



Landsat-based Monitoring of Landscape Dynamics at Mississippi National River and Recreation Area

2005-2010

Natural Resource Technical Report NPS/GLKN/NRTR—2013/745



ON THE COVER

View of the Mississippi River in St. Paul, Minnesota.

Photograph by: NPS photo/Ted Gostomski.

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Abstract

The Great Lakes Inventory and Monitoring Network (GLKN) implemented the long-term disturbance monitoring protocol at Mississippi National River and Recreation Area (MISS). Disturbances, or distinct changes in vegetation cover, are an important part of how this riverine system functions. Monitoring disturbances in and around parks provides information to mitigate negative impacts of internal and external threats to park resources. For this analysis, disturbances in and around MISS were delineated for six years (2005-2010), using a combination of Landsat satellite imagery and high resolution aerial photos. We employed a set of computer algorithms, collectively known as LandTrendr, in conjunction with a dense time series of Landsat imagery (one set for each year) to track vegetation changes in and around the park. LandTrendr was used to identify apparent disturbances, after which high resolution imagery (airphotos) was used to substantiate evidence of a disturbance, and hence, validate whether the disturbance occurred. For each validated disturbance, we identified the agent of change (fire, forest harvest, development, agricultural use, and blowdowns) in addition to the year of occurrence, and pre- and post-disturbance vegetation classes. Summary analyses showed that disturbances inside and outside the park were dominated by development, with small amounts of agricultural use and forest harvests occurring outside the park.

Acknowledgments

We would like to acknowledge staff at the Mississippi National River and Recreation Area for helping design the land cover monitoring program's scope and extent for the analysis.

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

We would also like to thank those who reviewed and provided useful comments on an earlier draft of 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
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.

List of Terms and Acronyms (continued)

NGA	National Geospatial Agency
NLCD	National Land Cover Data: created by USGS to produce a consistent land cover map for the U.S using Landsat imagery. Currently there are three NLCD datasets; 1990, 2001 (versions 1 & 2), and 2006. http://www.mrlc.gov/
NVCS	National Vegetation Classification System: currently the National Standard for classifying the vegetation of the United States, maintained by NatureServe. http://biology.usgs.gov/npsveg/nvcs.html
Panchromatic	Incorporates all wavelengths of visible light.
RGB	Red, green, and blue: sometimes referred to as ‘true color’, it is the portion of the electromagnetic spectrum the film, or sensor, is quantifying.
SACN	Saint Croix National Scenic Riverway
SLC	Scan Line Corrector: device on-board the Landsat 7 (ETM+) satellite which compensates for the forward motion of the spacecraft so that the resulting scans are aligned parallel to each other.
SLC-off	Scan Line Corrector – off: this device failed in 2003, creating data gaps in each Landsat 7 (ETM+) image acquired after 31 May 2003.
TM	Thematic Mapper: one of the Earth observing sensors introduced into the Landsat program on March 1, 1984. http://landsat.usgs.gov/about_landsat5.php
USGS	United States Geological Survey
VOYA	Voyageurs National Park
WROC	Wisconsin Regional Orthophotography Consortium

Introduction

Disturbance Monitoring Overview

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

Previous Landscape Dynamics Studies in the 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) (Vogelmann et al. 1998). The study found that 2.5% of the watershed experienced change, with forest and agriculture categories experiencing the largest declines in area (approximately 2.3%). In addition, 49.3% of the changes were transitions from undeveloped to developed land with the greatest percentage of the overall watershed change occurring within 0-10 km of the shoreline. More recently, Stueve et al. (2011a) investigated the amount of disturbance in the Lake Superior and Michigan basins from 1985-2008 using vegetation change tracker (VCT). They found that from 1985-1999, 4.0% (0.26/yr) of the land was disturbed in the lower Lake Superior basin and from 2000-2008, 2.9% (0.32/yr) of the land was disturbed. 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. 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 being close behind at 1.66%. The lowest rates of conversion were found in federally unmanaged lands (0.17%) with county unmanaged the next least disturbed land type (0.22%).

Brown (2003) investigated the relationship and trends in land use and forest cover on private parcels in the Upper Midwest (the northern forested regions of Minnesota, Wisconsin, and

Michigan) from 1970 to 1990 and found that land development increased in all 106 counties. In addition, the percentage of land in agriculture declined between the 1980s and 1990s, but held steady in some counties when observed over the entire time period (1970s to 1990s). This could reflect the conversion of previously-cleared forest lands for agriculture back to a forested cover type. 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, hurricanes, extreme wind events).

More localized to the Mississippi River corridor, Yuan et al. (2005) used multi-seasonal Landsat imagery to map land cover through time (1986, 1991, 1998, and 2002) in the Twin Cities Metro area. They found that developed land increased from 23.7% in 1986 to 32.8% in 2002, or 0.57% annually. More rural land classes (agriculture, forest, and wetland) dropped from 69.6% to 60.5%, an annual rate of 0.59%. De Jager et al. (2011) used historical (1890 and 1975) and present (1989 and 2000) land cover data to model future changes in the upper Mississippi River floodplain. They found that land cover in 1890 was significantly different than all more recent time periods and that from 1975 to 2000, the upper Mississippi River floodplain remained quite stable. The major shifts in land cover change were increases in open water, marsh, and development and declines in forest and grassland.

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. 2010a, 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)

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 watershed since the late 1800s, seeing 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 parts of the Mississippi River basin will help inform resource managers at the park about pressures affecting the areas under their jurisdiction. Given the location of the park and because it is a corridor park, it is especially vulnerable to the effects of adjacent landowners (Hansen and Rotella 2002, Wiersma et al. 2004, DeFries et al. 2007).

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 Mississippi National River and Recreation Area 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 NPS Inventory and Monitoring program was developed: to provide consistent, long-term monitoring of ecologically significant parameters affecting national park lands.

GLKN Approach to Disturbance Monitoring at MISS

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 1985 to present, the longest record of satellite imagery available today.

To detect and delineate landscape changes we used a method called LandTrendr (Landsat-based detection trends in disturbance and recovery), which was developed by a group of research scientists at Oregon State University (Kennedy et al. 2010b). To briefly explain, LandTrendr is the process of capturing interesting features (disturbances) while removing the background, or noise. Sources of this noise include variation in atmospheric condition, changes in sun angle

illumination, and small phenological changes. Details of the LandTrendr process can be found in Kennedy et al. (2010b). Lastly, this method also proved to be the most cost-efficient program for the Network in terms of cost per hectare. The cost of implementing the protocol at MISS was only 5¢ per hectare. We would like to make it clear that we do not track the changes in agricultural uses, e.g., the conversion of pasture to row crops, or the rotation among row crops. This is not to say we do not think they are an important factor in determining water quality of the river, it is just not something that we can reliably quantify with this methodology. To efficiently and effectively track these very specific changes, an entirely separate analysis would have to be undertaken.

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 2005 through 2010. 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 2011, 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 300 meter buffer, in addition to three subwatersheds of the Mississippi River, totaling ca. 175,000 hectares (Figure 1). The size of the analysis area was limited by the amount of time the Network could spend validating disturbances. It should be noted the ability to monitor large areas of land outside the park is due to the fact that Landsat imagery is used as the foundation of the monitoring process.

Study Area

The study was conducted using three Landsat scenes (27/29, 27/28, and 26/29), which included the Mississippi National River and Recreation Area (MISS) and three adjacent subwatersheds (Figure 1). The administrative boundary of the park comprises an area of 21,781 ha (16,107 and 5,674 ha of land and water, respectively). The administrative boundary includes lands owned by State and local governments and lands in private ownership. Recently (2011) the park acquired a piece of property (11.9 ha) from the Bureau of Mines. However this land was not denoted as park-owned land in this analysis. In addition to the park administrative boundary, we analyzed a 300 m buffer around the park, as well as three subwatersheds (Figure 2), totaling ca. 175,000 ha of land (Table 2). The three subwatersheds were chosen to represent the variation of land use and vegetation types present in the north to south extent of the analysis area and represent 84% of the total analysis area (Table 3). The Minnesota River subwatershed delineated and included in this analysis is only a portion of the entire watershed, as delineated by the National Hydrography Dataset. In fact, this watershed is quite large (4.4 million ha), and we monitor 65,628 ha or 1.5% of it. The remaining two subwatersheds included in this analysis, Rice Creek and Crow River, are included in their entirety. To simplify language in the report we refer to the partial Minnesota River analysis area as the Minnesota River subwatershed.

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

Analysis area	Size (ha)	Percent of analysis area
MISS	21,784	12
Non-MISS	153,773	88
Total	175,557	100

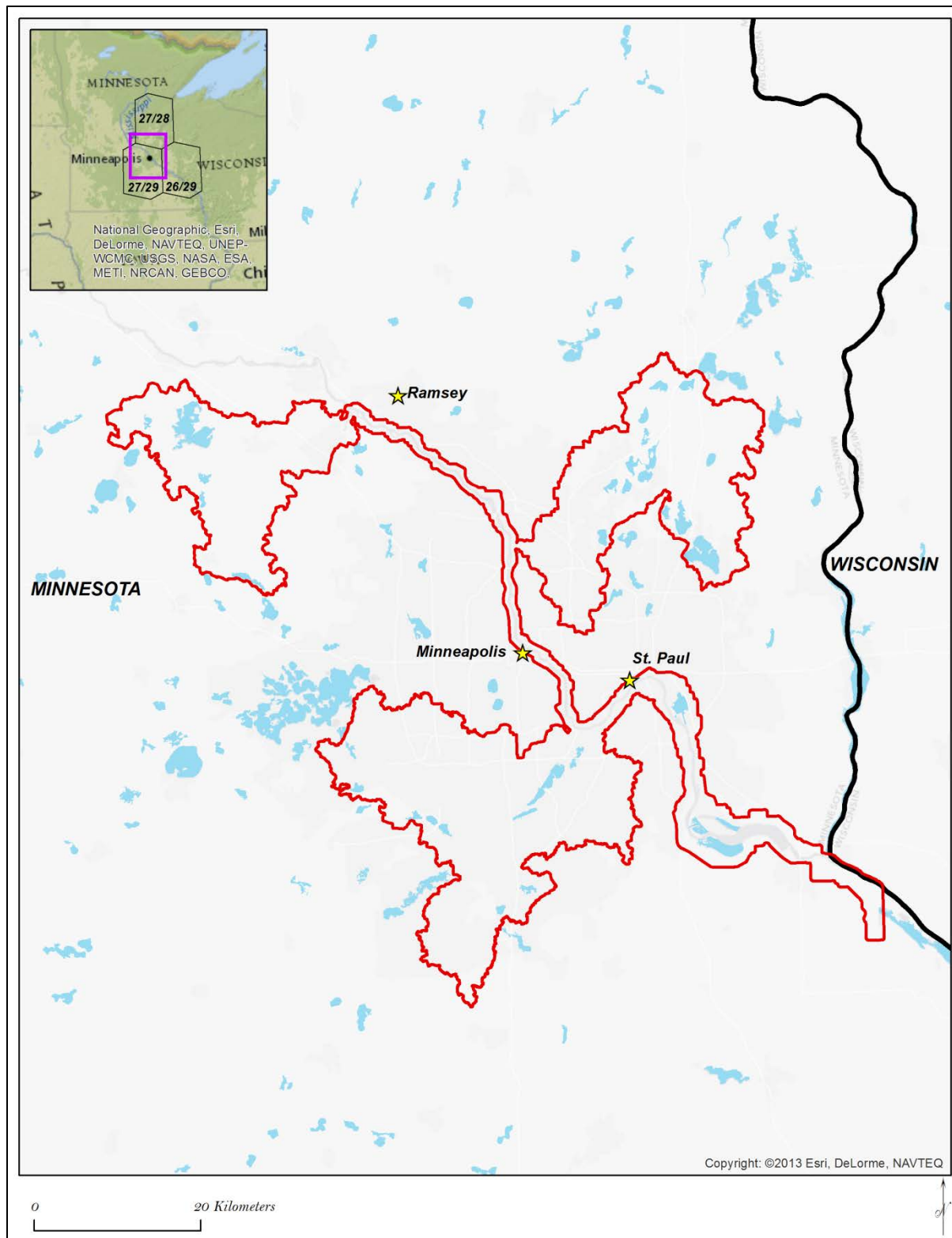


Figure 1. Study area for long-term monitoring of landscape-scale disturbances in and around Mississippi National River and Recreation Area, Minnesota. The inset shows the extent (purple line) of the larger map and the extent (black lines) of the three Landsat scenes (27/28, 2729, and 26/29) processed and analyzed for this report. The larger map shows the extent of the analysis area (red line).

