



Landsat-based Monitoring of Landscape Dynamics at Sleeping Bear Dunes National Lakeshore

2006–2011

Natural Resource Report NPS/GLKN/NRR—2014/895



ON THE COVER

Example of defoliation on South Manitou Island at Sleeping Bear Dunes National Lakeshore.
Photograph courtesy of the National Park Service.

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Abstract

The Great Lakes Inventory and Monitoring Network (GLKN) implemented the long-term disturbance monitoring protocol at Sleeping Bear Dunes National Lakeshore (SLBE) and completed the initial analysis in 2014. Disturbances, defined here as 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 SLBE 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 an annual 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 and the year of occurrence, after which high resolution imagery was used to validate the occurrence and determine the agent of change. Summary analyses showed that disturbances inside and outside the park were dominated by insect defoliation from a combination of native and non-native insects. Both inside and outside the park, percent of land disturbed peaked in 2009, due mainly to a large amount of the landscape experiencing tree defoliation. Other disturbance agents present during the analysis time period included forest harvest, development, and land conversion to agriculture. Among the watersheds included in the analysis area, the Platte River watershed had the highest percent of land disturbed at nearly 15%. Private land ownership, comprising 70% of the analysis area, also contributed the greatest amount of disturbed land. Lastly, SLBE had the second highest rate of disturbance among park units analyzed to date in the Great Lakes Network, though this was largely due to forest canopy defoliation, which is most often a transient event, not a disturbance that causes mortality or changes the land cover type.

Acknowledgments

We would like to acknowledge the staff at Sleeping Bear Dunes National Lakeshore for helping determine the land cover monitoring program's scope and extent for the analysis.

The LandTrendr research group (<http://landtrendr.forestry.oregonstate.edu/>) at Oregon State 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 also thank J. Norris, B. Route, and K. Skerl 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 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.
NBR	Normalized burn ratio: $(\text{near infrared} - \text{shortwave infrared}) / (\text{near infrared} + \text{shortwave infrared})$
NHD	National Hydrography Dataset. www.nhd.usgs.gov
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); 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, Wolter 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 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 to 2008 using Vegetation Change Tracker (VCT). They found that 3.2% of the land (0.23%/yr) was disturbed in the upper Lake Michigan basin during 1985–1999, and 2.4% of the land was disturbed during 2000–2008 (0.27%/yr). This study was performed on an extremely large scale, providing less information on smaller subunits of the Lake Michigan 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 the 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 category (3.6%). The lowest rates of conversion were found on federal lands (0.17%) with county 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, Kennedy et al. 2012, 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 or extreme wind events).

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 in northern Wisconsin watersheds since the late 1800s, seeing large changes in the sedimentation load and flow dynamics. Verry et al. (1983) studied the effect of forest composition within watersheds and how this affected the spring runoff events. They found that forested watersheds comprised of mixed age forest 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 Sleeping Bear Dunes National Lakeshore will help inform resource managers at the park about pressures affecting the areas under their jurisdiction.

Although many landscape dynamics studies have been performed in the upper Great Lakes region, there is a lack of this type of research in the Sleeping Bear Dunes 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 (NPS) Inventory and Monitoring program was developed: to provide consistent, long-term monitoring of ecologically significant parameters affecting national park lands.

Study Area

The study was conducted in the northwest Lower Peninsula of Michigan in Leelanau, Benzie, Grand Traverse, and Manistee counties (Figure 1). This area included Sleeping Bear Dunes National Lakeshore (SLBE), which includes the Manitou islands and a portion of the mainland. The region contains large amounts of northern hardwood forest and significant amounts of agriculture, largely in the form of fruit orchards. Over 200,000 ha of land were included in this study, 11% of the land being located within the SLBE boundary (Table 2).

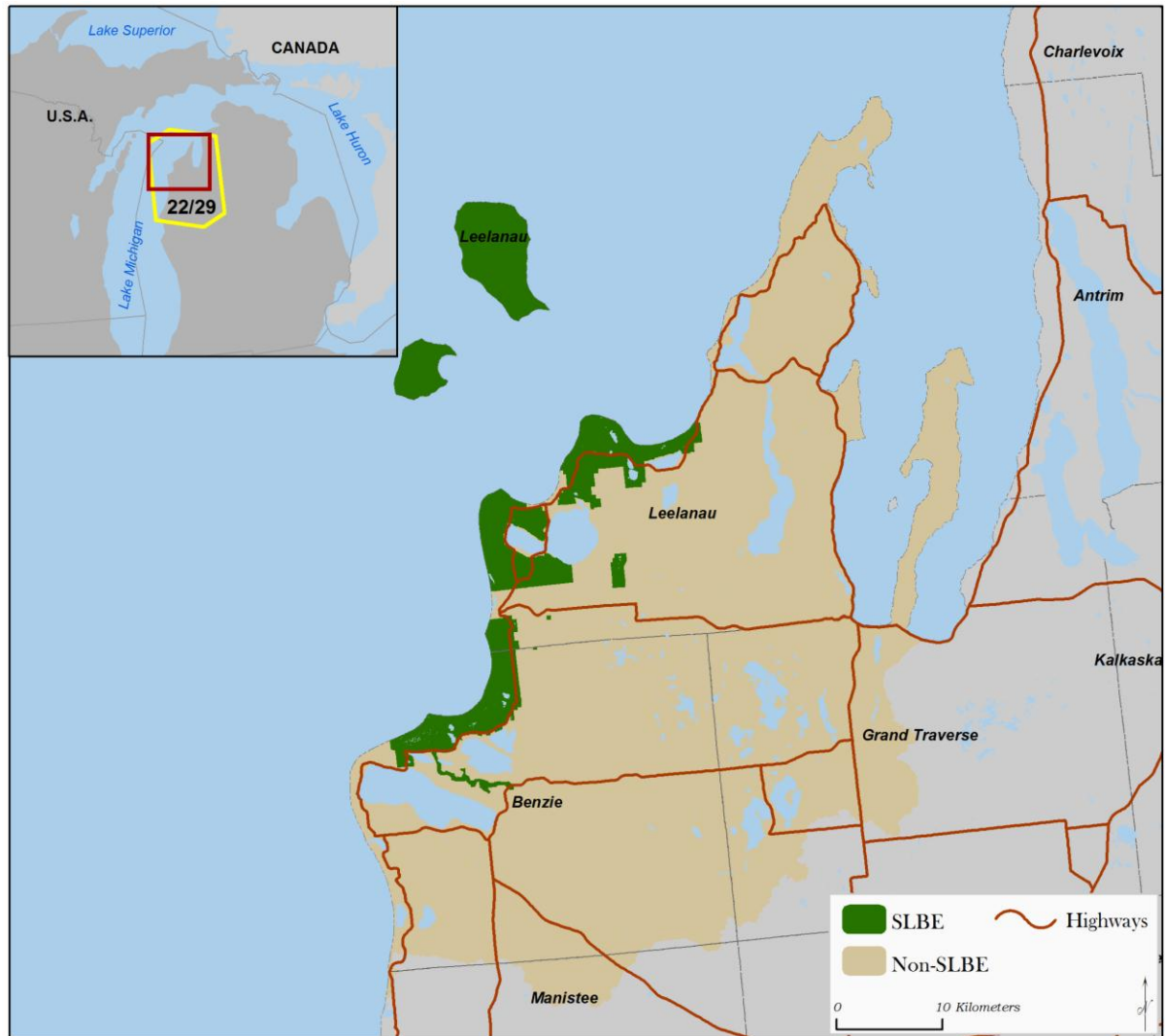


Figure 1. Study area for long-term monitoring of landscape-scale disturbances in and around Sleeping Bear Dunes National Lakeshore, Michigan. The inset shows the extent (yellow line) of the Landsat scene (22/29) processed and analyzed for this report. The larger map shows park administered lands (dark green) and the extended analysis area (light brown) outside the park.

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

Analysis area	Size (ha)	Percent of analysis area
SLBE	24,102	11
Non-SLBE	191,871	89
Total	215,974	100

Table 3. Land area of SLBE islands and mainland and the percent contribution to SLBE.

SLBE zone	Size (ha)	Percent of SLBE
Manitou islands	8,023	33
Mainland	16,079	67
Total	24,102	100

GLKN Approach to Monitoring Disturbances

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 (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). Briefly, 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 SLBE was only 8¢ per hectare.

Following methods outlined in the landscape dynamics protocol (Kennedy et al. 2010a), we identified and categorized changes in land cover and land use 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. In consultation with park natural resource managers we decided to monitor park lands plus 10 watersheds adjacent to the park, totaling about 215,000 hectares (see Figure 1). The size of the analysis area was limited by the amount of time available for validating disturbances. The ability to monitor large areas of land outside the park is due to our use of Landsat imagery as the foundation, allowing free access to multiple years of intermediately-scaled imagery.

Vegetation

Overall, forest comprises 45% of the analysis area, mainly in the south and central portion of the study area (Figure 2). In the north and eastern parts of the analysis area, cultivated (agriculture) and herbaceous (also likely agricultural) cover types are more prevalent and contribute 11% and 10%, respectively, to the overall area. The only area with significant amounts of developed land classes is Traverse City (Figure 3).

Proportionally, the vegetation within SLBE differs from that found outside. Outside the park, agricultural lands and developed classes are much more prevalent (Figure 3). Inside the park there is a significant amount of barren land (sand dunes), not present outside the park.

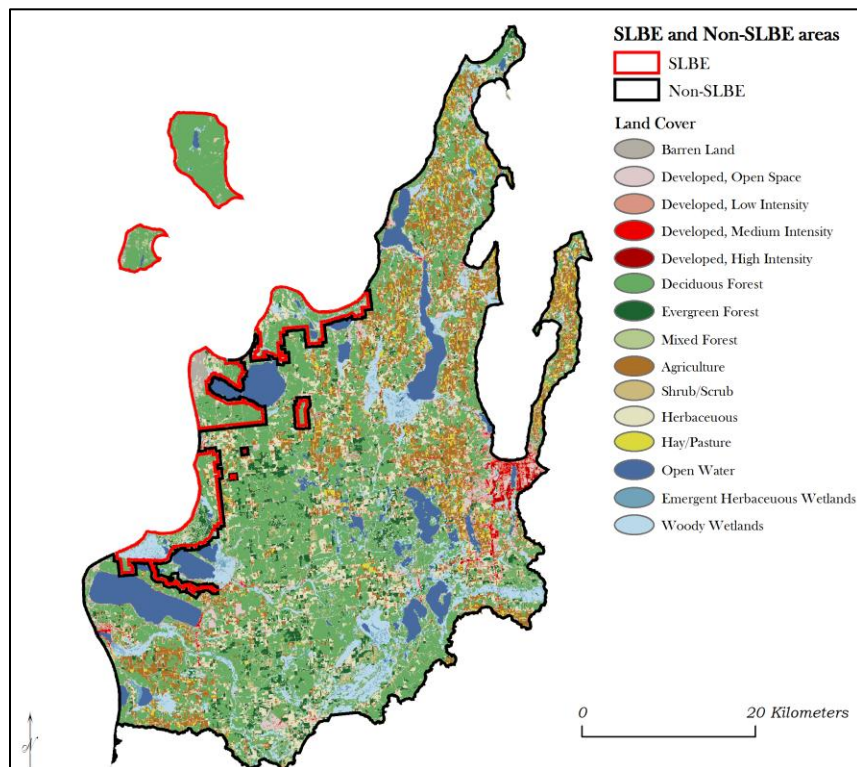


Figure 2. Vegetation classes within the analysis areas (SLBE and Non-SLBE). Data from 2006 NLCD.

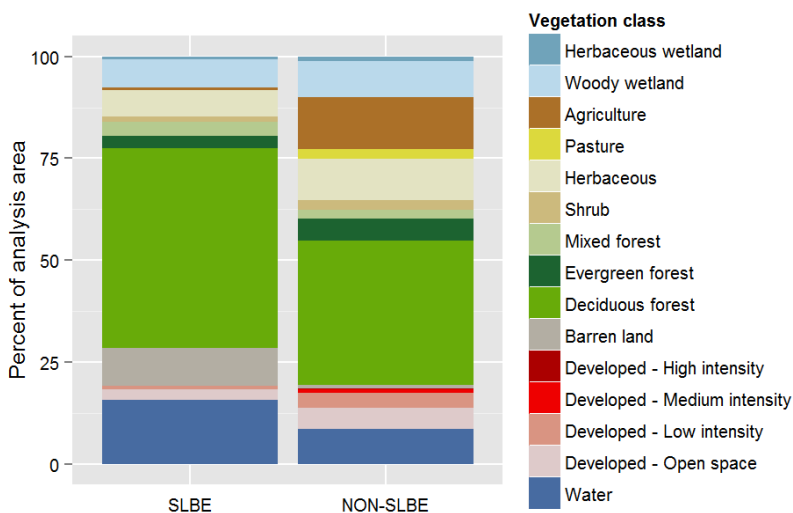


Figure 3. Relative abundance of vegetation classes within each of the analysis area. Data from 2006 NLCD.

Ownership

We summarized disturbances by ownership class as denoted by the Michigan Gap Analysis Program (GAP) ownership layers. These ownership layers are known to contain errors, primarily due to ever-changing land ownership, but account for a relatively small fraction of the landscape and hence we consider them to be acceptable. Ownership is broken into two tiers, where owner 01 is a more detailed descriptor and owner 02 is less detailed. The primary difference is that in owner 02 the state-owned lands are grouped together.

The analysis area is largely held in private ownership, accounting for over 70% of the ownership (Figure 5). Other large land owners were State Forest and National Lakeshore, with about 15% and 10%, respectively. Spatially, the State Forest lands were largely in the south and central part of the analysis area (Figure 4).

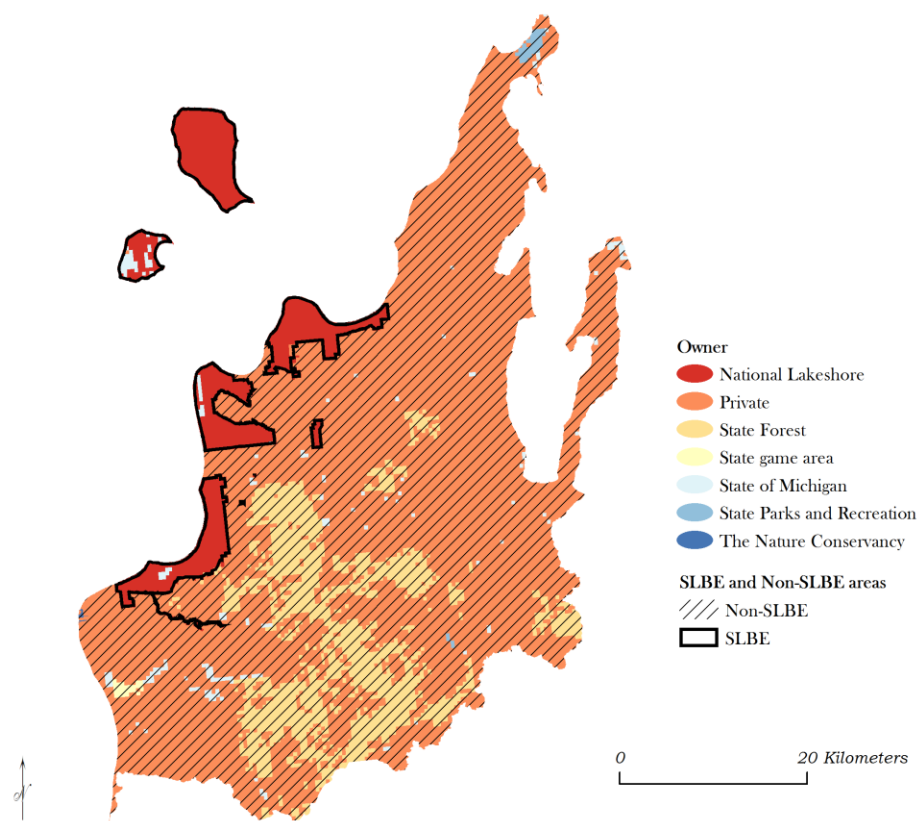


Figure 4. Spatial distribution of land ownership within the analysis area. Data from the Michigan GAP analysis dataset.

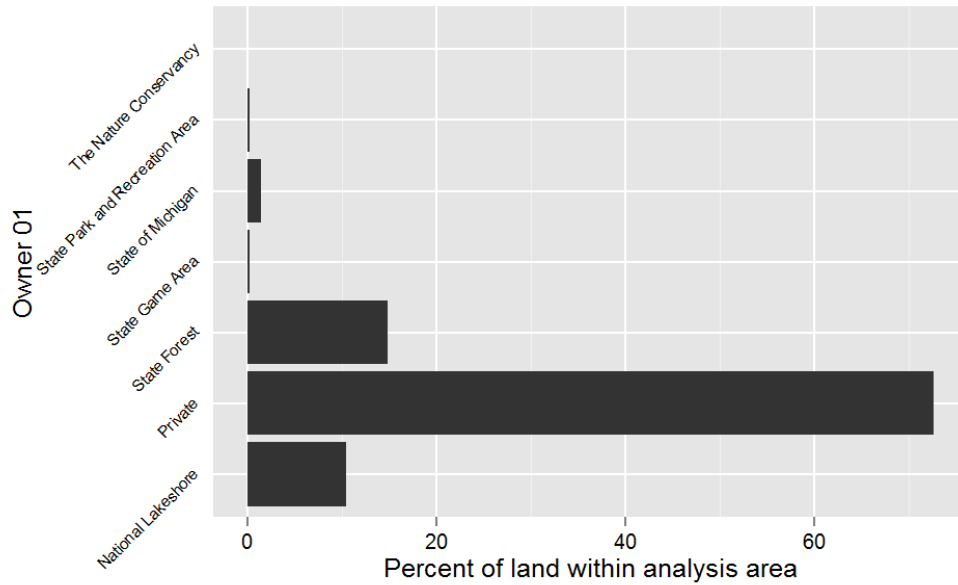


Figure 5. Percent of land within the analysis area, summarized by owner 01, the more detailed ownership type. Data from the Michigan GAP analysis dataset.

Watersheds

We used watershed boundaries from 10 digit hydrologic unit codes (HUC 10) to help define the overall analysis area. There were seven HUC 10s within the analysis area, with the park containing parts of four separate watersheds (Figure 6).

The largest watershed within the analysis area is the Betsie River, with just under 30% followed by the Platte River watershed with just over 20%. The other five watersheds collectively occupy the remaining 50% of the land. North and South Manitou islands are within the Lake Michigan watershed, which is the smallest watershed in this analysis area (Figure 7).

