 (a), with 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.

Disturbances for the analysis area were derived from the vertex files in several steps. Segments were accepted for further processing only if their relative magnitude value was greater than a pre-defined threshold parameter. This filtering is an effective means of reducing false changes from overfitting of anomalous or ephemeral spectral features in the time-series. Lastly, the LandTrendr pixel outputs are grouped into patches based on the year the change began and the duration of change. For this protocol, the patches are first screened by duration, so that the dataset only includes pixels that experienced rapid change of <4 years in duration. The remaining pixels are then grouped into patches based on the year of change onset. Patches must be nine pixels (0.8 ha) or larger to be included in the monitoring dataset.

Validation of Disturbances

Validation of possible disturbances followed details given in Kirschbaum and Gafvert (2010) 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 pre- and post-disturbance vegetation classes (Table 4) and agent of change (Table 5) 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. If a disturbance occurred within a polygon, additional attributes (fields) were populated within the feature class (Table 7). These included most likely pre- and post-disturbance vegetation class, disturbance agent, post-timber harvest remaining percent cover, and whether the polygon was a candidate for a field visit.

Table 4. Vegetation classes used in the analysis, and their respective characteristics.

Vegetation class	Characteristics
Forest (closed)	>60% tree cover, >3m height
Forest (semi-closed)	30–60% tree cover, >3m height
Forest (open)	<30% tree cover, >3m height
Herbaceous/grassland	>60% cover of herbaceous species, <1m height
Water	Permanent (>10 years) bodies of water
Impervious surface	Black top, cement, or any surface in which water cannot penetrate readily
Pervious surface	Barren land
Impervious/vegetated	Low and medium intensity developed areas which create a mosaic of impervious and vegetated surfaces, such as those regularly found in suburban areas.

Table 5. Disturbance agents and definitions for each.

Disturbance agent	Definition
Agriculture	Disturbance caused by human activity which results in agricultural land use (row crops, pasture, hay, orchard).
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 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 detected.
Forest harvest	Forest harvests, including clearcuts and thinnings, new logging roads, and post-harvest prescriptions such as herbicide application or scarification.
Forest pathogen	Disturbances (mortality or defoliation) in the overstory due to insects (e.g., forest tent caterpillar, spruce budworm) or diseases (e.g., oak wilt, beech bark disease).

Table 6. Aerial photos and high resolution satellite imagery used for validation. For explanation of acronyms used in this table, see List of Terms and Acronyms on page xiii and xiv.

Date	Resolution (meters)	Spectrum	Funding source	Type	Analysis area coverage
1992/1998	1	B&W	APFO-NAPP	Airphoto	Partial analysis area
Spring 2004	0.25	RGB	GLKN	Airphoto	Entire PIRO
Summer 2005	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2008	0.3	RGB	NGA	Airphoto	Entire
Summer 2009	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2010	1	RGB	APFO-NAIP	Airphoto	Entire
Spring 2011	0.15	RGB & CIR	GLKN	Airphoto	Entire PIRO
Summer 2011	0.3	RGB	Luce County	Airphoto	Luce County
Summer 2011	1 and 0.3	RGB	APFO-NAIP	Airphoto	Partial analysis area
Summer 2012	1	RGB	APFO-NAIP	Airphoto	Entire

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

Field	Definition
Location	PIRO or Non-PIRO
Start class	Starting vegetation class(es) as noted in Table 4. 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 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(s) responsible for the change. For a list of possible agents, see Table 5.
Disturbance agent percent	The percent of the polygon disturbed by a particular agent.
Post-timber harvest remaining percent tree cover	In instances where there was not a clearcut, the interpreter estimates the percent of tree cover remaining ($\pm 10\%$)
Land owner	The land owner data from the GAP analysis program is used for attribution. For those disturbances in which a disturbance straddles multiple owners, the ownership in which the majority of the disturbance occurred is denoted.
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 disturbance was true.
Lab interpreter	Initials of interpreter who validated the polygon.

Cross-validation of polygons

One interpreter validated all disturbances for PIRO. However, in the future it is likely that more than one interpreter or different interpreters will validate disturbances. To assess the level of subjectivity and repeatability in the validation process, 10% of the polygons were randomly selected and evaluated by an independent interpreter. For the PIRO analysis, there was greater than 80% agreement between the two interpreters. Complete results of this cross-validation process are presented in Appendix D.

Results

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

Percent of Land Disturbed

PIRO

During the six-year study period, a total of 11.8% (3,127 ha) of the land inside the park administrative boundary was disturbed. Disturbances inside the park were highest in 2006 (twice as high as any other year), then remained at a lower level for the remainder of the analysis period. The lowest percent of disturbance occurred in 2008 (Figure 8).

Non-PIRO

Collectively, 8.8% (17,834 ha) of the land outside the park was disturbed during the six-year period (Figure 8). The amount of land disturbed each year remained relatively stable throughout the time period, with lows occurring in 2008 and 2011.

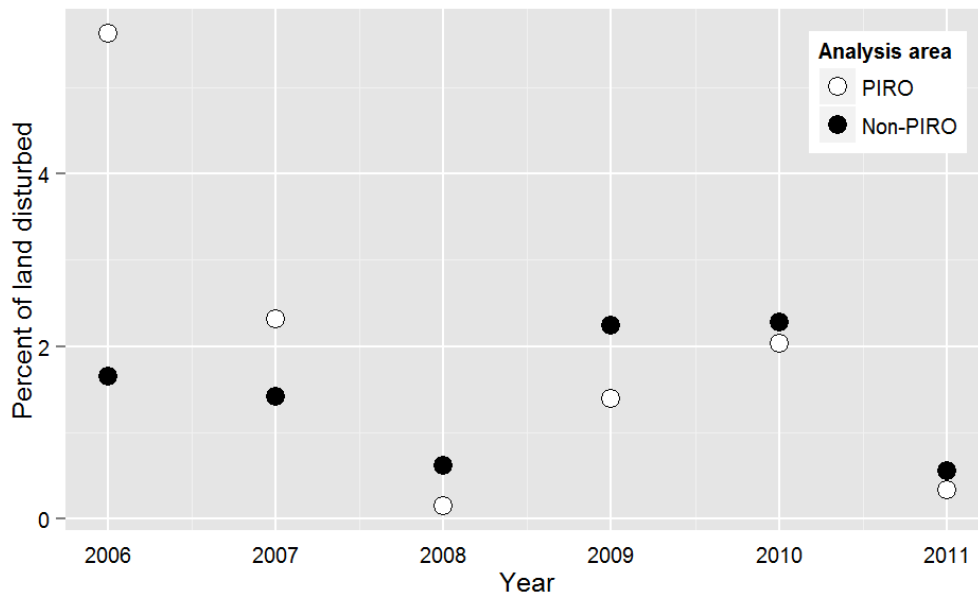


Figure 8. Percent of land disturbed within each analysis area, by year.

Disturbance Agents

PIRO

All but one disturbance agent (blowdown) was detected inside the park administrative boundary. The most common disturbance agent, present in all years, was forest harvest. Forest harvest (partial) peaked in 2006 as well as forest pathogen.

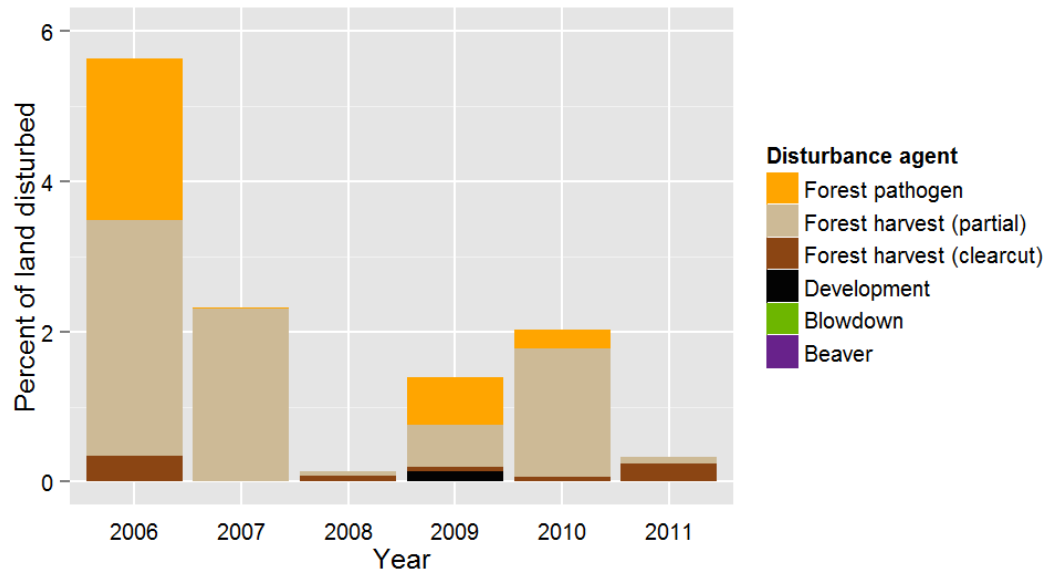


Figure 9. Percent of land disturbed inside the PIRO administrative boundary, by causal agent and year.

Non-PIRO

On lands outside the park administrative boundary, forest harvest (partial and clearcut) was the largest contributor to disturbances in each of the analysis years (Figure 10). In each of the years, there was more partial forest harvest than clearcut. Additional disturbances during the analysis period included forest pathogen, present in 2006, 2009, and 2010, and development in all years except 2007 and 2010.

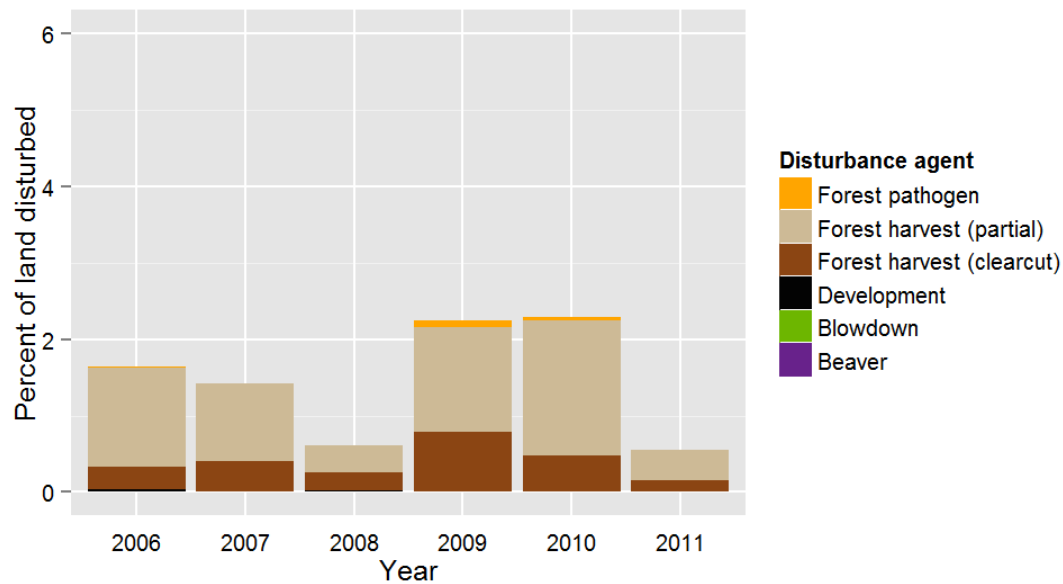


Figure 10. Percent of land disturbed outside PIRO during the analysis period, by causal agent and year.

Land Cover Dynamics

During the validation process the interpreter can denote up to three separate pre- and post-disturbance vegetation classes for polygons that encompass multiple cover types. For more details on how pre- and post- vegetation disturbance classes are defined and chosen, see Kirschbaum and Gafvert (2010).

PIRO

The majority of forest that was disturbed during the analysis period remained in the forested vegetation type. Depending on the amount of forest canopy cover remaining after a forest harvest, the ending class fell into one of three percent-cover remaining forest classes. For example, in 2007 the majority of forest that was disturbed fell from closed canopy to semi-closed as a result of the forest harvest activities. However, in 2006, the majority of the closed canopy forest remained in the closed forest category due to the low amount of trees being removed. In 2009, a significant amount (36 ha) of impervious surface was created as a result of re-routing and paving State Highway H-58 within the park administrative boundary (Figure 11 and Figure A2 in Appendix A).

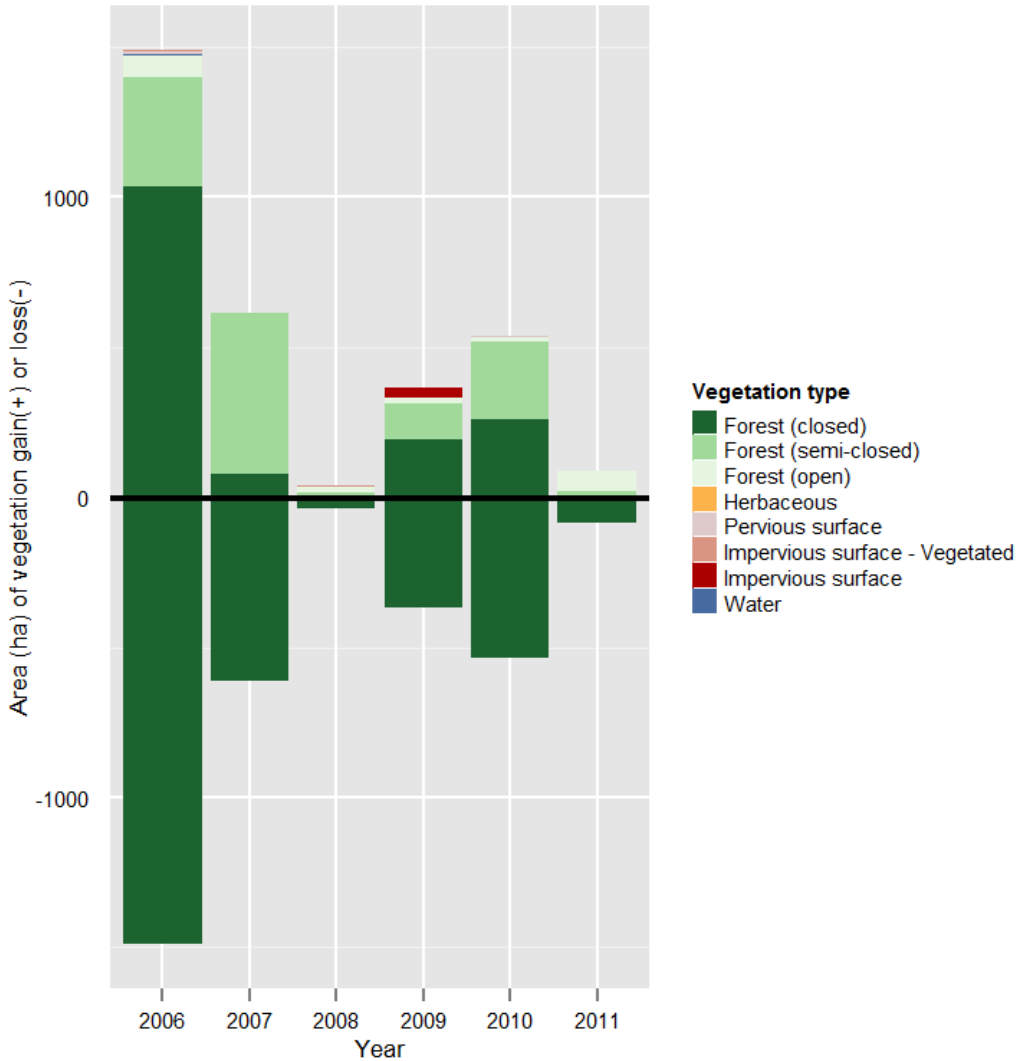


Figure 11. Area (in ha) of vegetation cover type lost (-) and gained (+) at PIRO during the analysis period (2006–2011). In some cases the vegetation type lost is the same as vegetation type gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to alter the vegetation class.

Non-PIRO

Outside the PIRO administrative boundary, only the forest type was disturbed, with the vast majority being in the closed canopy cover class. The resulting cover classes from these disturbances were largely semi-closed and open forest classes (Figure 12). These cover classes were the result of the forest harvests which are prevalent on the landscape.