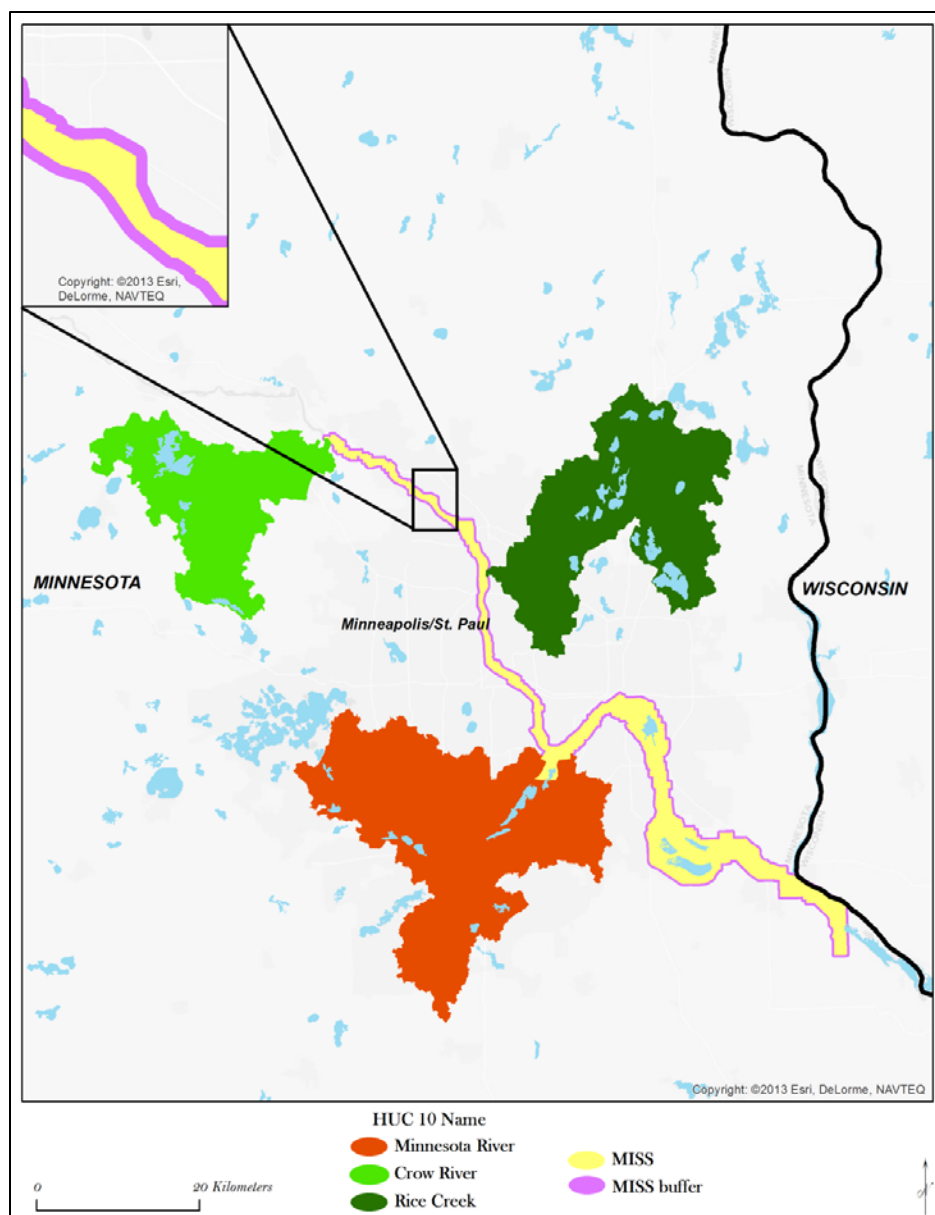


Figure 2. Location of the three subwatersheds (Minnesota River, Crow River, and Rice Creek) within the analysis area. The inset shows an example of the park administrative boundary (yellow) and the 300 m buffer (purple) adjacent to the park.

Table 3. Land area of each subwatershed and the percent contribution of each to the overall analysis area.

Watershed	Size (ha)	Percent of analysis area
Crow River	33,838	19
Rice Creek	47,664	27
Minnesota River	65,593	37
Total	147,095	83

Vegetation

Overall, developed land comprises 41% of the analysis area, with agriculture and forests contributing 22% and 14%, respectively (Figure 3, Table C1 in Appendix C).

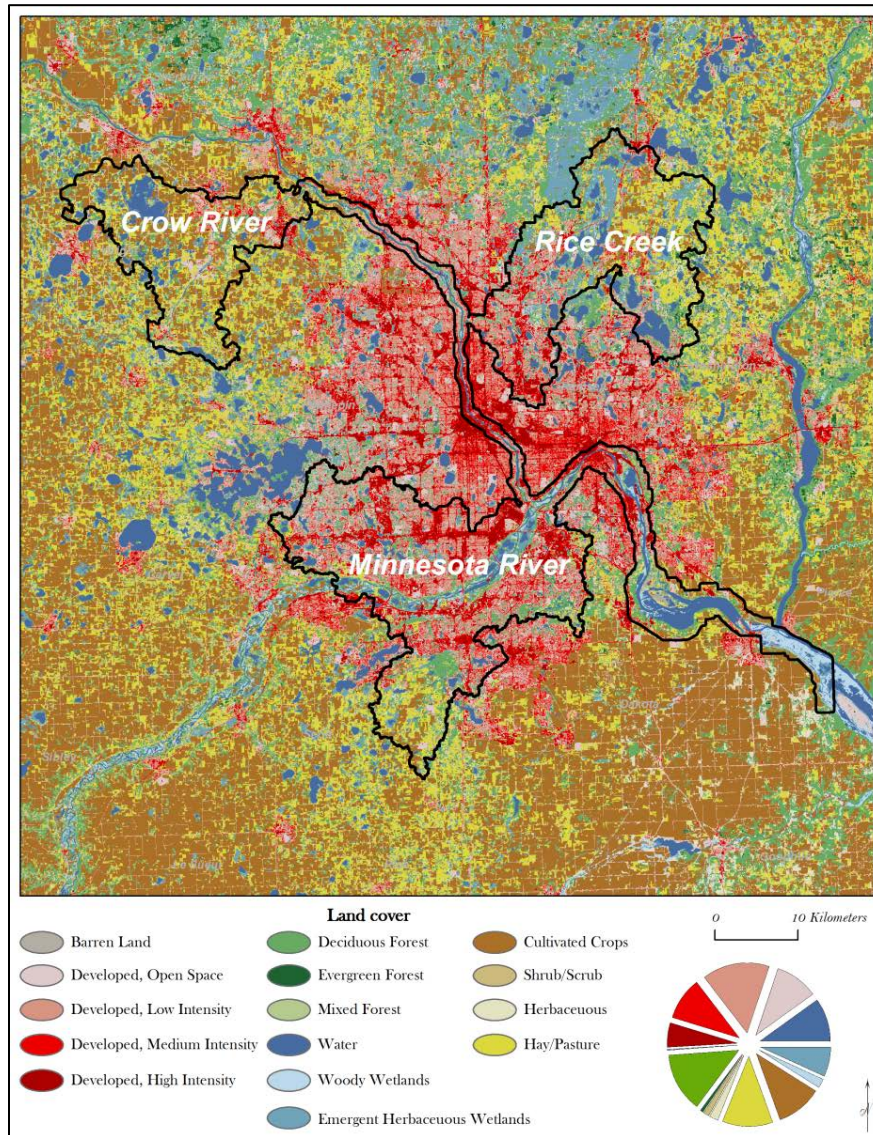


Figure 3. Vegetation classes within the analysis area (black line), and a pie chart showing the relative abundance of each class within the analysis area. Data from 2006 NLCD.

More specific to the individual watersheds, the Crow River is dominated by agricultural land use, with equal amounts of developed and forested land (Figures 4 and 5). Rice Creek has lower amounts of agricultural land, with higher amounts (35%) of developed land and herbaceous wetlands (ca. 15%). The Minnesota River had the highest proportion of developed area among the three subwatersheds, with nearly 60% of the subwatershed contained in the four levels of

developed classes (Figure 4). Lastly, the Mississippi River corridor, which contains the park administrative boundary and a 300 m buffer, is also dominated by developed classes, with large amounts of water and woody wetlands in the southern portion of the corridor (Figure 5).

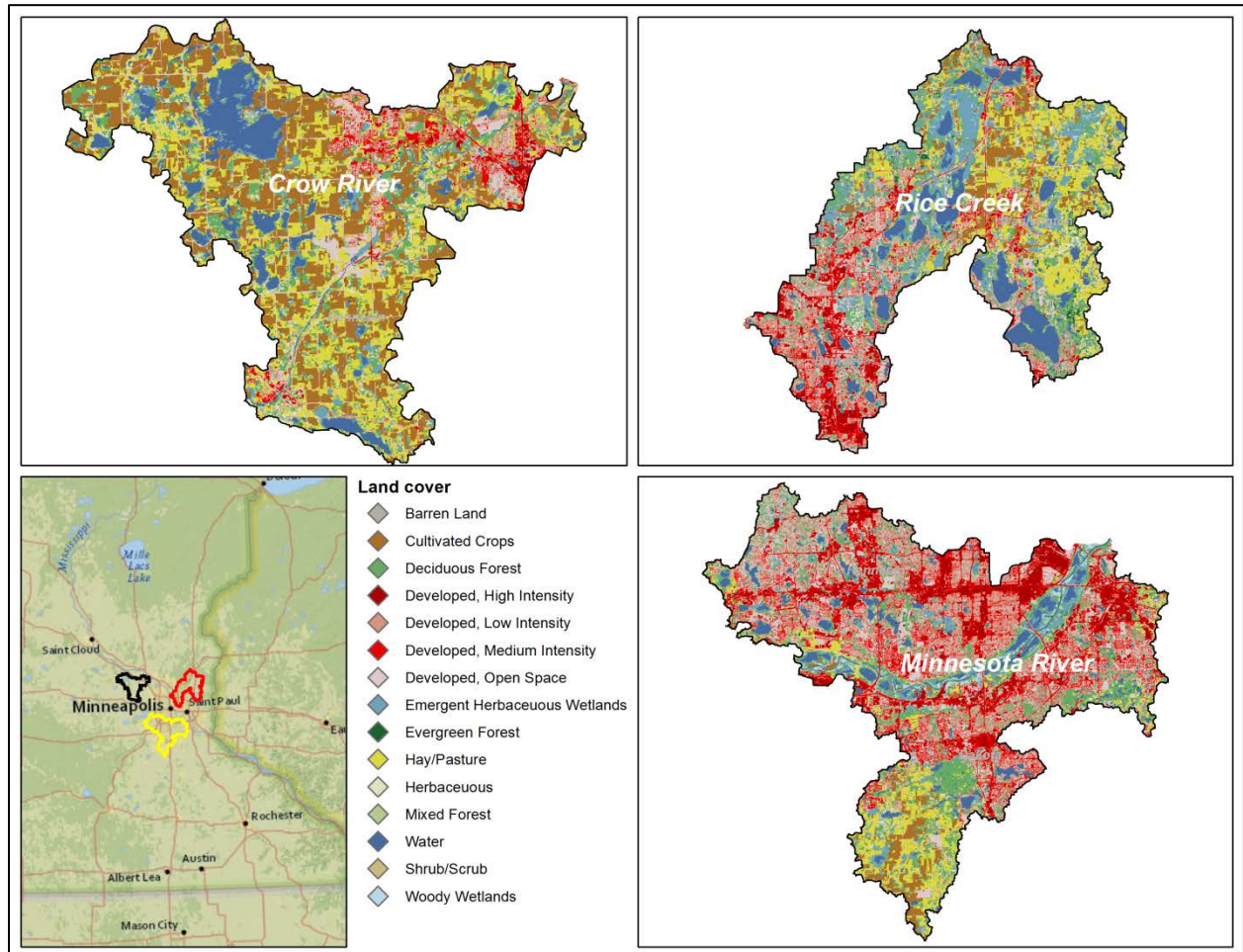


Figure 4. Vegetation within each of the three subwatersheds in the analysis area. Data from 2006 NLCD.