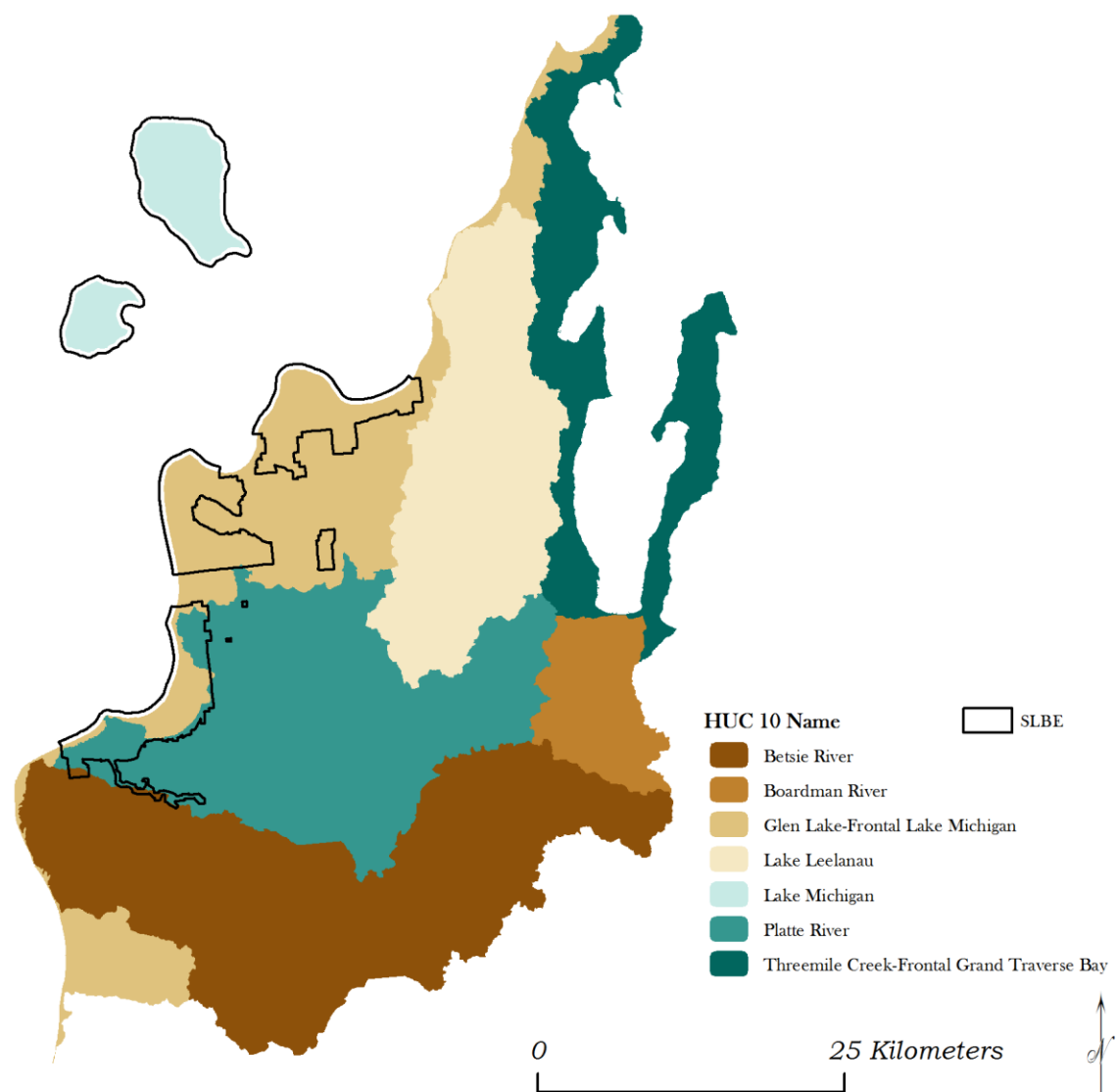


Figure 6. Spatial distribution of watersheds (HUC 10) within the analysis area. Data from the Michigan NHD dataset.

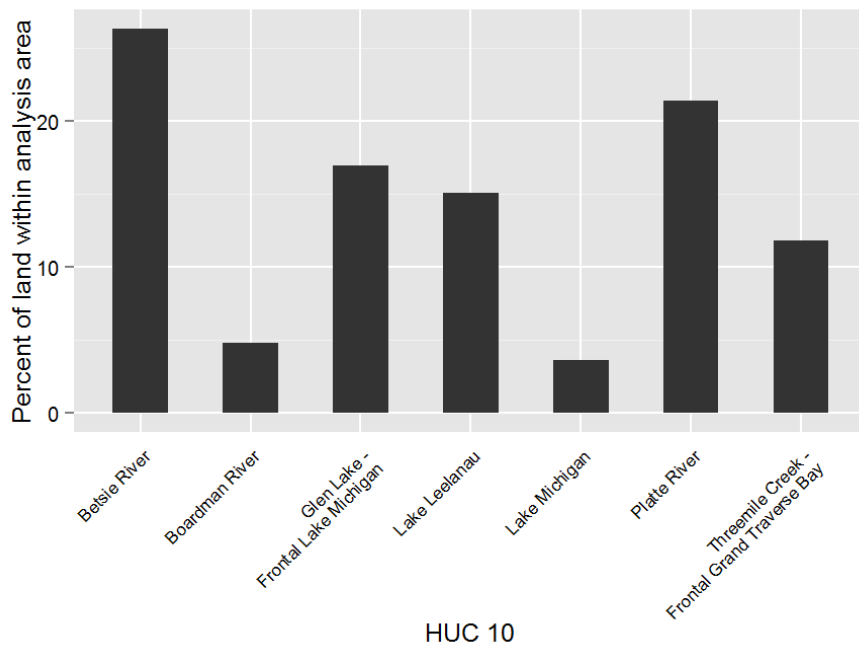


Figure 7. Percent of land within the analysis area grouped by watershed using HUC 10.

Methods

Image Data and Processing

One Landsat scene (22/29) was acquired for analysis (see inset of 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 are 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 8). For each year since 1984, the goal was to acquire enough imagery in the optimal phenological window such that one cloud-free composite for each year covering 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_slc_off_background.php). In total, 69 images were downloaded and processed for analysis. Each collection of images by scene will be referred to as a Landsat time-series (LTS).

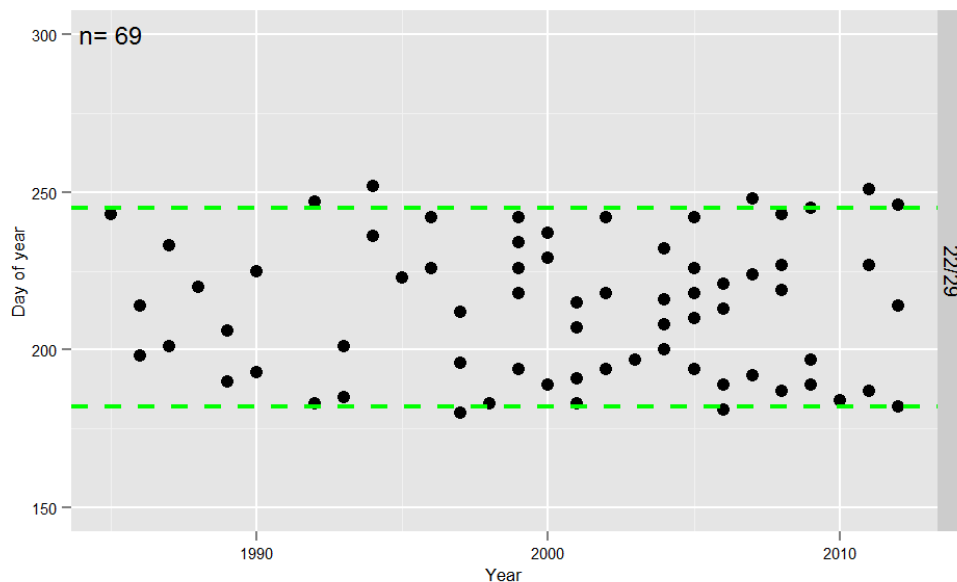


Figure 8. Day and year of Landsat images used for analysis for scene 22/29 with green dotted lines delineating the time period between 1 July and 31 August.

Preprocessing of images (atmospheric correction and cloud screening) within each scene followed details given in Zhu et al. (2012) and is 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 using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS), which uses 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.

LandTrendr algorithms operate on a single detection index which can be any single band of information. Although the algorithm itself can only be run on a single detection index, LandTrendr can be run multiple times, on different indices, 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 forest clearcuts, while NBR is more sensitive to subtle disturbances such as partial forest harvests. For the remainder of the report, we will refer to these indices collectively as disturbance indices (DI).

After the DI's are chosen, a composite image is created. The image data from this scene was converted to disturbance index 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, the 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 unmasked DI value for that pixel in each year), the vertex years, 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.

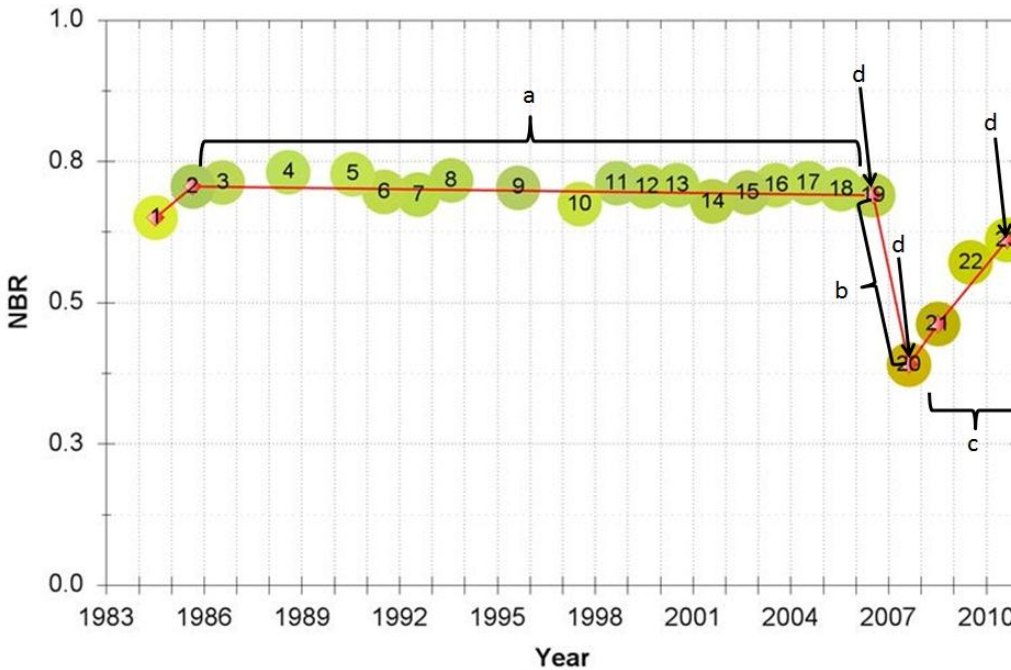


Figure 9. Diagram of how the LandTrendr segmentation algorithm processes a single pixel. The x-axis is the image year and the y-axis is the NBR value. Generally, NBR values correspond to the amount of vegetation present. This graph shows a single pixel's NBR value from 1984 to 2011. We would interpret 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 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 first year of observed change, even if the event occurred later in the previous year. Patches must be nine pixels (0.8 ha) or larger to be included in the monitoring dataset, hence we can only reliably capture disturbances larger than 0.8 ha.

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 identified 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 (e.g., surrounding environment) 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 cause 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 percent cover, and whether the polygon required a field visit for further verification. If a polygon spanned boundaries (HUC 10, land owner, inside/outside park) we attributed the polygon with whatever the majority of the polygon represented.

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 water cannot easily penetrate.
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.

Disturbance agent	Definition
Agriculture	Disturbance caused by human activity which results in agricultural land use (row crops, pasture, hay).
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. These blown down trees are evident in high resolution airphotos and are usually oriented in the direction of the wind event.
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.
Forest harvest	Forest harvests, including clearcuts and thinnings, new logging roads, and post-harvest prescriptions such as herbicide application or scarification.
Forest pathogen	Disturbances 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 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
Summer 2001	1	RGB	APFO-NAIP	Airphoto	Benzie, Leelanau counties
Summer 2005	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2006	1	RGB	APFO-NAIP	Airphoto	Entire
Spring 2007	0.15	RGB & CIR	GLKN	Airphoto	SLBE
Summer 2009	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2010	1	RGB	APFO-NAIP	Airphoto	Entire
Spring 2012	0.15	RGB	GLKN	Airphoto	SLBE
Spring 2012	1	RGB	County	Airphoto	Benzie, Leelanau counties
Summer 2012	1	RGB	APFO-NAIP	Airphoto	Entire

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

Field	Definition
Location	SLBE or Non-SLBE
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 (2010).
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	The interpreter estimates the percent of tree cover remaining ($\pm 10\%$).
Land owner	The land owner data is from the GAP analysis program.
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.

Cross-validation of polygons

One interpreter validated all disturbances for SLBE. 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. Complete results of this cross-validation process are presented in Appendix D.

Results

Percent of Land Disturbed

SLBE

During the six-year study period, a total of 5.3% (1,286 ha) of the land inside the park administrative boundary was disturbed. The percent of land area disturbed inside the park was low (generally <1%) from 2006–2008, increased to about 3% in 2009, and then returned to <1% for the remainder of the analysis period, with under 6 ha disturbed in years 2007, 2008, and 2011 (Figure 10; Appendix C).

Non-SLBE

Collectively, 8.5% (16,308 ha) of the land outside the park was disturbed during the six-year period (Figure 10). The pattern of disturbance was similar to those within the park with over 71% of the disturbances occurring in 2009 (6.1% of land area that year), with the remaining years collectively adding 2.4% of land disturbed.

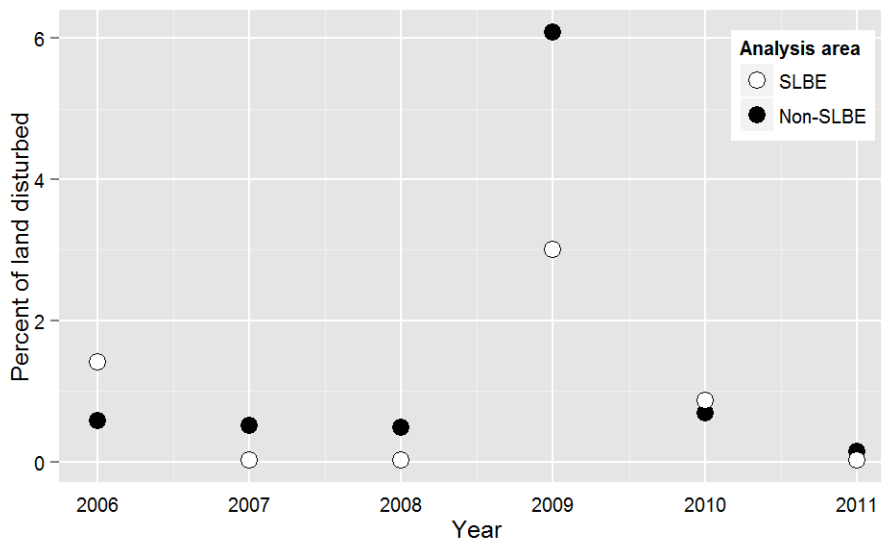


Figure 10. Percent of land disturbed within each analysis area, by year.

Disturbance Agents

SLBE

The disturbances inside the park boundary were dominated by forest pathogen, the peak occurring in 2009. There were also significant amounts of forest pathogen present in 2006 and 2010. In addition to forest pathogen, there were disturbances caused by forest harvest (partial) in 2009 (Figure 11). The small amounts of disturbances present in 2007, 2008, and 2011 were spread out among agriculture, beaver, development and forest harvest and totaled 14 ha. Many of these disturbances were due to park management activities for cultural landscape maintenance and invasive species control (K. Skerl, personal communication, 9 December 2014).

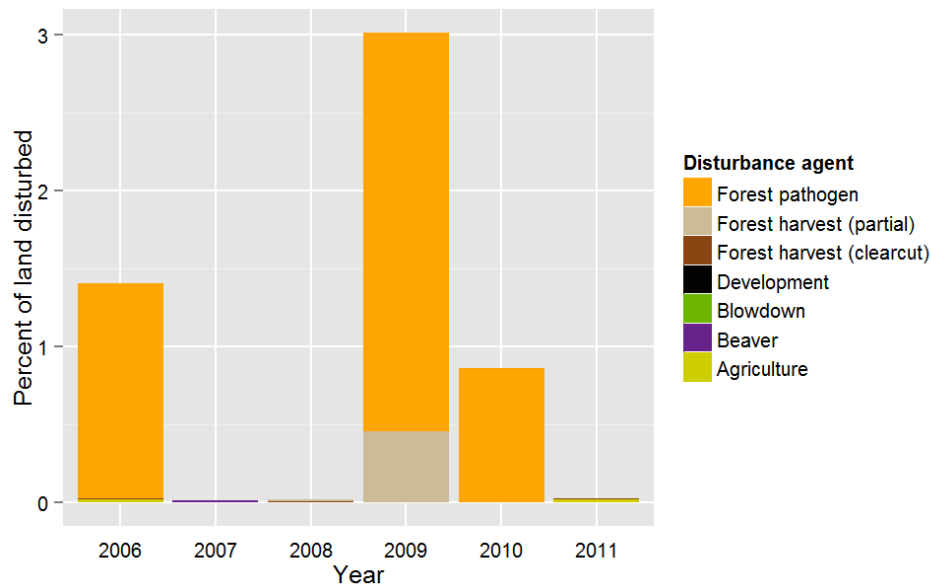


Figure 11. Percent of land disturbed inside the SLBE administrative boundary, by causal agent and year.

Non-SLBE

On lands outside the park administrative boundary, forest harvest (partial and clearcut) was the largest contributor to disturbances except years 2009 and 2010 (Figure 12). There were also significant amounts of forest pathogen in 2008–2010, with a large spike in 2009 (Figure 12). The lowest amount of disturbance occurred in 2011 which was dominated by forest harvest (clearcut) and a total percent disturbed of 0.15%.

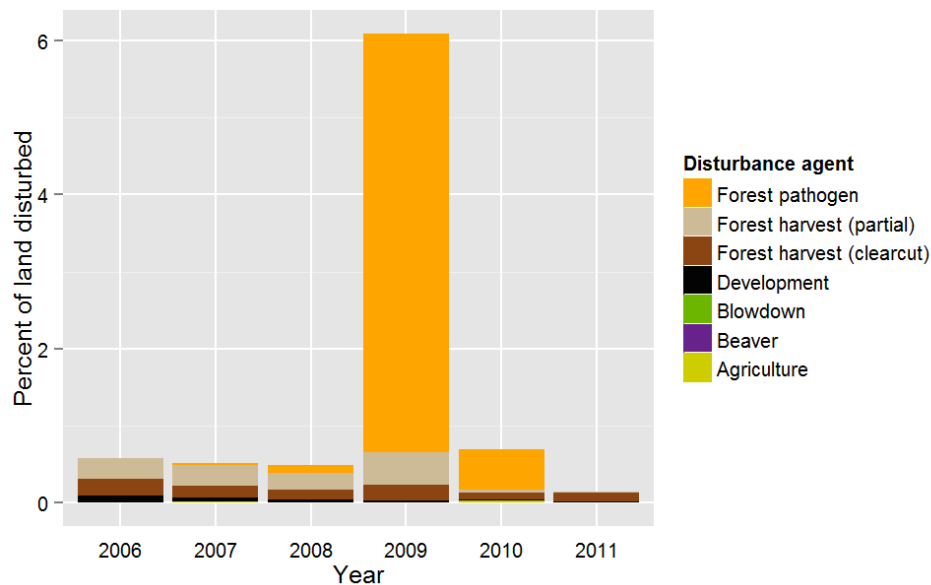


Figure 12. Percent of land disturbed outside SLBE during the analysis period, by causal agent and year.