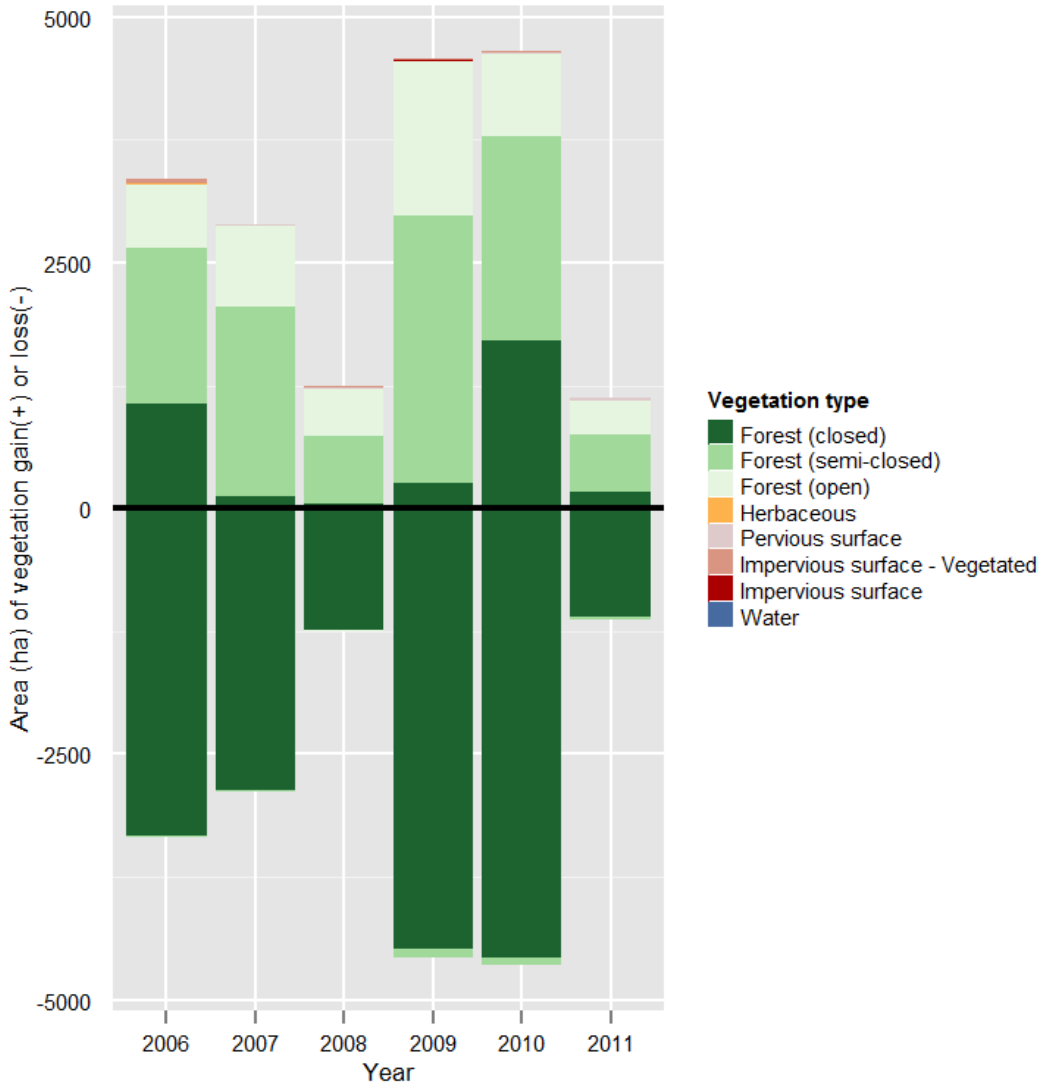


Figure 12. Area (in ha) of vegetation cover type lost (-) and gained (+) outside the PIRO administrative boundary during the analysis period (2006–2011).

Disturbance Agents by Ownership Type

If an owner name or owner description category is not represented on the graph, there were no disturbances in that ownership category. Ownership data for lands in Michigan were obtained from the Michigan Gap Analysis website (<http://www.fw.msu.edu/~maurerb/gap/stewardship.html>).

Owner description

As a percentage of the analysis area, privately-owned lands contributed the greatest amount of disturbed land while also comprising nearly 40% of the analysis area (Figure 13). The majority of the disturbances were due to partial forest harvests, with additional disturbances due to clearcuts, forest pathogens, and development (Table C8 in Appendix C). Following private lands, the State of Michigan had the next highest disturbance rate, though still less than half the rate on privately-held lands. State lands also had the same types of disturbances as private lands, with a higher proportion

of forest clearcutting than private lands. The remaining three land owner types—unknown, U.S. Forest service (US-FS), and U.S. National Park Service (US-NPS)—all had similar contributions to the overall disturbance percentage, with US-NPS having the largest percentage of forest pathogen during the analysis period. Similar to State of Michigan lands, the Forest Service had nearly equal proportions of clearcutting and partial harvest, while also occupying the third greatest amount of land within the analysis area (Figure 13).

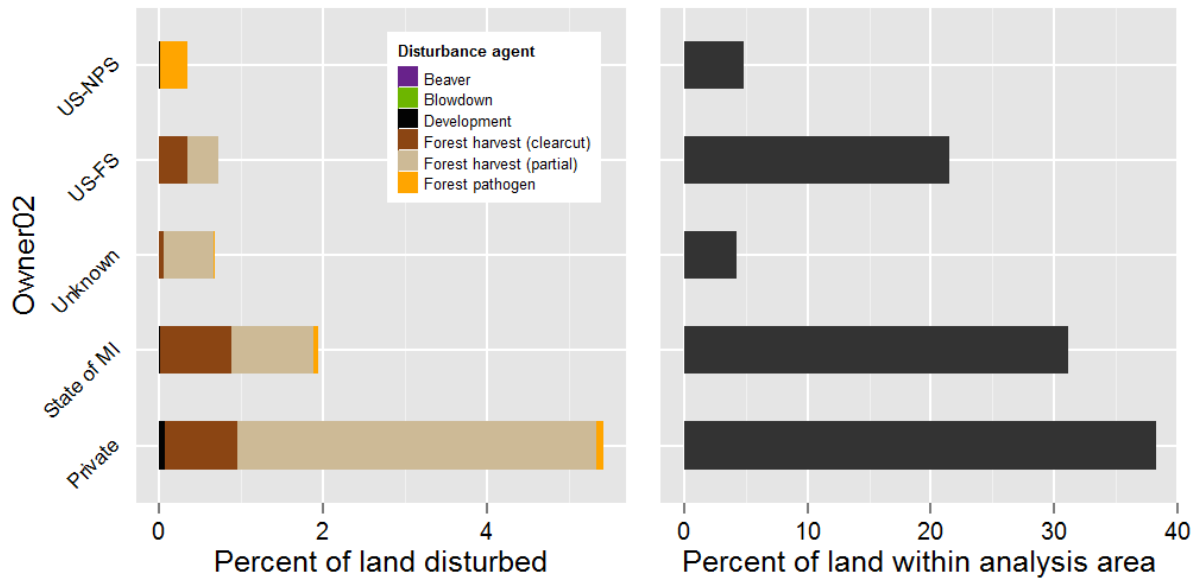


Figure 13. Percent of land disturbed inside the entire analysis area, by five broad ownership types (left) and the percent of analysis area occupied by each owner (right).

Discussion

PIRO is similar to two other parks in the Network—MISS and SACN—in that there is a significant portion of non-NPS ownership within the park boundary. PIRO has 58% in other ownership, SACN has 40% non-NPS, and MISS is almost entirely non-NPS, as the MISS corridor is predominantly within the Minneapolis-St. Paul metropolitan area. These ownership patterns impact the functioning of park natural resources through increased fragmentation, road density, and wildlife movement.

When we look more closely at the two different zones within the park (core and IBZ) we can see the different management strategies in the disturbance agents present. As we would expect, there is a lack of forest harvest within the core, whereas forest harvest is the dominant disturbance agent in the IBZ (Figure 14). Interestingly, the harvest rate within the IBZ is nearly twice that found outside the park. This could be due to the fact that nearly all land within the IBZ is managed solely for timber products, while the land outside the park is more diverse and contains a larger proportion of land not suitable for forest harvest.

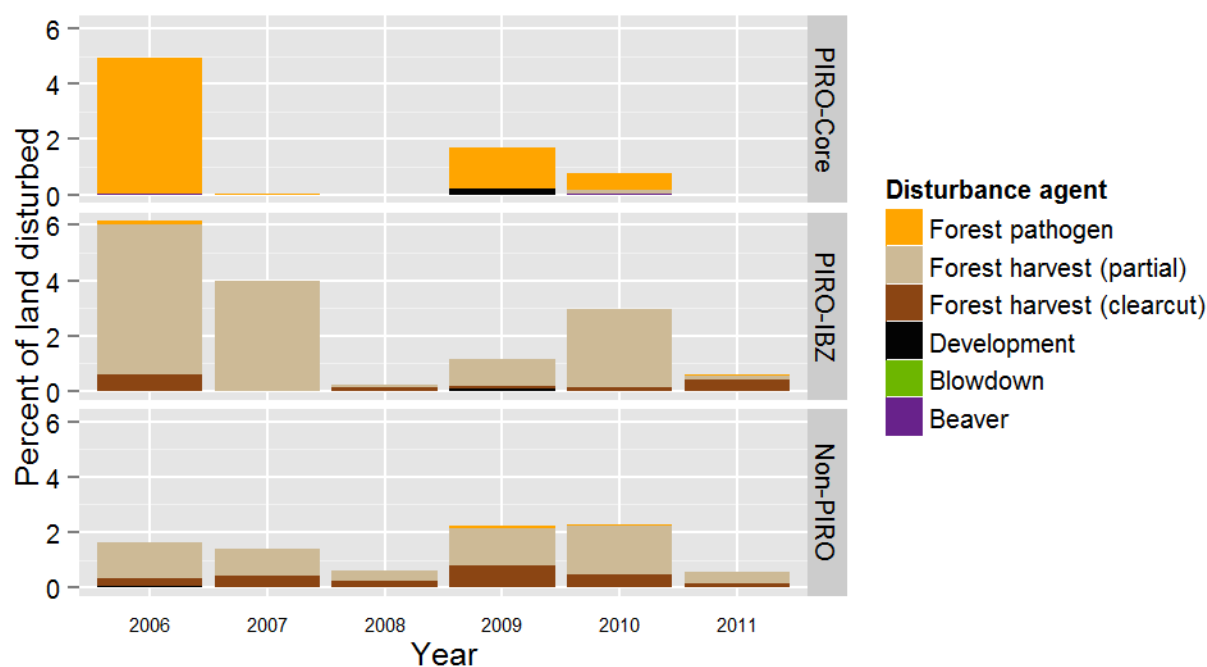


Figure 14. Percent of land inside each zone affected by disturbance agent, 2006–2011.

Much of the forest pathogen disturbance that occurred within the park was located east of Beaver Lake and was the result of beech bark disease. In most cases of beech bark disease, the tree eventually dies, leaving a gap in the canopy. An example of these gaps can be seen in the inset of Figure 15. Fortunately, while beech is a large component of the hardwood forests in and around PIRO, sugar maple is present in even greater densities (Sanders and Grochowski 2010). The sugar maple currently located in the midstory will likely fill the gaps created by the beech mortality.

However, sugar maple located in the understory could be out-competed by the beech stump sprouts which grow quickly. More information regarding the advancement, timing, and implications of beech bark disease specific to PIRO can be found in (Sanders and Grochowski 2010).

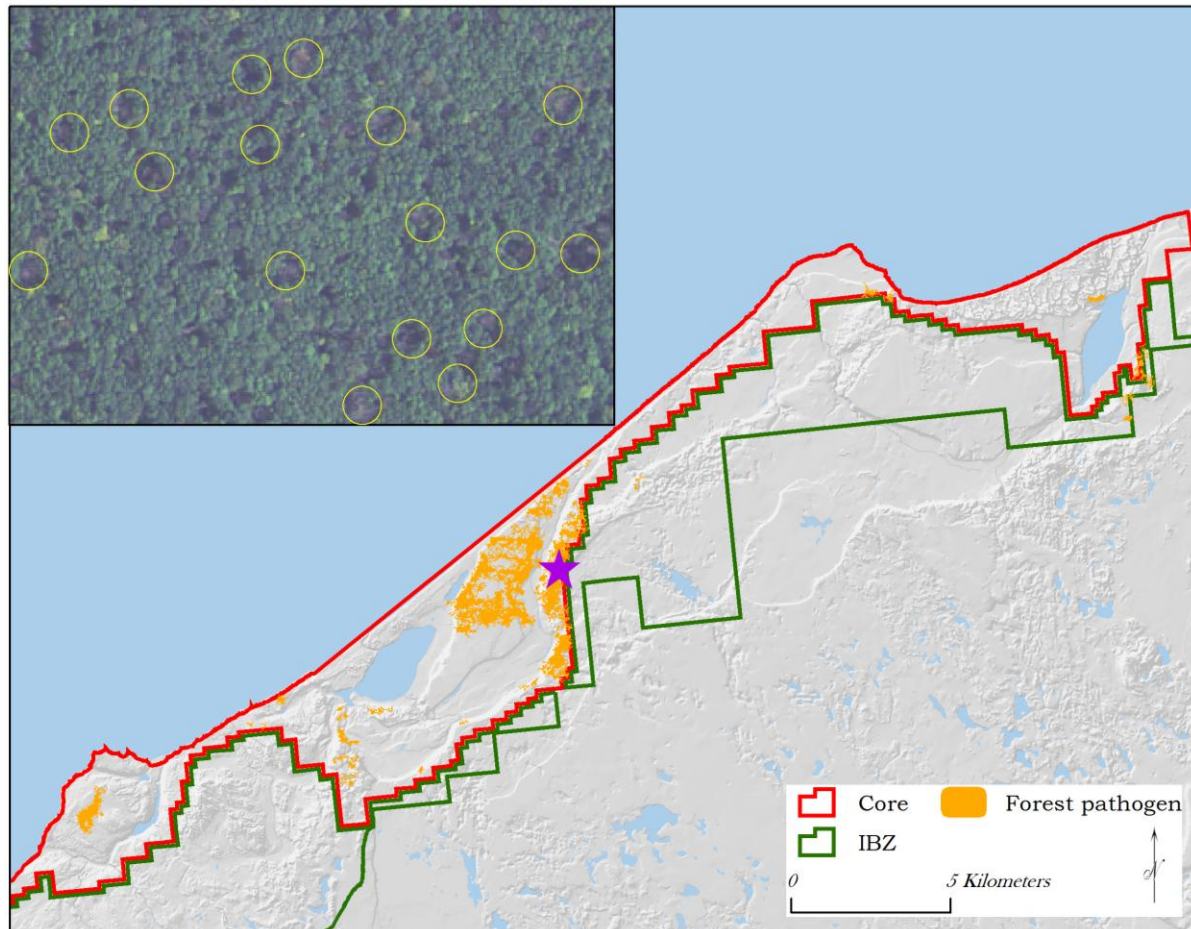


Figure 15. Spatial distribution of forest pathogen disturbances inside PIRO. Inset shows the density of tree mortality in a 2012 airphoto with yellow circles around dead beech trees. The purple star indicates the location of the airphoto inset.

As was previously noted, forest harvest was the predominant disturbance agent within the PIRO-IBZ. Most of the forest harvest that occurred within the park boundary was partial harvest. Among the forest harvests that came up to the border of the core zone, there were two over 200 ha (500 acres). Both of these were partial harvests, one occurring southwest of Beaver Lake in the Little Beaver Creek drainage, and the other southwest of Grand Sable Lake, in the Rhody Creek drainage (Figure 16).