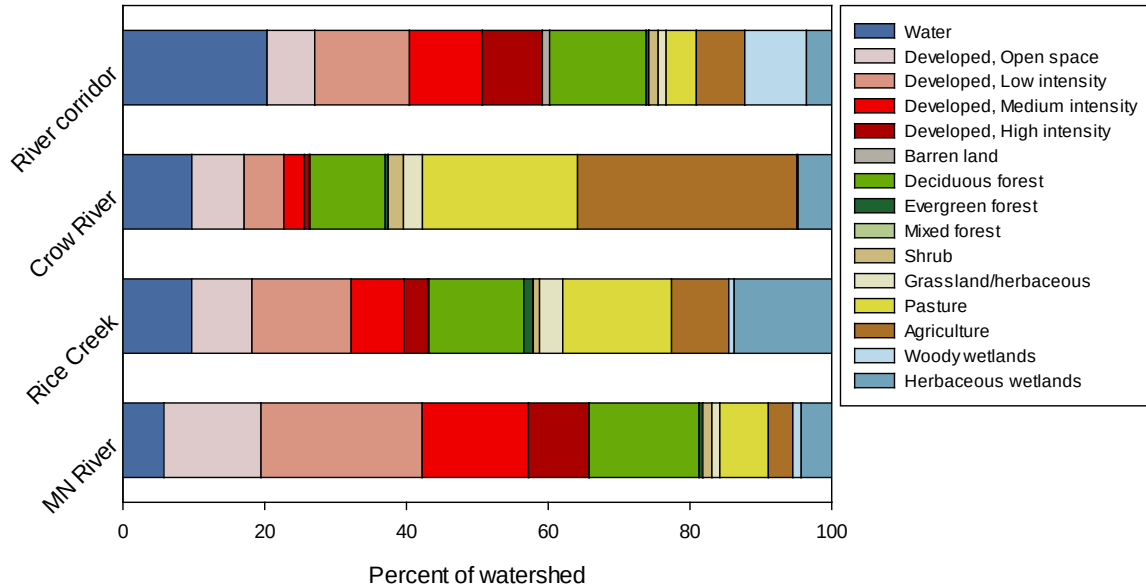


Figure 5. Relative abundance of vegetation classes within each of the three subwatersheds and the Mississippi River corridor (MISS boundary plus 300 m buffer) included in the analysis.

Ownership

We summarized disturbances by ownership description and owner name as denoted by the MN Gap Analysis Program (GAP) ownership layers. We realize the ownership layer contains mistakes, but for this landscape study we accept the minor errors. An example of such an error is the fact that MISS does own nine islands and one parcel of land, totaling approximately 26 hectares, depending on river water levels. Ownership description is grouped into eight categories: county, federal, other public, private, private conservancy, private industrial, private non-industrial, and state (Table 4). Owner name is a more detailed description of the ownership and contains values such as specific cities/towns, counties, and state and federal agencies (Table 4).

Table 4. Owner names included in each owner description, as denoted by the source data.

Owner description	Owner name
County	Anoka, Dakota, Hennepin, Ramsey, Scott, Washington, Wright
Federal	Army Corps of Engineers, Bureau of Land Management, US Fish and Wildlife Service
Other public	City of Anoka, City of Blaine, City of Forest Lake, City of Minneapolis, City of St. Paul, ISD No 12, Minnesota Zoological Garden
Private	Private

Table 4. Owner names included in each owner description, as denoted by the source data (continued).

Private Conservancy	The Nature Conservancy
Private Industrial	Metro Airports Com, Minnesota Mining and Manufacturing Company, Northwestern Refining Company
Private Non-industrial	First Trust Co of St. Paul, Kelly Land and Cattle Company, Prelice Corporation, Stanley Knoll Farms
State	Minnesota DNR, State of Minnesota

The analysis area is largely held in private ownership, accounting for nearly 90% of the ownership (Figure 6). There was only one other ownership which accounted for >2% of the land inside the analysis area: the Minnesota DNR. These ownership patterns are also reflected in the eight grouped categories, where private ownership outpaced all other grouped ownership types (Figure 7). County, state, and federal ownership were the remaining significant owner types.



Figure 6. Percent of land within the analysis, summarized by owner name. Ownership representing <0.01% of the analysis area is not displayed on the bar graph. Data from the MN GAP analysis datasets.

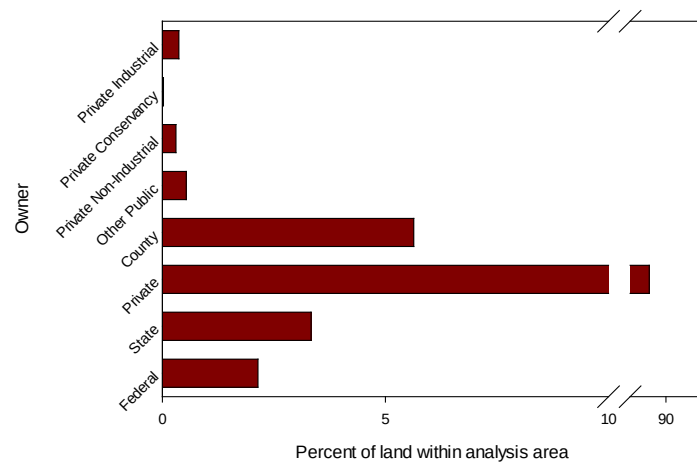


Figure 7. Percent of land within the analysis area summarized by owner description. Data from the MN GAP analysis datasets.

Methods

Image Data and Processing

Due to the location of Landsat scenes in reference to MISS, three scenes (27/28, 26/29, and 27/29) 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 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 of the entire study area could be used in the analysis. To aid in the production of the cloud-free composite, we also acquired a number of scan line corrector-off (SLC-off) images. These images include strips where there are no data due to a Landsat hardware malfunction, but nonetheless can be used to fill in critical gaps in the time series (http://landsat.usgs.gov/products_slc_offbackground.php). In total, 152 images were downloaded and processed for analysis. Each collection of images by scene will be referred to as a Landsat time-series (LTS).

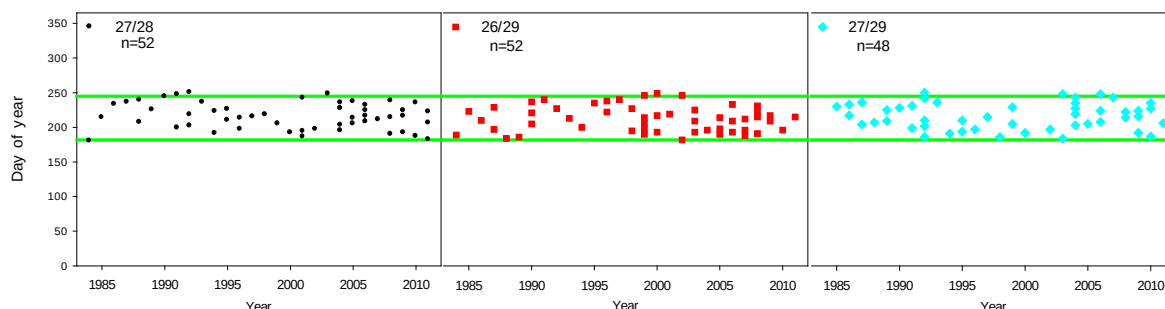


Figure 8. Day and year of Landsat images used for analysis of the three scenes, with green lines delineating the time period between 1 July and 31 August.

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

Next we applied the LandTrendr segmentation algorithms to every pixel in each scene's processing area. 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. For this analysis we used the normalized burn ratio (NBR), which contrasts the short-wave infrared with the near-infrared bands (Key and Benson 2006). The segmentation process then proceeds as follows. A diagram providing an example of how the segmentation algorithm processes an individual pixel is provided below (Figure 9).

First, image data from the LTS files were converted to NBR values and matched on a pixel-by-pixel basis with the cloud mask. If the pixel was pre-determined to be part of a cloud, this pixel was not used. When multiple images from a given year were available, the image closest to the median date of the LTS in that scene was preferred, but if the pixel was again masked (cloud, cloud-shadow, or missing data), the pixel value from the image next-closest to the median was used. This was repeated as necessary until an unmasked pixel was available or until no more images were available. The time-series of these source data was then sent to the segmentation algorithms, which are controlled by a number of parameters affecting the balance between over- and under-fitting (Table 6). The first phase of segmentation is to determine the vertex years that define the end points of segments, and the second phase is to determine the best straight-line trajectory fit through those vertices using a flexible mix of either point-to-point or regression lines. The values returned from the segmentation algorithm are the yearly source data (representing the best unmasked NBR value for that pixel in each year), the years at which vertex years were found, the fitted NBR values for those vertices, and the yearly fitted NBR data (the NBR value of each point in the segments describing the trajectory). These data were written out as separate files to be used by subsequent mapping algorithms.

Table 5. Parameters used in the LandTrendr process.

Process	Parameter	Value
Segmentation	Spectral index	Normalized burn ratio
	Maximum number of trajectory segments	6
	Maximum p-value for fitting	0.05
	Recovery threshold	0.25
	Despiking threshold	0.9
	Best model proportion	0.75
Filtering	Percent loss threshold at 1 yr	15
	Percent loss threshold at 20 yr	10
	Pre-disturbance cover threshold	40
	Percent gain threshold for growth	5
Mapping	Minimum mapping unit	11 pixels (ca. 1 ha)

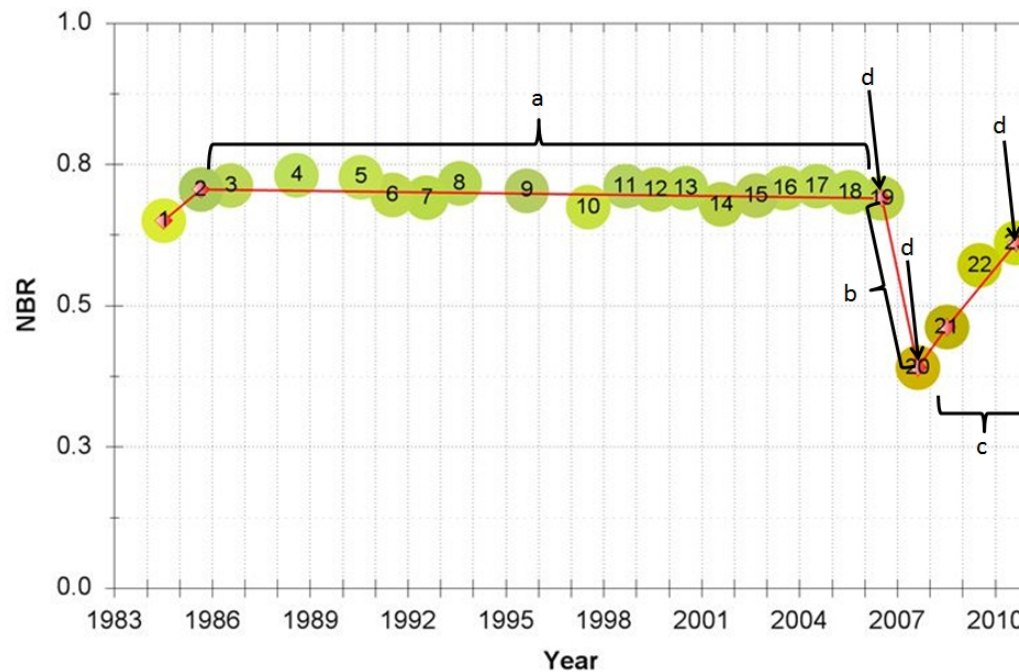


Figure 9. Diagram of how the LandTrendr segmentation algorithm processes a single pixel. The x-axis is the year of image acquisition and the y-axis is defined by the NBR value. Generally, NBR values range from low to high dependent on the amount of vegetation present. This graph shows a single pixel's 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 area were derived from the vertex files in several steps. For each pixel, disturbance segments were defined as those showing a decline in NBR value. A simple regression model was used to convert the NBR values to estimates of percent vegetative cover developed at 163 plots (Table 7 and Figure 10). The magnitude of disturbance for a segment was defined as the difference between the calculated vegetation cover values of the starting and ending vertices. This magnitude was divided by the pre-disturbance cover value to create a relative magnitude value truncated to ensure a range of 0 to 100%. Segments were accepted for further processing only if their relative magnitude value was greater than a threshold parameter (see Table 6 for parameters). 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 yrs in duration. The remaining pixels are then grouped into patches based on the year of change onset. Only pixels with the same year of onset can belong to the same patch. Patches must be nine pixels (0.8 ha) or larger to be included in the monitoring dataset.

Table 6. Percent cover model parameters and summary statistics used in LandTrendr.

Model parameter	Value
NBR	141.066
y intercept	-7.132
Degrees of freedom	162
Adjusted R-squared	0.79
Residual standard error	11.51

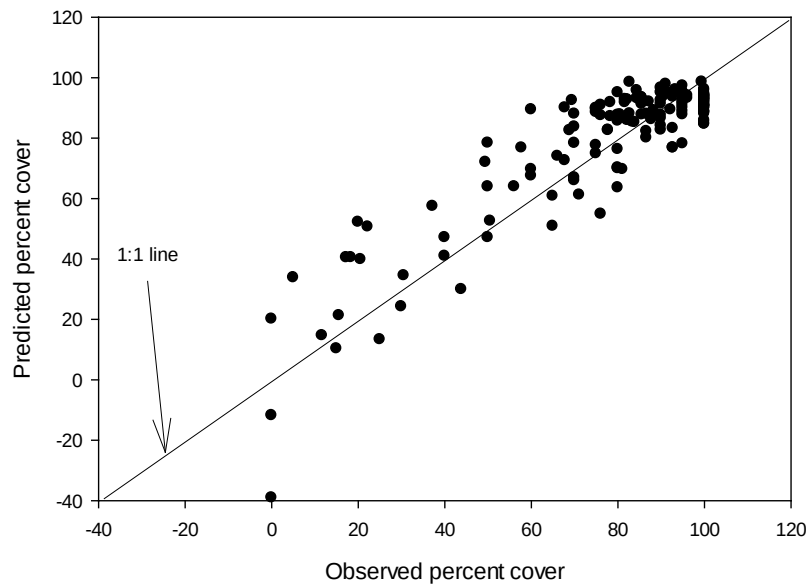


Figure 10. Predicted versus observed percent cover results from model predictions.