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).

SLBE

Nearly all of the closed forest that was disturbed during the analysis period stayed as closed forest, the result of the insect defoliation event that occurred in the region (Figure 13). There was a small amount of forest converted to herbaceous in 2006 and 2011, which were caused by agricultural disturbances, or conversion from forested to non-forested grassland.

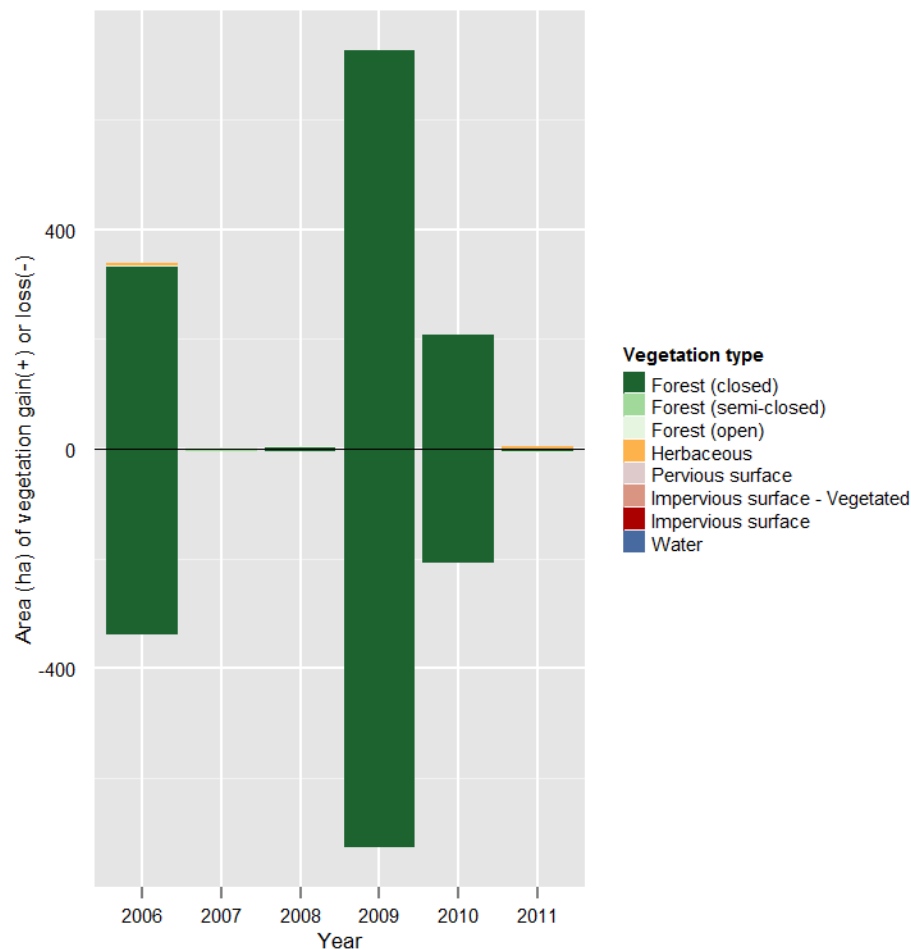


Figure 13. Area (in ha) of vegetation cover type lost (-) and gained (+) at SLBE during the analysis period (2006–2011). In some cases the vegetation type lost is the same as vegetation type gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to alter the vegetation class.

Non-SLBE

Outside the SLBE administrative boundary, essentially only closed forest was disturbed and as a result of the insect defoliation event that did not induce tree mortality, remained in the closed forest

class (Figure 14). However, each year we documented a small fraction of the closed forest being converted to semi-closed forest, open forest, or open fields (herbaceous) (Figure 14). Most of the open forest classes were the result of forest harvests (partial and clearcut). Although these forest harvests typically transform a closed forest to a semi-closed or open forest, as the forest matures it will quickly transform back into a closed forest. Hence, only the forest that ended as non-forest (herbaceous, pervious surface, etc.) is truly being lost.

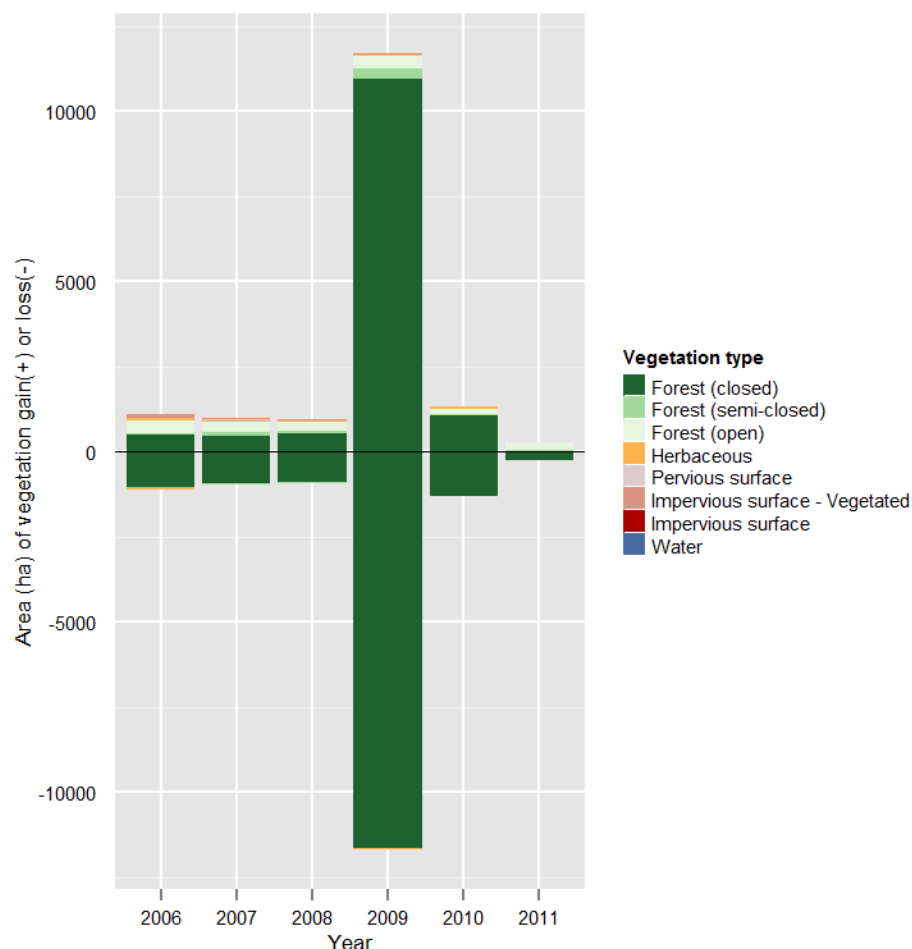


Figure 14. Area (in ha) of vegetation cover type lost (-) and gained (+) outside the SLBE administrative boundary during the analysis period (2006–2011).

Disturbance Agents by Ownership Type

The majority of the disturbances were caused by forest pathogens and this was true for all ownership classes (Figure 15). Privately-owned lands comprised >70% of the analysis area and had the greatest percent of disturbed land (Figure 15). A larger percent of privately-owned land was subjected to harvest (partial and clearcut) than State of Michigan (MI) or NPS lands. The forest harvests on State of Michigan and private land were nearly evenly split between partial harvests and clearcut. Following private lands, the State of Michigan had the next highest percent of analysis area disturbed. These lands had similar types of disturbances as private lands, but less development. The remaining land owner, the U.S. National Park Service (US-NPS), had the smallest percentage of

disturbance among owners, with 90% of the disturbances the result of forest pathogen. The remaining disturbances agents (agriculture, beaver, development, forest harvest) collectively contributed the remaining 10% (Figure 15).

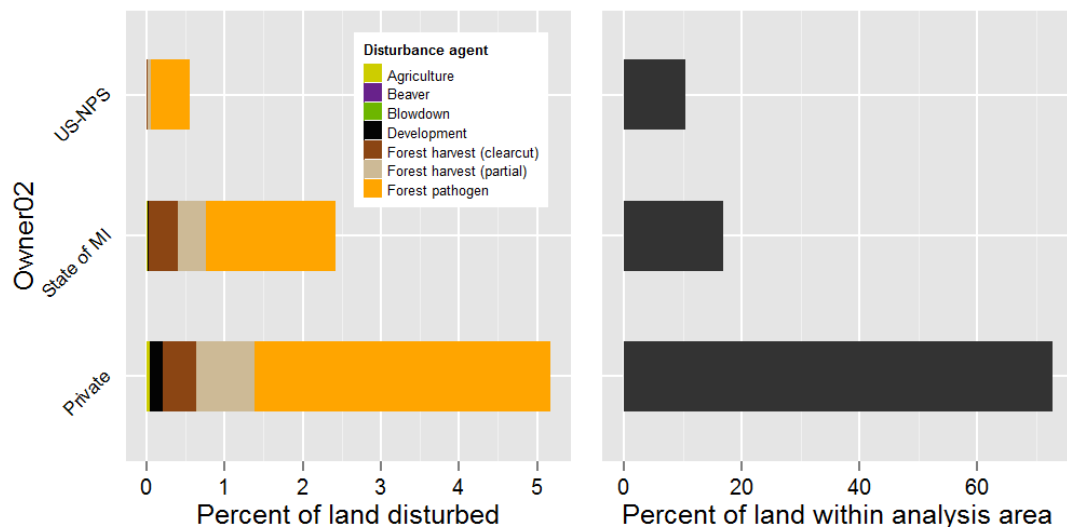


Figure 15. On left, percent of land disturbed inside the entire analysis area by three broad ownership types: Private, State of MI (Michigan), and US-NPS (U.S. National Park Service). On right, the percent of land within the analysis area occupied by each owner.

Disturbance Agents by Watershed

At nearly 15%, the Platte River watershed had the highest percent of its land disturbed during the analysis period. Nearly 10% of the total was due to forest pathogen with forest harvest contributing another 4.3% and agriculture and development causing the remaining 0.7% (Figure 16). The area with the second highest rate of disturbance was the Betsie River watershed which had 10% of the land experience disturbance, largely from forest pathogen (Figure 16). Forest pathogens caused disturbance in each watershed, with the largest amount present in the Platte River area. Forest harvests caused disturbance in most watersheds, absent in only the Lake Michigan (Manitou islands) and Threemile Creek watersheds. Lastly, we found development to be occurring in all watersheds except Lake Michigan, albeit at low levels (Figure 16). The two watersheds experiencing the largest amounts of forest harvests (Betsie and Platte rivers) were also the two with the largest proportions of evergreen forests (Figure 17).

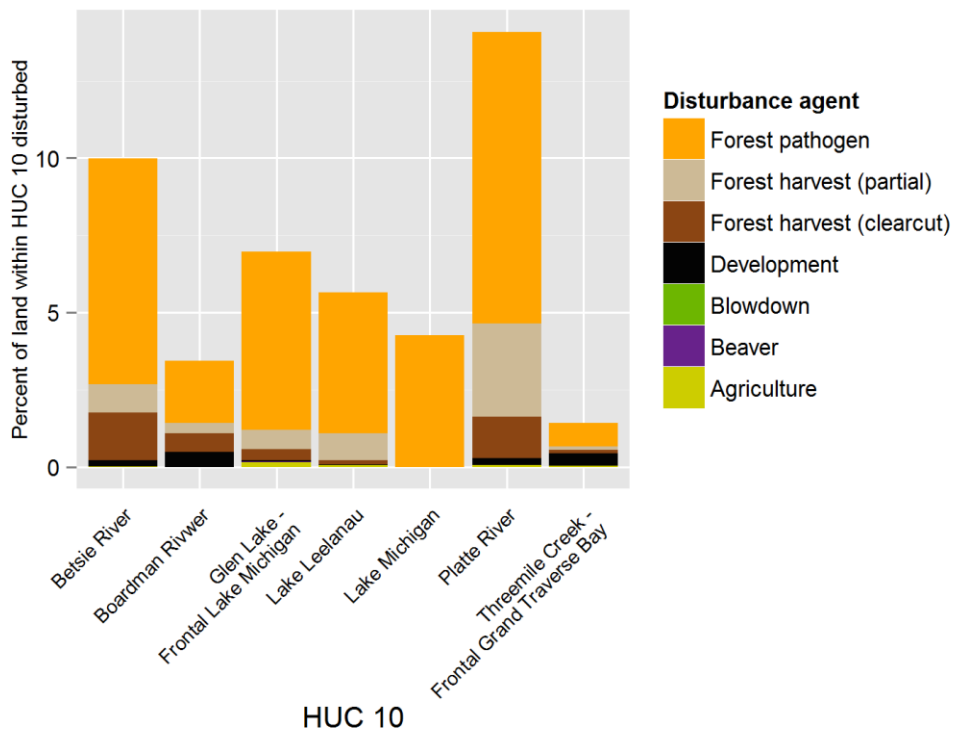


Figure 16. Percent of land disturbed within each watershed (HUC 10) by disturbance agent. For example, a total of 10% of the land within the Betsie River watershed was disturbed during the analysis time period.

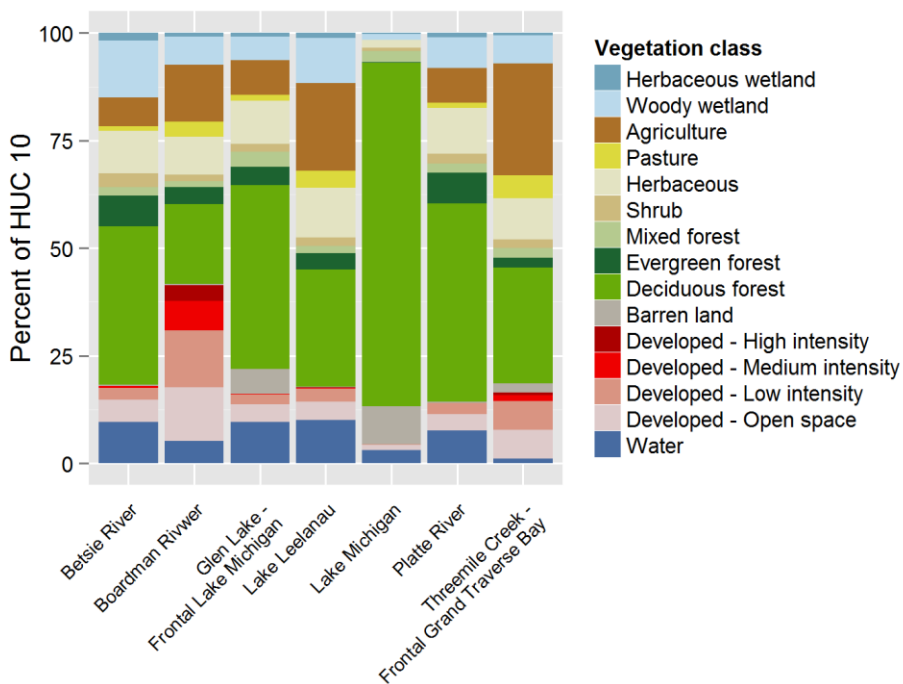


Figure 17. Relative abundance of vegetation classes within each of the watersheds.

Discussion

We found the major disturbance agent in the analysis area to be a widespread defoliation event in 2006, 2009, and 2010. There were multiple defoliators present, including forest tent caterpillars, gypsy moth, and prominent caterpillars (K. Skerl, personal communication, 9 December 2014). Spatially, this disturbance was distributed across most of the analysis area (Figure 18), but less in areas dominated by agricultural land use (Figure 2). Within the park, we found no disturbance on North Manitou Island, while South Manitou had a significant amount of defoliation. It is surprising that the gypsy moth did not make it to North Manitou, although it is quite likely we were not able to detect the defoliation. Due to the very specific timing and relatively short duration of the defoliation event, they are one of the most difficult disturbances to reliably detect using this technique. On the mainland there were a few forest harvests which came up to the boundary of the park, one on the north end of the park between Glen and School lakes. The other forest harvests occurred north of Platte Lake and were largely partial harvests (thinnings).

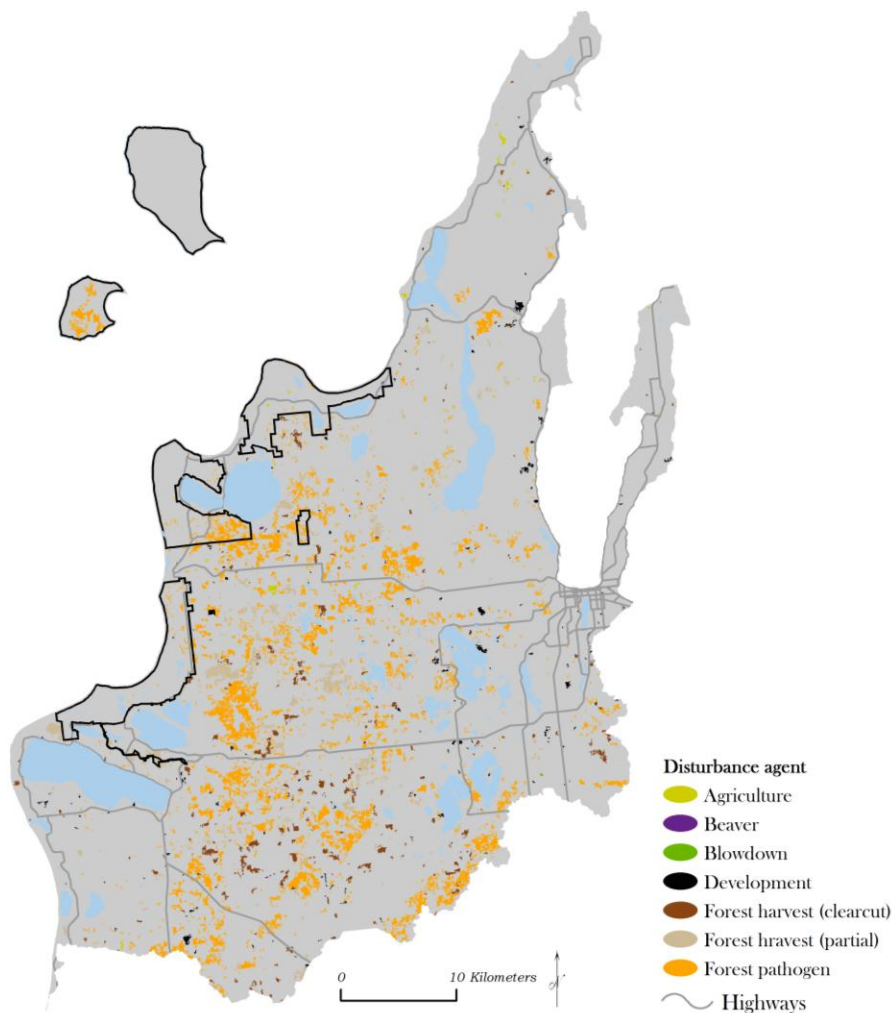


Figure 18. Spatial distribution of disturbances within the analysis area.