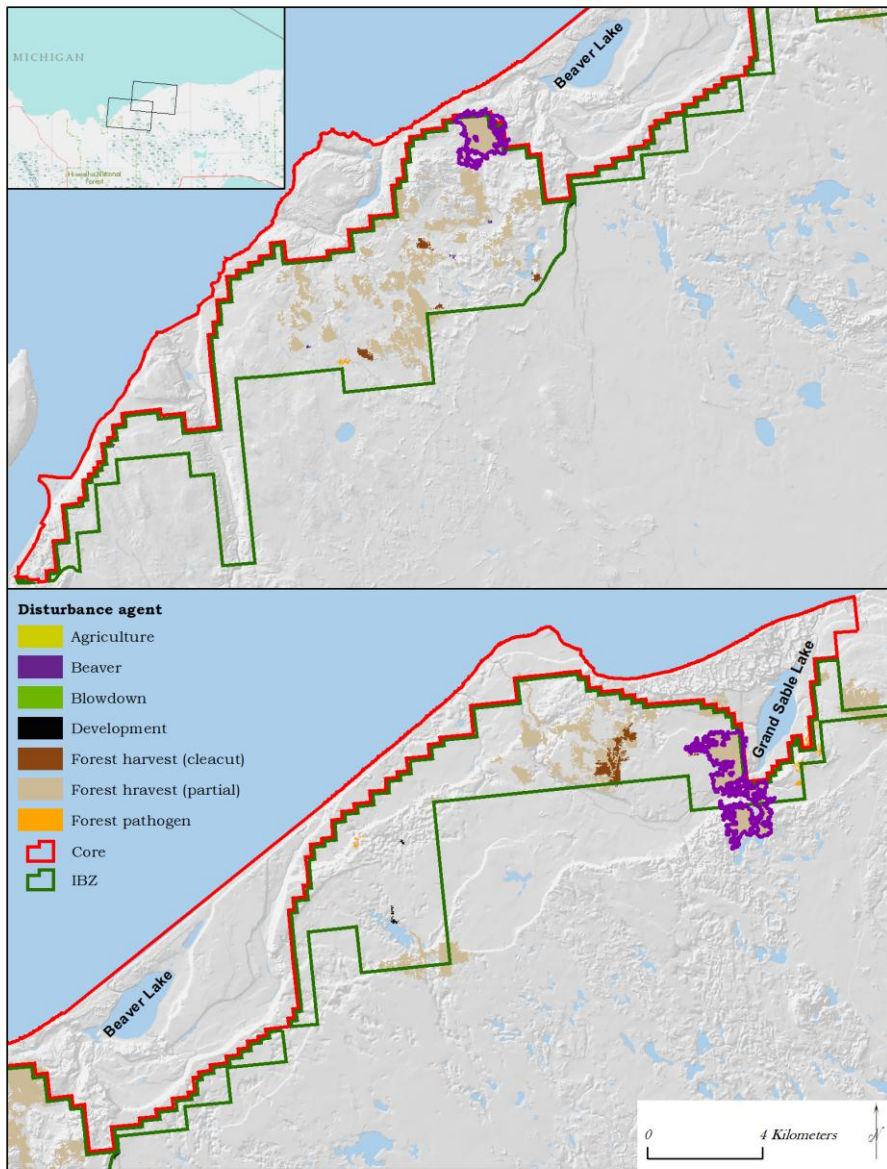


Figure 16. Spatial distribution of disturbances, by causal agent, within the PIRO-IBZ area, 2006–2011. Large (>200 ha) partial harvests are outlined in purple. Top map is west half of PIRO, bottom map is east half of PIRO.

Outside the park boundary, the bulk of the disturbances (forest harvest) occurred in the eastern region of the analysis area (Figure 17). The area contained in the purple box was a mix of partial harvests and clearcuts that occurred from 2006 to 2011 and totals 4,801 ha (11,863 acres). Throughout the rest of the analysis area, disturbances tended to be smaller and more dispersed with more of the harvests being clearcuts.

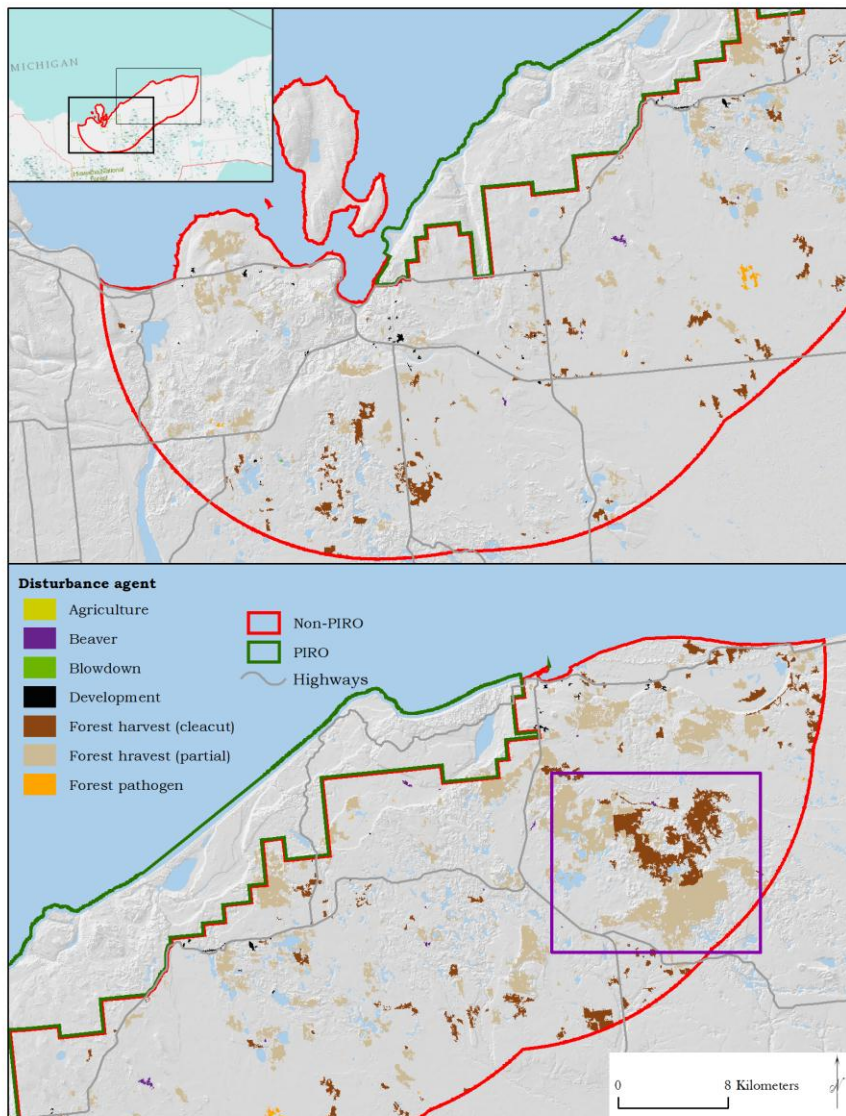


Figure 17. Spatial distribution of disturbances by causal agent within the Non-PIRO area, 2006–2011. Top map is west half of analysis area, bottom map is east half of analysis area.

Pictured Rocks NL Comparison to Other Great Lakes Network Parks

This is the sixth park analyzed in the Network. The overall analysis areas differed among parks depending on whether a watershed or simple buffer approach seemed most appropriate. Simple distance buffers around parks were chosen at VOYA, ISRO, and PIRO. For the remaining parks—APIS, MISS, SACN, and SLBE—which are more affected by surface water flowing into the park, watersheds were used to define analysis areas. At PIRO, all of the watersheds outside the park flow south to Lake Michigan, so the decision was made to analyze a 20 km buffer outside the park boundary. Maps of the analysis areas can be found in Appendix F. All analysis areas (inside park plus outside park area) were all greater than 150,000 ha.

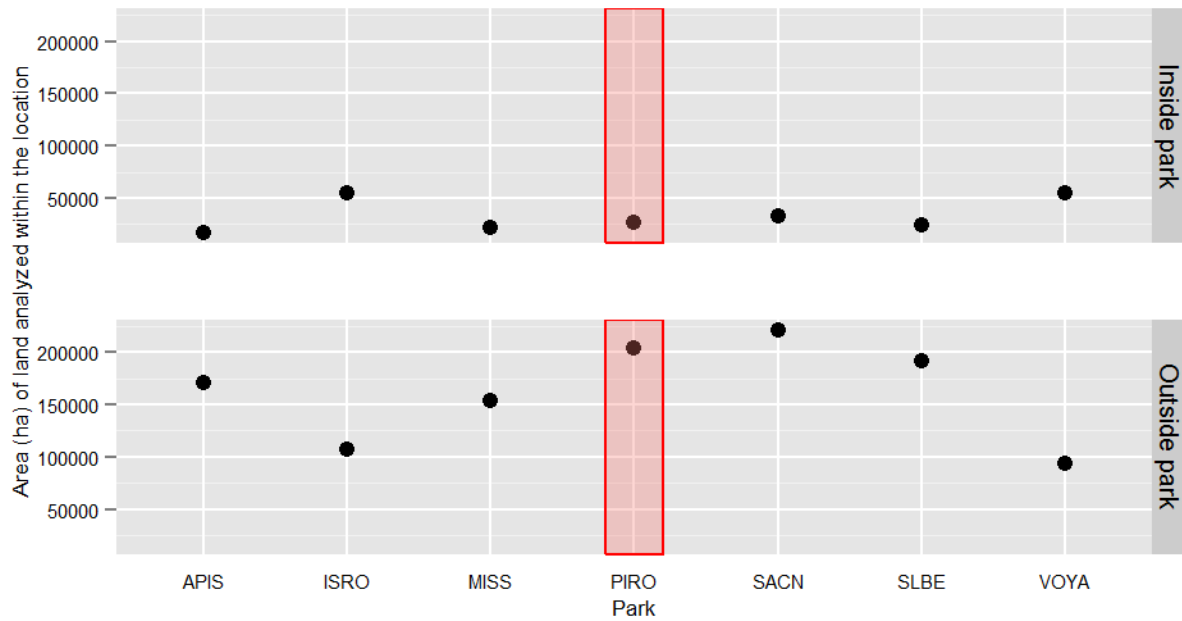


Figure 18. Land area (ha) monitored at each park, both inside (top) and outside (bottom) the parks' administrative boundaries.

Inside the park administrative boundary, PIRO had the highest rate of disturbance of all parks analyzed to date (Figure 19). The amount of land disturbed outside the PIRO park boundary was second only to VOYA. The area outside of VOYA includes a significant portion of Canada, where large-scale forest harvests are more common (Figure F1). This is quite different than the land outside PIRO, where over half is in public ownership (see Figure 4).

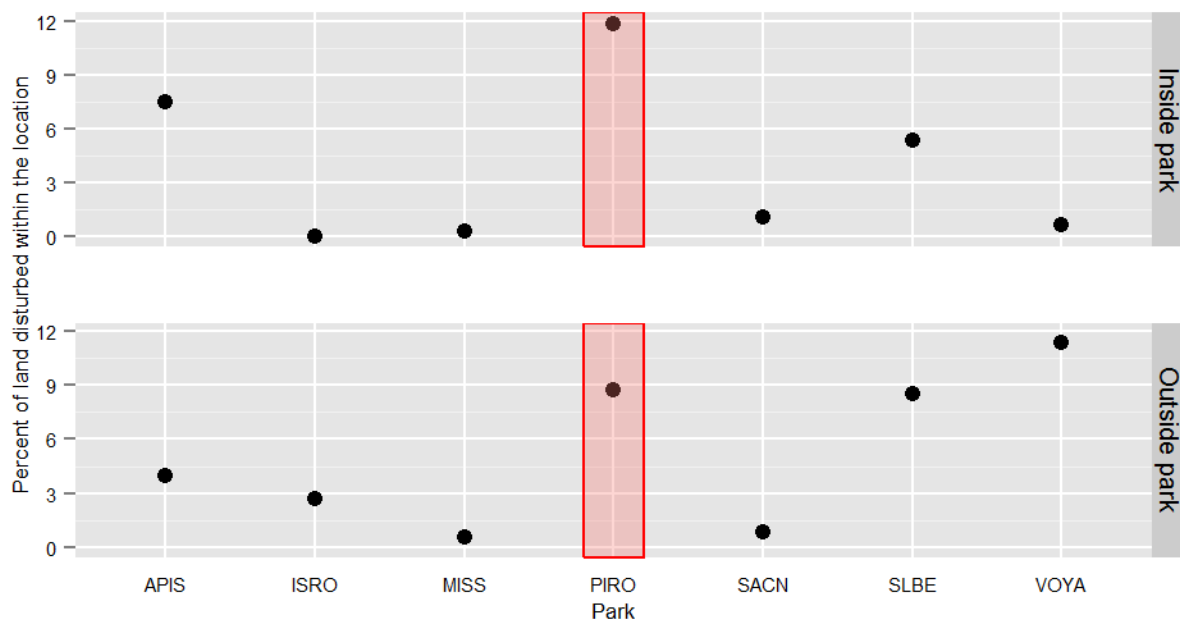


Figure 19. Percent of land disturbed inside the parks (top) and outside the parks (bottom).

Due to the IBZ within the park administrative boundary, PIRO shows the largest percentage of disturbance due to forest harvest inside the park than any other in the Network. It also is one of three parks with significant amounts of forest pathogen, ranking third behind APIS and SLBE (Figure 20). However, unlike the other two parks, where the saddle prominent caterpillar (APIS) and the gypsy moth (SLBE) only defoliated a large proportion of the deciduous trees on the landscape without killing them, beech bark disease at PIRO resulted in tree mortality.

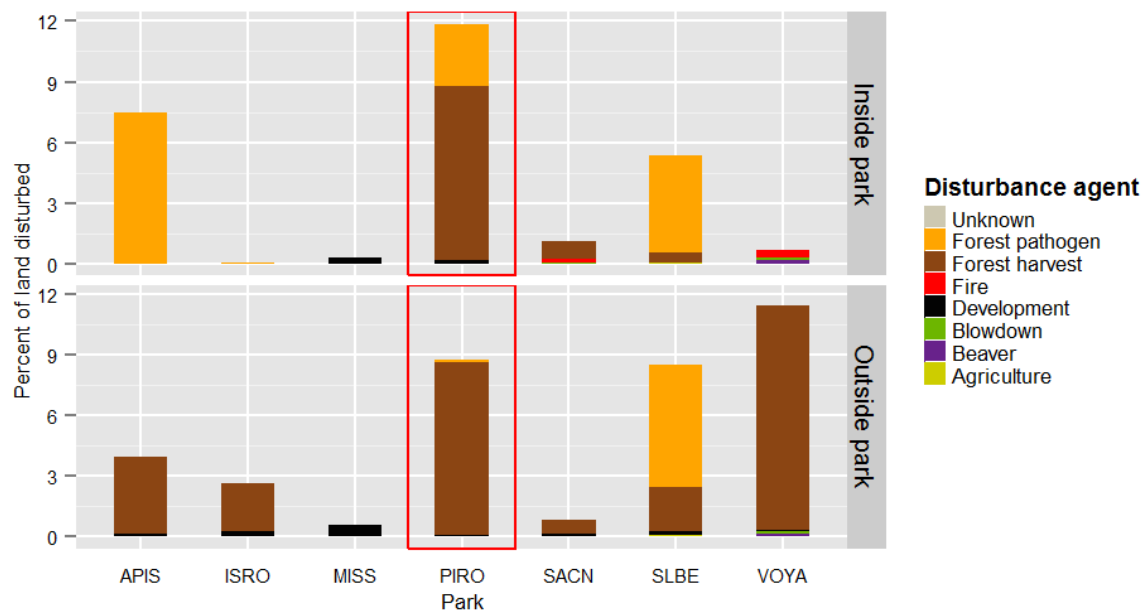


Figure 20. Percent of land disturbed inside the parks (top) and outside the parks (bottom), by causal agent.

Of the parks analyzed thus far in the Great Lakes Network, the PIRO analysis area is most closely related to the VOYA analysis area in terms of population, roads, and dominant vegetation. Similar to VOYA, PIRO is located in a very sparsely populated area, one of the least populated analysis areas in the Great Lakes Network (Figure 21). The only census block within the PIRO analysis area with more than 20 people/km² includes Munising. However, while roads data often closely reflect the population data (and does so at VOYA), PIRO has many more roads in and around the park (Figure 21). Nevertheless, PIRO has large tracts of forested areas, and it is in part because of those and because of the area's low population that forestry-related activities are the dominant disturbance agent.