Although this process creates one composite image per year based upon unmasked pixels, or pixels which do not have cloud or cloud shadow present, there are years where there is not an unmasked pixel to use in the time series. We summarized the percent of analysis area which had an unmasked pixel present between years 2004 and 2011 (Figure 11). Although we did not summarize disturbances for years 2004 and 2011, they were included in the summary because these two years are critical in the time series analysis. Hence, if these two years had very few unmasked pixels, it may influence detection of disturbances. Additionally, if there were any years within the analysis window (2005-2010) when large amounts of pixels were masked, it could result in misleading disturbance numbers for that particular year. The year with the lowest percent of unmasked pixels was 2005, when 70% of the analysis areas had unmasked pixels. The remaining years had excellent coverage, with no other year having less than 95% of analysis area covered by unmasked pixels.

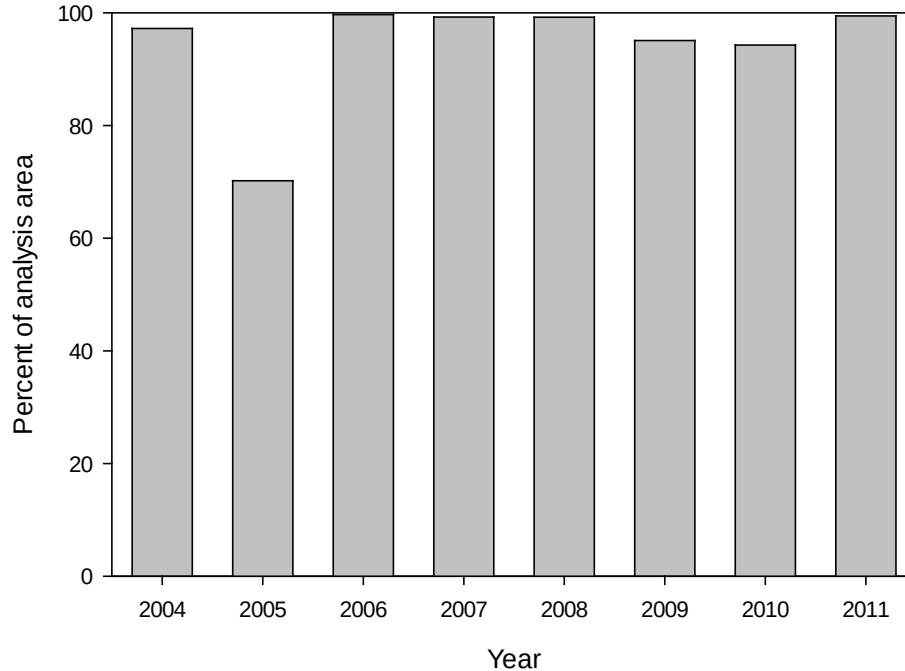


Figure 11. Percent of analysis area with unmasked (useable) pixels each year.

Validation of Disturbances

Validation of possible disturbances followed details given in Kirschbaum and Gafvert (2010a), and is briefly summarized here. After disturbance polygons were created, the next step was to validate whether a change actually occurred in the polygon. In addition to validating whether changes occurred, additional information such as the pre- and post-disturbance vegetation classes (Table 8) and agent of change (Table 9) were added during the validation process. Using high resolution imagery (Table 10), we were able to determine whether changes had indeed occurred, and by using contextual information we were able to determine the disturbance agent. In addition to using high resolution imagery, we also used an application called TimeSync (Cohen et al. 2010). This program allows the user to view composite image chips of the entire stack of Landsat imagery for pre-determined locations as well as the associated spectral trajectory of the pixel through time.

By viewing the high resolution aerial photos of the disturbance, its corresponding location on the series of Landsat image chips, and its spectral trajectory, we could make a well-informed decision regarding the validity and nature of change. To limit the potential for bias, two interpreters validated all disturbances. If a disturbance occurred within a polygon, additional attributes (fields) were populated within the feature class. These included most likely pre- and post-disturbance class as classified by the 2001 or 2006 National Land Cover Database (Homer et al. 2004), disturbance agent, post-timber harvest remaining percent cover, and whether the polygon was a candidate for field visit (Table 10). If the disturbance occurred before 2006, the 2001 NLCD (version 2) was used for the starting class.

Table 7. Vegetation classes used in the analysis, and their respective characteristics.

Vegetation class	Characteristics
Evergreen forest	>50% tree cover, >60% evergreen, >3m height
Deciduous forest	>50% tree cover, >60% evergreen, >3m height
Mixed forest	>50% tree cover, <60% evergreen, <60% deciduous, >3m height
Evergreen woodland	30-50% tree cover, >60% evergreen, >3m height
Deciduous woodland	30-50% tree cover, >60% deciduous, >3m height
Mixed woodland	30-50% tree cover, <60% evergreen, <60% deciduous, >3m height
Shrub	<30% tree cover, 1-3m 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 8. 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).
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 delineated.
Harvest	Forest harvests, including clearcuts and thinnings, new logging roads, and post-harvest prescriptions such as herbicide application or scarification.
Forest pathogen	Disturbances (mortality) in the overstory due to insects (e.g., forest tent caterpillar, spruce budworm) or diseases (e.g., oak wilt).

Table 9. Aerial photos and high resolution satellite imagery used for validation. For explanation of acronyms used in this table, see list of acronyms on page xv and xvi.

Date	Resolution (meters)	Spectrum	Funding source	Type	Analysis area coverage
1992/1998	1	B&W	APFO-NAPP	Airphoto	Entire
Summer 2003	1	RGB	APFO-NAIP	Airphoto	Partial
Summer 2004	2	RGB	APFO-NAIP	Airphoto	Partial
Summer 2005	2	RGB	APFO-NAIP	Airphoto	Entire
Summer 2006	2	RGB	APFO-NAIP	Airphoto	Partial
Summer 2008	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2009	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2010	1	RGB	APFO-NAIP	Airphoto	Entire

Table 10. Attributes filled in during the validation process at each polygon.

Field	Definition
Location	MISS or Non-MISS
Start class	Starting vegetation class(es), as noted in the 2001 NLCD (version 2) or 2006 NLCD, depending on when the disturbance occurred. 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 4.
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 estimated the percent of tree cover remaining ($\pm 10\%$)
Land owner	The land owner data from the GAP analysis program is used for attribution.
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

Two interpreters validated disturbances for MISS. To investigate the possible effects of multiple interpreters, such as systematic bias, 10% of each user's polygons were randomly selected and evaluated by the other interpreter. The results of this process are presented in Appendix D.

Results

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

Percent of Land Disturbed

MISS

During the six-year study period, a total of 0.28% (61 ha) of the land inside the park administrative boundary was disturbed. Disturbances inside the park steadily increased from 2005 to 2007, and then remained at a lower level for the remainder of the analysis period (Figure 12).

Non-MISS

Collectively, 0.58% (883 ha) of the land outside the park was disturbed during the six-year period (Figure 12 and Table C3 in Appendix C). The amount of land disturbed each year was higher from 2005 to 2007 (255 ha/yr), after which the area disturbed remained steady at approximately 40 ha/yr.

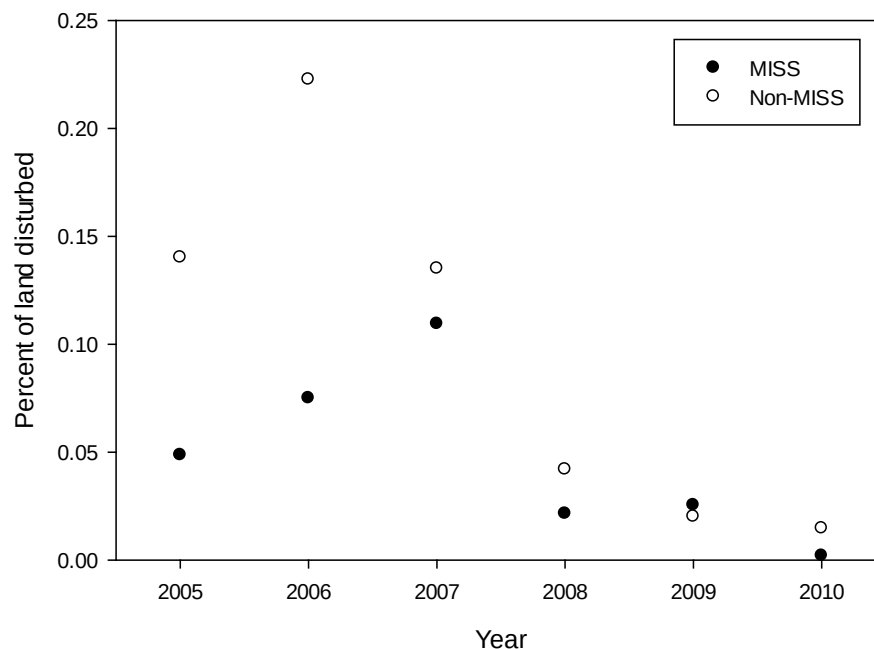


Figure 12. Percent of land disturbed within each analysis area, by year.

Disturbance Agents

MISS

Only one disturbance agent (development) was detected during the six-year analysis period (Figure 13). Disturbances due to development activities were detected in each year of the

analysis period, with very little land disturbed in 2010. The administrative boundary of the park is dominated by private ownership (72%), with approximately 26 ha owned by the park.

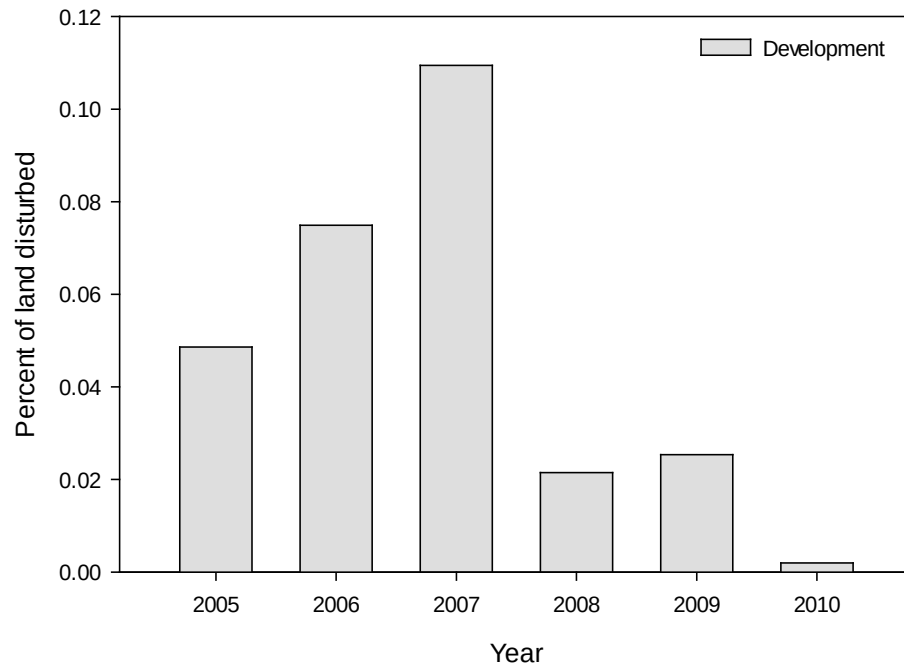


Figure 13. Percent of land disturbed inside the MISS administrative boundary, by causal agent and year.

Non-MISS

On lands outside the park administrative boundary, development was again the largest contributor to disturbances in each of the analysis years (Figure 14). Development peaked in 2006, when 0.21% (330 ha) of the land outside the park was disturbed (Table C14 in Appendix C). After 2006, land disturbed due to development activities steadily declined to a low of 22 ha in 2010. There were also small amounts of disturbance due to agriculture and forest harvest in each of the first three years that were absent in the last three years (Table C4 in Appendix C).