Sleeping Bear Dunes NL Compared to Other Great Lakes Network Parks

This is the seventh park we have analyzed for landscape-scale disturbance in the Great Lakes Network. The size and ecological boundaries of 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 Voyageurs (VOYA), Isle Royale (ISRO), and Pictured Rocks (PIRO). For the remaining parks—Apostle Islands (APIS), Mississippi River (MISS), St. Croix River (SACN), and SLBE—which are more affected by surface water flowing into the park, watershed boundaries were used to define analysis areas. Three of the seven HUC 10 watersheds within the analysis area at SLBE flow into or through the park. Because this park is affected by upstream activities in these watersheds, the decision was made to choose the analysis area based upon watershed boundaries. Maps of the analysis areas for all parks can be found in Appendix F. All analysis areas (inside park plus outside park area) were all greater than 150,000 ha (Figure 19).

Among parks monitored thus far, SLBE had the second-highest total percent of land disturbed within the analysis area (Figure 20). Most (ca. 66%) of the disturbance at SLBE was due to insect defoliation, whereas the majority of PIRO's disturbances were due to forest harvests (Figures 20 and 21).

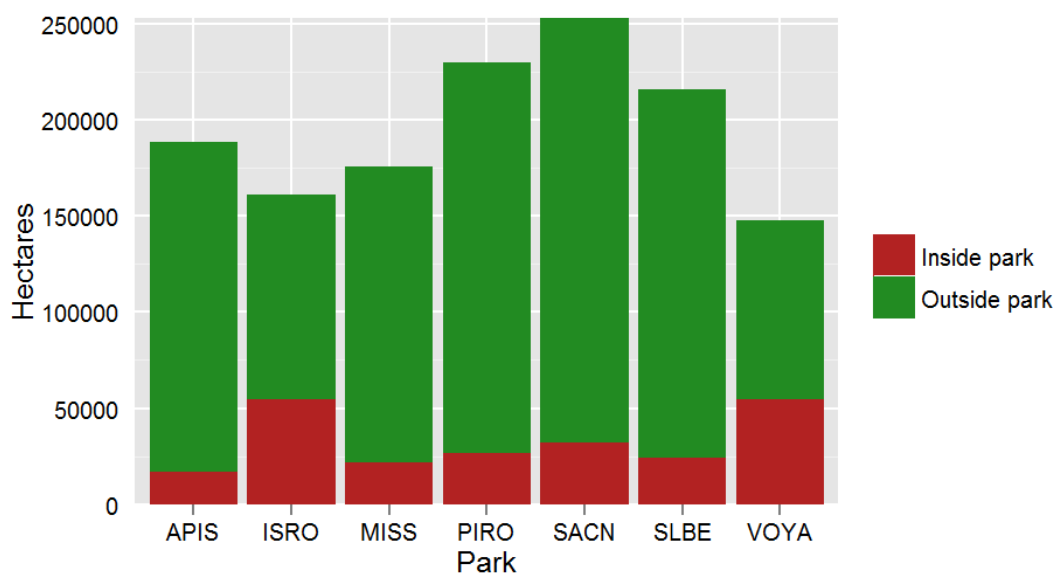


Figure 19. Land area monitored at each park in the Great Lakes Network. See List of Terms and Acronyms on pages xiii–xiv for key to park acronyms.

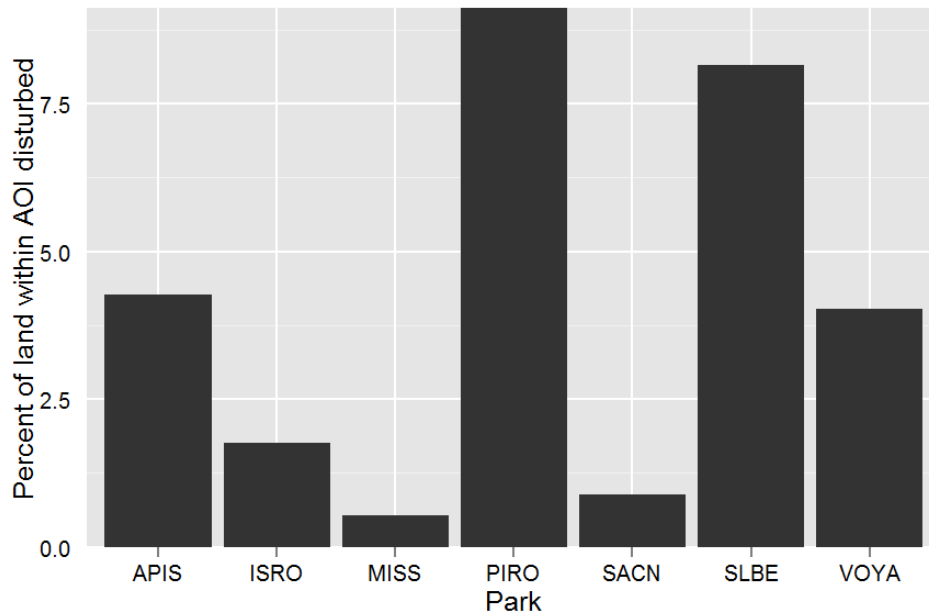


Figure 20. Percent of land disturbed within each analysis area (AOI, or area of interest). See List of Terms and Acronyms on pages xiii–xiv for key to park acronyms.

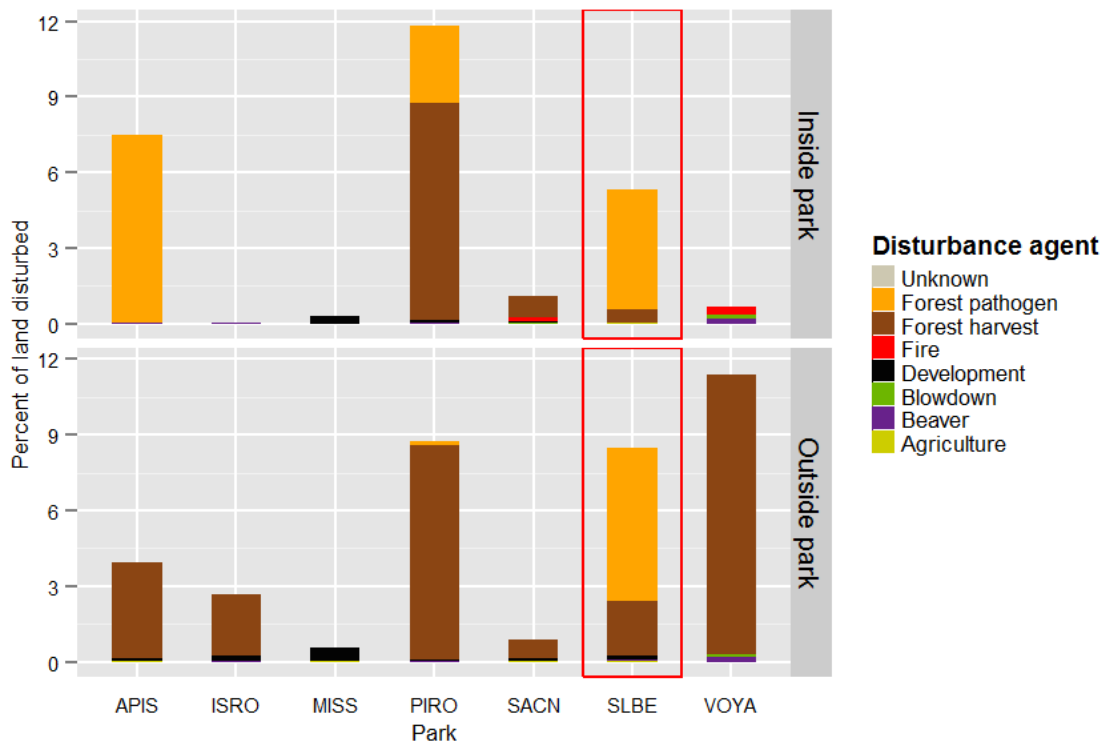


Figure 21. Percent of land disturbed inside the parks (top graph) and outside the parks (bottom graph) by causal agent. See List of Terms and Acronyms on pages xiii–xiv for key to park acronyms.

Conclusions

In this report we document six years of disturbance activity, providing a foundation for continued monitoring of the same types of activities and a long-term record of disturbance. This same analysis is scheduled to occur again in 2019. Future analyses may reveal trends in disturbance patterns or whole-scale changes in disturbance regime (size, location, frequency). For example, hypothesized effects of climate change such as increased high intensity storm events causing windthrow, or outbreaks of insect or disease due to higher mean annual temperatures, can be documented. Thus, over time, the relevance of information provided by this analysis will become increasingly valuable.

We have summarized the first period (2006–2011) of disturbance analysis at SLBE into five points:

- 1) The SLBE analysis area experienced the second highest percent of land disturbed among seven parks analyzed thus far. However, over half of all the land disturbed was due to temporary defoliation by multiple insects.
- 2) We did not see significant amounts of forested lands converted to agricultural uses.
- 3) A small amount of closed forest around SLBE was converted to other land cover classes each year. This incremental but continual conversion of land bordering the park could eventually affect park resources if it continues or increases.
- 4) Disturbances due to development within the analysis area totaled nearly 400 ha during the analysis period, but were generally restricted to within 10 km of Traverse City, Michigan.
- 5) The Platte River watershed experienced the highest proportion of disturbance, with nearly 15% of the land within the watershed experiencing some type of disturbance.
- 6) Although the analysis area experienced a large amount of disturbance due to tree defoliation, we did not detect any resulting tree mortality.

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Appendix A: Spatial Distribution of Disturbances Inside SLBE.

This appendix documents the spatial distribution of disturbances within the park boundary. Distribution maps are followed by snapshots of before and after aerial photography highlighting disturbances of particular interest. These include a number of apparent agricultural conversions and forest harvests. Though these occurred inside the park boundary, we recognize these may be inholdings, or land only recently acquired by the park. Nonetheless, we want to document these changes in land cover.

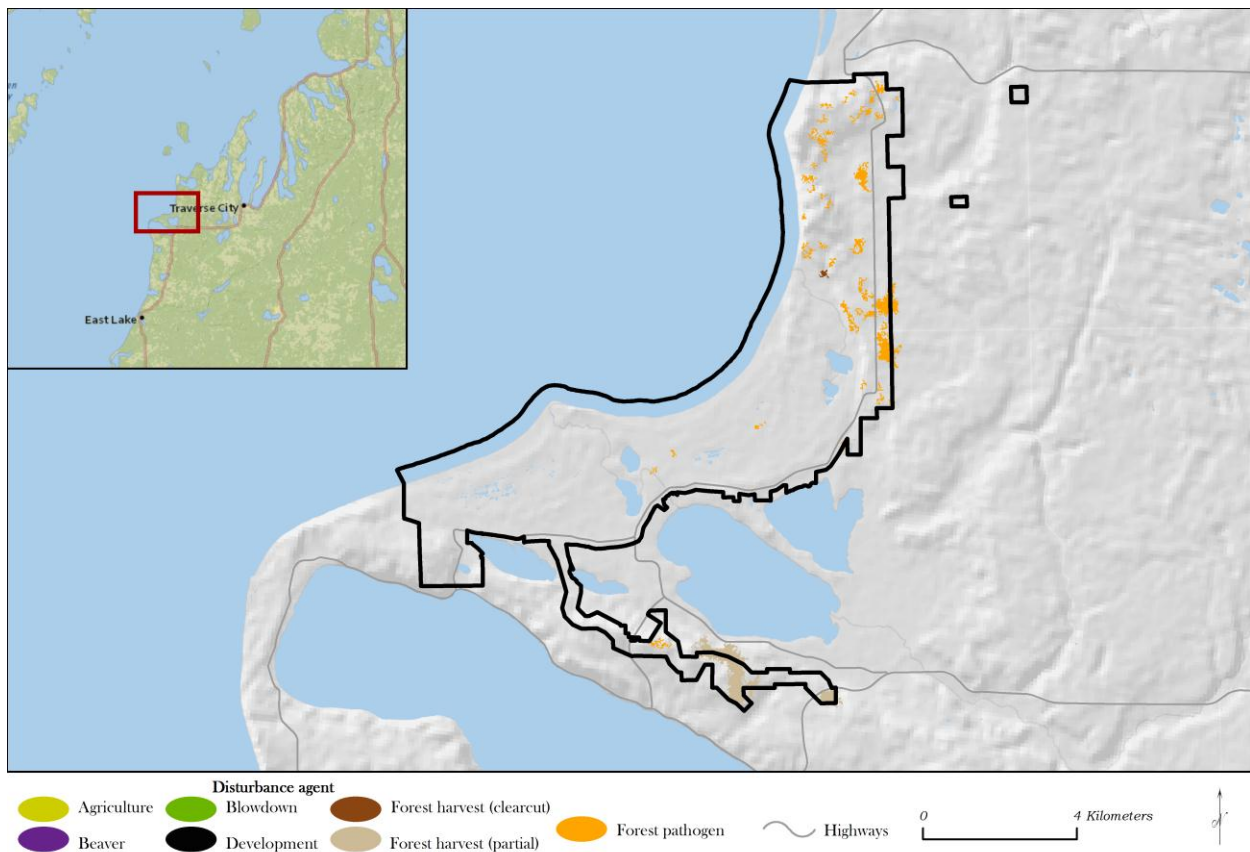


Figure A1. Close-up of disturbances inside SLBE during the analysis period.

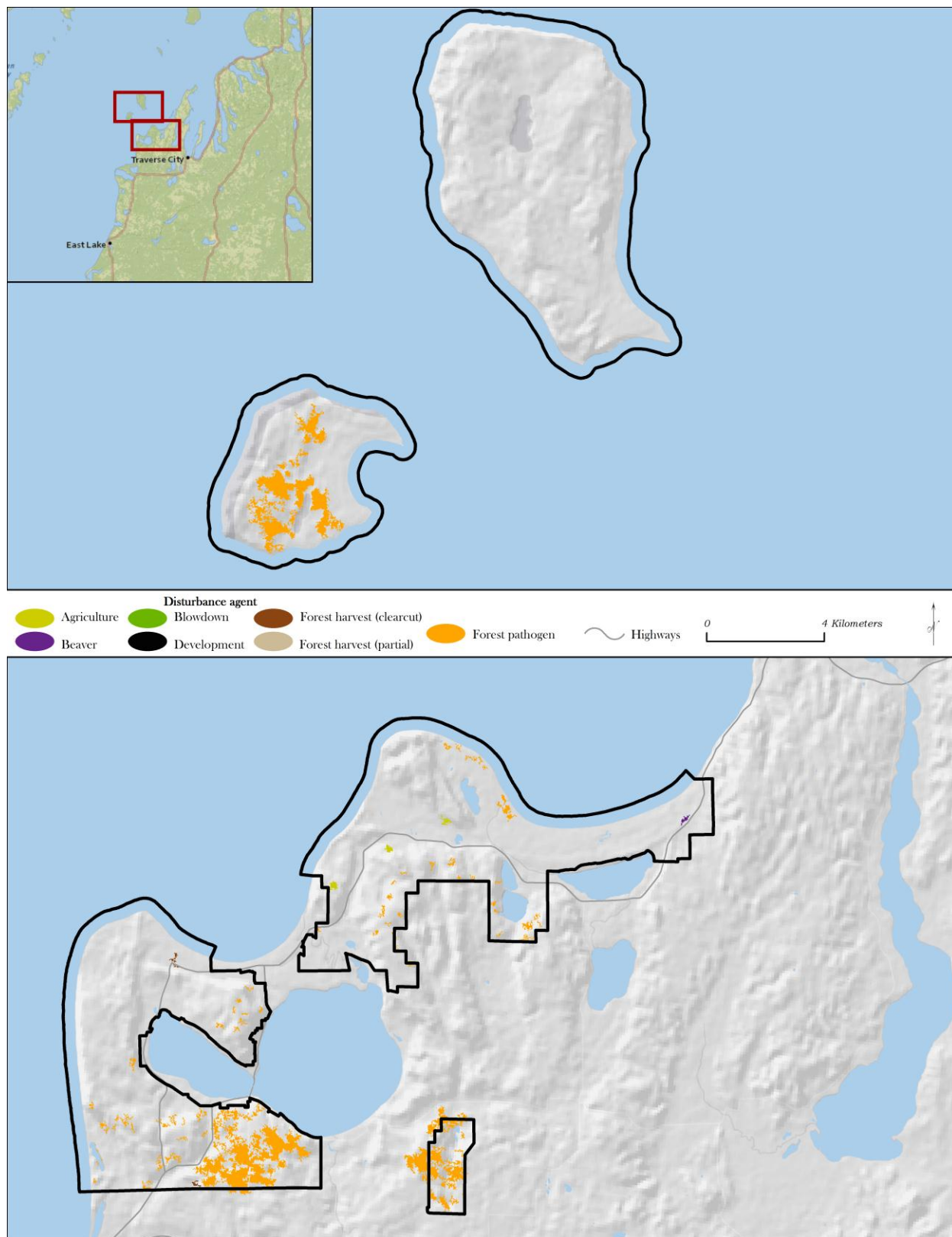


Figure A2. Close-up of disturbances inside SLBE during the analysis period.

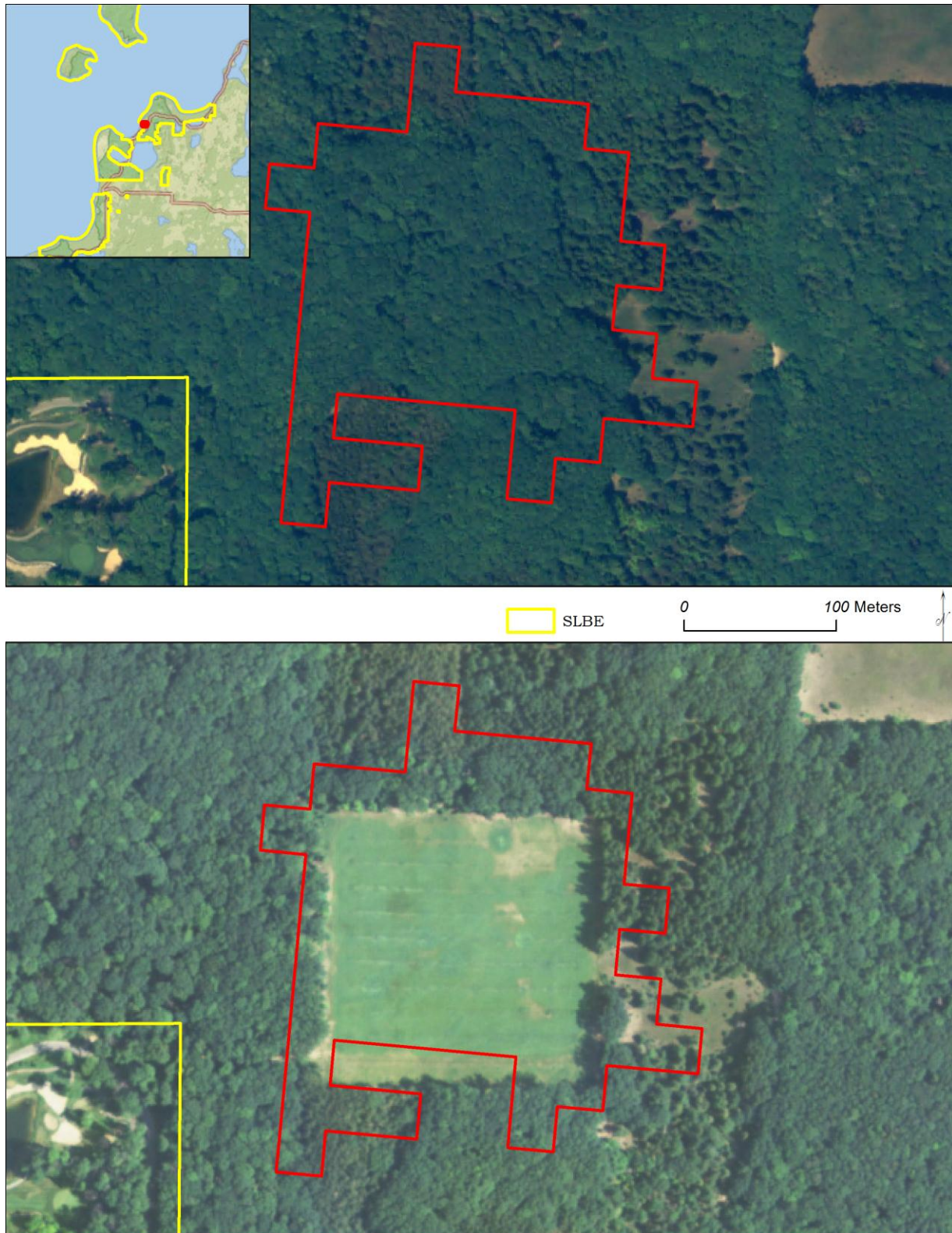


Figure A3. This was a homestead resort sewage sprayfield construction in 2006 under terms of an easement held on NPS lands (K. Skerl, personal communication, 9 December 2014). Top shows 2005 airphoto, bottom shows 2012 airphoto.