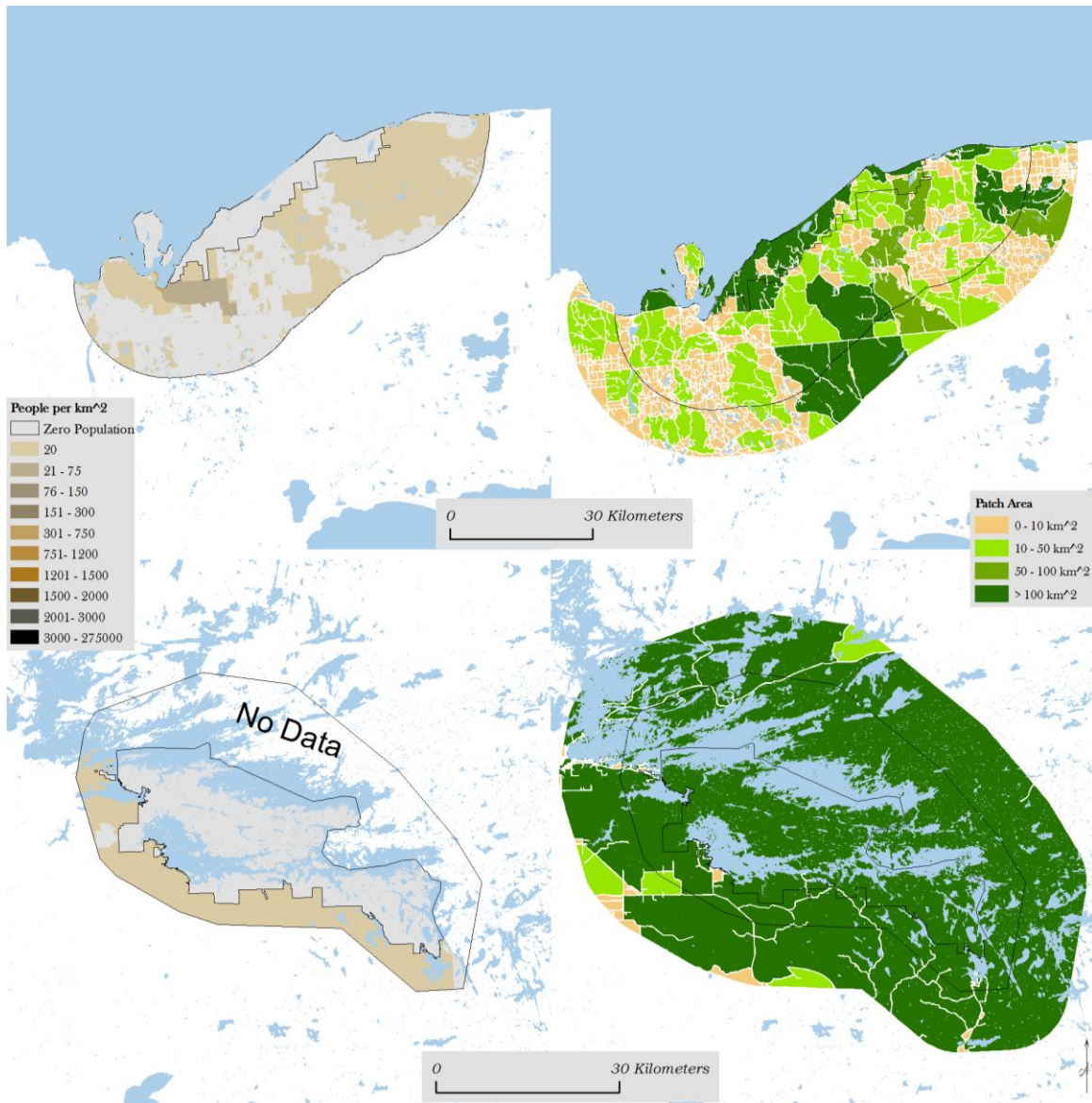


Figure 21. Area-weighted population and forest patch area metrics (based upon road presence) for PIRO (top) and VOYA (bottom) analysis areas. Population data from U.S. Census Bureau (<http://www.census.gov>), and 2012 road data from ESRI (www.arcgis.com).

Conclusions

During this first period of disturbance analysis (2006–2011):

- 1) PIRO experienced the highest percent of land disturbed within its administrative boundary of all parks analyzed thus far. However, over half of all the land disturbed was due to forest harvest activities, which are allowed within a particular zone (IBZ) of the park.
- 2) PIRO experienced the second highest percent of land disturbed outside the park, again dominated by forest harvests.
- 3) Although PIRO had the highest rate of disturbance, most of the disturbance was due to partial forest harvests, in which a forest still persists albeit at a lower percentage of canopy closure.
- 4) PIRO had one of the highest rates of disturbance due to forest pathogens, and is the only park thus far with tree mortality due to forest pathogen.
- 5) The PIRO-IBZ was harvested at a rate of 2.5% per year, a full 1% more than the rate outside the park boundary (Non-PIRO).
- 6) While there were high rates of disturbance both inside and outside the PIRO administrative boundary, the majority of these disturbances did not result in land use change. If these forests are sustainably managed by landowners, it provides the local economy with jobs while also providing a matrix of stand ages and types that are beneficial to multiple wildlife species.

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 to provide trend analyses of the disturbance regimes at work in the park and the neighboring area. Instead, this report represents a foundation from 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. Thus, over time, the relevance of information contained in these reports will become increasingly clear.

Literature Cited

- Aldrich, R. C. 1975. Detecting disturbances in a forest environment. *Photogrammetric Engineering and Remote Sensing* 41:39-48.
- Benz, U. C., P. Hofmann, G. Willhauck, I. Lingenfelder, and M. Heynen. 2004. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. *ISPRS Journal of Photogrammetry and Remote Sensing* 58:239-258.
- Brown, D. G. 2003. Land use and forest cover on private parcels in the upper Midwest USA, 1970 to 1990. *Landscape Ecology* 18:777-790.
- Chen, X. X., J. E. Vogelmann, M. Rollins, D. Ohlen, C. H. Key, L. M. Yang, C. Q. Huang, and H. Shi. 2011. Detecting post-fire burn severity and vegetation recovery using multitemporal remote sensing spectral indices and field-collected composite burn index data in a ponderosa pine forest. *International Journal of Remote Sensing* 32:7905-7927.
- Cihlar, J. 2000. Land cover mapping of large areas from satellites: status and research priorities. *International Journal of Remote Sensing* 21:1093-1114.
- Cohen, W. B., M. Fiorella, J. Gray, E. Helmer, and K. Anderson. 1998. An efficient and accurate method for mapping forest clearcuts in the Pacific Northwest using Landsat imagery. *Photogrammetric Engineering and Remote Sensing* 64:293-300.
- Cohen, W. B., and S. N. Goward. 2004. Landsat's role in ecological applications of remote sensing. *BioScience* 54:535-545.
- Cohen, W. B., Z. Yang, and R. E. Kennedy. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync - Tools for calibration and validation. *Remote Sensing of Environment* 114:2911-2924.
- Coppin, P., I. Jonckheere, K. Nackaerts, B. Muys, and E. Lambin. 2004. Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing* 25:1565-1596.
- Coppin, P. R., and M. E. Bauer. 1995. The potential contribution of pixel-based canopy change information to stand-based forest management in the northern U.S. *Journal of Environmental Management* 44:69-82.
- Deel, L. N., B. E. McNeil, P. G. Curtis, S. P. Serbin, A. Singh, K. N. Eshleman, and P. A. Townsend. 2012. Relationship of a Landsat cumulative disturbance index to canopy nitrogen and forest structure. *Remote Sensing of Environment* 118:40-49.
- Desclee, B., P. Bogaert, and P. Defourny. 2006. Forest change detection by statistical object-based method. *Remote Sensing of Environment* 102:1-11.

- Eshleman, K. N., B. E. McNeil, and P. A. Townsend. 2009. Validation of a remote sensing based index of forest disturbance using streamwater nitrogen data. *Ecological Indicators* 9:476-484.
- Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution and Systematics* 34:487-515.
- Fitzpatrick, F. A., J. C. Knox, and H. E. Whitman. 1999. Effects of historical land-cover changes on flooding and segmentation, North Fish Creek, Wisconsin. USGS Water-Resources Investigations Report 99-4083.
- Gimmi, U., and V. C. Radeloff. 2013. Assessing Naturalness in Northern Great Lakes Forests Based on Historical Land-Cover and Vegetation Changes. *Environmental Management*:1-12.
- Gimmi, U., S. L. Schmidt, U. Gafvert, and V. C. Radeloff. 2009. Decreasing effectiveness of protected areas due to increasing development in the surroundings of U.S. National Park Service holdings after park establishment. National Resource Technical Report NPS/GLKN/NRTR—2009/178. National Park Service, Fort Collins, USA.
- Gimmi, U., S. L. Schmidt, T. J. Hawbaker, C. Alcántara, U. Gafvert, and V. C. Radeloff. 2011. Increasing development in the surroundings of U.S. National Park Service holdings jeopardizes park effectiveness. *Journal of Environmental Management* 92:229-239.
- Harvey, K. R., and G. J. E. Hill. 2001. Vegetation mapping of a tropical freshwater swamp in the Northern Territory, Australia: A comparison of aerial photography, Landsat TM and SPOT satellite imagery. *International Journal of Remote Sensing* 22:2911-2925.
- Hay, G. J., T. Blaschke, D. J. Marceau, and A. Bouchard. 2003. A comparison of three image-object methods for the multiscale analysis of landscape structure. *ISPRS Journal of Photogrammetry and Remote Sensing* 57:327-345.
- Healey, S. P., W. B. Cohen, Z. Q. Yang, and O. N. Krankina. 2005. Comparison of tasseled cap-based Landsat data structures for use in forest disturbance detection. *Remote Sensing of Environment* 97:301-310.
- Heurich, M., T. Ochs, T. Andresen, and T. Schneider. 2010. Object-orientated image analysis for the semi-automatic detection of dead trees following a spruce bark beetle (*Ips typographus*) outbreak. *European Journal of Forest Research* 129:313-324.
- Huang, C., S. N. Goward, J. G. Masek, N. Thomas, Z. Zhu, and J. E. Vogelmann. 2010. An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment* 114:183-198.
- Huang, C., S. N. Goward, K. Schleeweis, N. Thomas, J. G. Masek, and Z. Zhu. 2009. Dynamics of national forests assessed using the Landsat record: Case studies in eastern United States. *Remote Sensing of Environment* 113:1430-1442.

- Kennedy, R., A. Kirschbaum, U. Gafvert, P. Nelson, Z. Yang, W. Cohen, E. Pfaff, and B. Gholson. 2010a. Landsat-based monitoring of landscape dynamics in the national parks of the Great Lakes Inventory and Monitoring Network (Version 1.0). National Resource Report NPS/GLKN/NRR—2010/221. National Park Service, Fort Collins, Colorado.
- Kennedy, R. E., W. B. Cohen, A. A. Kirschbaum, and E. Haunreiter. 2007a. Protocol for Landsat-based monitoring of landscape dynamics at North Coast and Cascades Network parks. U.S. Geological Survey Techniques and Methods 2-G1. USGS Biological Resources Division, Reston, Virginia, USA.
- Kennedy, R. E., W. B. Cohen, and T. A. Schroeder. 2007b. Trajectory-based change detection for automated characterization of forest disturbance dynamics. *Remote Sensing of Environment* 110:370-386.
- Kennedy, R. E., Z. Yang, and W. B. Cohen. 2010b. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms. *Remote Sensing of Environment* 114:2897-2910.
- Kennedy, R. E., Z. Yang, W. B. Cohen, E. Pfaff, J. Braaten, and P. Nelson. 2012. Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment* 122:117-133.
- Kirschbaum, A., and U. Gafvert. 2010. Standard operating procedure #6: Lab validation of LandTrendr outputs. In R. Kennedy, A. Kirschbaum, U. Gafvert, P. Nelson, Z. Yang, W. Cohen, E. Pfaff, and B. Gholson, editors. Landsat-based monitoring of landscape dynamics in the national parks of the Great Lakes Inventory and Monitoring Network (version 1.0). National Resource Report NPS/GLKN/NRR—2010/221. National Park Service, Fort Collins, Colorado.
- Laliberte, A. S., A. Rango, K. M. Havstad, J. F. Paris, R. F. Beck, R. McNeely, and A. L. Gonzalez. 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. *Remote Sensing of Environment* 93:198-210.
- Law, B. E., D. Turner, J. Campbell, O. J. Sun, S. Van Tuyl, W. D. Ritts, and W. B. Cohen. 2004. Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. *Global Change Biology* 10:1429-1444.
- Lillesand, T. M., and R. W. Kiefer. 2000. Remote Sensing and Image Interpretation, 4th edition. John Wiley & Sons Inc., New York.
- Loope, W. L. 1991. Interrelationships of fire history, land use history, and landscape pattern within Pictured Rocks National Lakeshore, Michigan. *Canadian Field-Naturalist* 105:18-28.
- Lu, D., P. Mausel, E. Brondízio, and E. Moran. 2004. Change detection techniques. *International Journal of Remote Sensing* 25:2365-2401.

- Lu, P., A. Stumpf, N. Kerle, and N. Casagli. 2011. Object-oriented change detection for landslide rapid mapping. *IEEE Geoscience and Remote Sensing Letters* 8:701-705.
- Maheu-Giroux, M., and S. de Blois. 2005. Mapping the invasive species *Phragmites australis* in linear wetland corridors. *Aquatic Botany* 83:310-320.
- Masek, J. G., E. F. Vermote, N. E. Saleous, R. Wolfe, F. G. Hall, K. F. Huemmrich, F. Gao, J. Kutler, and T. K. Lim. 2006. A Landsat Surface Reflectance Dataset for North America, 1990-2000. *IEEE Geoscience and Remote Sensing Letters* 3:68-72.
- Meigs, G. W., R. E. Kennedy, and W. B. Cohen. 2011. A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. *Remote Sensing of Environment* 115:3707-3718.
- Monahan, W. B., J. E. Gross, L. Svancara, and T. Philippi. 2012. A guide to interpreting NPScape data and analyses. . Natural Resources Technical Report NPS/NRSS/NRTR—2012/578. National Park Service, Fort Collins, Colorado.
- Morgan, J. L., S. E. Gergel, and N. C. Coops. 2010. Aerial photography: A rapidly evolving tool for ecological management. *BioScience* 60:47-59.
- National Park Service. 2013a. NPScape standard operating procedure: Conservation status measure - Protected area and ownership/governance. Version 2013-02-25. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado.
- National Park Service. 2013b. NPScape standard operating procedure: Housing measure - Current and projected housing density. Version 2013-03-15. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado.
- National Park Service. 2013c. NPScape standard operating procedure: Roads measure - Road density, distance from roads, and area without roads. Version 2013-03-15. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado.
- Potapov, P., M. C. Hansen, S. V. Stehman, K. Pittman, and S. Turubanova. 2009. Gross forest cover loss in temperate forests: biome-wide monitoring results using MODIS and Landsat data. *Journal of Applied Remote Sensing* 3(1).
- Powell, S. L., W. B. Cohen, S. P. Healey, R. E. Kennedy, G. G. Moisen, K. B. Pierce, and J. L. Ohmann. 2010. Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: A comparison of empirical modeling approaches. *Remote Sensing of Environment* 114:1053-1068.
- Radke, R. J., S. Andra, O. Al-Kofahi, and B. Roysam. 2005. Image change detection algorithms: a systematic survey. *IEEE Transactions on Image Processing* 14:294-307.

- Rutchey, K., and L. Vilchek. 1999. Airphoto interpretation and satellite imagery analysis techniques for mapping cattail coverage in a northern everglades impoundment. *Photogrammetric Engineering and Remote Sensing* 65:185-191.
- Sanders, S., and J. Grochowski. 2010. Implementation of a Long-term Vegetation Monitoring Program at Pictured Rocks National Lakeshore. Natural Resource Technical Report NPS/GLKN/NRTR—2010/405.
- Schroeder, T. A., M. A. Wulder, S. P. Healey, and G. G. Moisen. 2011. Mapping wildfire and clearcut harvest disturbances in boreal forests with Landsat time series data. *Remote Sensing of Environment* 115:1421-1433.
- Sonnenschein, R., T. Kuemmerle, T. Udelhoven, M. Stellmes, and P. Hostert. 2011. Differences in Landsat-based trend analyses in drylands due to the choice of vegetation estimate. *Remote Sensing of Environment* 115:1408-1420.
- Stueve, K. M., I. W. Housman, P. L. Zimmerman, M. D. Nelson, J. B. Webb, C. H. Perry, R. A. Chastain, D. D. Gormanson, C. Huang, S. P. Healey, and W. B. Cohen. 2011a. Snow-covered Landsat time series stacks improve automated disturbance mapping accuracy in forested landscapes. *Remote Sensing of Environment* 115:3203-3219.
- Stueve, K. M., C. H. Perry, M. D. Nelson, S. P. Healey, A. D. Hill, G. G. Moisen, W. B. Cohen, D. D. Gormanson, and C. Huang. 2011b. Ecological importance of intermediate windstorms rivals large, infrequent disturbances in the northern Great Lakes. *Ecosphere* 2(1).
- Theobald, D. M. 2005. Landscape Patterns of Exurban Growth in the USA from 1980 to 2020. *Ecology and Society* 10:32.
- Turner, D. P., W. D. Ritts, J. M. Styles, Z. Yang, W. B. Cohen, B. E. Law, and P. E. Thornton. 2006. A diagnostic carbon flux model to monitor the effects of disturbance and interannual variation in climate on regional NEP. *Tellus Series B-Chemical and Physical Meteorology* 58:476-490.
- Veraverbeke, S., W. W. Verstraeten, S. Lhermitte, and R. Goossens. 2010. Illumination effects on the differenced Normalized Burn Ratio's optimality for assessing fire severity. *International Journal of Applied Earth Observation and Geoinformation* 12:60-70.
- Vermote, E. F., N. El Saleous, C. O. Justice, Y. J. Kaufman, J. L. Privette, L. Remer, J. C. Roger, and D. Tanre. 1997. Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: Background, operational algorithm and validation. *Journal of Geophysical Research-Atmospheres* 102:17131-17141.
- Verry, E. S. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in North Central Minnesota. Water Resources Bulletin, American Water Resources Association. Volume 19, Number 1.