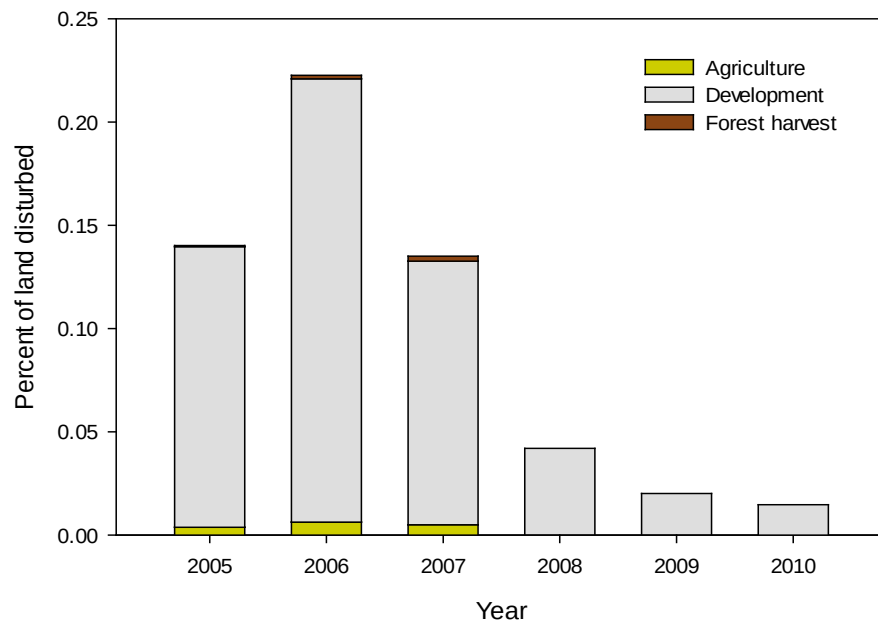


Figure 14. Percent of land disturbed outside MISS during the analysis period, by causal agent and year.

Land Cover Dynamics

It is possible to identify 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 (2010a). To facilitate displaying data in this report, pre- and post-disturbance classes have been combined into generalized groupings (Table 11).

Table 11. Generalized pre- and post-disturbance vegetation classes used to describe disturbance polygons, with the composition of each generalized class.

Generalized class	Groups in this general class
Upland forest	Upland evergreen forest, upland deciduous forest, upland mixed forest
Upland woodland	Upland evergreen woodland, upland deciduous woodland, upland mixed woodland
Upland shrub/herb	Upland shrub, upland herbaceous
Lowland forest	Lowland evergreen forest, lowland deciduous forest, lowland mixed forest
Lowland shrub/herb	Lowland shrub, lowland herbaceous
Water	Water
Impervious surface	Impervious surface
Pervious surface	Pervious surface
Impervious/vegetated	Impervious/vegetated

MISS

Due to the prevalence of development within this analysis area, each year there were changes from a vegetated class to a non-vegetated class (impervious, pervious, and impervious/vegetated). In 2005, ca. 6.5 ha land was converted to impervious surface, with other significant amounts of pervious surface gained in 2006-2009 (Figure 15). In 2007, ca. 15 ha of lowland forest were lost, mainly converted to upland shrub/herb with some conversion to lowland shrub/herb.

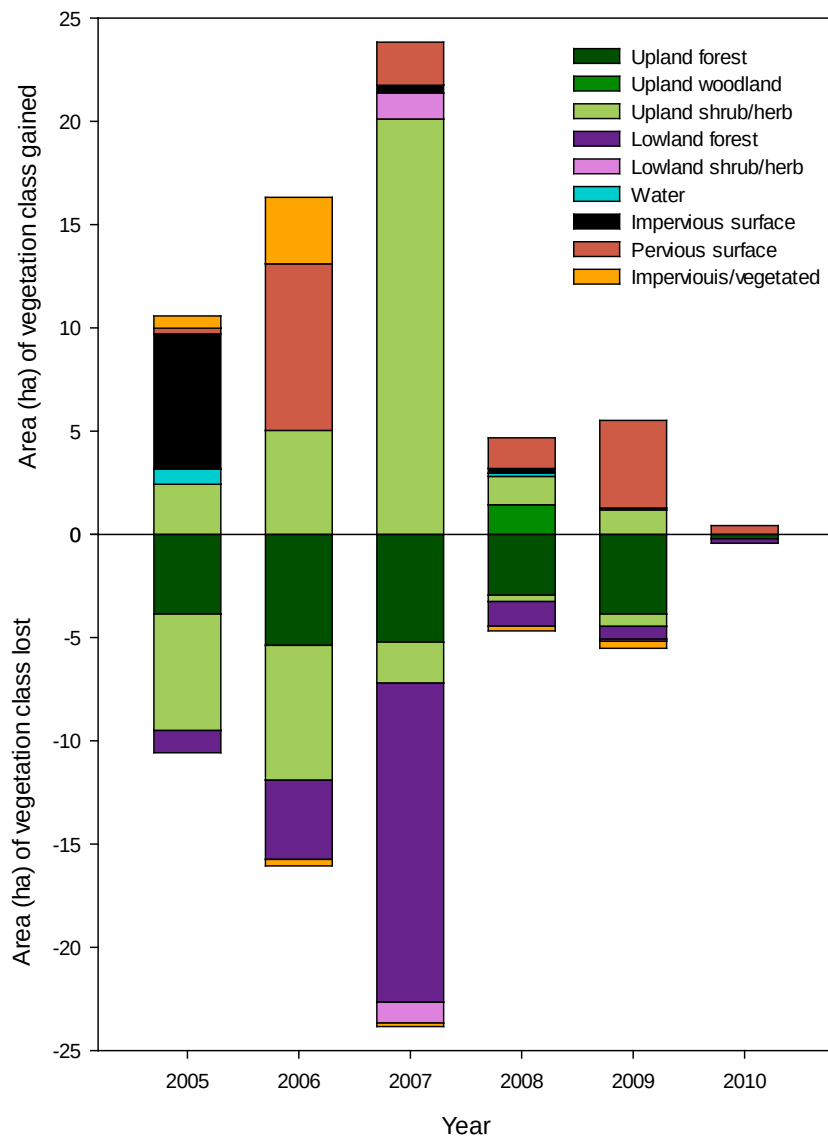


Figure 15. Area (in ha) of vegetation cover type lost (-) and gained (+) at MISS during the analysis period (2005-2010). In some cases (year 2006) the vegetation lost is the same amount and type as vegetation gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to alter the vegetation type.

Non-MISS

Outside the MISS administrative boundary, there was much more land conversion to “developed” classes, i.e., impervious, pervious, and impervious/vegetated (Figure 16). The majority of the pervious surface gained during the analysis period occurred in 2005, 2006, and 2007, with smaller amounts in the remaining years (Figure 16 and Table C7 in Appendix C). Larger amounts of impervious surface were created in 2006 and 2007 (ca. 70 ha annually).

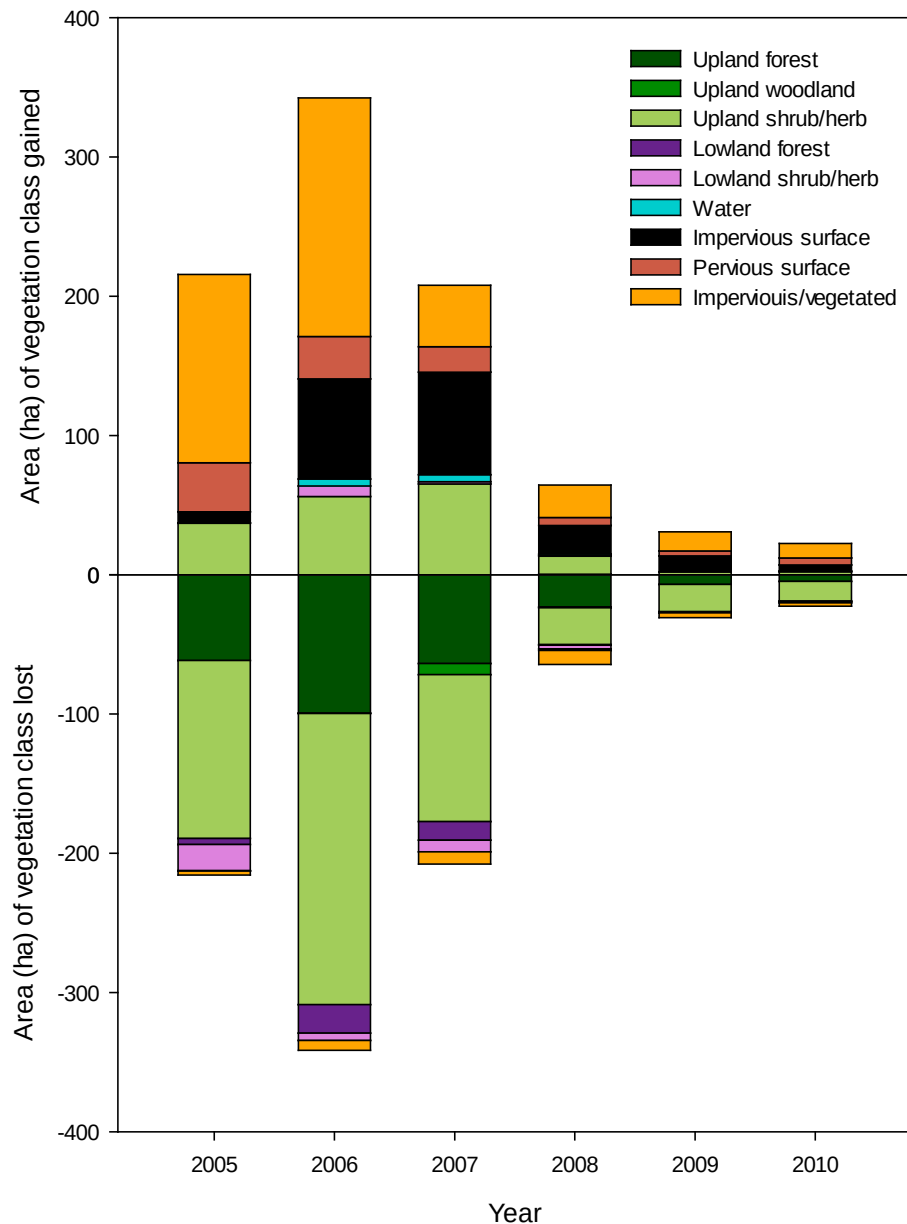


Figure 16. Area (in ha) of vegetation cover type lost (-) and gained (+) outside the MISS administrative boundary during the analysis period (2005-2010). In some cases (year 2006) the vegetation lost is the same amount and type as vegetation gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to alter the vegetation type.

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 Minnesota were obtained from the complete MN GAP stewardship database available at the MN DNR data deli (<http://deli.dnr.state.mn.us/>).

Owner description

As a percent of the analysis area, privately-owned lands contributed the greatest amount of disturbed land (Figure 17). They also comprise over 90% of the analysis area (Figure 17). Development was the largest disturbance agent (841 ha) in private ownership, with disturbances by agriculture and forest harvest contributing much smaller amounts—20 and 4 ha, respectively (Table C8 in Appendix C). Development was the predominant disturbance agent on all other lands as well, with some additional disturbance by agriculture and forest harvest. Lands owned by “other public” contained the second highest amount of disturbed area (37 ha), though these lands accounted for a very small portion of the total analysis area. All remaining ownership types were dominated by development activity.

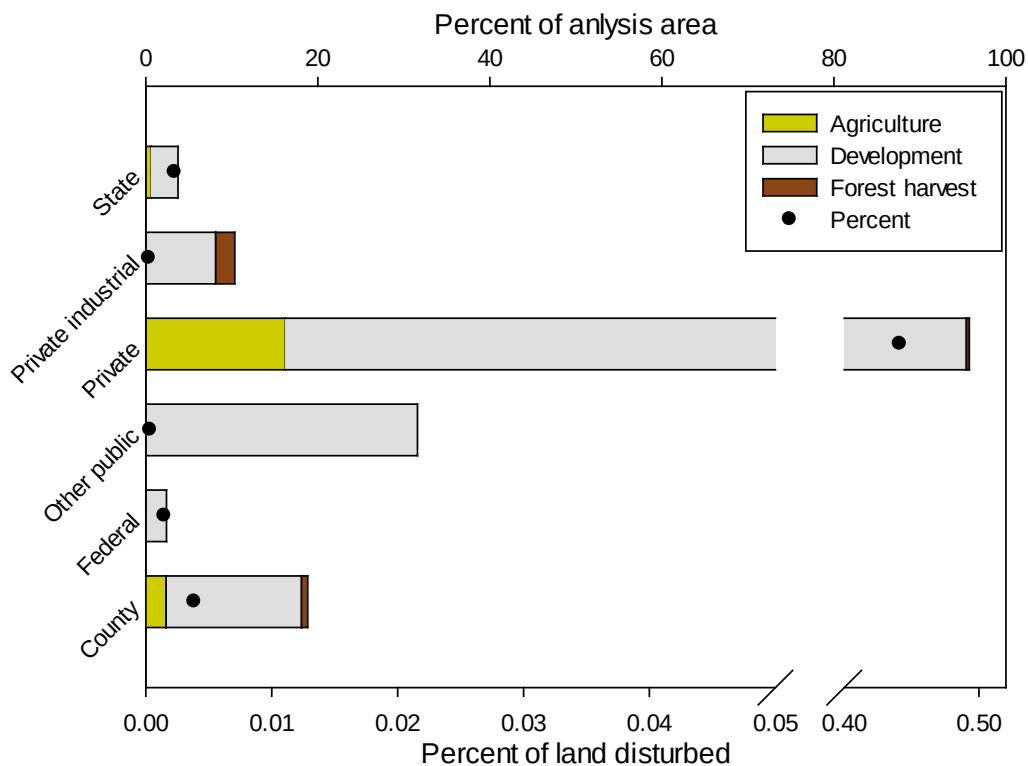


Figure 17. Percent of land disturbed inside the entire analysis area, by six broad ownership types, overlaid by the percent of analysis area occupied by each owner (black circle).