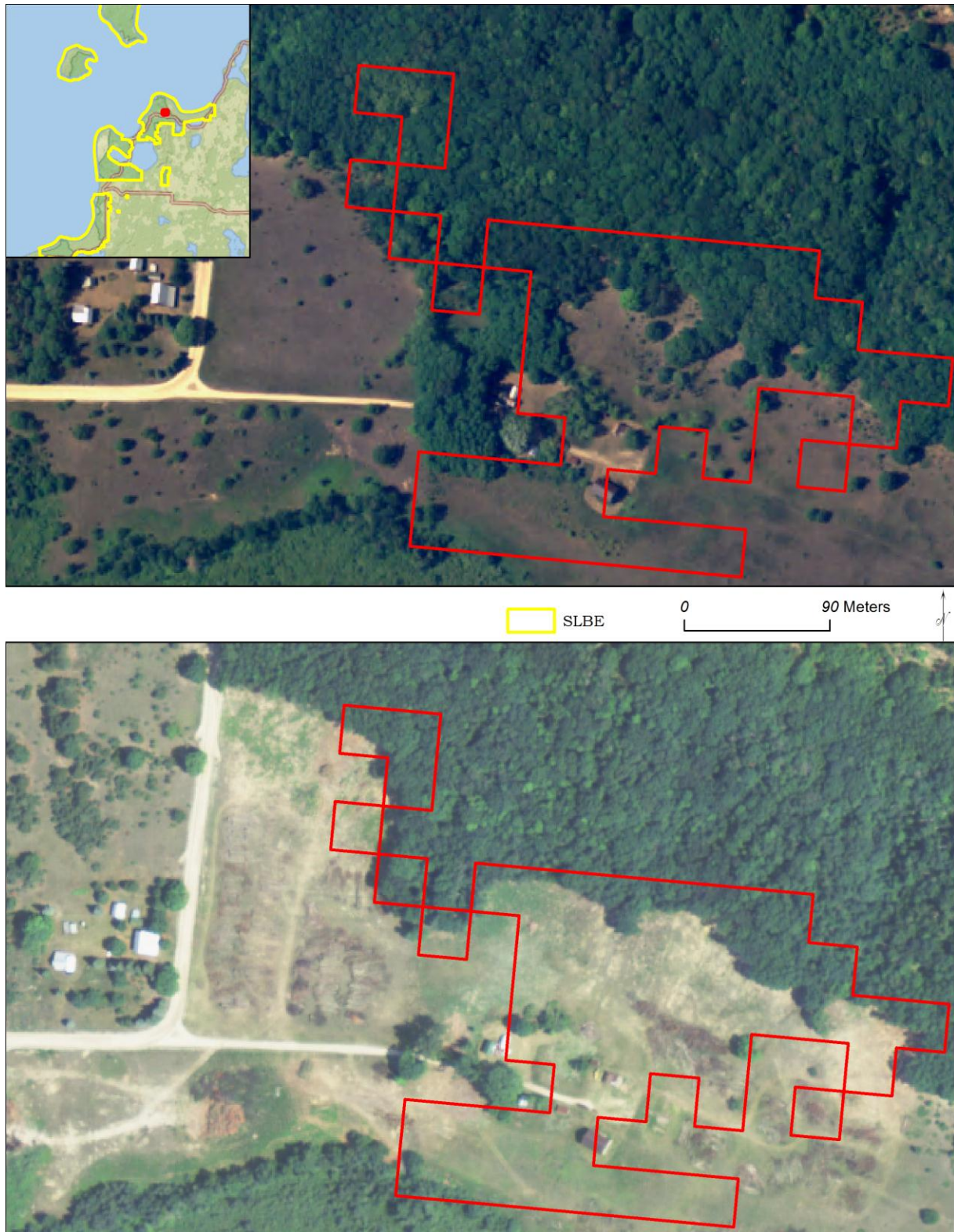


Figure A4. This was a cultural landscape field clearing in 2011 by SLBE, in addition to some black locust treatments (K. Skerl, personal communication, 9 December 2014). Top shows 2005 airphoto, bottom shows 2012 airphoto.

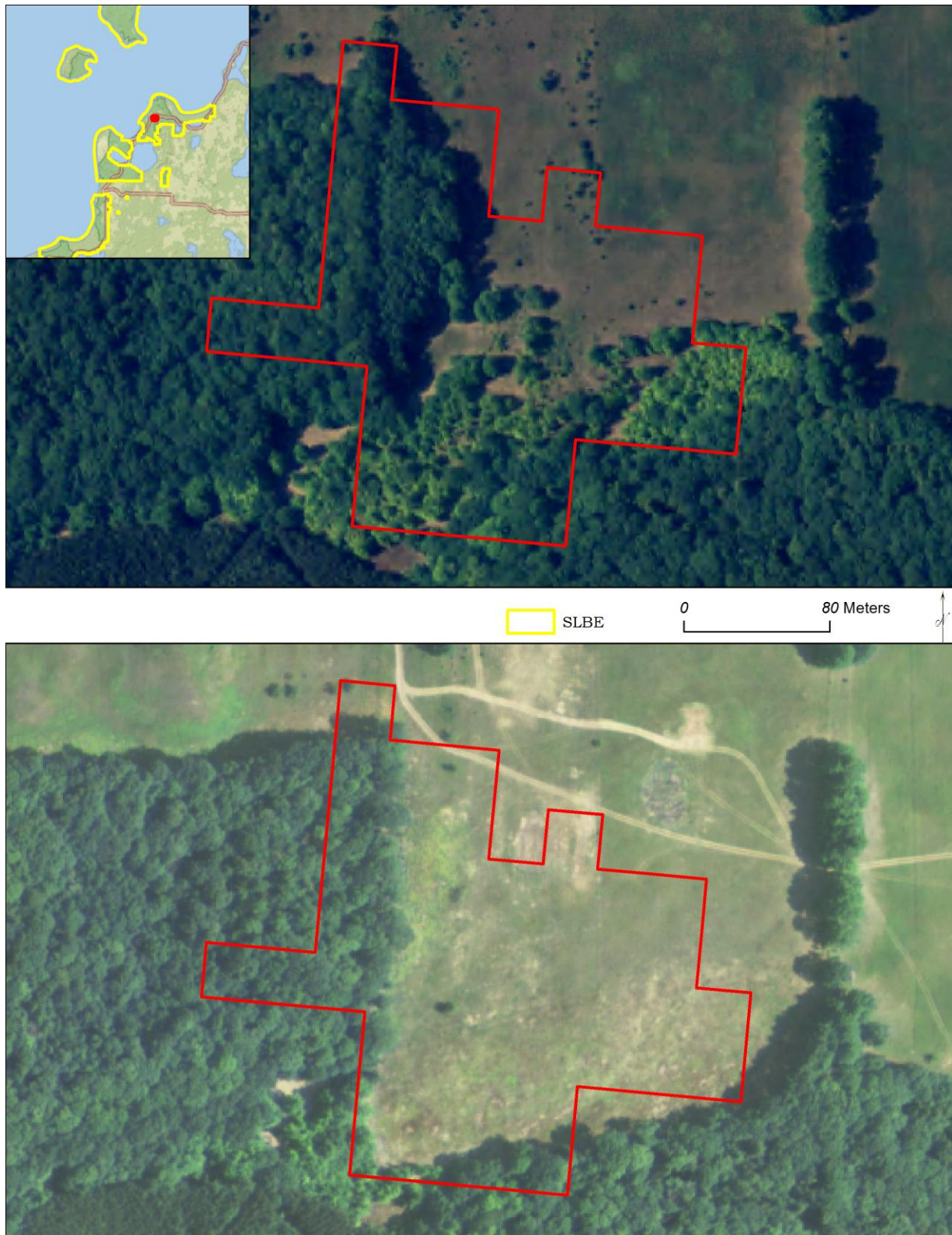


Figure A5. This was a cultural landscape field clearing in 2011 by SLBE (K. Skerl, personal communication, 9 December 2014). Top shows 2005 airphoto, bottom shows 2012 airphoto.

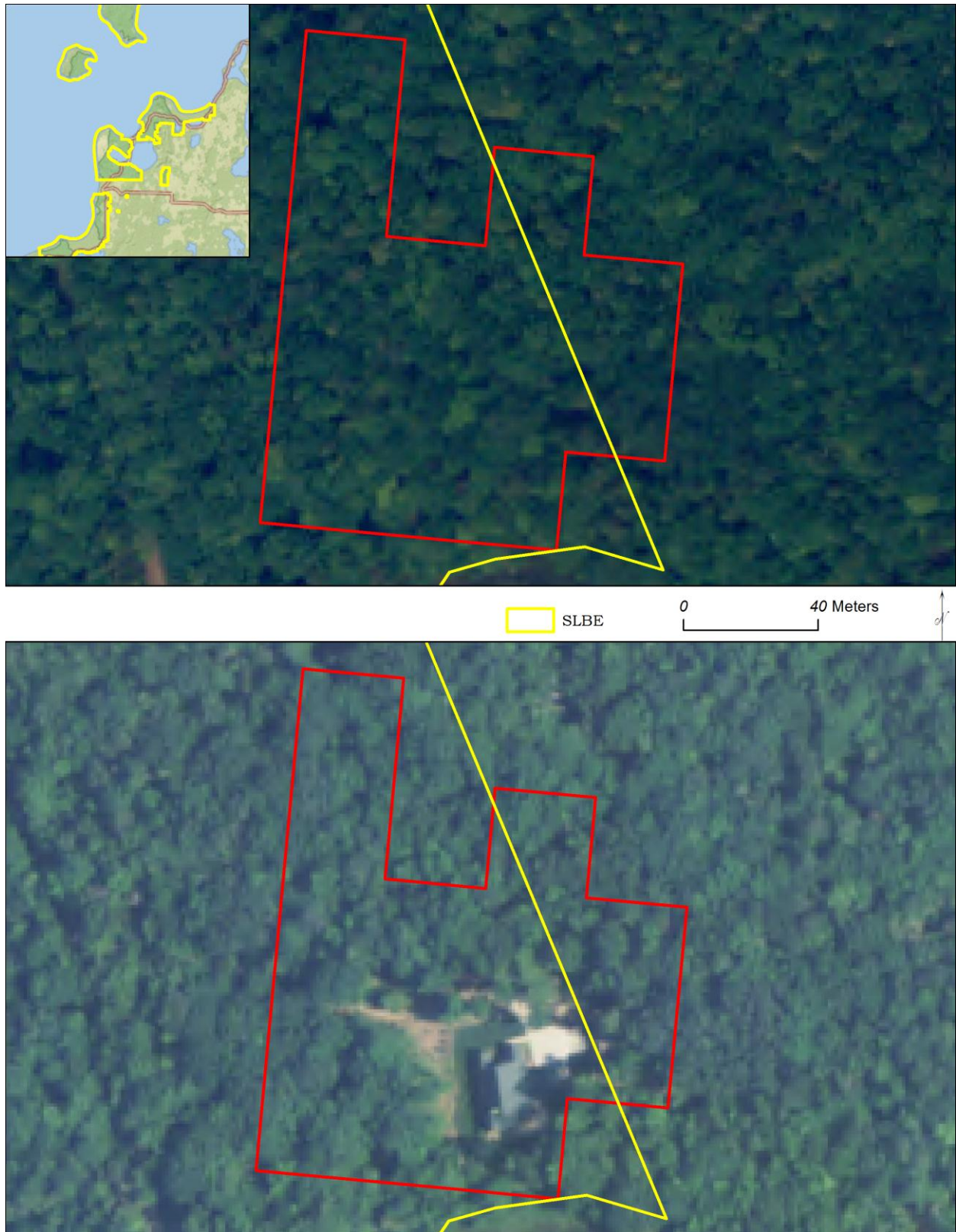


Figure A6. Disturbance due to development that occurred in 2008. Top shows 2005 airphoto, bottom shows 2012 airphoto.

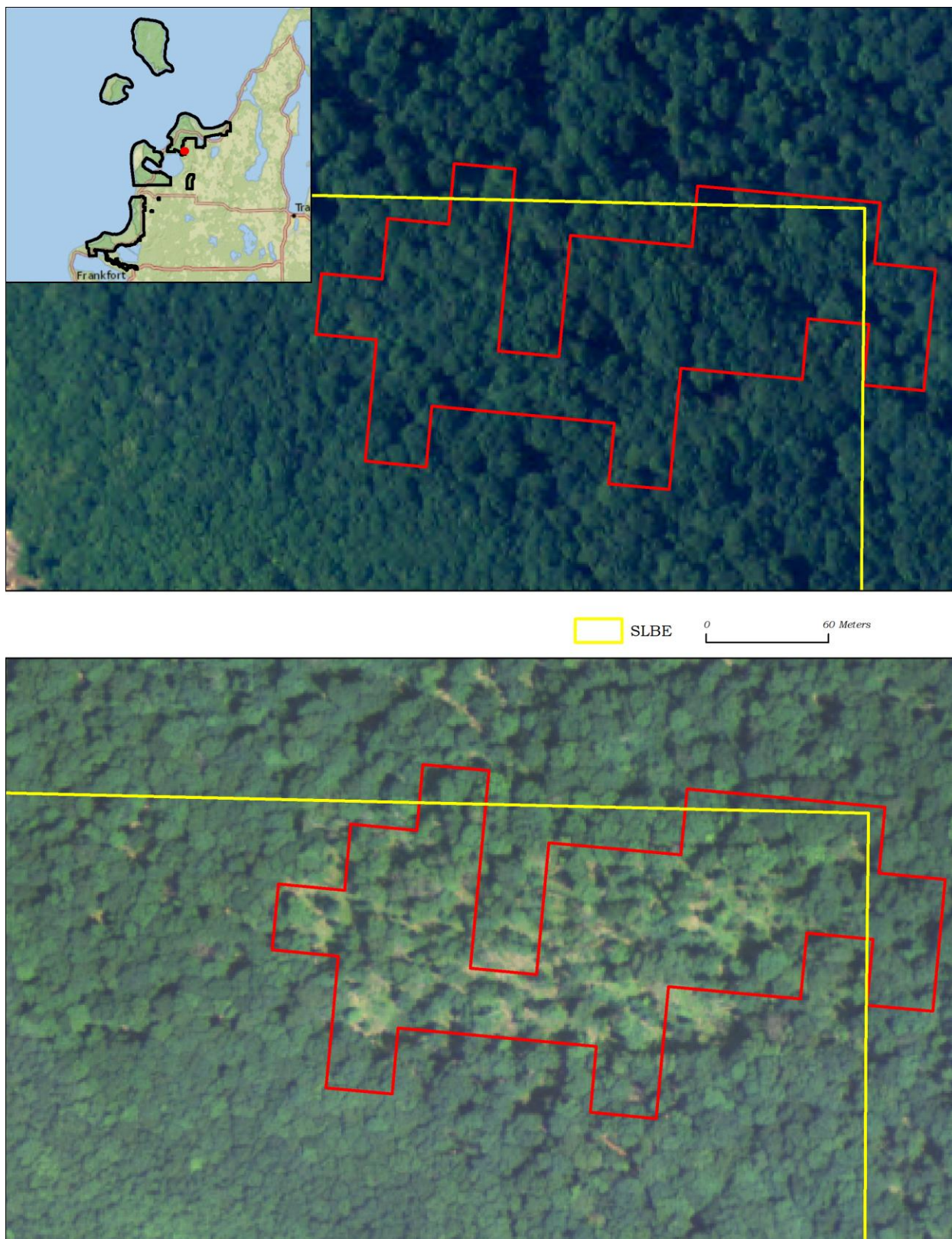


Figure A7. Partial forest harvest that occurred in 2008. Top shows 2005 airphoto, bottom shows 2012 airphoto.

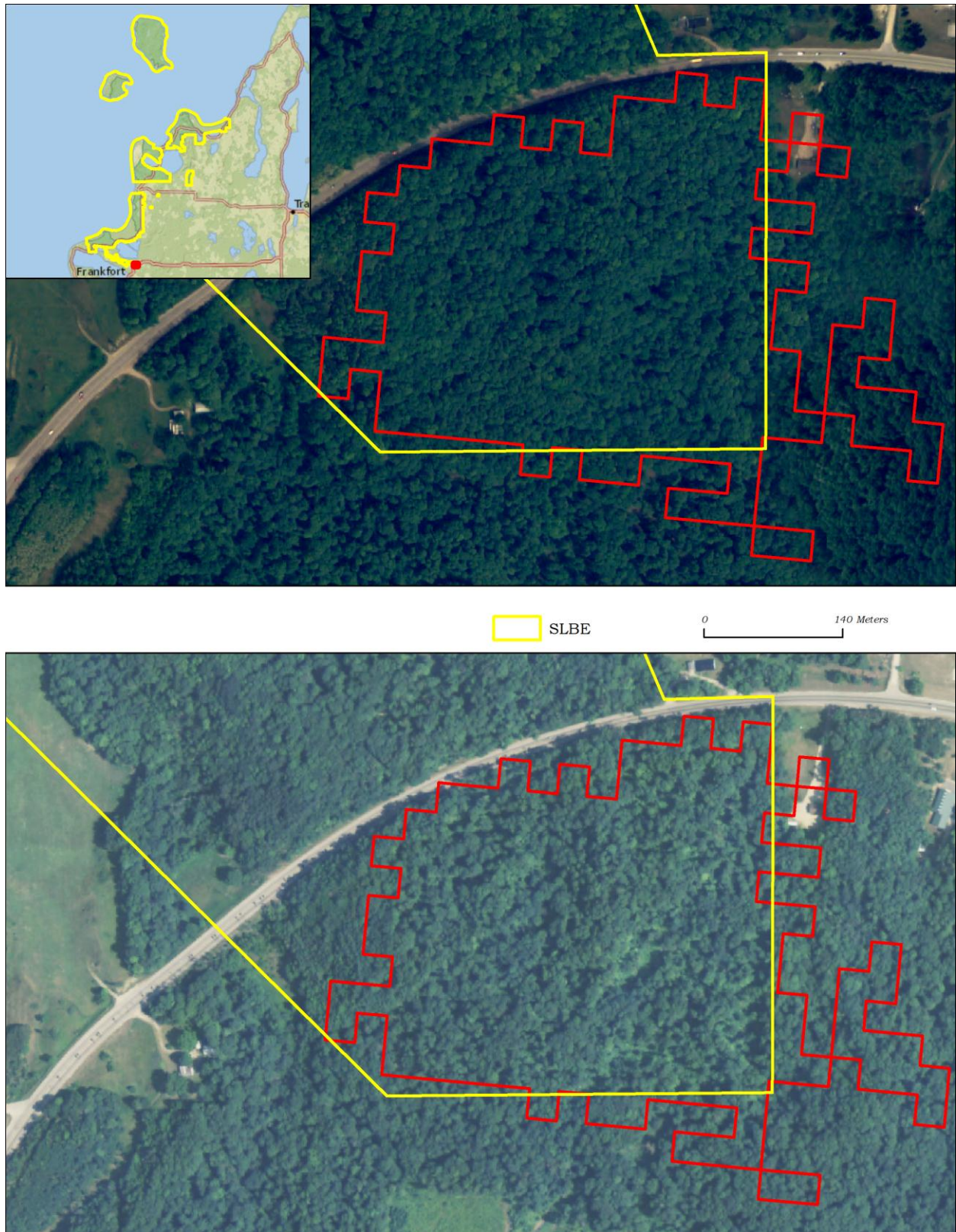


Figure A8. Partial forest harvest that occurred in 2009. Top shows 2005 airphoto, bottom shows 2012 airphoto. This harvest occurred prior to the park acquiring the land.