- Walter, V. 2004. Object-based classification of remote sensing data for change detection. *ISPRS Journal of Photogrammetry and Remote Sensing* 58:225-238.
- Wang, L., W. P. Sousa, and P. Gong. 2004. Integration of object-based and pixel-based classification for mapping mangroves with IKONOS imagery. *International Journal of Remote Sensing* 25:5655-5668.
- Ward, J. V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation* 83:269-278.
- White, M. A., and G. E. Host. 2003. Changes in disturbance frequency, age and patch structure from pre-Euro-American to settlement to present in northcentral and northeastern Minnesota. Minnesota Forest Resources Council Report LT-1203a, St. Paul, Minnesota.
- White, M. A., and G. E. Host. 2008. Forest disturbance frequency and patch structure from pre-European settlement to present in the mixed forest province of Minnesota, USA. *Canadian Journal of Forest Research* 38:2212-2226.
- With, K. A. 2002. The landscape ecology of invasive spread. *Conservation Biology* 16:1192-1203.
- Wolter, P. T., C. A. Johnston, and G. J. Niemi. 2006. Land use land cover change in the US Great Lakes basin 1992 to 2001. *Journal of Great Lakes Research* 32:607-628.
- Wolter, P. T., and M. A. White. 2002. Recent forest cover type transitions and landscape structural changes in northeast Minnesota. *Landscape Ecology* 17:133-155.
- Wulder, M. A., and S. E. Franklin. 2007. Understanding Forest Disturbance and Spatial Pattern, Remote Sensing and GIS Approaches. CRC Press Boca Raton, Florida.
- Yu, X., J. Hyypä, H. Kaartinen, and M. Maltamo. 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning. *Remote Sensing of Environment* 90:451-462.
- Zhu, Z., and C. E. Woodcock. 2012. Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment* 118:83-94.
- Zhu, Z., C. E. Woodcock, and P. Olofsson. 2012. Continuous monitoring of forest disturbance using all available Landsat imagery. *Remote Sensing of Environment* 122:75-91.

Appendix A: Spatial Distribution of Disturbances at PIRO

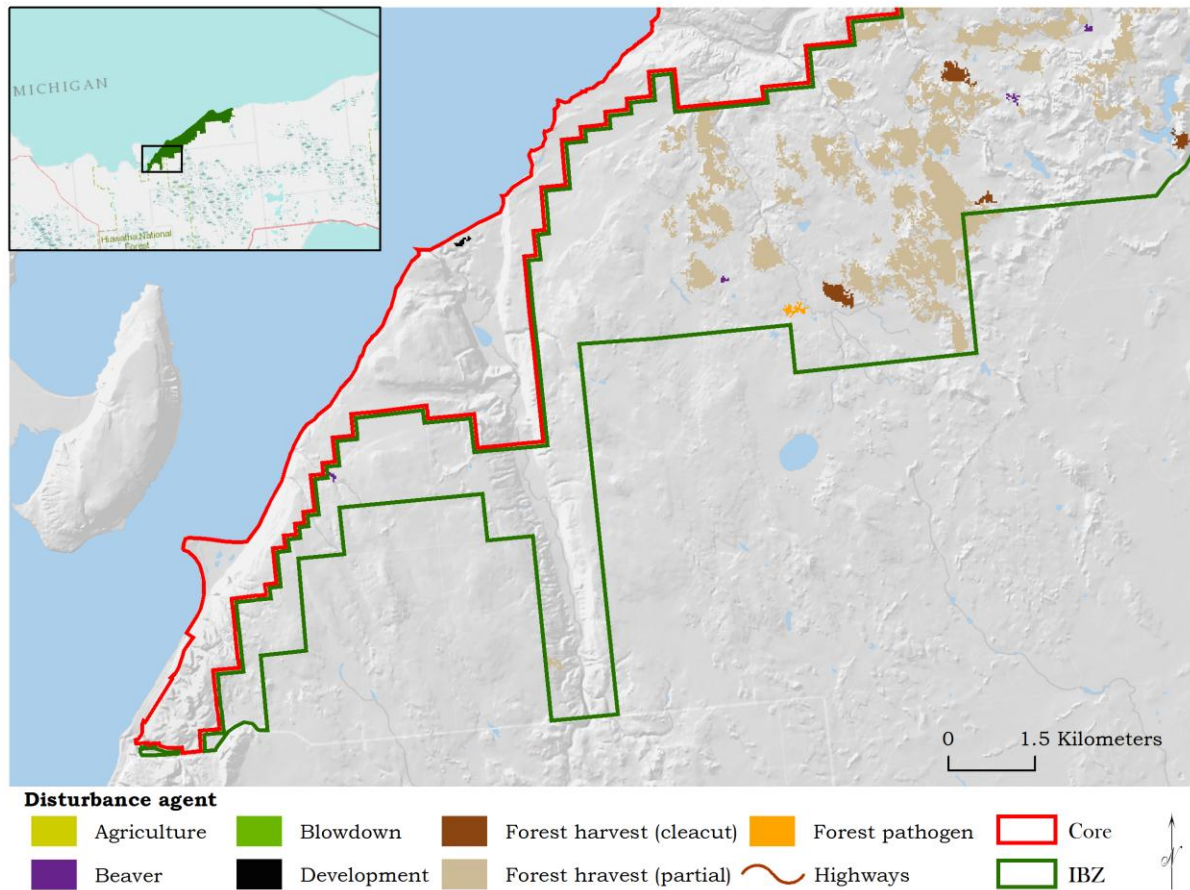


Figure A1. Close-up of disturbances inside PIRO, 2006–2011.

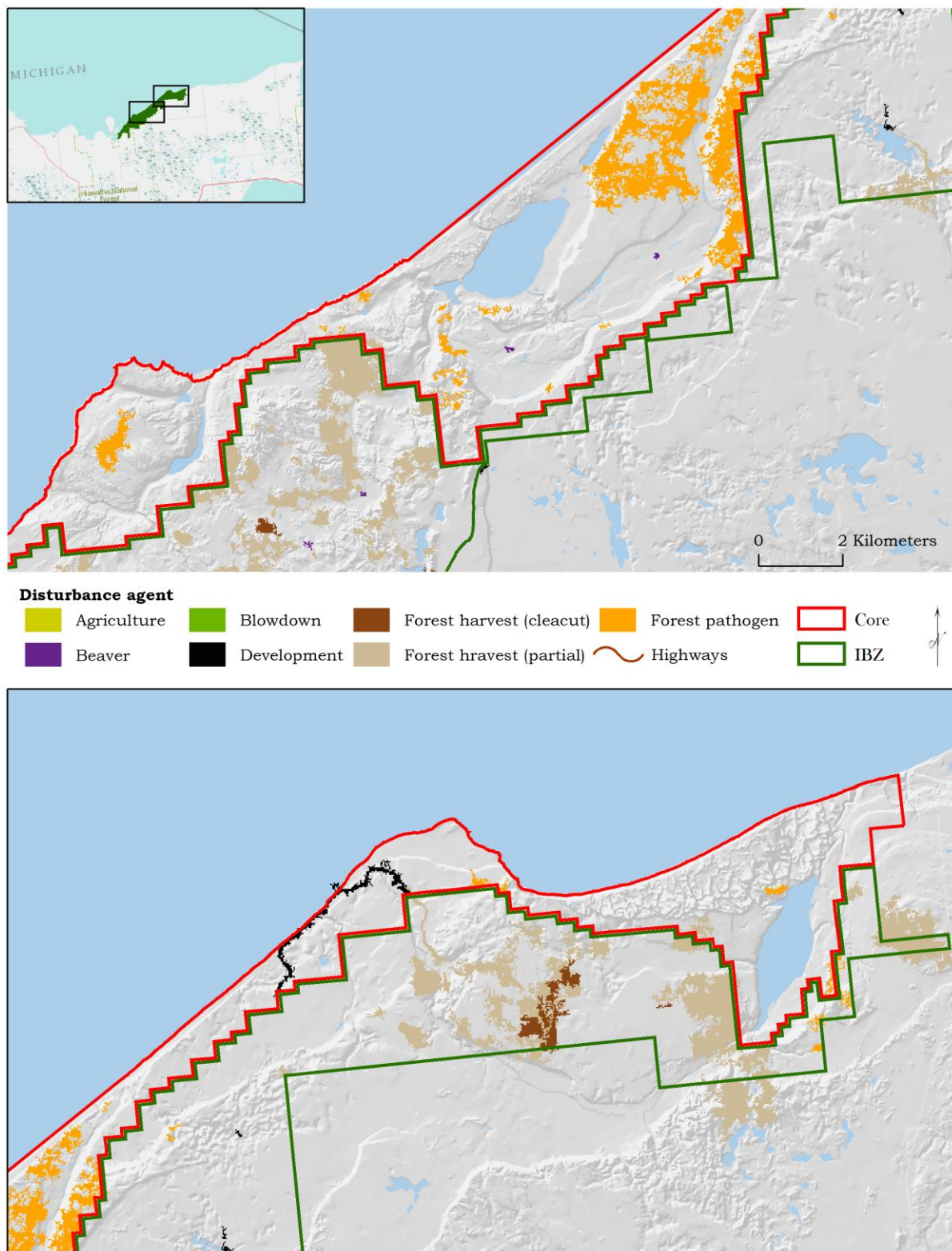


Figure A2. Close-up of disturbances inside PIRO, 2006–2011.

Appendix B: Spatial Distribution of Disturbances Outside PIRO

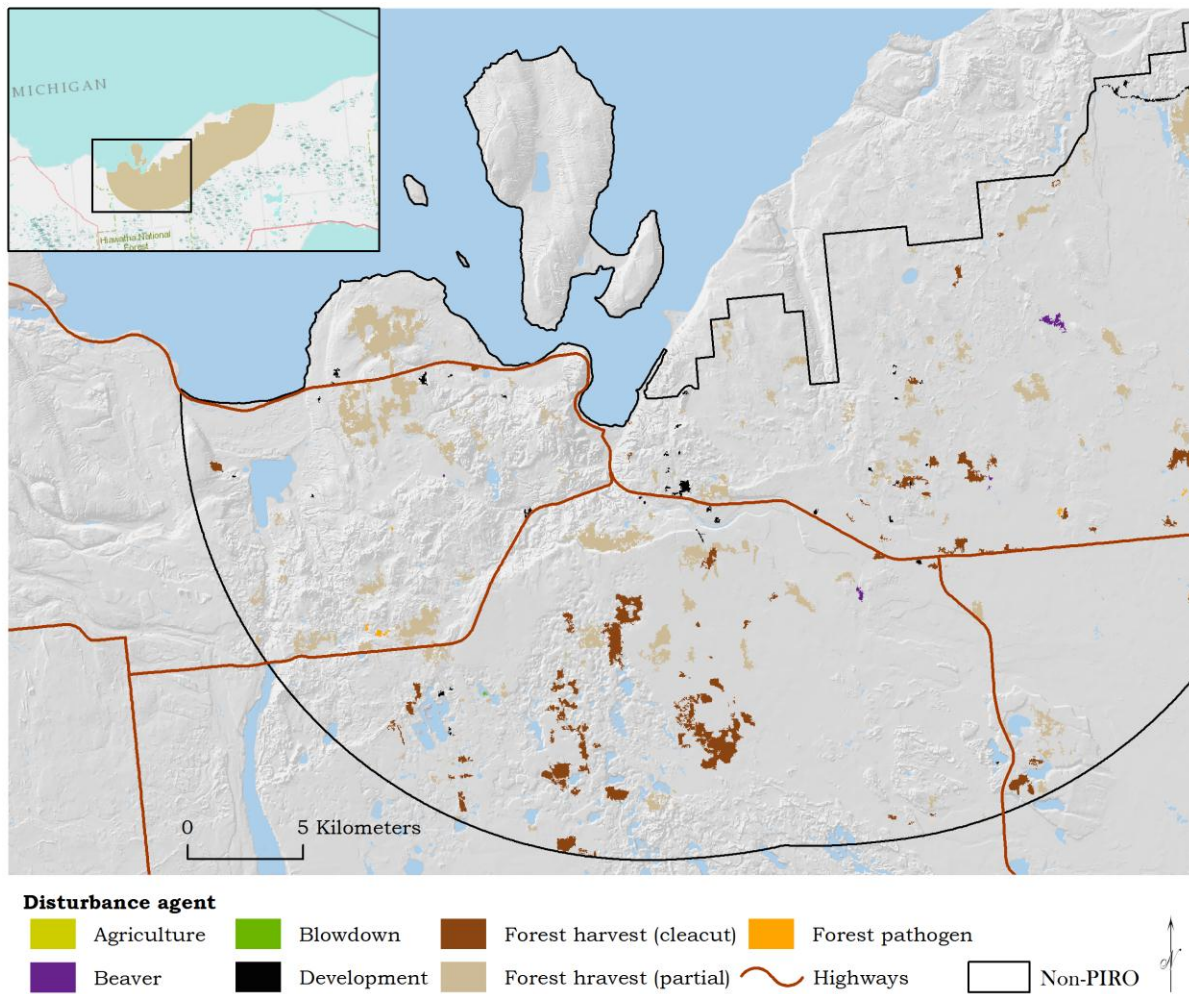


Figure B1. Close-up of disturbances outside PIRO, 2006–2011.

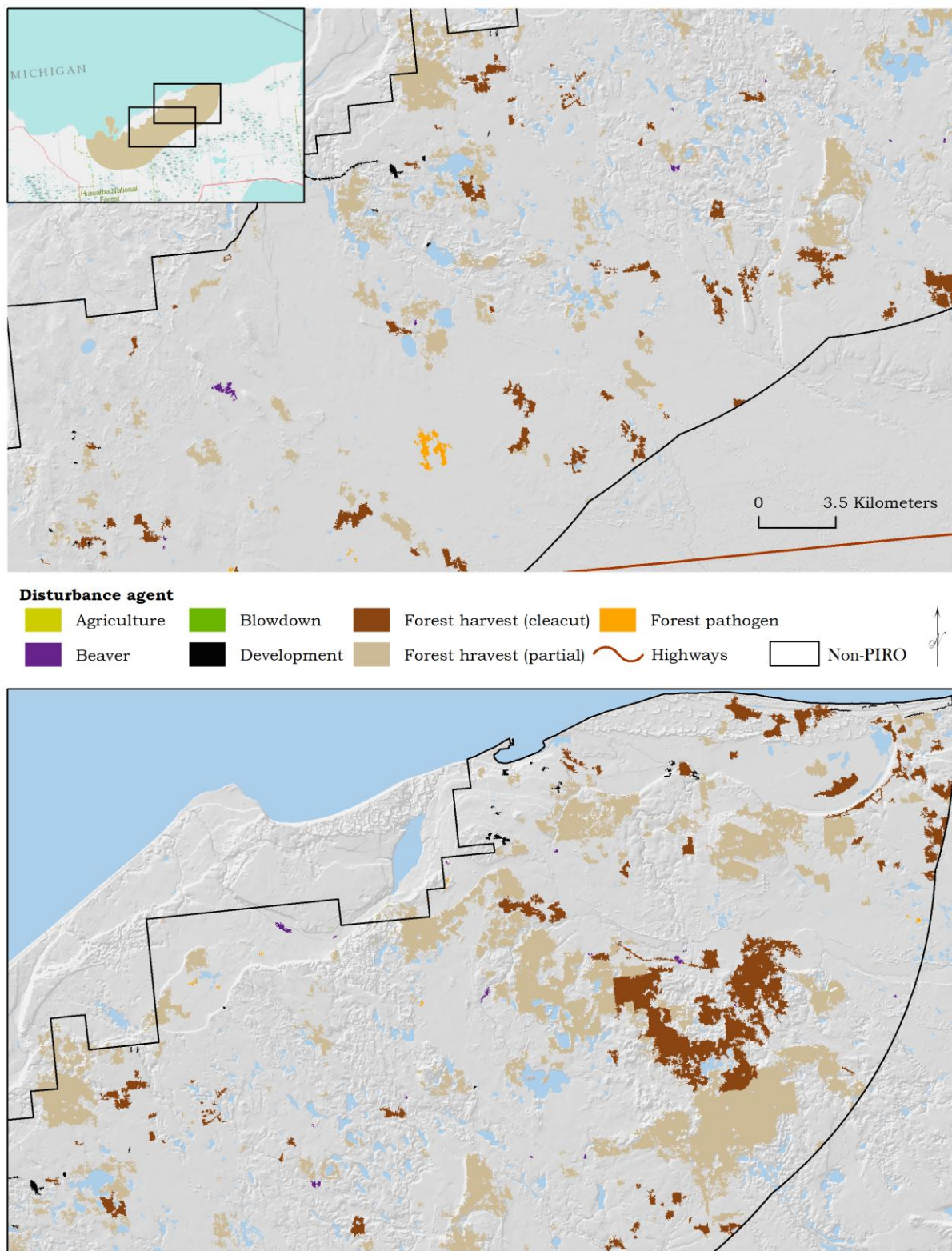


Figure B2. Close-up of disturbances outside PIRO, 2006–2011.