Owner name

If ownership is looked at more closely, privately-owned land accounted for 92% of all disturbances, while also occupying ca. 90% of the total analysis area (Figure 18). Of the remaining disturbed areas, the City of Forest Lake, Dakota County, and Metro Airports Commission accounted for 32 ha, 12 ha, and 12 ha, respectively (Table C9 in Appendix C). All other ownership categories combined for a total disturbed area of 23 ha, largely due to development activities (Table C9 in Appendix C).

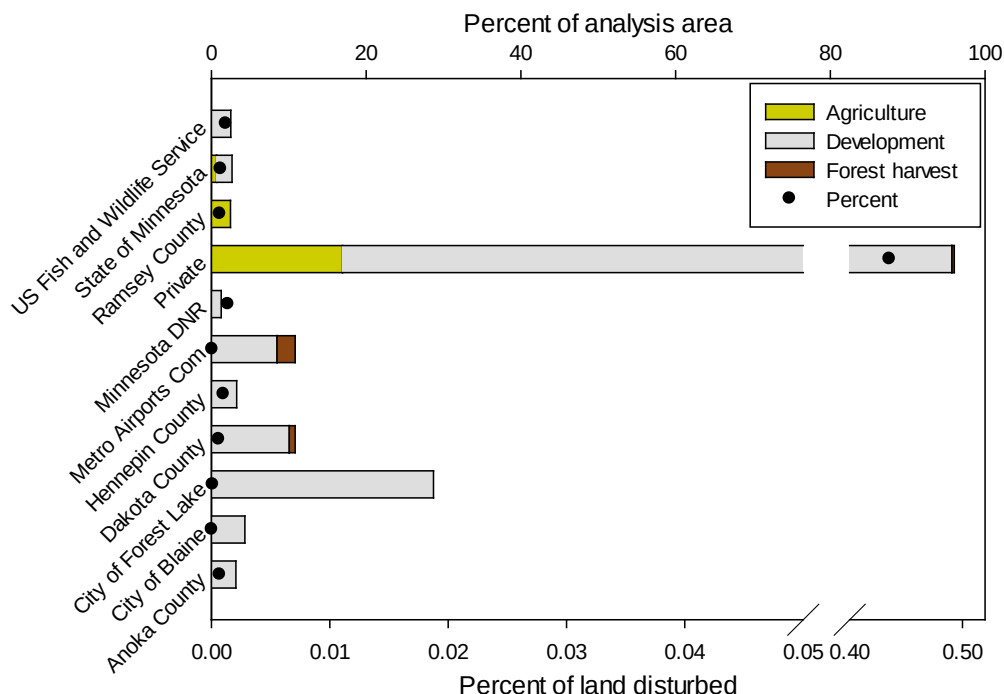


Figure 18. Percent of land disturbed inside the entire analysis area, by detailed ownership types, overlaid by the percent of analysis area occupied by each owner (black circle).

Disturbance Agents by Subwatershed

Disturbance agents can also be summarized by the three subwatersheds (HUC 10) in the analysis area. The Rice Creek subwatershed experienced the largest amount of disturbance among the three, with almost 0.8% of its land disturbed during the analysis period. Most of the disturbance was due to development (335 ha), with much smaller disturbances by agriculture and forest harvest—17 ha and 5 ha, respectively (Figure 19 and Table C10 in Appendix C). The Minnesota and Crow subwatersheds experienced less disturbance and both were dominated by development.

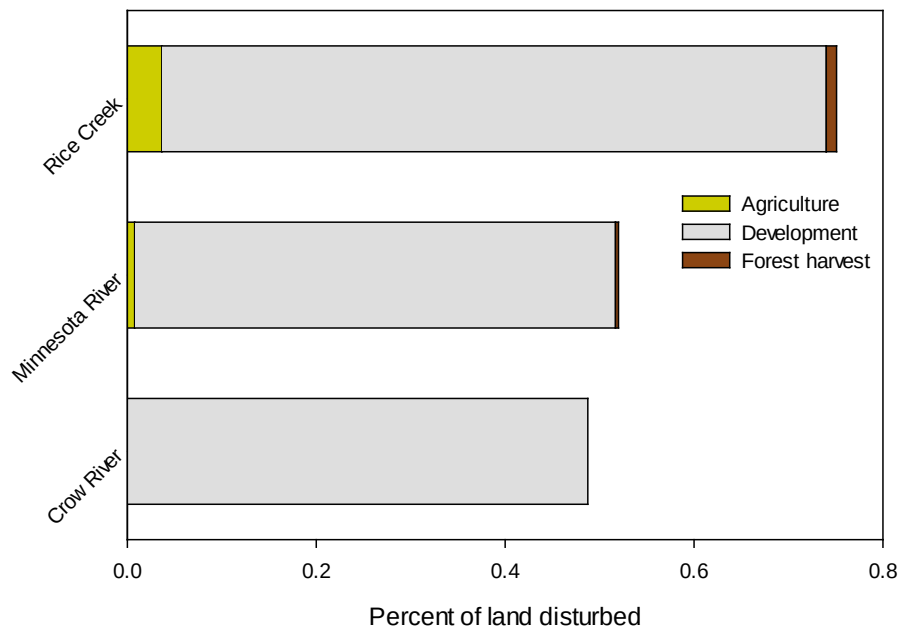


Figure 19. Percent of each subwatershed (HUC 10) affected during the analysis period, by disturbance agent..

Discussion

Unlike all other parks we have analyzed thus far (VOYA, ISRO, APIS, and SACN), less than 1% of the land within the MISS administrative boundary is owned by the National Park Service (Figure 20). The park has many partnerships with land owners within the administrative boundary, giving the NPS some input into the decision making process. These partnerships also allow the park to engage multiple user communities in caring for the health of the river. Nearly 75% of the area within the park boundary is privately owned, with the next largest land owner being the Minnesota DNR, at nearly 10%.

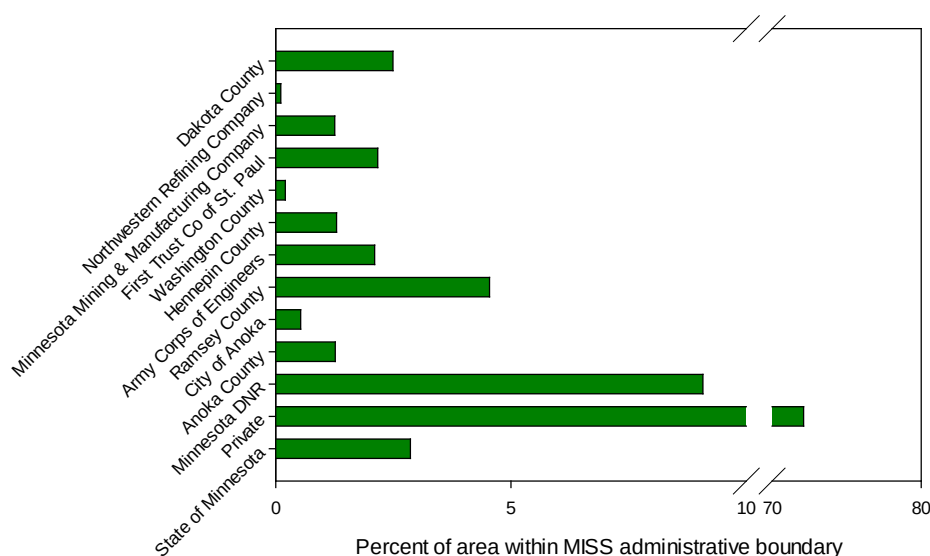


Figure 20. Percent of area within the MISS administrative boundary within different ownership types. Data from MN GAP analysis.

The only disturbance agent present within the park was development. Most of this development occurred in 2007, when nearly 25 ha of land was disturbed (see Figure 13). In each year some upland forest was converted to a non-upland forest class. Also, in each year there were some vegetated areas converted to impervious surfaces, a by-product of the development occurring in the expanding Twin Cities region.

Outside the administrative boundary, development was again the most prevalent agent of change during each year of the analysis period. Spatially, the Rice Creek subwatershed contained the greatest proportion of disturbances within the analysis area, though it was not the largest subwatershed in the analysis area (Figure 21). The Minnesota River subwatershed occupied the largest land area within the analysis area and experienced the second-most land disturbed, almost solely due to development.

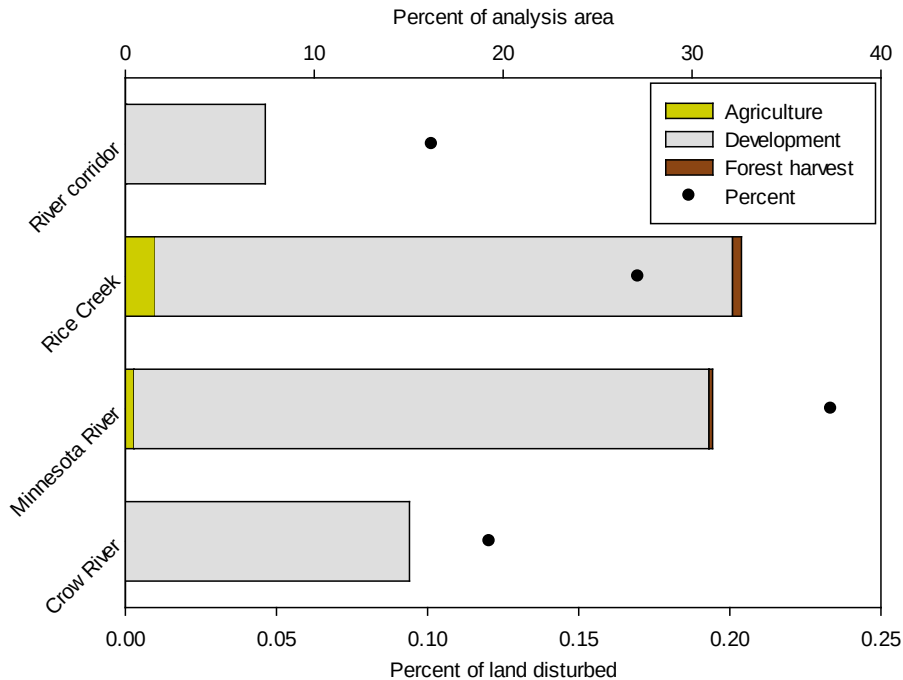


Figure 21. Percent of land disturbed inside the analysis area overlaid by percent of analysis area occupied by subwatershed and all other land (River corridor).

Although the Minnesota River subwatershed did not have the greatest amount of disturbances by area, it did have the largest number of disturbances ($n=123$), and the second smallest mean patch size (Figure 22). The Mississippi River corridor had both the smallest mean patch size and the lowest total number of disturbances among the different areas. The subwatershed with the largest mean patch size was Rice Creek, which incidentally also had the largest percent of disturbed land area.

Summarizing population and road density within each of the subwatersheds illustrates how heavily populated the Minnesota River subwatershed is, compared to the other two subwatersheds (Figure 23). Not surprisingly, there is also a positive relationship between the road and population densities. The lowest road and population densities occur in the Crow River subwatershed, which is furthest from the metropolitan area and has one-sixth the road density of the Minnesota River subwatershed.

When disturbances are totaled for the entire analysis area an interesting pattern emerges that generally coincides with the total number of housing starts in the United States (Figure 24). We will see if this pattern holds during the next analysis period, when we expect to see new housing starts increase with the housing market recovery.