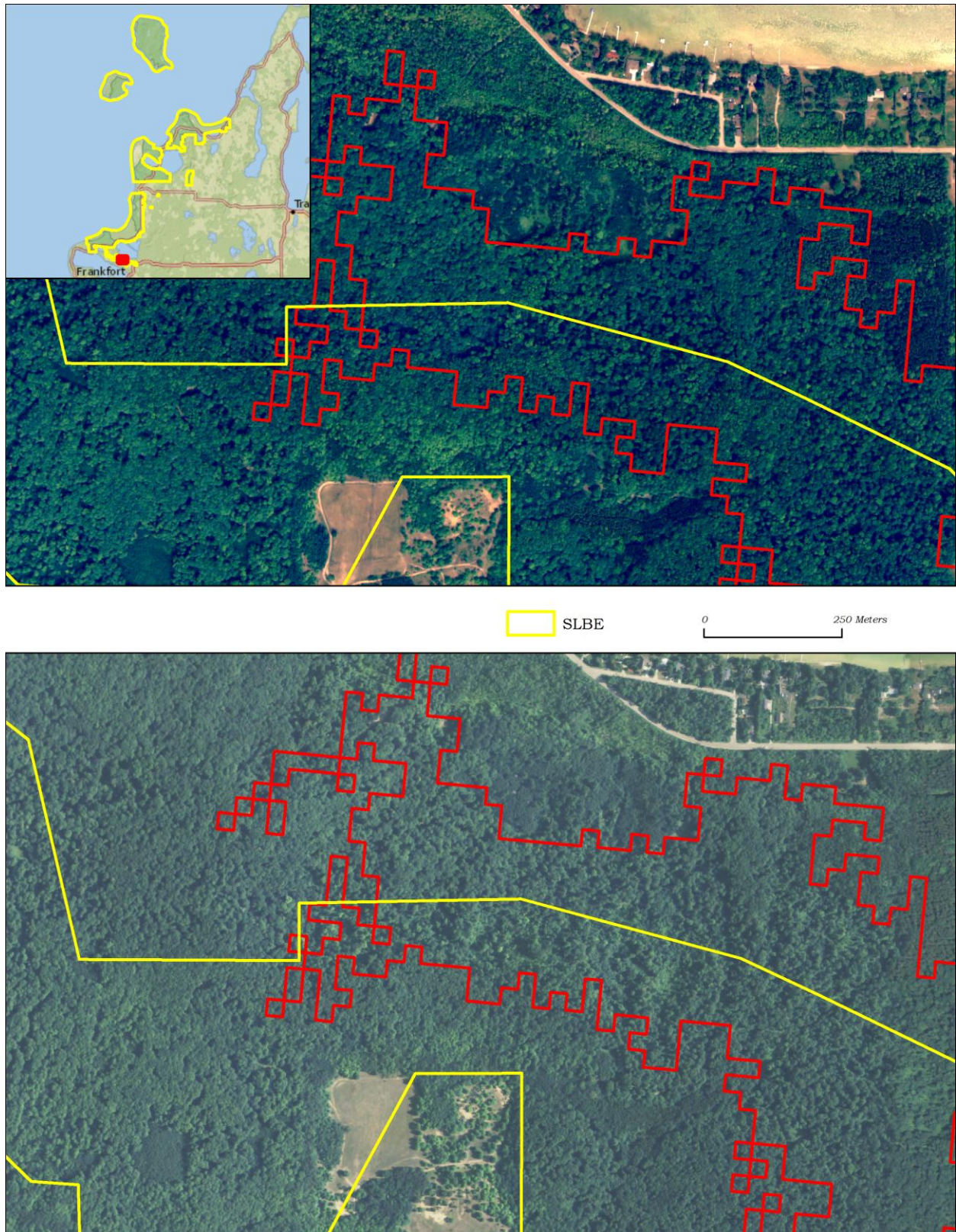


Figure A9. Partial forest harvest that occurred in 2009. Top shows 2005 airphoto, bottom shows 2012 airphoto. This harvest occurred prior to the park acquiring the land.

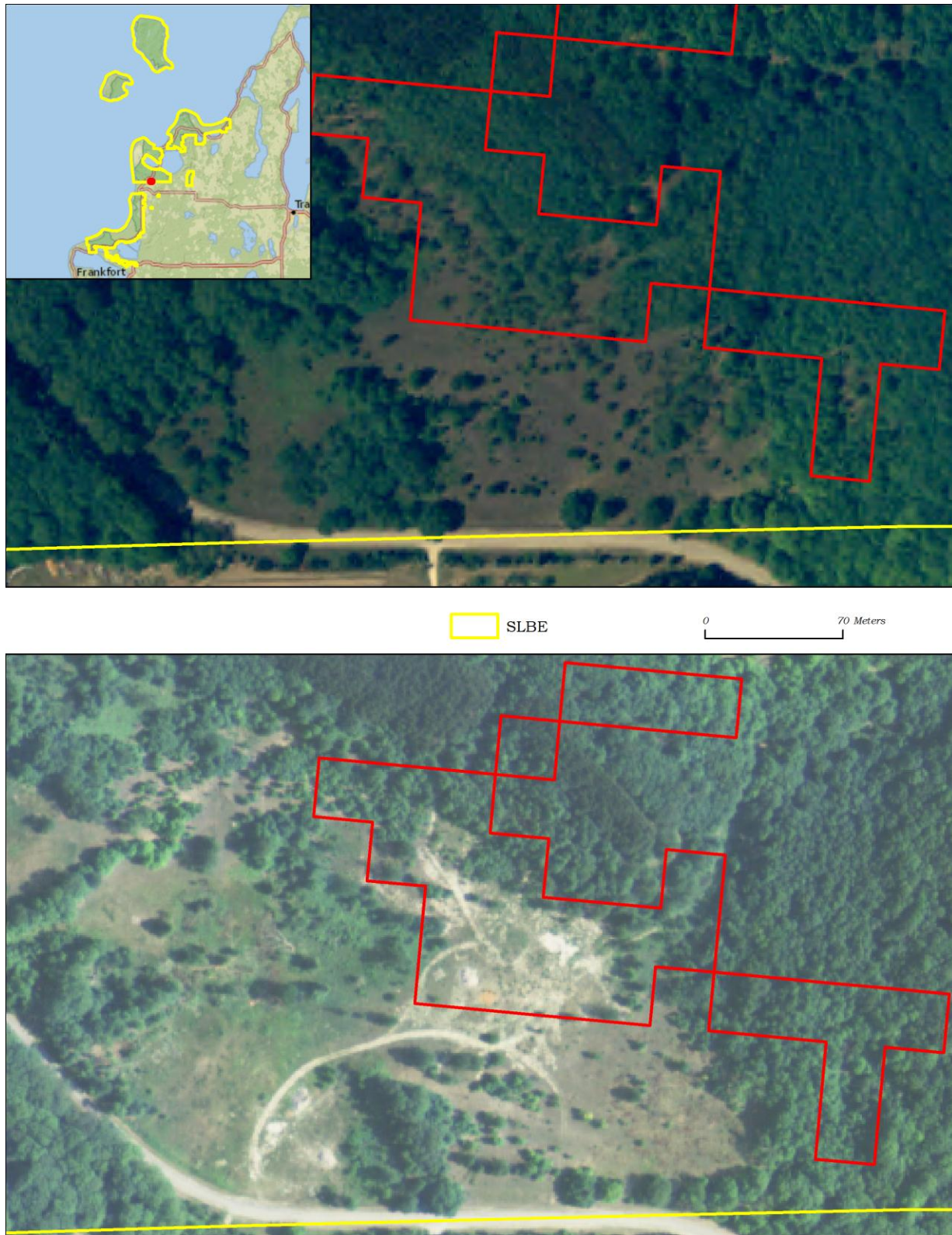


Figure A10. Forest harvest that occurred in 2011. Top shows 2005 airphoto, bottom shows 2012 airphoto. This was a black locust removal by SLBE and partners (K. Skerl, personal communication, 9 December 2014).

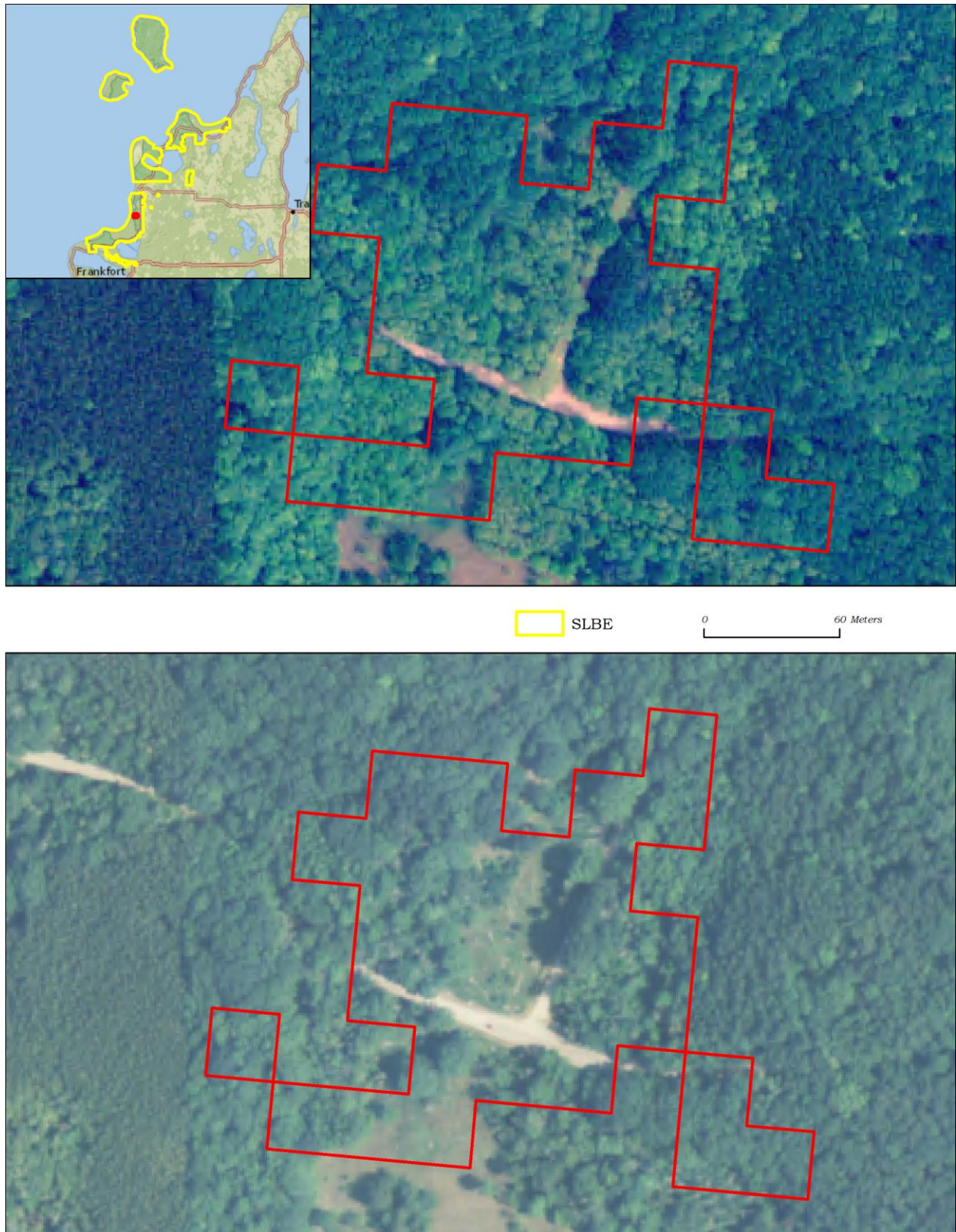


Figure A11. Black locust removal in 2006 (K. Skerl, personal communication, 9 December 2014). Top shows 2005 airphoto, bottom shows 2012 airphoto.

Appendix B: Spatial Distribution of Disturbances Outside SLBE.

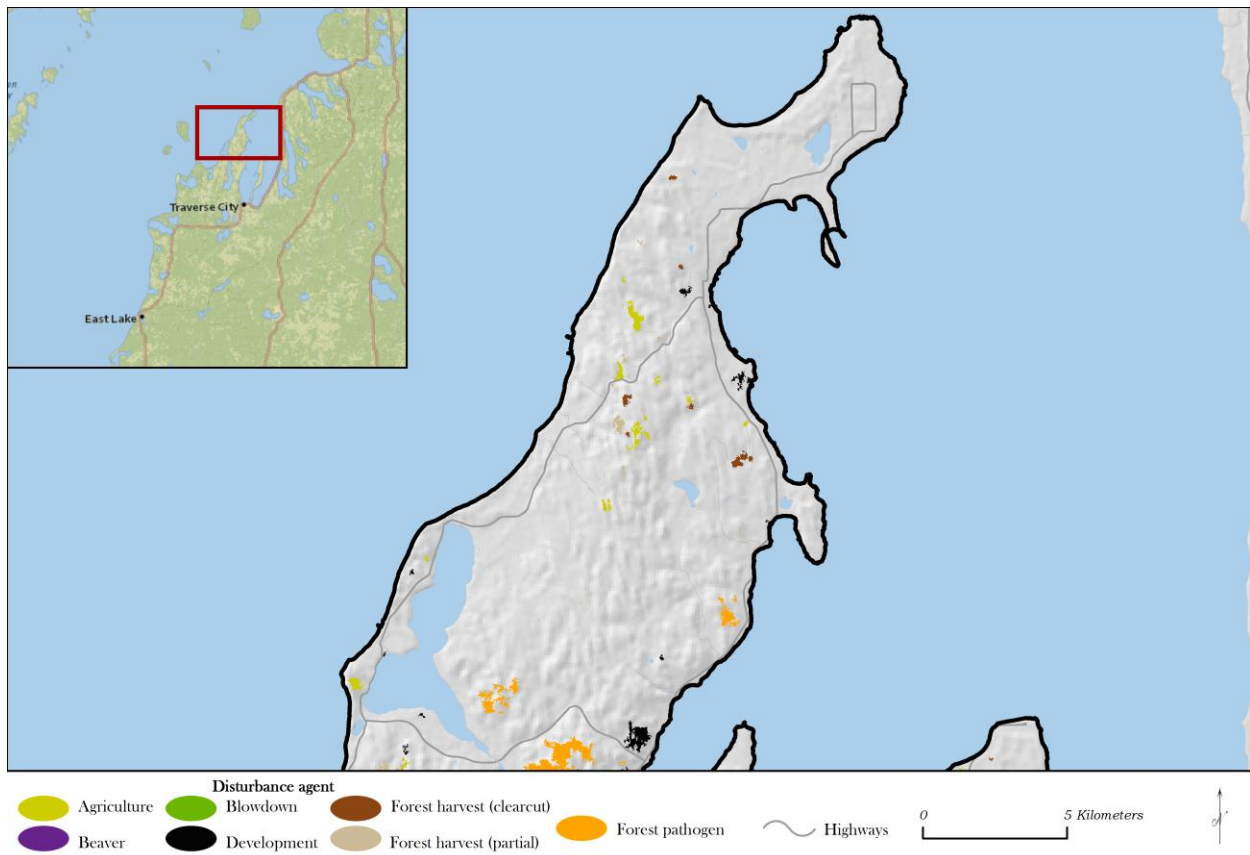


Figure B1. Close-up of disturbances outside SLBE during the analysis period.

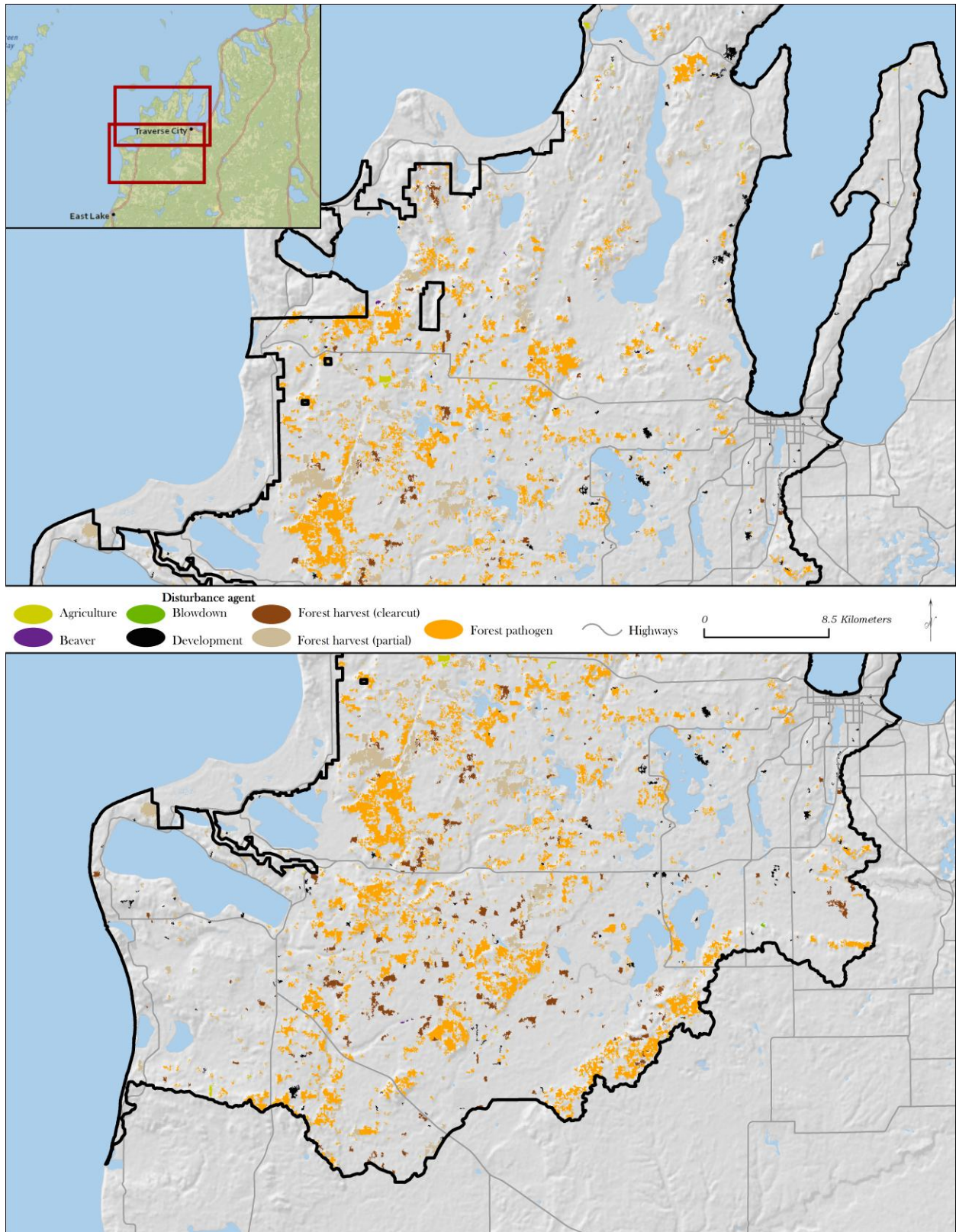


Figure B2. Close-up of disturbances outside SLBE during the analysis period.