Appendix C: Supplemental Tables

Table C1. Area (ha) and percent of each vegetation class within the analysis area. Data summarized from the 2006 NLCD.

Class name	Percent of analysis area	Area (ha)
Open water	3.16	7498.98
Developed, open space	1.91	4526.10
Developed, low intensity	0.48	1130.13
Developed, medium intensity	0.07	172.44
Developed, high intensity	0.02	42.93
Barren land	0.41	966.24
Deciduous forest	45.73	108655.56
Evergreen forest	12.34	29308.59
Mixed forest	3.34	7923.96
Shrub	1.53	3623.49
Grassland/herbaceous	4.46	10607.49
Pasture	0.05	114.12
Cultivated crops	0.11	272.61
Woody wetlands	22.49	53421.84
Emergent herbaceous wetlands	3.92	9319.41

Table C2. Percentage and area (ha) of land disturbed by year and analysis area.

Year	PIRO (ha)	PIRO (%)	Non-PIRO (ha)	Non-PIRO (%)
2006	1487.40	5.63	3352.16	1.65
2007	612.58	2.32	2887.22	1.42
2008	37.58	0.14	1248.20	0.61
2009	366.38	1.39	4571.01	2.24
2010	535.28	2.03	4645.10	2.28
2011	87.84	0.33	1130.52	0.56
Total	3127.08	11.84	17834.21	8.76

Table C3. Percentage and area (ha) of land disturbed by year and analysis area.

Year	PIRO-Core (ha)	PIRO-Core (%)	PIRO-IBZ (ha)	PIRO-IBZ (%)
2006	550.26	4.94	937.14	6.14
2007	3.55	0.03	609.03	3.99
2008	0.00	0.00	37.58	0.25
2009	190.17	1.71	176.21	1.15
2010	83.99	0.75	451.30	2.96
2011	0.00	0.00	87.84	0.58
Total	827.97	7.43	2299.10	15.07

Table C4. Area (ha) disturbed by disturbance agent, year, and analysis area.

Analysis area	Year	Area of land disturbed (ha)						Total
		<i>Beaver</i>	<i>Blowdown</i>	<i>Development</i>	<i>Forest pathgon</i>	<i>Forest harvest (clearcut)</i>	<i>Forest harvest (partial)</i>	
PIRO	2006	2.29	0.00	0.99	569.61	88.76	825.76	1487.40
	2007	0.00	0.00	0.00	3.55	0.00	609.03	612.58
	2008	0.00	0.00	1.58	2.61	20.07	13.32	37.58
	2009	1.26	0.00	35.95	166.80	16.79	145.58	366.38
	2010	1.46	0.00	0.00	65.55	16.81	451.47	535.28
	2011	0.00	0.00	0.00	1.35	65.38	21.11	87.84
	Total	5.00	0.00	38.52	809.47	207.81	2066.27	3127.08
Non-PIRO	2006	11.47	0.00	63.43	44.89	600.18	2632.19	3352.16
	2007	4.12	1.57	7.79	0.00	811.47	2062.27	2887.22
	2008	0.83	0.00	35.63	0.00	473.17	738.57	1248.20
	2009	2.82	0.00	23.65	190.00	1590.05	2764.49	4571.01
	2010	12.29	0.00	14.63	70.13	960.60	3587.44	4645.10
	2011	3.04	0.00	23.90	1.08	294.74	807.75	1130.52
	Total	34.57	1.57	169.04	306.10	4730.21	12592.72	17834.21

Table C5. Percent of land disturbed inside each location (PIRO, Non-PIRO) by disturbance agent, year, and analysis area.

Analysis area	Year	Percent of land disturbed						Total
		<i>Beaver</i>	<i>Blowdown</i>	<i>Development</i>	<i>Forest pathogen</i>	<i>Forest harvest (clearcut)</i>	<i>Forest harvest (partial)</i>	
PIRO	2006	<0.01	0	<0.01	2.16	0.34	3.13	5.63
	2007	0	0	0	0.01	0.00	2.31	2.32
	2008	0	0	<0.01	<0.01	0.08	0.05	0.14
	2009	<0.01	0	0.14	0.63	0.06	0.55	1.39
	2010	<0.01	0	0	0.25	0.06	1.71	2.03
	2011	0	0	0	<0.01	0.25	0.08	0.33
	Total	0	0	0.14	3.05	0.79	7.82	11.84
Non-PIRO	2006	<0.01	0	0.03	0.02	0.29	1.29	1.65
	2007	<0.01	<0.01	<0.01	0	0.40	1.01	1.42
	2008	<0.01	0	0.02	0	0.23	0.36	0.61
	2009	<0.01	0	0.01	0.09	0.78	1.36	2.24
	2010	<0.01	0	<0.01	0.03	0.47	1.76	2.28
	2011	<0.01	0	0.01	<0.01	0.14	0.40	0.56
	Total	0	0	0.07	0.15	2.32	6.18	8.76

Table C6. Summary of the starting classes from the validated disturbance polygons. In some instances the starting class is the same as the ending class because not enough of the overstory was removed.

Analysis area	Year	Area (ha) of land cover types disturbed in the analysis period (starting class)							
		<i>Forest (closed)</i>	<i>Forest (semi-closed)</i>	<i>Forest (open)</i>	<i>Herbaceous</i>	<i>Water</i>	<i>Impervious surface</i>	<i>Pervious surface</i>	<i>Impervious/vegetated</i>
PIRO	2006	-1486.41	-0.99	0	0	0	0	0	0
	2007	-612.58	0	0	0	0	0	0	0
	2008	-36.79	0	-0.79	0	0	0	0	0
	2009	-366.38	0	0	0	0	0	0	0
	2010	-534.34	0	0	0	-0.95	0	0	0
	2011	-87.84	0	0	0	0	0	0	0
	Total	-3124.35	-0.99	-0.79	0	-0.95	0	0	0
Non-PIRO	2006	-3338.41	-6.49	-6.10	-1.17	0	0	0	0
	2007	-2875.84	-6.11	-2.14	0	-3.13	0	0	0
	2008	-1233.82	-1.53	-12.85	0	0	0	0	0
	2009	-4488.20	-81.65	0	-1.16	0	0	0	0
	2010	-4574.16	-70.40	0	-0.54	0	0	0	0
	2011	-1102.60	-25.80	-1.49	-0.63	0	0	0	0
	Total	-17613.02	-191.98	-22.58	-3.50	-3.13	0	0	0

Table C7. Summary of the ending classes from the validated disturbance polygons. In some instances the starting class is the same as the ending class because not enough of the overstory was removed.

Analysis area	Year	Area (ha) of land cover types disturbed in the analysis period (ending class)							
		<i>Forest (closed)</i>	<i>Forest (semi-closed)</i>	<i>Forest (open)</i>	<i>Herbaceous</i>	<i>Water</i>	<i>Impervious surface</i>	<i>Pervious surface</i>	<i>Impervious/vegetated</i>
PIRO	2006	1035.92	364.26	71.96	0.72	0.59	0	12.96	0.99
	2007	77.71	534.87	0	0	0	0	0	0
	2008	0.67	12.65	22.68	0	0	0	0	1.58
	2009	193.91	119.44	17.80	0.35	0.25	34.62	0	0
	2010	261.08	255.94	16.33	0.95	0	0	0.99	0
	2011	0	21.11	66.73	0	0	0	0	0
	Total	1569.30	1308.27	195.51	2.02	0.85	34.62	13.95	2.57
Non-PIRO	2006	1061.01	1580.12	652.37	5.74	0.54	1.40	8.15	42.84
	2007	128.26	1927.44	811.93	3.92	0.99	0.89	11.85	1.93
	2008	43.96	685.44	482.97	1.50	0	0	7.39	26.94
	2009	250.82	2733.26	1567.30	0	2.82	0.81	13.21	2.79
	2010	1701.79	2087.75	828.13	0	2.25	3.74	13.10	8.35
	2011	162.55	587.32	337.72	2.43	2.55	7.48	25.91	4.56
	Total	3348.39	9601.33	4680.42	13.60	9.14	14.32	79.60	87.41

Table C8. Area (ha) of land disturbed inside the analysis area by owner, grouped into five ownership classes.

Owner	Beaver	Blowdown	Development	Forest pathogen	Forest harvest (clearcut)	Forest harvest (partial)
Private	13.06	0	152.06	194.99	2045.02	10070.17
State of Michigan	18.35	0	18.78	105.21	2005.30	2309.50
Unknown	0.59	0	9.76	22.84	110.56	1408.55
US Forest Service	5.90	1.57	2.03	12.85	777.14	870.77
US NPS	1.67	0	24.93	779.67	0	0

Table C9. Percent of land by owner within the PIRO analysis area.

Owner	Percent
National Wildlife Refuge	0.05
National Forest	21.51
National Lakeshore	11.49
State of Michigan	0.11
State Forest	28.33
State Park and Recreation Area	0.02
State Wildlife Reserve	0.25
Private	38.25

Appendix D: Results from Interpreter Cross Validation

For this report, one interpreter validated all disturbance polygons generated. To ensure repeatability and to quantify the subjectivity of the validation process we employ a cross validation exercise. In this exercise a random subsample of 10% of the polygons are chosen. A separate interpreter then validates each of the polygons in the subsample. When finished, each polygon in the subsample is compared to the same polygon from the other interpreter. By directly comparing each of the polygons in the subsample, we can keep interpreter bias to a minimum and learn from one another's interpretations. This appendix provides the summary results from this cross-validation exercise.

Table D1. Confidence of interpreter true/false interpretations. Polygons which were unambiguous have matching interpretations; polygons that are ambiguous are given different interpretations (off-diagonal of the matrix). As an example, the 64 non-matching values can be interpreted as follows: interpreter 1 called something false 64 times when interpreter 2 called it true.

		Interpreter 2		Total interpreted	Proportion unambiguous
		FALSE	TRUE		
Interpreter 1	FALSE	390	64	454	0.86
	TRUE	17	81	98	0.83

The proportion unambiguous is lower than it has been in the past. However, this is a simple statistic which only takes into account the total number of polygons cross validated. If we summarize the total number of hectares disturbed by disturbance agent for each interpreter we see a slightly different picture (Figure D1). Here the number of hectares for each interpreter is nearly identical and it shows that Interpreter 1 classified more polygons as clearcut than Interpreter 2. The difference between a clearcut and partial harvest is defined by the percent of tree canopy remaining after the forest harvest, in particular, if the remaining canopy is less than 30% it is deemed a clearcut, if it is more than 30%, then it is classified as a partial harvest.

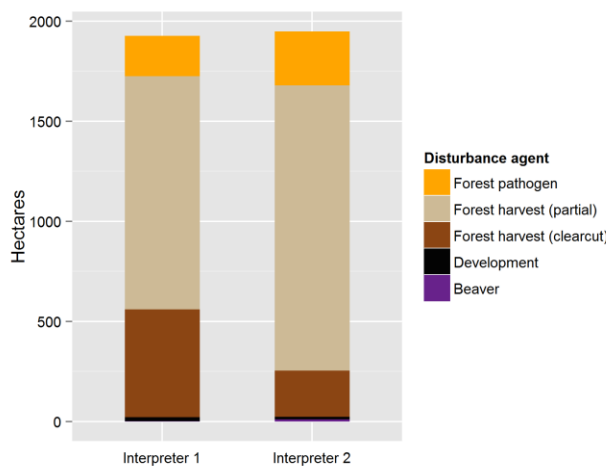


Figure D1. Area (ha) of land disturbed by disturbance agent as indicated by each interpreter.

We can also see the difference between partial harvests and clearcuts reflected in the starting and ending classes of the disturbance polygons. In figure D2, we can see that both interpreters generally agreed on the starting class (forest) but when the ending class was designated, there was disagreement between the two interpreters. The difference between forest, woodland, and shrub is defined as the percent tree cover remaining which is an estimate made by the interpreter using the best available airphotos. Generally, though, there is still good agreement between the two interpreters at PIRO.

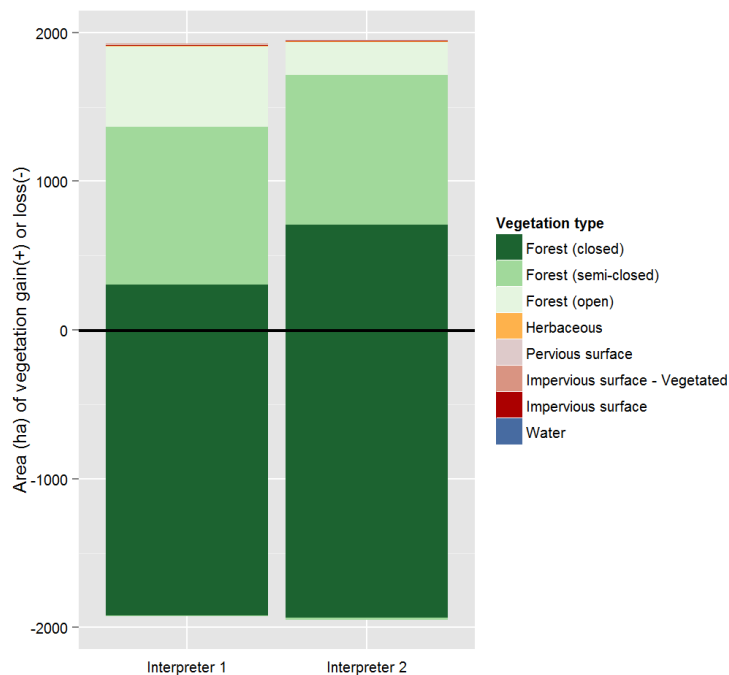


Figure D2. Area (ha) of vegetation gained and lost as indicated by each interpreter.

We also looked more closely at the polygons where we did not agree. For example, of the 64 polygons interpreter 2 thought were true and interpreter 1 thought was false, what was the disturbance agent? We summarized this answer in Figure D3, below. Not surprisingly, the majority of ‘confused’ polygons were due to forest pathogen or partial forest harvest. Both of these disturbance agents tend to be more subtle in their appearance. We can also see the total area these ‘confused’ polygons contribute to the overall cross-validation summary (Figure D4).