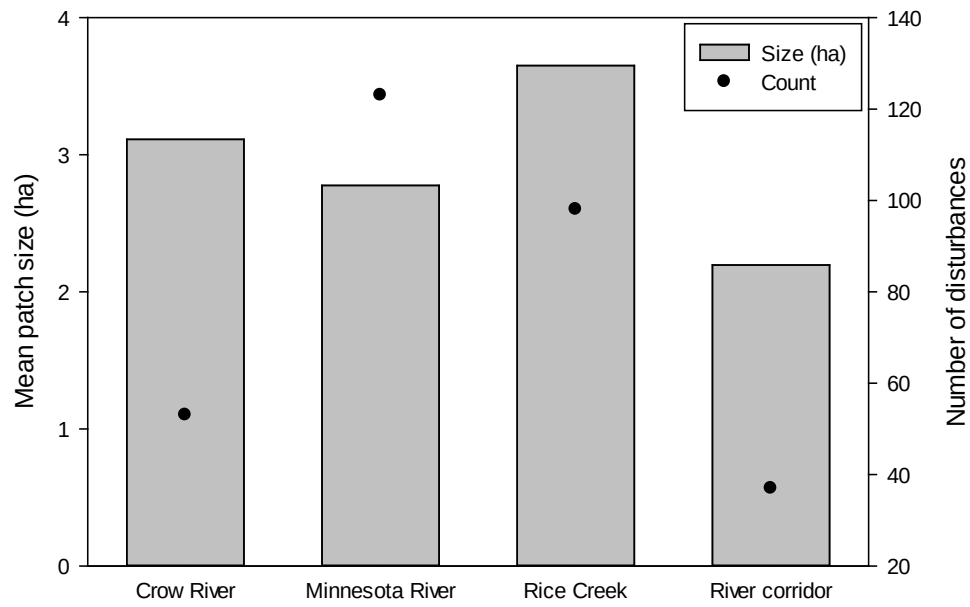


Figure 22. Mean patch size (ha) and total number of patches (disturbances) within each subwatershed and all other land (River corridor).

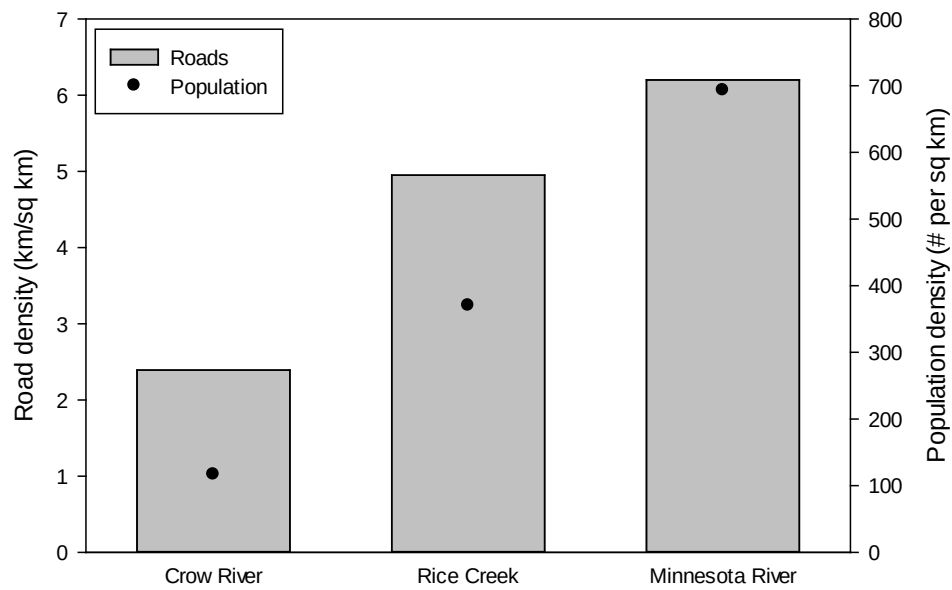


Figure 23. Population density (per square km) and road density (km/sq km) within each of the subwatersheds in the analysis area (U.S. Census Bureau 2010).

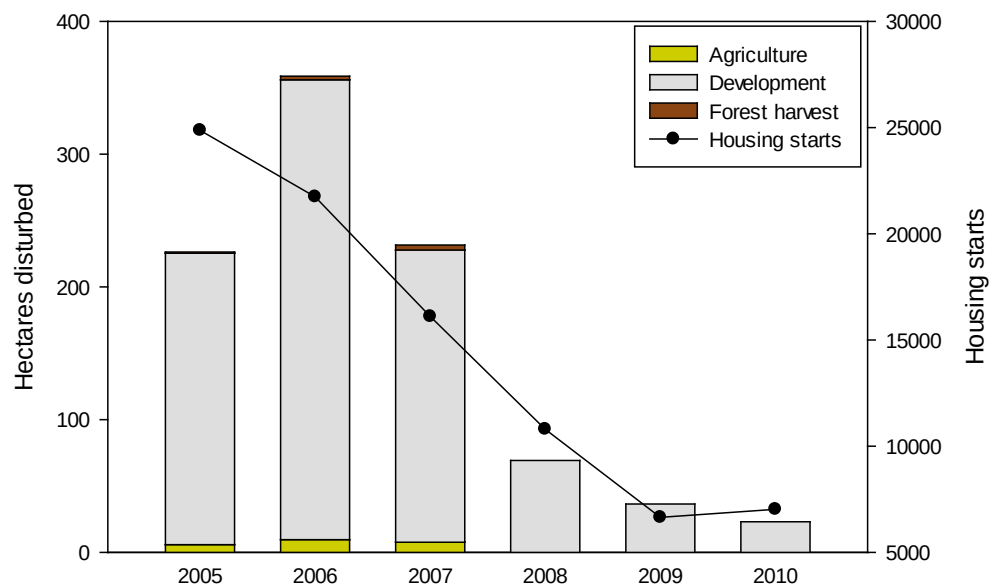


Figure 24. Total area (ha) disturbed inside the analysis area by year and disturbance agent, overlaid with the total number of housing starts in the United States for that year. Housing data from U.S Department of Commerce: Census Bureau (U.S. Department of Commerce 2013).

Comparison Across Park Units

This is the fifth park analyzed in the Network, with Voyageurs (VOYA) and Isle Royale (ISRO) national parks, Apostle Islands (APIS) National Lakeshore, and Saint Croix National Scenic Riverway (SACN), being analyzed in 2009, 2010, 2011, and 2012, respectively (Kirschbaum and Gafvert 2010b, 2012, Kirschbaum et al. 2012, Kirschbaum and Gafvert 2013). Inside the park administrative boundary, MISS had lower amounts of disturbance than SACN and VOYA, and higher rates than ISRO and APIS (Figure 25). Outside the park boundary, MISS had the lowest amount of disturbance, likely due to the proximity of the large metropolitan area and the fact that the majority of the land use conversion happened prior to the analysis period.

While viewing the disturbance agents present inside park boundaries across the five parks, one agent present at MISS in greater proportion than all other parks is development. As mentioned previously, this is because a small proportion of the land within the administrative boundary is managed by the NPS. The land within the administrative boundary did not experience any other type of disturbance, also an anomaly compared to other parks (Figure 26).

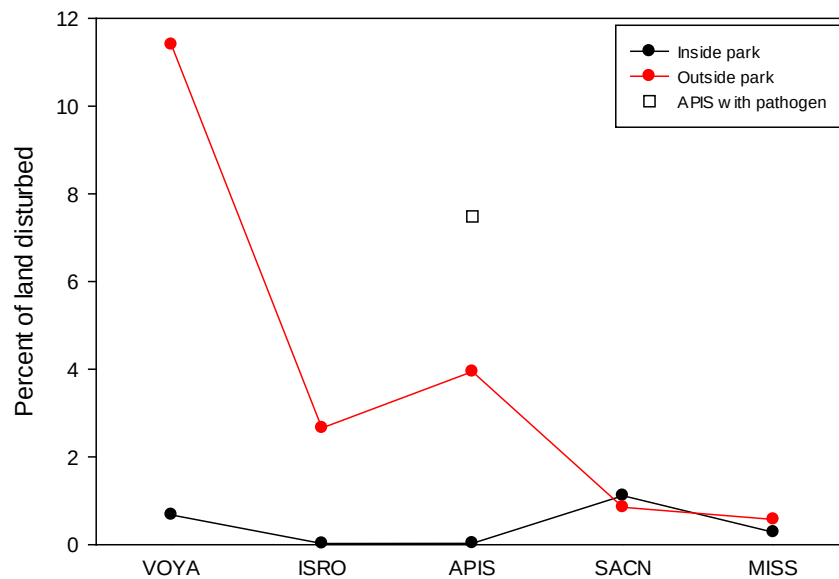


Figure 25. Percent of land disturbed inside the parks (black line and circle) versus outside the parks (red line and circle). The hollow square symbol includes a large forest pathogen event inside APIS that is not accounted for in the overall in-park measure for APIS.

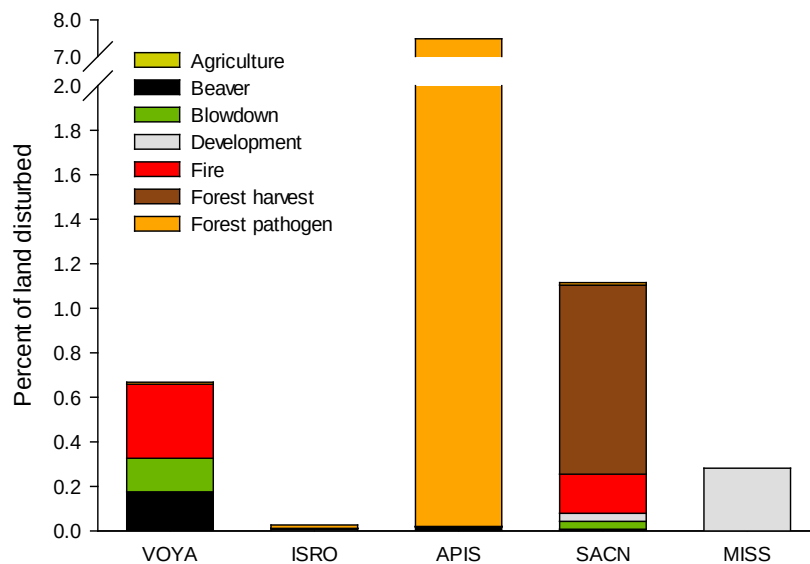


Figure 26. Percent of disturbed land at ISRO, VOYA, and APIS by causal agent.

The percent of land disturbed outside MISS was the lowest among all other parks thus far, and ten times less than land surrounding VOYA (Figure 27). Of course, the lands surrounding VOYA are heavily managed for large scale timber production, versus the urban landscape surrounding the MISS boundary. Although the land outside MISS had the lowest proportion of land disturbed, it had the largest proportion of permanent land conversion, this due to the large amount of disturbances from development. Therefore, an argument could be made that, although there was much more land disturbed outside VOYA, there could be more deleterious effects from the small amount of disturbance outside MISS due to the likely increases in runoff, fertilizer inputs (lawns), and fragmentation of natural landscapes.

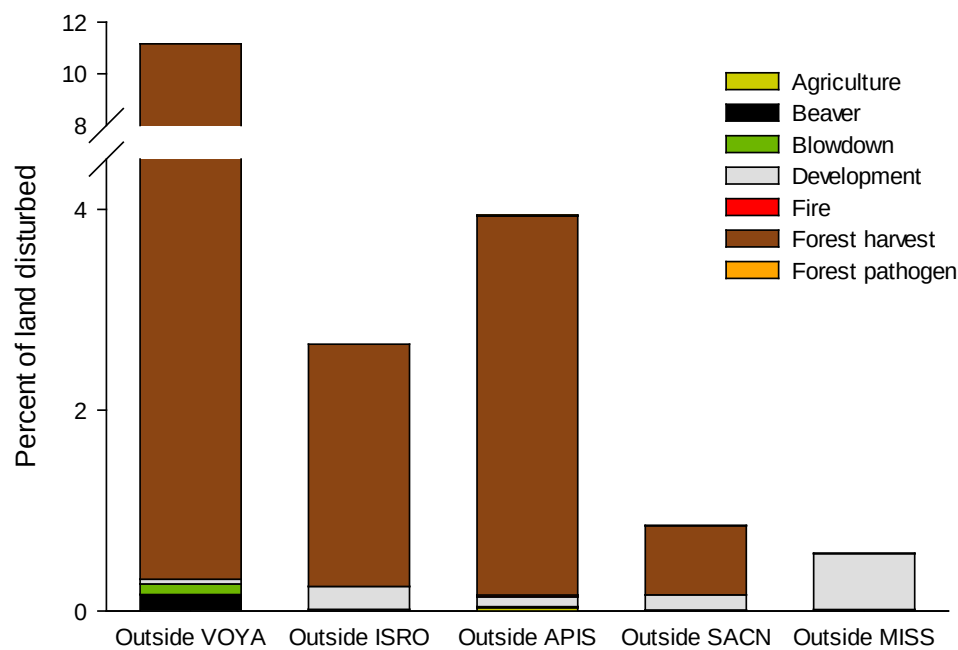


Figure 27. Percent of land disturbed by disturbance agent outside each of the respective parks.