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	7.86	18398
Developed, open space	4.96	11599
Developed, low intensity	3.51	8203
Developed, medium intensity	0.66	1534
Developed, high intensity	0.26	618
Barren land	1.69	3956
Deciduous forest	37.88	88652
Evergreen forest	5.18	12133
Mixed forest	2.24	5235
Shrub	2.30	5389
Grassland/herbaceous	9.94	23270
Pasture	2.13	4984
Cultivated crops	11.57	27066
Woody wetlands	8.73	20419
Emergent herbaceous wetlands	1.10	2567

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

Year	SLBE (ha)	SLBE (%)	Non-SLBE (ha)	Non-SLBE (%)
2006	338.85	1.41	1113.61	0.58
2007	3.46	0.01	987.77	0.51
2008	4.63	0.02	932.89	0.49
2009	725.58	3.01	11681.64	6.09
2010	208.08	0.86	1322.87	0.69
2011	6.04	0.03	269.40	0.14
Total	1286.63	5.34	16308.19	8.50

Table C4. Hectares disturbed by disturbance agent, year, and analysis area.

Analysis area	Year	Area of land disturbed (ha) by disturbance agent							Total
		<i>Agriculture</i>	<i>Beaver</i>	<i>Blowdown</i>	<i>Development</i>	<i>Forest pathogen</i>	<i>Forest harvest (clearcut)</i>	<i>Forest harvest (partial)</i>	
SLBE	2006	4.86	0.00	0.00	0.00	332.91	1.08	0.00	338.85
	2007	0.00	2.92	0.00	0.00	0.00	0.54	0.00	3.46
	2008	0.00	0.00	0.00	0.25	0.00	1.94	2.43	4.63
	2009	0.00	0.00	0.00	0.00	615.78	0.00	109.80	725.58
	2010	0.00	0.00	0.00	0.00	208.08	0.00	0.00	208.08
	2011	4.87	0.00	0.00	0.00	0.00	1.17	0.00	6.04
	Total	9.73	2.92	0.00	0.25	1156.77	4.73	112.23	1286.63
Non-SLBE	2006	9.69	0.00	1.01	172.49	0.00	407.57	522.85	1113.61
	2007	26.82	3.87	0.00	96.65	50.83	284.06	525.54	987.77
	2008	4.74	0.00	0.00	59.06	191.88	260.39	416.81	932.89
	2009	9.61	0.97	0.00	35.03	10433.60	407.51	794.91	11681.64
	2010	44.04	6.12	0.00	13.17	993.37	177.96	88.22	1322.87
	2011	9.94	1.08	0.00	8.10	0.00	216.74	33.55	269.40
	Total	104.84	12.04	1.01	384.50	11669.68	1754.23	2381.89	16308.19

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

Analysis area	Year	Percent of land disturbed by disturbance agent							Total
		<i>Agriculture</i>	<i>Beaver</i>	<i>Blowdown</i>	<i>Development</i>	<i>Forest pathogen</i>	<i>Forest harvest (clearcut)</i>	<i>Forest harvest (partial)</i>	
SLBE	2006	0.02	0	0	0	1.38	<0.01	0	1.41
	2007	0	0.01	0	0	0	<0.01	0	0.01
	2008	0	0	0	<0.01	0	<0.01	0.01	0.02
	2009	0	0	0	0	2.55	0	0.46	3.01
	2010	0	0	0	0	0.86	0	0	0.86
	2011	0.02	0	0	0	0	<0.01	0	0.03
	Total	0.04	0.01	0	0	4.80	0	0.47	5.34
Non-SLBE	2006	<0.01	0	<0.01	0.09	0	0.21	0.27	0.58
	2007	0.01	<0.01	0	0.05	0.03	0.15	0.27	0.51
	2008	<0.01	0	0	0.03	0.10	0.14	0.22	0.49
	2009	<0.01	<0.01	0	0.02	5.44	0.21	0.41	6.09
	2010	0.02	<0.01	0	<0.01	0.52	0.09	0.05	0.69
	2011	<0.01	<0.01	0	<0.01	0	0.11	0.02	0.14
	Total	0.04	0	0	0.19	6.08	0.91	1.24	8.50

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)							
		Forest (closed)	Forest (semi-closed)	Forest (open)	Herbaceous	Water	Impervious surface	Pervious surface	Impervious/vegetated
SLBE	2006	-338.85	0	0	0	0	0	0	0
	2007	-2.92	-0.54	0	0	0	0	0	0
	2008	-3.95	-0.97	0	0	0	0	0	0
	2009	-725.58	0	0	0	0	0	0	0
	2010	-208.08	0	0	0	0	0	0	0
	2011	-4.24	0	-1.80	0	0	0	0	0
	Total	-1283.62	-1.51	-1.80	0.00	0.00	0.00	0.00	0.00
Non-SLBE	2006	-1041.36	-42.79	-7.36	-18.91	-0.86	0	0	-2.34
	2007	-953.78	-21.78	-7.29	-4.47	0	0	0	-0.44
	2008	-902.53	-28.59	-0.63	-0.29	0	0	0	-0.84
	2009	-11651.40	-15.45	-3.64	-11.15	0	0	0	0
	2010	-1315.39	-5.19	-1.64	-0.52	0	-0.13	0	0
	2011	-262.80	-2.20	-4.40	0	0	0	0	0
	Total	-16127.26	-116.00	-24.96	-35.34	-0.86	-0.13	0.00	-3.62

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>
SLBE	2006	332.91	0	1.08	4.86	0	0	0	0
	2007	0	0	2.00	0	1.46	0	0	0
	2008	2.73	0.78	1.17	0	0	0	0	0.25
	2009	725.58	0	0	0	0	0	0	0
	2010	208.08	0	0	0	0	0	0	0
	2011	0	0	1.17	4.87	0	0	0	0
	Total	1269.30	0.78	5.41	9.73	1.46	0.00	0.00	0.25
Non-SLBE	2006	490.59	40.99	376.86	69.48	0	5.24	9.20	121.26
	2007	460.42	110.41	284.19	58.49	0.39	0	17.01	56.87
	2008	513.47	96.39	272.09	24.08	0	6.61	4.13	16.12
	2009	10930.83	330.87	369.30	20.58	0	8.45	5.60	16.01
	2010	1048.27	44.63	168.79	49.22	0.61	0	2.85	8.50
	2011	16.47	20.41	214.16	9.94	0.32	0	0	8.10
	Total	13460.05	643.70	1685.38	231.79	1.32	20.29	38.79	226.86

Table C8. Area (ha) of land disturbed inside the analysis area by HUC 10.

HUC 10	Agriculture	Beaver	Blowdown	Development	Forest pathogen	Forest harvest (clearcut)	Forest harvest (partial)
Betsie River	3.81	4.95	1.01	112.07	4144.64	872.95	521.72
Boardman River	0	0	0	49.25	208.82	62.54	35.30
Glen Lake-Frontal Lake Michigan	52.63	10.01	0	16.50	2110.01	128.25	232.24
Lake Leelanau	15.84	0	0	13.02	1483.17	41.21	287.20
Lake Michigan	0	0	0	0	332.91	0	0
Platte River	31.26	0	0	93.75	4349.45	624.34	1391.75
Threemile Creek-Frontal Grand Traverse Bay	11.03	0	0	100.16	197.45	29.66	25.92

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

Owner	Percent
National Lakeshore	10.48
State of Michigan	1.42
State Forest	14.88
State Parks and Recreation	0.29
State Game Area	0.19
The Nature Conservancy	0.02
Private	72.73

Appendix D: Results from Interpreter Cross Validation.

We make every effort to reduce the amount of user bias that could be introduced into the validation process. We measured observer bias by randomly selecting 10% of each validator's polygons and having the other interpreter independently assess each one. This appendix provides the summary results from this cross-validation exercise.

The first decision an interpreter needs to make is whether the polygon is a true disturbance or has been falsely identified by LandTrendr. There were 626 polygons (10%) randomly selected for cross validation and of those polygons, the interpreters agreed on 528, or 84%. The majority (64%) of the agreement was due to the 340 polygons both interpreters agreed were false. This is excellent agreement among interpreters and unfortunately, interpreter cross validation does not often occur during these type of studies. Therefore, we cannot compare our numbers to other sources in the literature.

Table D1. Polygons that were unambiguous have matching interpretations; polygons that are ambiguous had different interpretations (off-diagonal of the matrix). As an example, the 33 non-matching values can be interpreted as follows: interpreter 1 called 33 polygons false when interpreter 2 called those same polygons true.

		Interpreter 2		Proportion unambiguous
		FALSE	TRUE	
Interpreter 1	FALSE	340	33	0.91
	TRUE	65	188	0.74

The proportion of disturbance polygons that were unambiguous for the SLBE analysis area was very low. However, this simple statistic 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 hectares as clearcut than Interpreter 2. However, the difference between a clearcut and partial harvest is relatively small and defined by the percent of tree canopy remaining. 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. These judgments can be difficult depending on the imagery available for the validation.

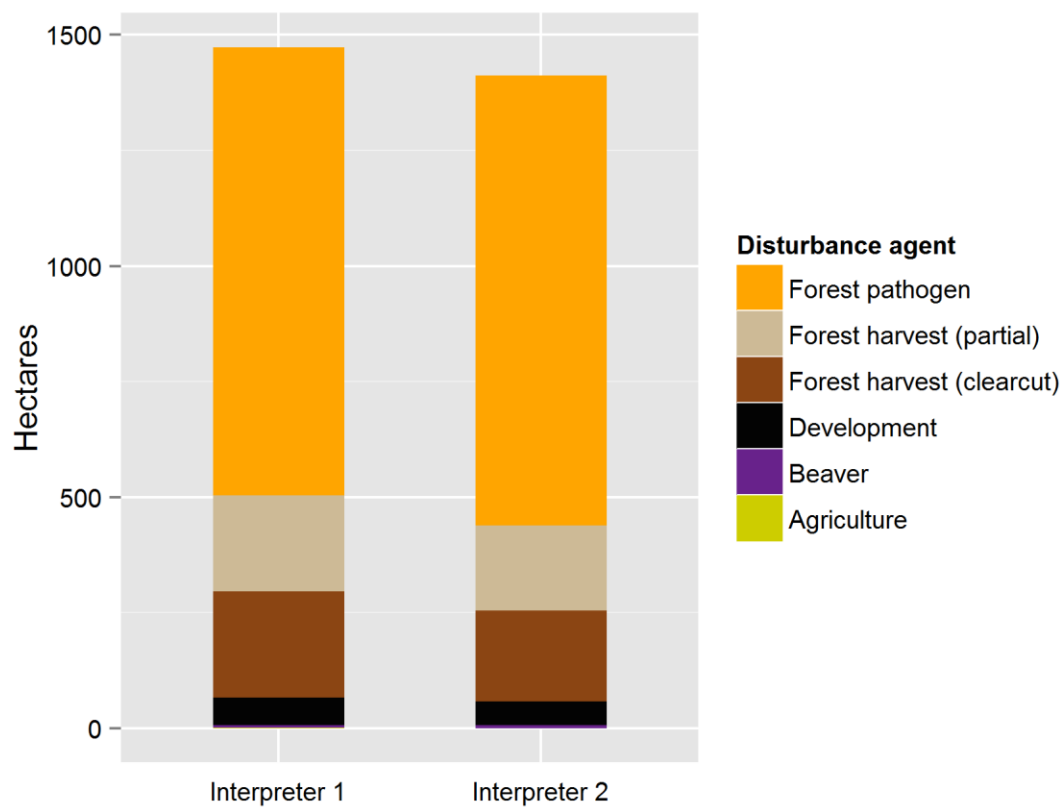


Figure D1. Area (ha) of land disturbed by disturbance agent as indicated by each interpreter.

In figure D2, we can see that both interpreters generally agreed on the starting and ending classes of the polygons. Overall, this is excellent agreement between interpreters.

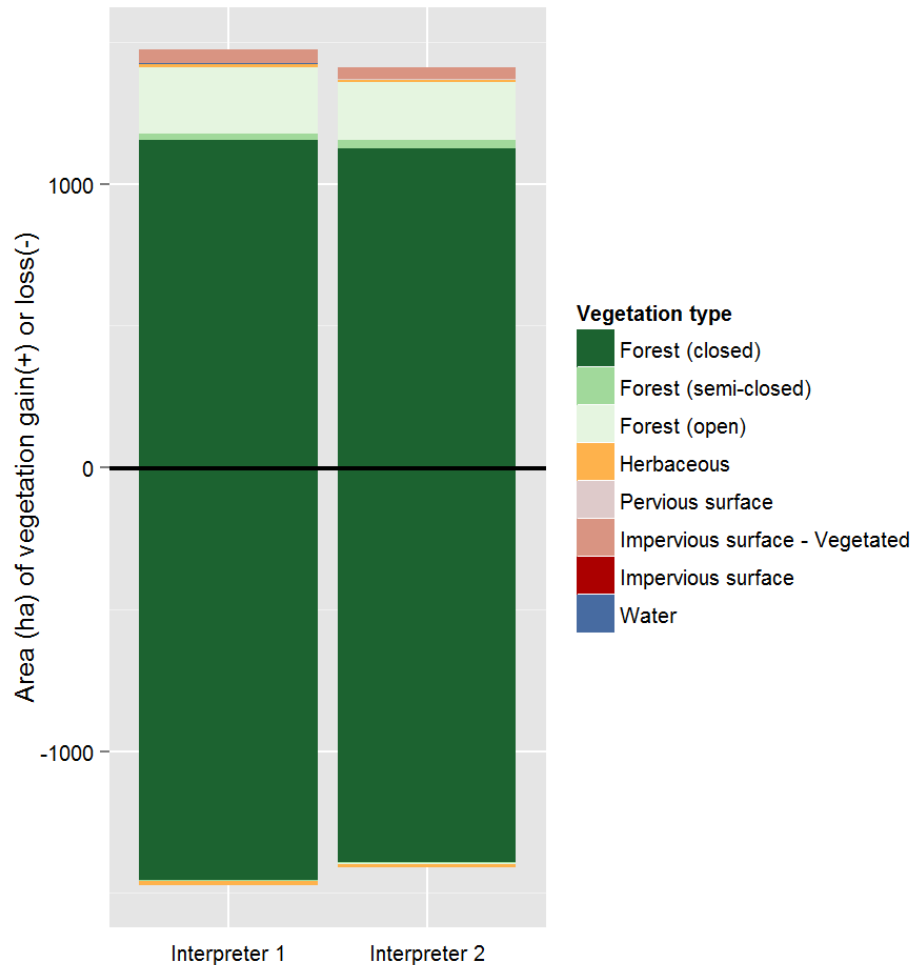


Figure D2. Area (ha) of vegetation gained and lost as indicated by each interpreter.

We also looked more closely at the polygons where the interpreters did not agree. For example, of the 65 polygons interpreter 2 thought were true and interpreter 1 thought were false, what was the disturbance agent responsible for the disturbance (first column, figure D3). 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. In the second column (Interpreter 2), these are the 33 polygons interpreter 2 thought were true and interpreter 1 thought were false. Again, it shows mostly the same pattern as the first column, where most of the confused polygons were due to forest pathogen and partial forest harvests. We can also see the total area these ‘confused’ polygons contribute to the overall cross-validation summary (Figure D4).

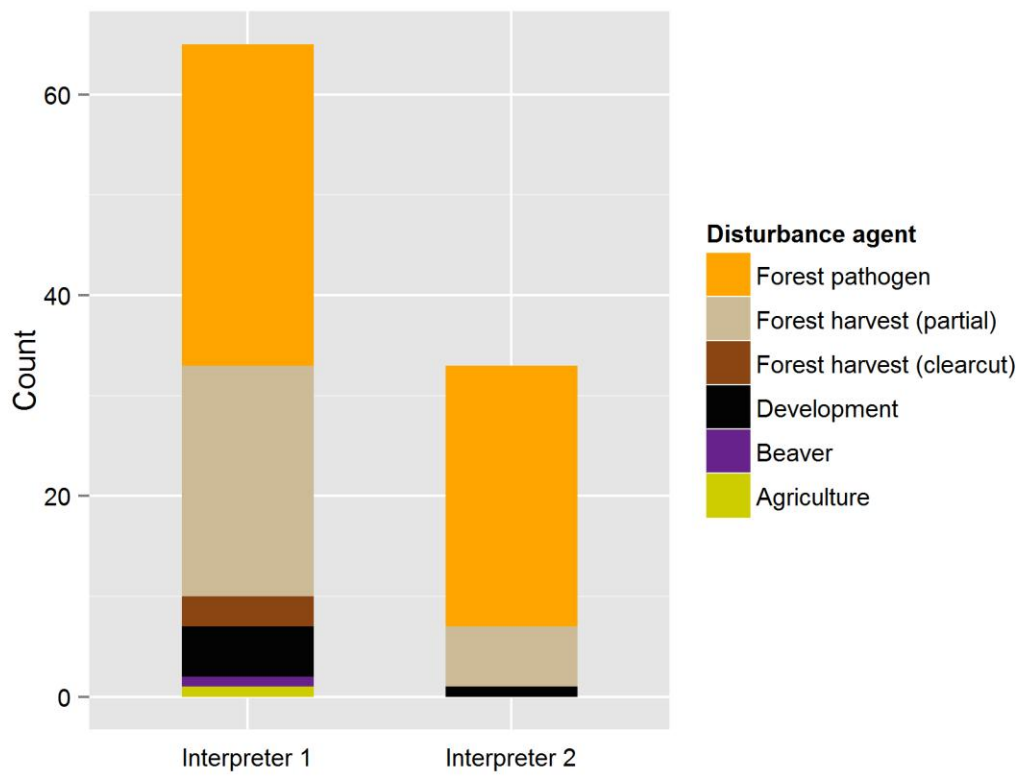


Figure D3. Count (n) of 'confused' polygons and the agent to which each interpreter attributed the change. For example, of the 17 polygons interpreter 1 thought were true and interpreter 2 thought were false, most of the polygons were classified as changed due to forest pathogen.