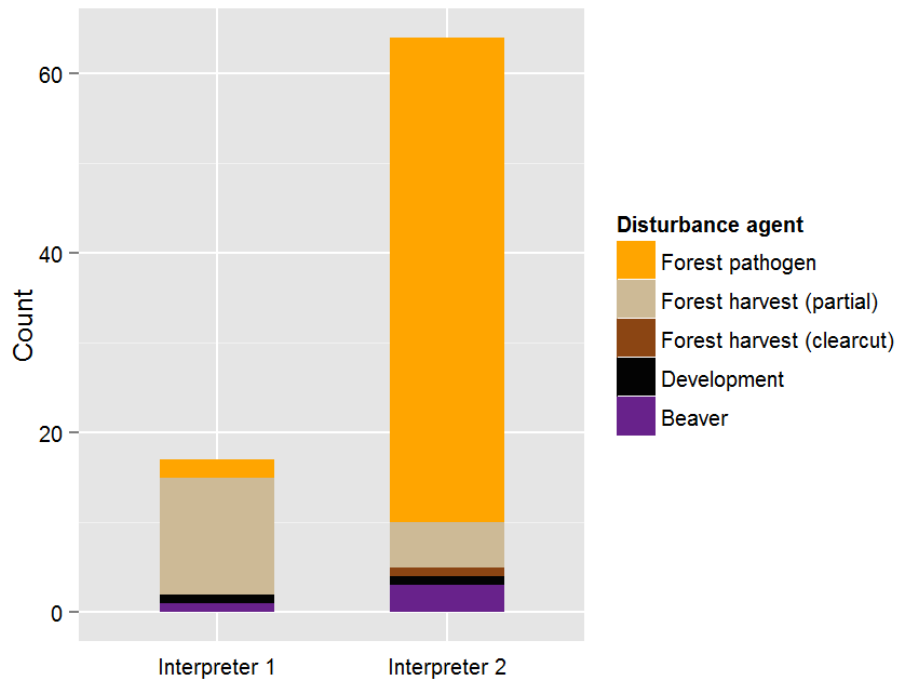


Figure D3. Count (n) of 'confused' polygons and the agent to which each interpreter attributed the change. For example, of the 17 polygons interpreter 1 thought were true and interpreter 2 thought were false, most of the polygons were classified as changed due to partial harvest.

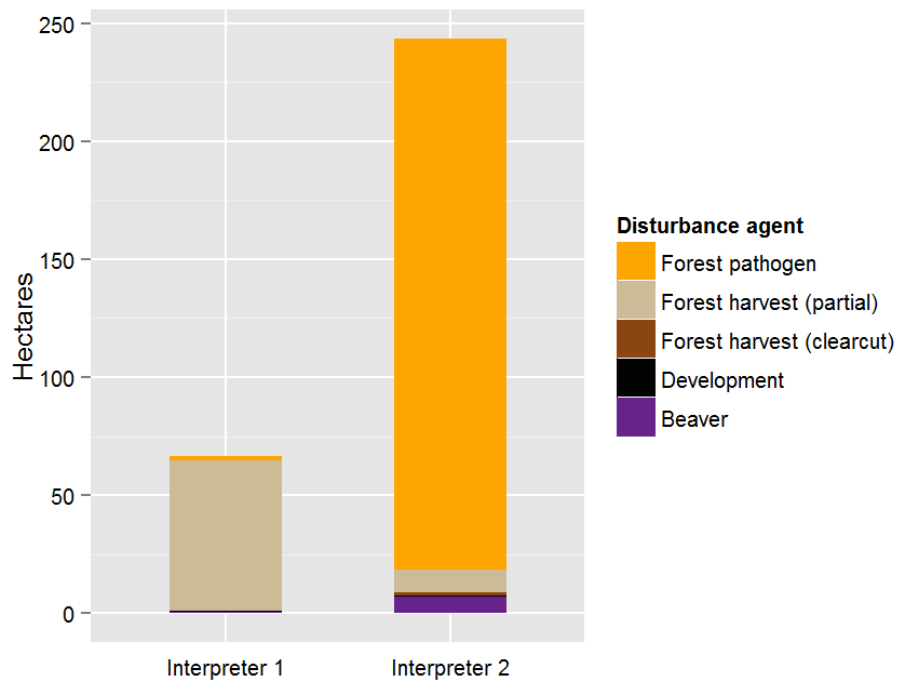


Figure D4. Same as figure D3, instead with hectares affected by each of confused polygons.

Overview of Confusion Matrices

A brief explanation is needed for the following confusion matrices. First, we have summarized the starting and ending vegetation classes to three different levels, as defined in the tables below. Only level 2 and 3 tables will be shown, as there were no groupings for level 1. Secondly, there is a disturbance agent and vegetation class called “none.” This is not an actual disturbance agent or vegetation class; instead it is the result of one of two possibilities. In the case of disturbance agent, if both interpreters agreed on the agent with “none,” this means that both interpreters agreed there was no disturbance, hence, no disturbance agent. However, if one interpreter called the agent “none,” or “false,” and the other called the agent “agriculture,” it means that one interpreter thought there was no disturbance and the other interpreter thought there was an agricultural disturbance. Because the protocol allows for multiple disturbance agents within a polygon, there could be a disagreement when one interpreter thought there were two disturbance agents and the other interpreter thought there was only one agent present. An example of this would be during a forest harvest where one interpreter thought there was only a clearcut, but the other interpreter thought there was a clearcut and a partial harvest in the polygon. This is reflected in table D4, where interpreter 1 classified “none” three times, while interpreter 2 classified the disturbance as a partial harvest.

Table D4. Confusion matrix comparing the decisions made by each interpreter on all disturbance polygons, true and false.

		Interpreter 2										Total interpreted	Proportion unambiguous
Interpreter 1	Disturbance agent	Agriculture	Beaver	Blowdown	Development	Fire	Flooding	Harvest (clearcut)	Harvest (partial)	Forest pathogen	None		
	Agriculture	0	0	0	0	0	0	0	0	0	0	0	0
	Beaver	0	3	0	0	0	0	0	0	0	0	3	1
	Blowdown	0	0	0	0	0	0	0	0	0	0	0	0
	Development	0	0	0	10	0	0	1	1	0	0	12	0.83
	Fire	0	0	0	0	0	0	0	0	0	0	0	0
	Flooding	0	0	0	0	0	0	0	0	0	0	0	0
	Harvest (clearcut)	0	0	0	0	0	0	17	2	0	1	20	0.85
	Harvest (partial)	0	0	0	0	0	0	0	40	4	0	44	0.91
	Forest pathogen	0	1	0	0	0	0	0	0	3	1	5	0.6
	None	0	0	0	0	0	0	2	1	0	155	158	0.98

Table D5. Confusion matrix comparing the decisions made by each interpreter on all disturbance polygons where both interpreters agreed that it was true. This table indicates how the interpreters agreed/disagreed on the starting classes.

	Starting vegetation class	Interpreter 2								Total interpreted	Proportion unambiguous
		Forest (closed)	Forest (semi-closed)	Forest (open)	Herbaceous	Water	Impervious surface	Pervious surface	Impervious-vegetated		
Interpreter 1	Forest (closed)	77	2	0	0	0	0	0	0	79	0.98
	Forest (semi-closed)	0	1	0	0	0	0	0	0	1	1
	Forest (open)	0	1	0	0	0	0	0	0	1	0
	Herbaceous	0	0	0	0	0	0	0	0	0	0
	Water	0	0	0	0	0	0	0	0	0	0
	Impervious surface	0	0	0	0	0	0	0	0	0	0
	Pervious surface	0	0	0	0	0	0	0	0	0	0
	Impervious-vegetated	0	0	0	0	0	0	0	0	0	0
	None	2	0	0	0	0	0	0	0	160	0.99

Table D6. Confusion matrix comparing the decisions made by each interpreter on all disturbance polygons where both interpreters agreed that it was true. This table indicates how the interpreters agreed/disagreed on the ending classes.

	Ending vegetation class	Interpreter 2								Total interpreted	Proportion unambiguous
		Forest (closed)	Forest (semi-closed)	Forest (open)	Herbaceous	Water	Impervious surface	Pervious surface	Impervious-vegetated		
Interpreter 1	Forest (closed)	20	1	0	0	0	0	0	0	21	0.95
	Forest (semi-closed)	18	10	0	0	0	0	0	0	28	0.36
	Forest (open)	2	3	17	0	0	0	0	1	23	0.75
	Herbaceous	0	0	2	2	0	0	0	0	4	0.5
	Water	0	0	0	0	0	0	0	0	0	0
	Impervious surface	0	0	0	0	0	3	0	0	3	1
	Pervious surface	0	0	1	0	0	0	2	0	3	0.67
	Impervious-vegetated	0	0	0	1	0	0	0	2	3	0.67
	None	0	1	2	1	0	1	0	0	153	0.97

Appendix E: NPScape Metrics for Analysis Area

NPScape is a landscape dynamics monitoring project that provides landscape-level data, tools, and evaluations for natural resource management, planning, and interpretation. We have taken these tools and datasets and processed a portion of them that we felt were particularly relevant to the park. See Monahan et al. (2012) for more information on the importance of any of the outputs below.

Areas without roads

The input for this tool was the 2005 ESRI roads database. The output shows the patch sizes of areas without roads within the analysis area and for a 10 km buffer outside the analysis area. More information regarding this metric and tool function can be found in the NPScape Roads Standard Operating Procedure (National Park Service 2013c). The two large areas without roads that stand out are the park area and the area near Seney National Wildlife Refuge. The other larger area on the east side of the analysis area is near the headwaters of the North Branch Two Hearted River (Figure E1).

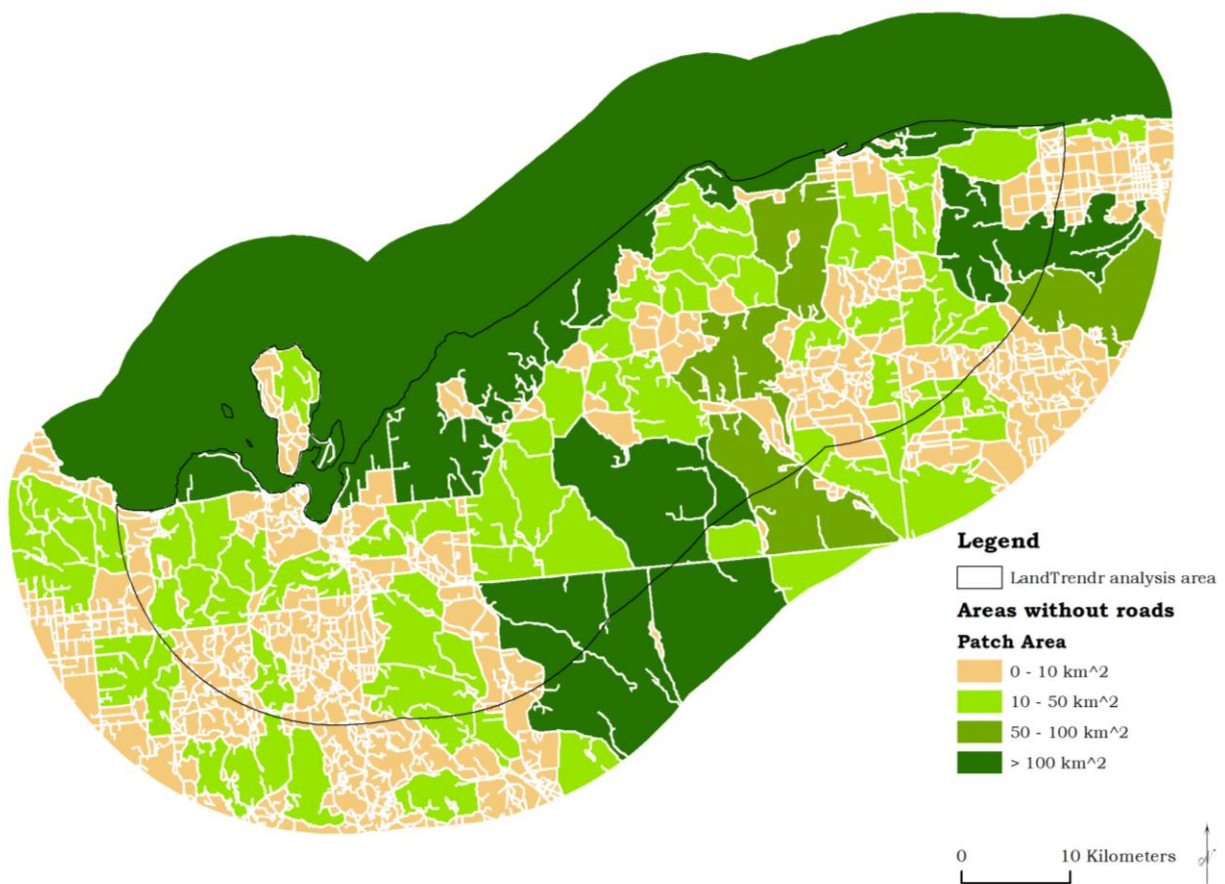


Figure E1. Output map showing the areas without road sizes.

Housing density

Housing density from 1970 to 2100 was analyzed using the Spatially Explicit Regional Growth Model dataset, SERGoM (Theobald 2005). Areas of no data represent protected lands (publicly-owned, or private lands with conservation easements). The dataset reports population for each decade from 1970 to 2010 and predicts future housing densities up until 2100. In 2010, as would be expected, the two highest concentrations of housing density are around Munising and Grand Marais (Figure E2). Only one time period is included in this map and the housing density map projected for 2100 has little to no change. More information regarding the tool can be found in the NPScape Housing Standard Operating Procedure (2013b).

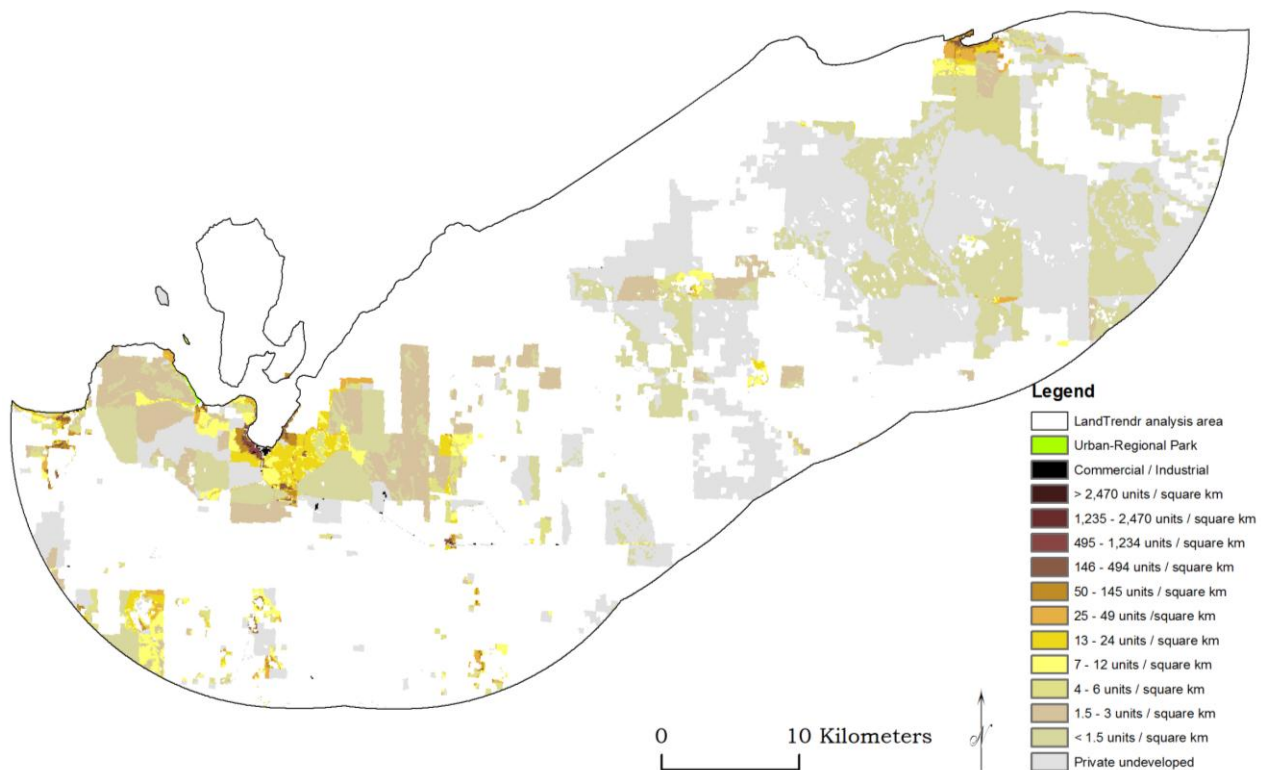


Figure E2. Output map showing the housing density inside the analysis area, circa 2010.

Conservation status

From the GAP metadata, “The GAP Status Code is a measure of management intent to conserve biodiversity defined as: Status 1: An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management. Status 2: An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.”

Over half of the analysis area is categorized as status 2, with a small portion of the land in the southeast portion of the analysis area in GAP status 1. This is important ecologically and suggests that this region will not suffer from large amounts of land use change. More information regarding the tool and dataset can be found in the NPScape Conservation Status Standard Operating Procedure (2013a).