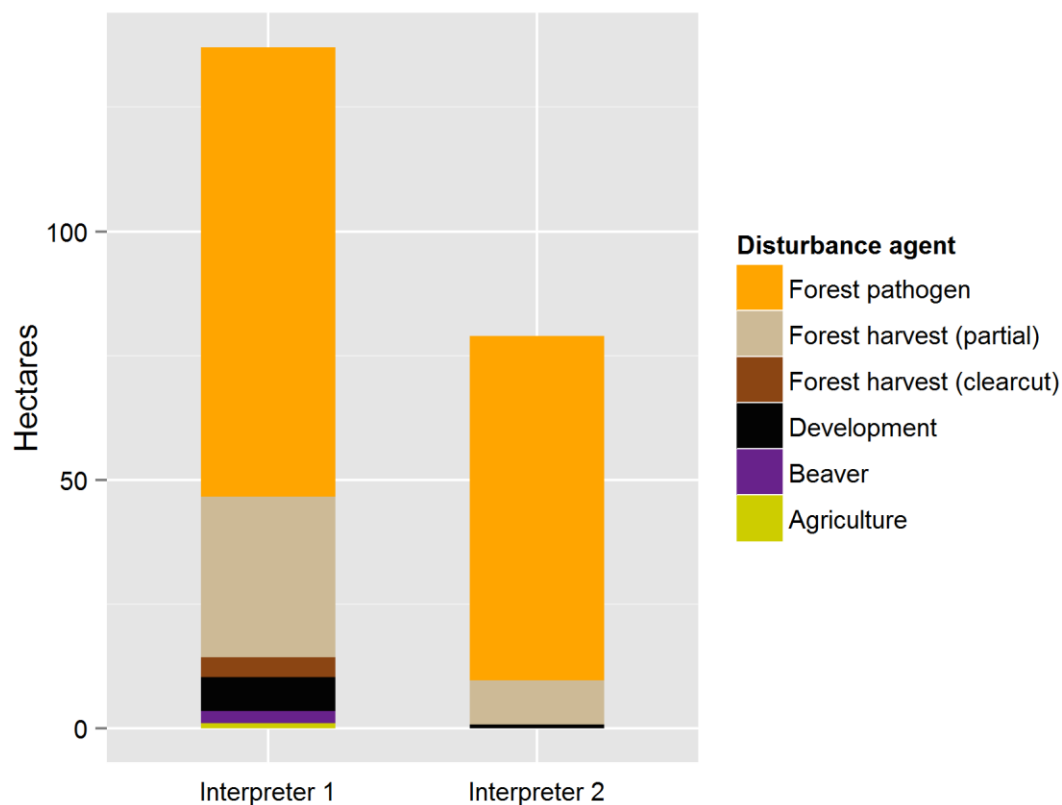


Figure D4. Same as figure D3, instead with hectares affected by each of confused polygons.

Disturbance Agent and Vegetation Class Error Matrices

The first table summarizes the results of disturbance agent classification from the two interpreters. Numbers on the diagonal (gray boxes) indicate agreement between the two interpreters. Numbers off the diagonal indicate disagreement about a particular disturbance’s causal agent. For example, interpreter 2 had three disturbances by development that interpreter 1 thought were partial forest harvest, forest pathogen, and none. The agent ‘none’, can occur when one interpreter indicates multiple disturbance agents for a polygon and the other interpreter indicates less agents.

Overall, there was good agreement among interpreters with agreement generally above 70% (Table D4). The lowest agreement was in the partial harvest category (62%) and was the result of confusion with forest pathogen and forest harvest (clearcut).

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	1	0	0	0	0	0	0	0	0	1	1
	Blowdown	0	0	0	0	0	0	0	0	0	0	0	0
	Development	0	0	0	17	0	0	3	0	2	2	24	0.71
	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	23	2	0	2	27	0.85
	Harvest (partial)	0	0	0	1	0	0	0	13	5	2	21	0.62
	Forest pathogen	0	0	0	1	0	0	0	3	122	2	128	0.95
	None	0	0	0	1	0	0	1	3	1	357	363	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.

		Interpreter 2									Total interpreted	Proportion unambiguous
Interpreter 1	Starting vegetation class	Forest (closed)	Forest (semi-closed)	Forest (open)	Herbaceous	Water	Impervious surface	Pervious surface	Impervious-vegetated	None		
	Forest (closed)	182	0	0	0	0	0	0	0	0	182	1
	Forest (semi-closed)	1	2	0	0	0	0	0	0	0	3	0.67
	Forest (open)	0	0	0	0	0	0	0	0	0	0	0
	Herbaceous	1	0	0	1	0	0	0	1	0	3	0.33
	Water	0	0	0	0	0	0	0	0	0	0	0
	Impervious surface	0	0	0	0	0	0	0	0	0	0	0
	Pervious surface	0	0	0	0	0	0	0	0	0	0	0
	Impervious-vegetated	0	0	0	0	0	0	0	1	0	1	1
	None	1	1	1	0	0	0	0	0	372	375	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.

		Interpreter 2								Total interpreted	Proportion unambiguous	
		Forest (closed)	Forest (semi-closed)	Forest (open)	Herbaceous	Water	Impervious surface	Pervious surface	Impervious-vegetated			None
Interpreter 1	Ending vegetation class											
	Forest (closed)	138	1	1	0	0	0	1	1	0	142	0.97
	Forest (semi-closed)	1	2	0	0	0	0	0	0	0	3	0.67
	Forest (open)	0	2	23	1	0	0	0	0	0	26	0.88
	Herbaceous	0	0	3	1	0	0	0	0	0	4	0.25
	Water	0	0	0	0	0	0	0	0	0	0	
	Impervious surface	0	0	0	0	0	0	0	1	0	1	0
	Pervious surface	0	0	0	0	0	0	0	0	0	0	
	Impervious-vegetated	2	0	1	0	0	0	0	13	0	16	0.81
None	0	0	2	1	0	0	0	1	153	157	0.97	

Appendix E: 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).

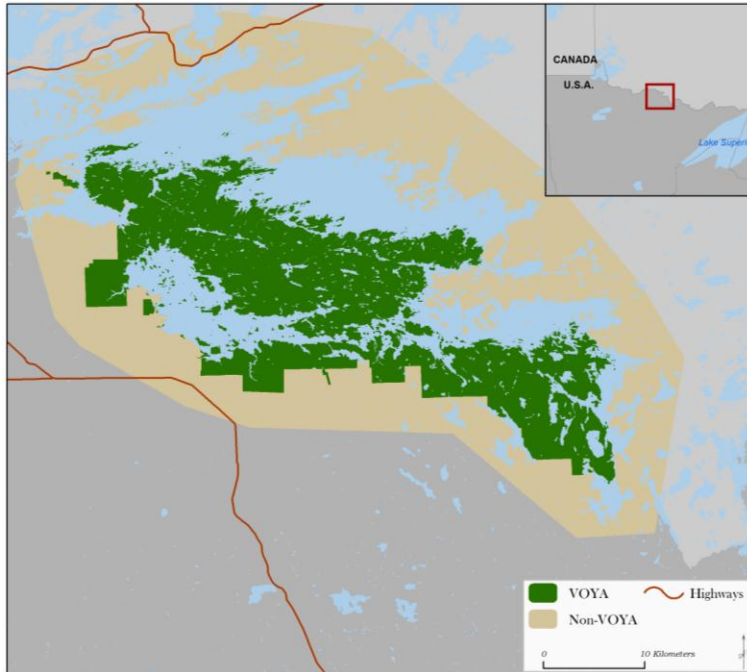


Figure E1. Analysis area for Voyageurs National Park (VOYA).

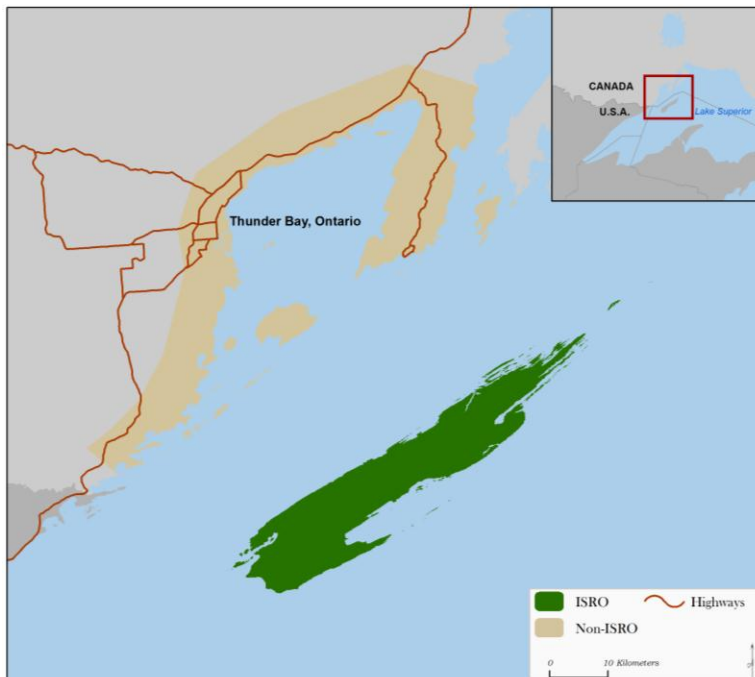


Figure E2. Analysis area for Isle Royale National Park (ISRO).

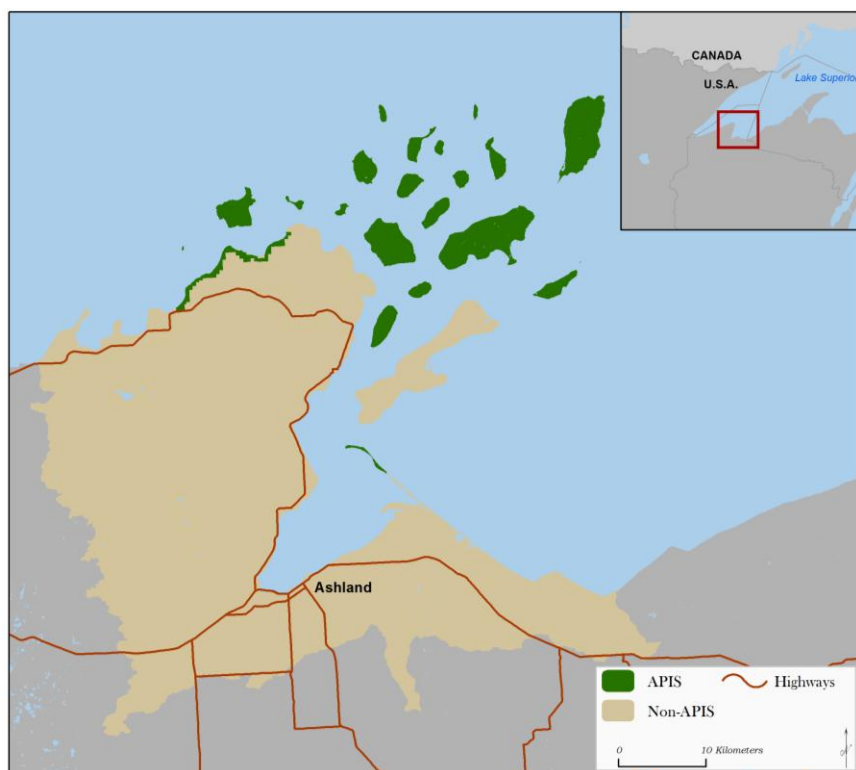


Figure E3. Analysis area for Apostle Islands National Lakeshore (APIS).

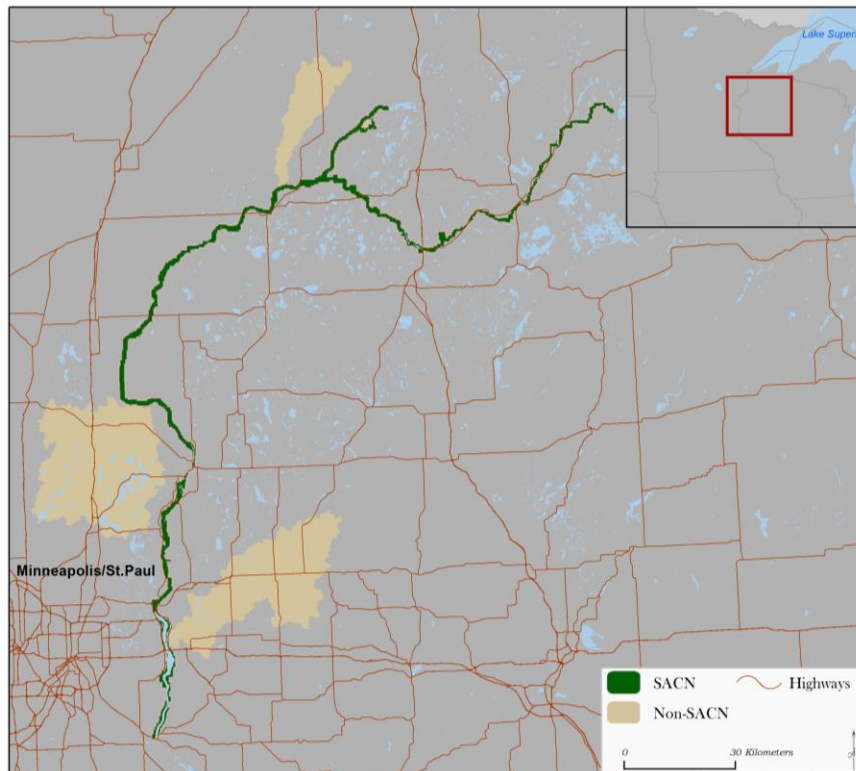


Figure E4. Analysis area for St. Croix National Scenic Riverway (SACN).

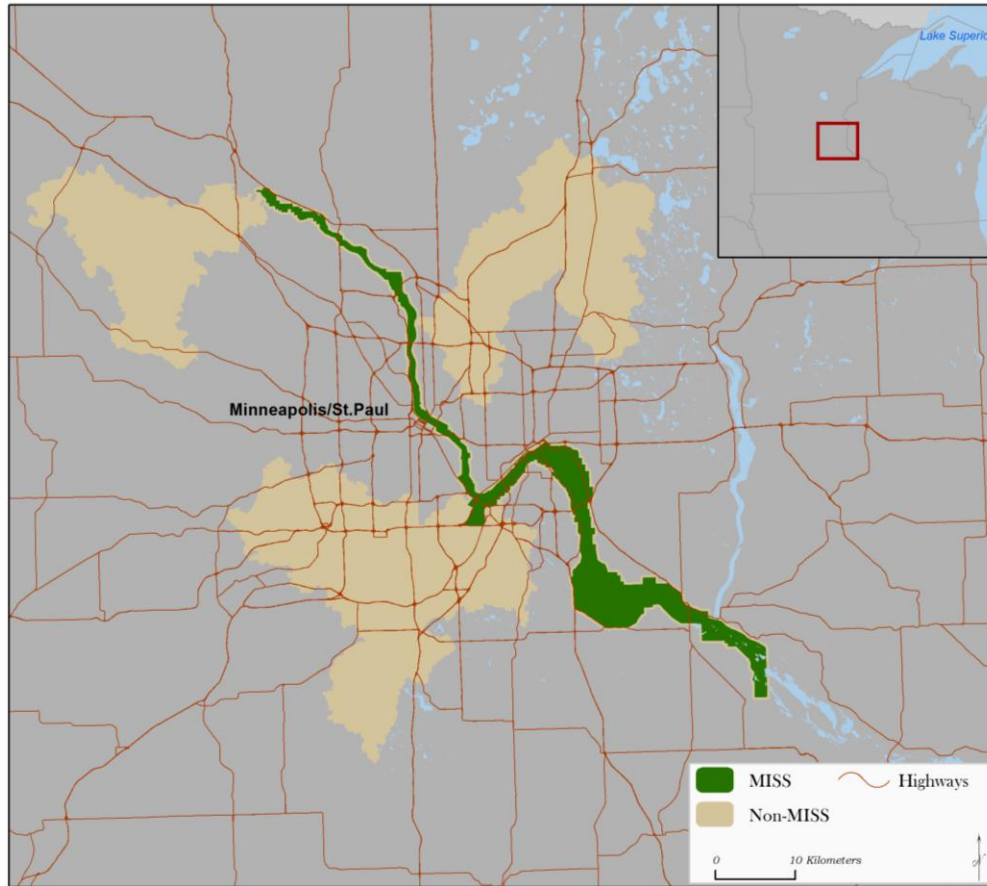


Figure E5. Analysis area for Mississippi National River and Recreation Area (MISS).

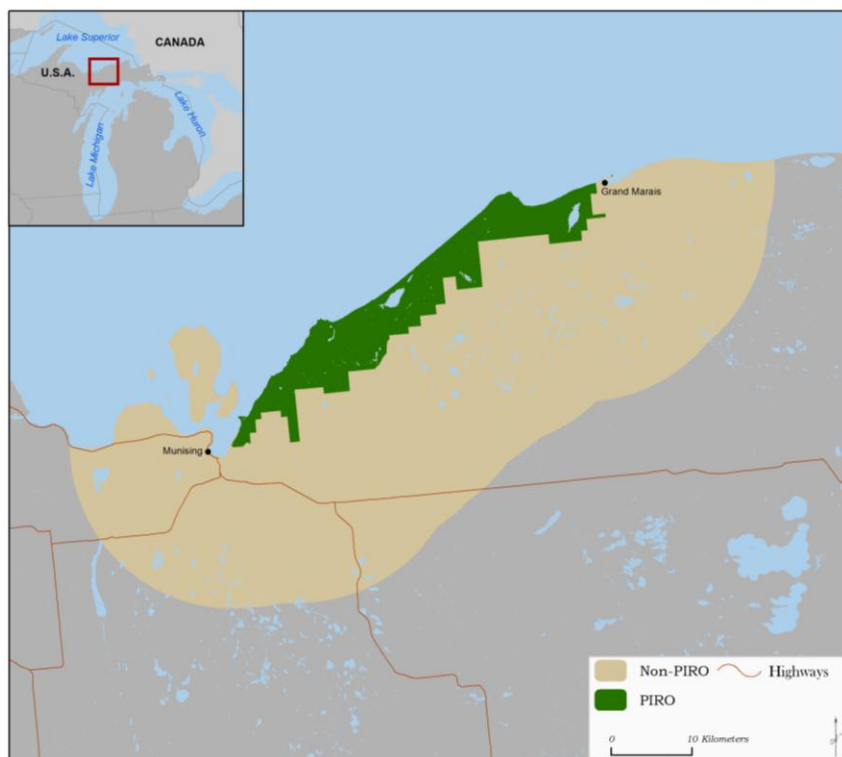


Figure E6. Analysis area for Pictured Rocks National Lakeshore (PIRO).

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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