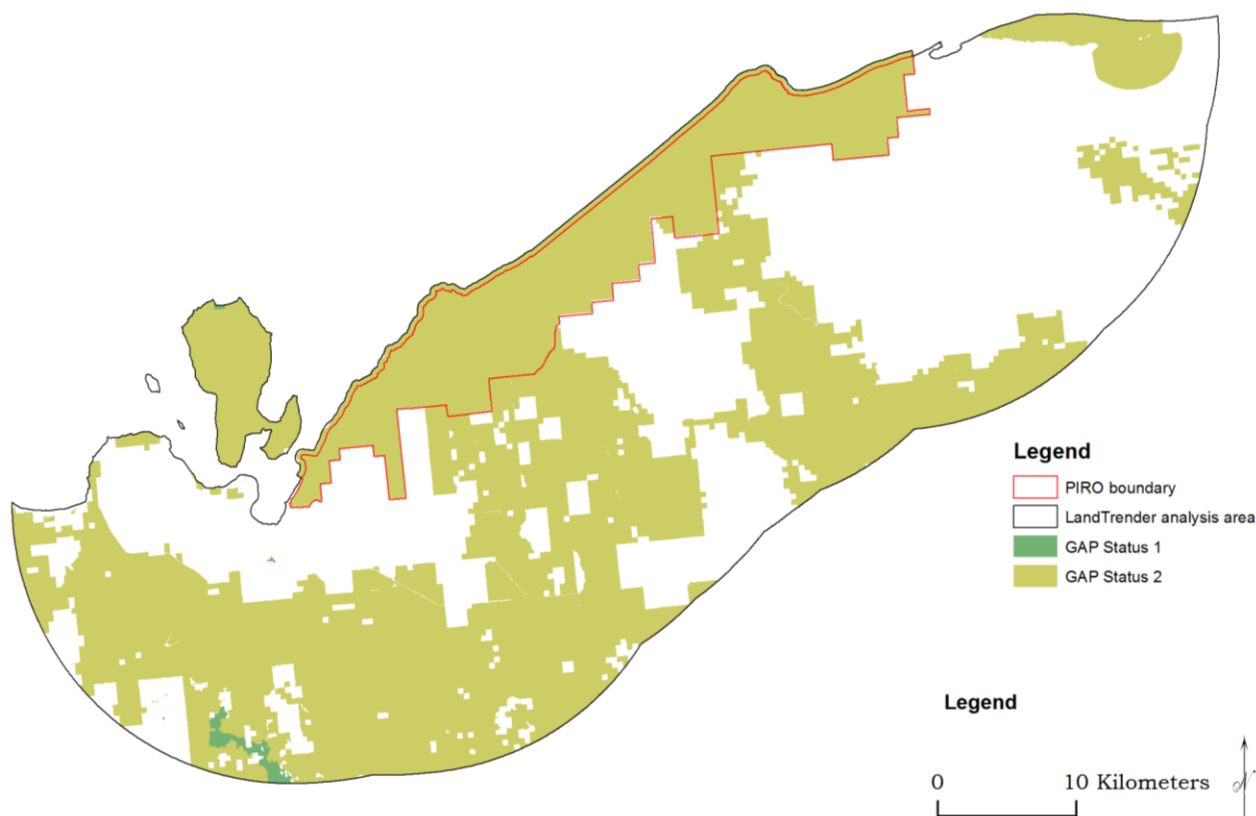


Figure E3. Output map showing the GAP status of the analysis area.

Forest density

The forest density metric is calculated by collapsing all forest-like classes in the 2006 National Land Cover Dataset (NLCD), then using a moving window to represent the context of surrounding pixels, rather than the content of a specific pixel. We used a roaming window size of 7 x 7 pixels, where each pixel is 30 meters on a side. Since this landscape is dominated by forested land cover, it is not surprising to see the large amounts of forest land designated as intact. This means that within a 7 x 7 window, 100% of the pixels surrounding the center pixel were classified as forest. Then the window moves to the next pixel and repeats the calculation. According this analysis, this region has not suffered from large amounts of land use change. More information regarding the tool and dataset can be found in the NPScape Pattern Measure Standard Operating Procedure (2013a).

Table E1. Area density class definitions for forest cover within the moving window.

Area density class	Area density (p)
Intact	$p=1.0$
Interior	$0.9 \leq p < 1.0$
Dominant	$0.6 \leq p < 0.9$
Transitional	$0.4 \leq p < 0.6$
Patchy	$0.1 \leq p < 0.4$
Rare	$0.0 \leq p < 0.1$
None	$p=0.0$

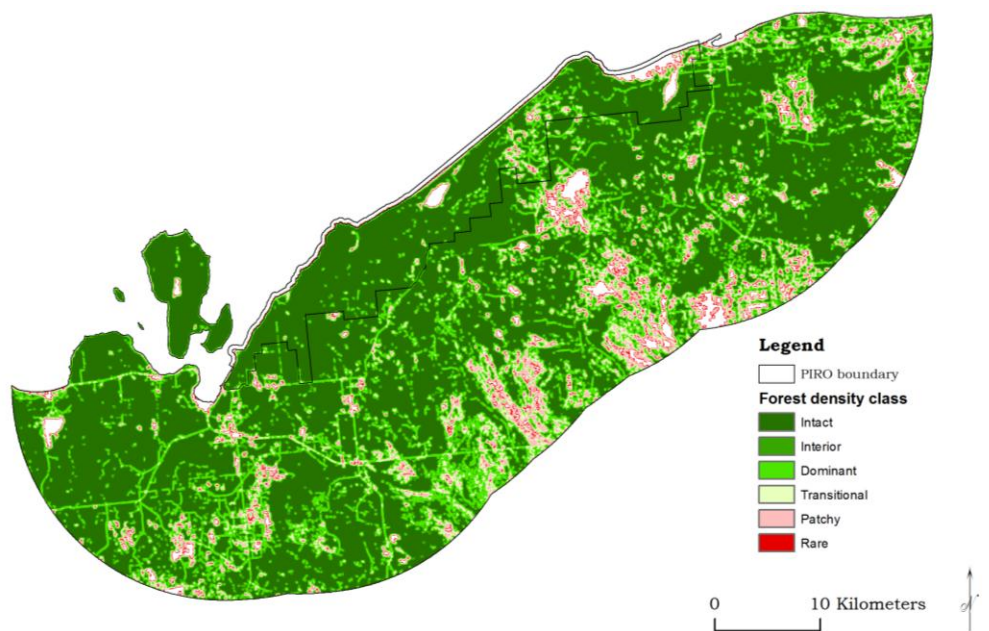


Figure E4. Output map showing the forestry density classes of the analysis area.

Appendix F: Study Areas at Previous Parks

As was mentioned previously, analysis areas for parks have varied from a simple buffer approach (VOYA, ISRO, PIRO) to including watersheds flowing into the park (APIS, SACN, MISS, SLBE).

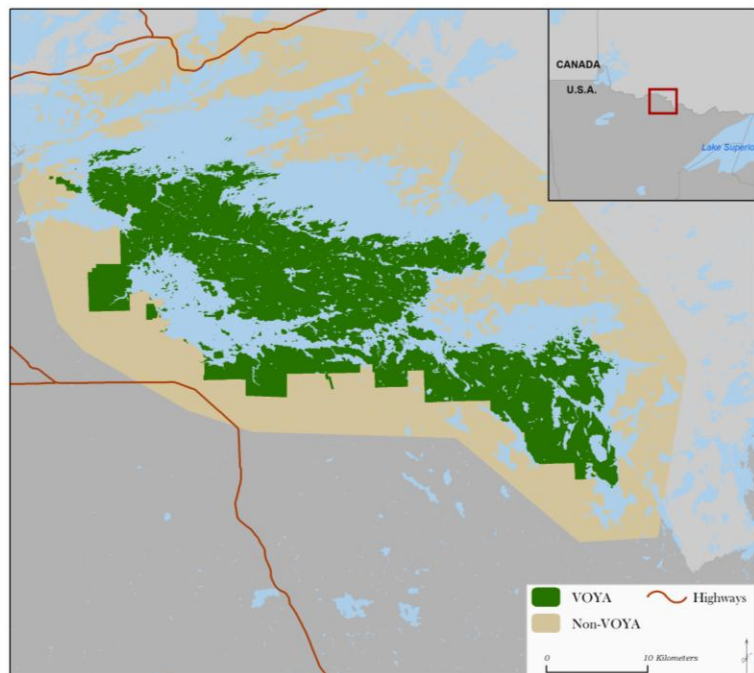


Figure F1. Analysis area for VOYA.

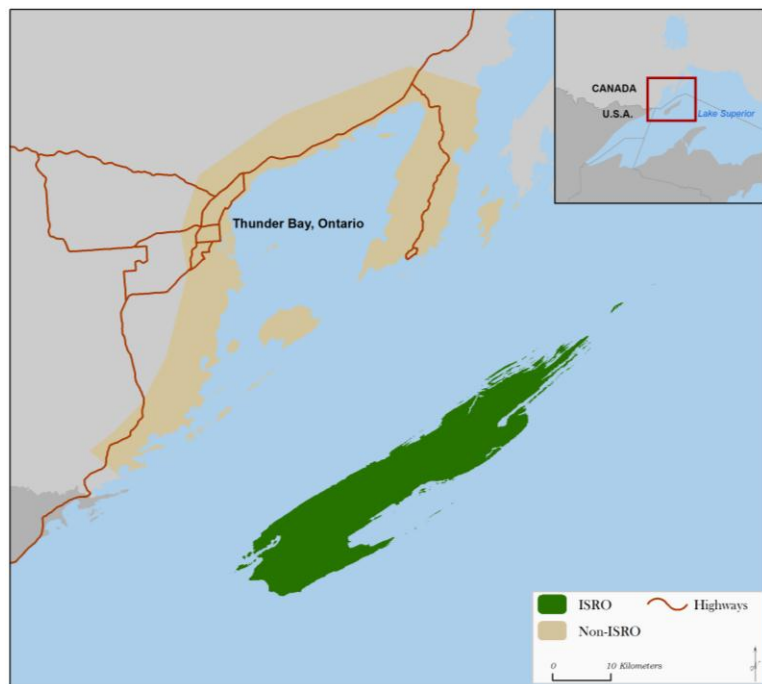


Figure F2. Analysis area for ISRO.

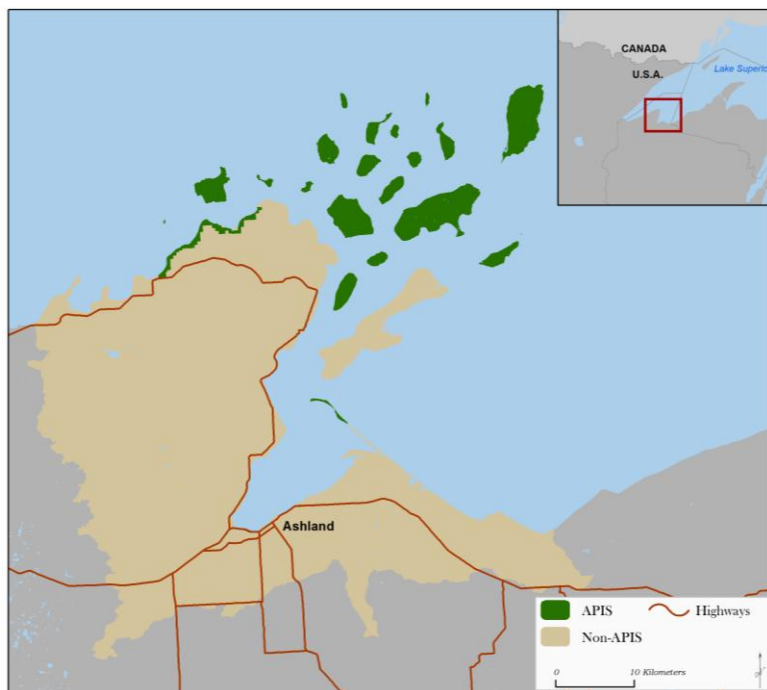


Figure F3. Analysis area for APIS.

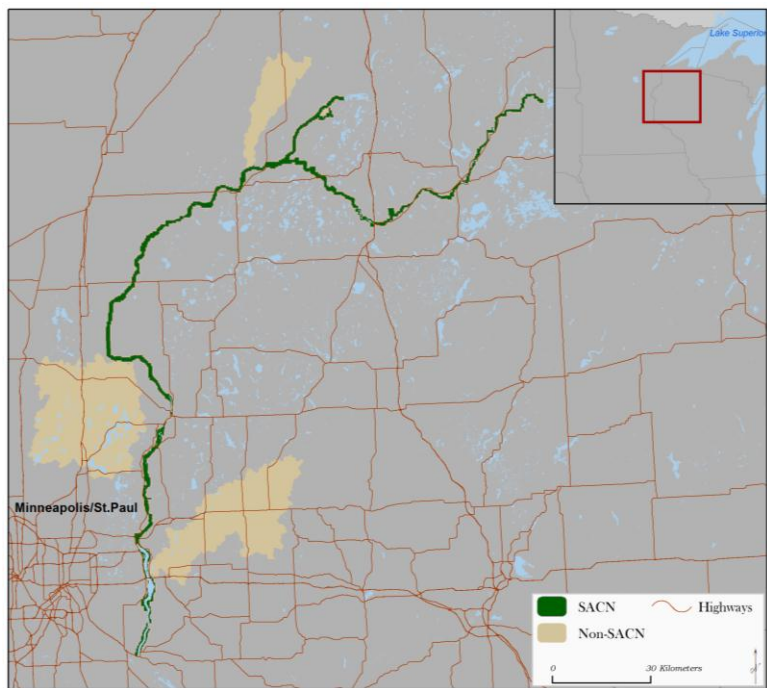


Figure F4. Analysis area for SACN.

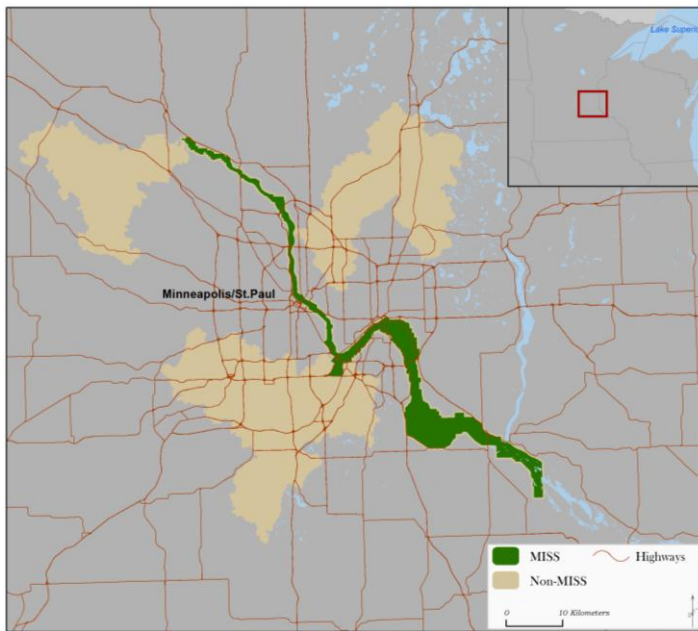


Figure F5. Analysis area for MISS.

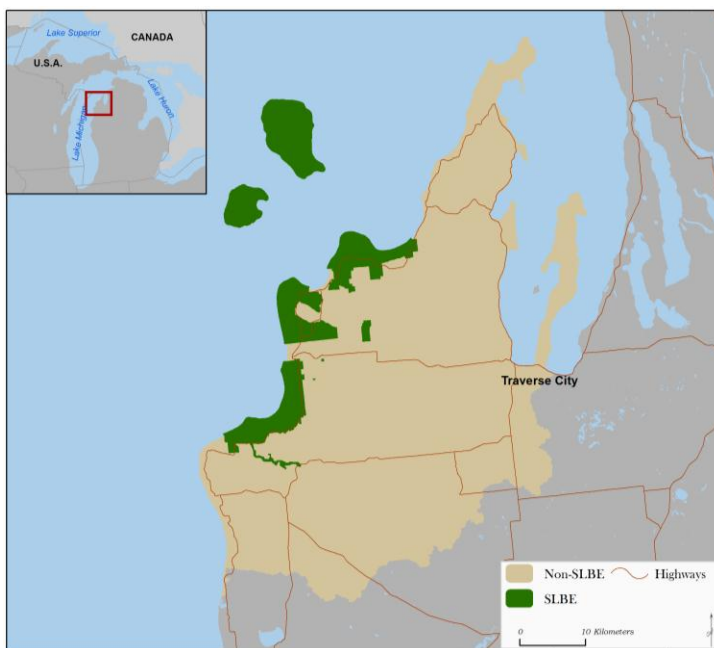


Figure F6. Analysis area for SLBE.

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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