Conclusions

We have summarized the first period of disturbance analysis at MISS into six points:

- 1) MISS experienced the second-lowest amount of land disturbed within the administrative boundary of all parks analyzed thus far. However, nearly all of the land disturbed was due to development activities, quite different than any other park analyzed to-date.
- 2) There was a similar trend in the amount of development occurring inside and outside the park during the analysis period. Development peaked in 2006/2007 and then declined, probably as a result of the economic downturn.
- 3) Surprisingly, the Minnesota River subwatershed had the second-highest rate of disturbance within its analysis area, even though more than half of the land within the subwatershed has already been converted to developed classes.
- 4) Among the five parks, MISS had the lowest percentage of land disturbed outside the park. This is primarily because forest harvest, which affects large tracts of land, was almost totally absent from the analysis area. Instead, agriculture and development were the prominent disturbance agents in the areas surrounding the Twin Cities.
- 5) As the metropolitan area expands, we expect to see an increased disturbance rate in the Crow River subwatershed and a decreased rate in the Minnesota River area, as more of the land there is already developed.
- 6) This long-term monitoring project specifically focuses on larger, discrete changes in land cover type and use. As such, it does not capture changes in agricultural uses or practices that can generate quite different sediment and nutrient loads within the basin. These more static changes are not captured as “disturbances,” but the difference in “till” and “no-till” management within corn and soybeans, not to mention various types of fertilizing regimes, can and do have large effects on water quality and should not be discounted.

In this report we have documented six years of disturbance activity, which is too short of a time period to draw any sweeping conclusions or provide trend analyses of the disturbance regimes at work in the park and the neighboring area. Instead, this report represents a foundation 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.

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Appendix A: Spatial Distribution of Disturbances at MISS.

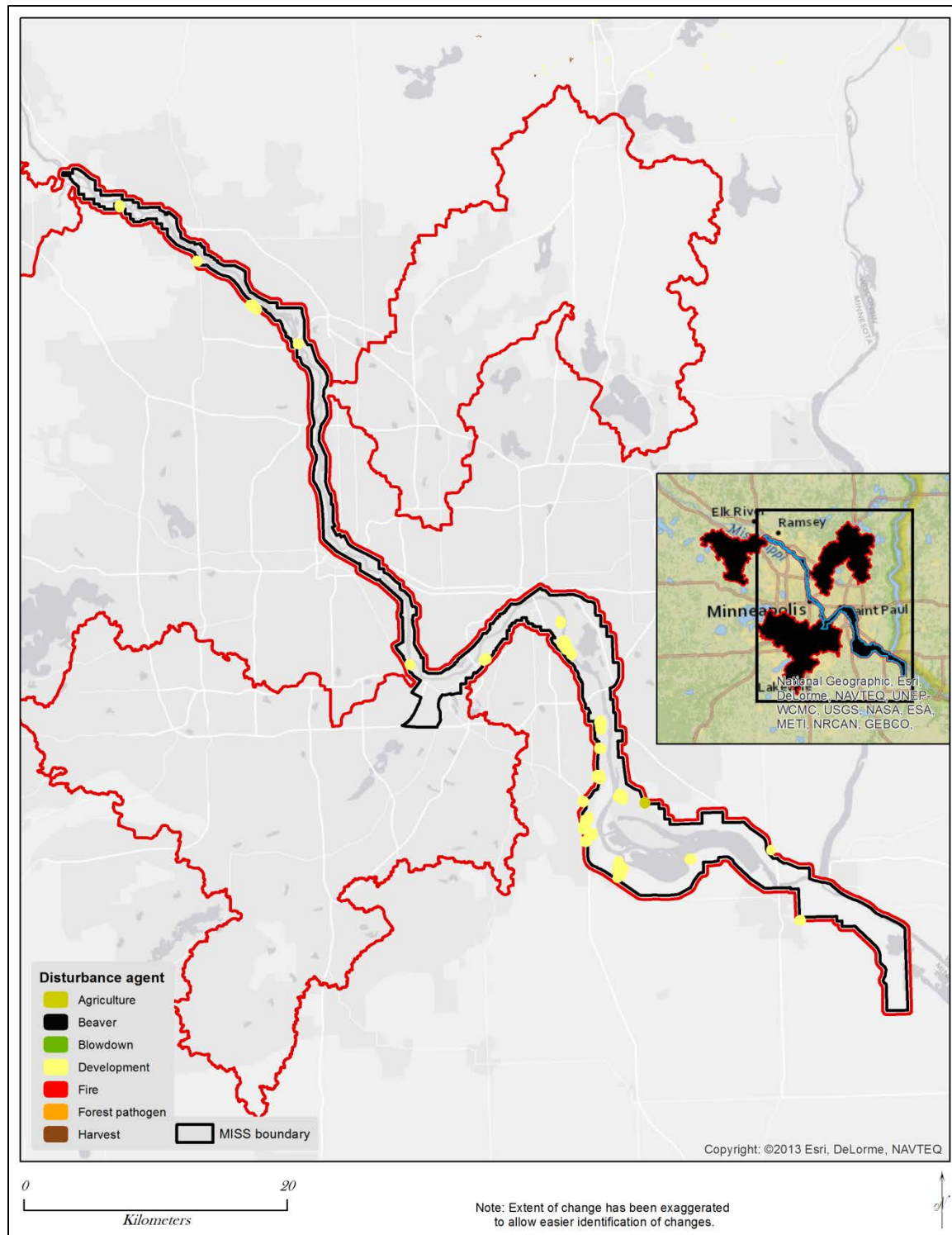


Figure A1. Spatial distribution of disturbances inside MISS boundary and within the 300 meter buffer area during the analysis period.

Appendix B: Spatial Distribution of Disturbances in Subwatersheds.

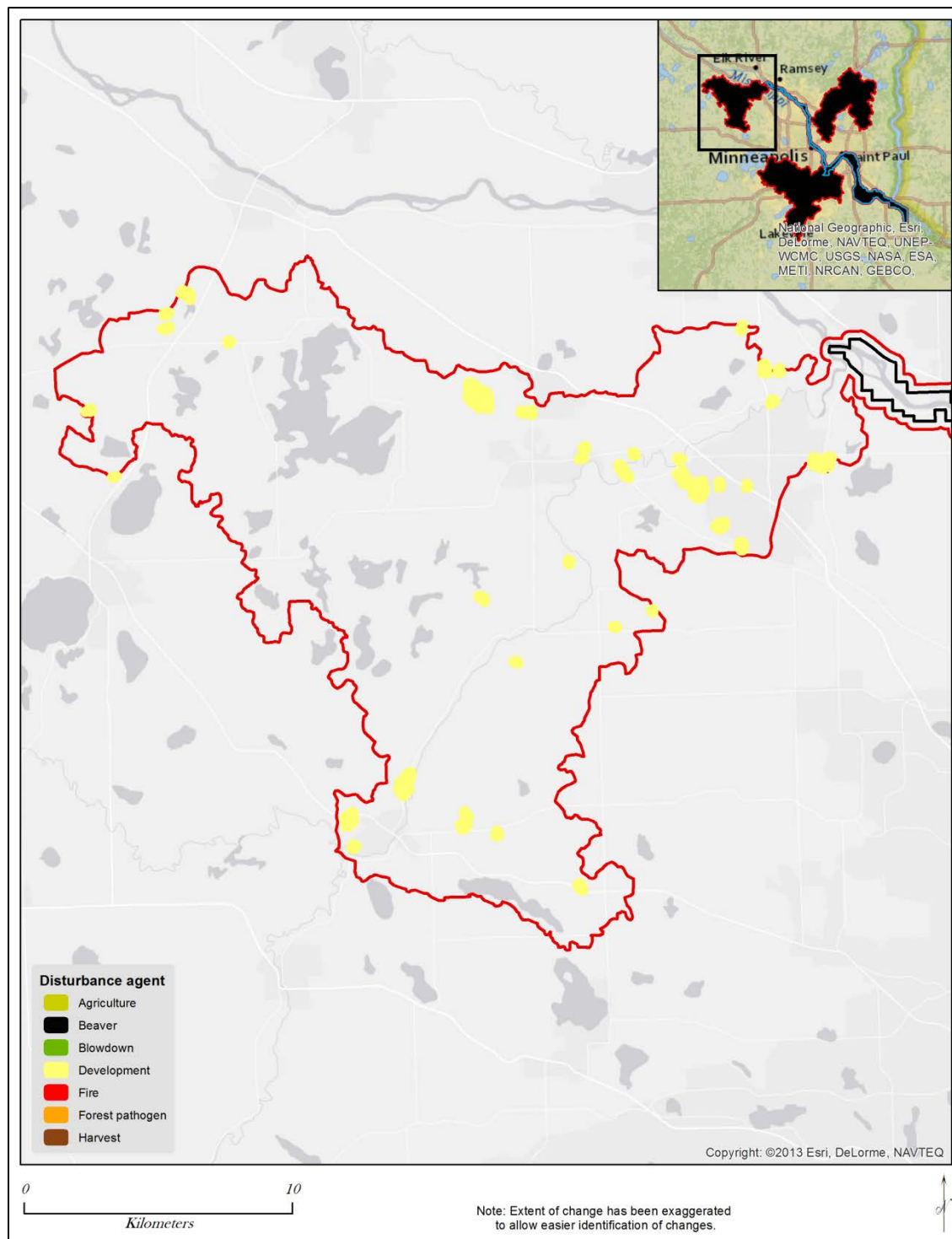


Figure B1. Spatial distribution of disturbances in the Crow River basin during the analysis period.

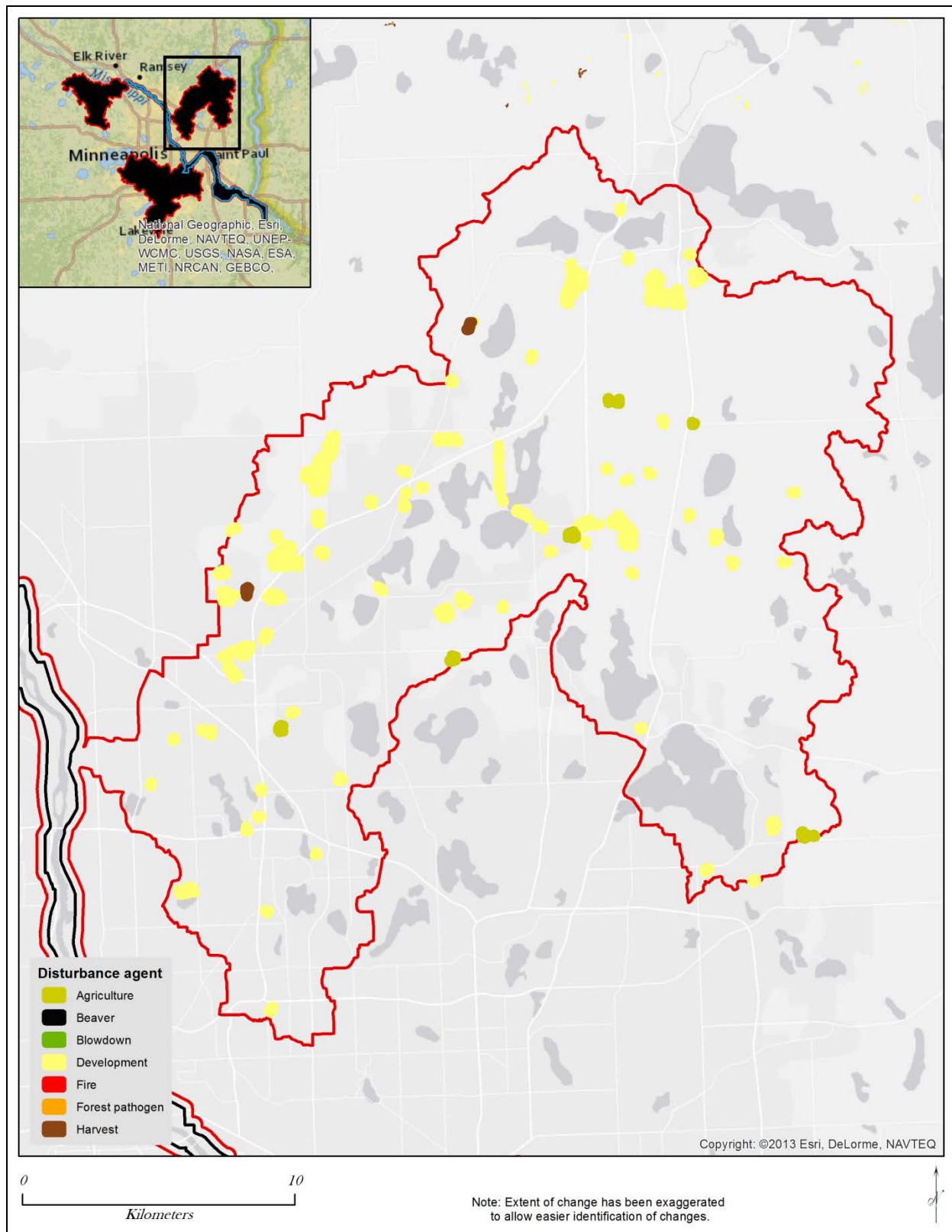


Figure B2. Spatial distribution of disturbances in the Rice Creek basin during the analysis period.

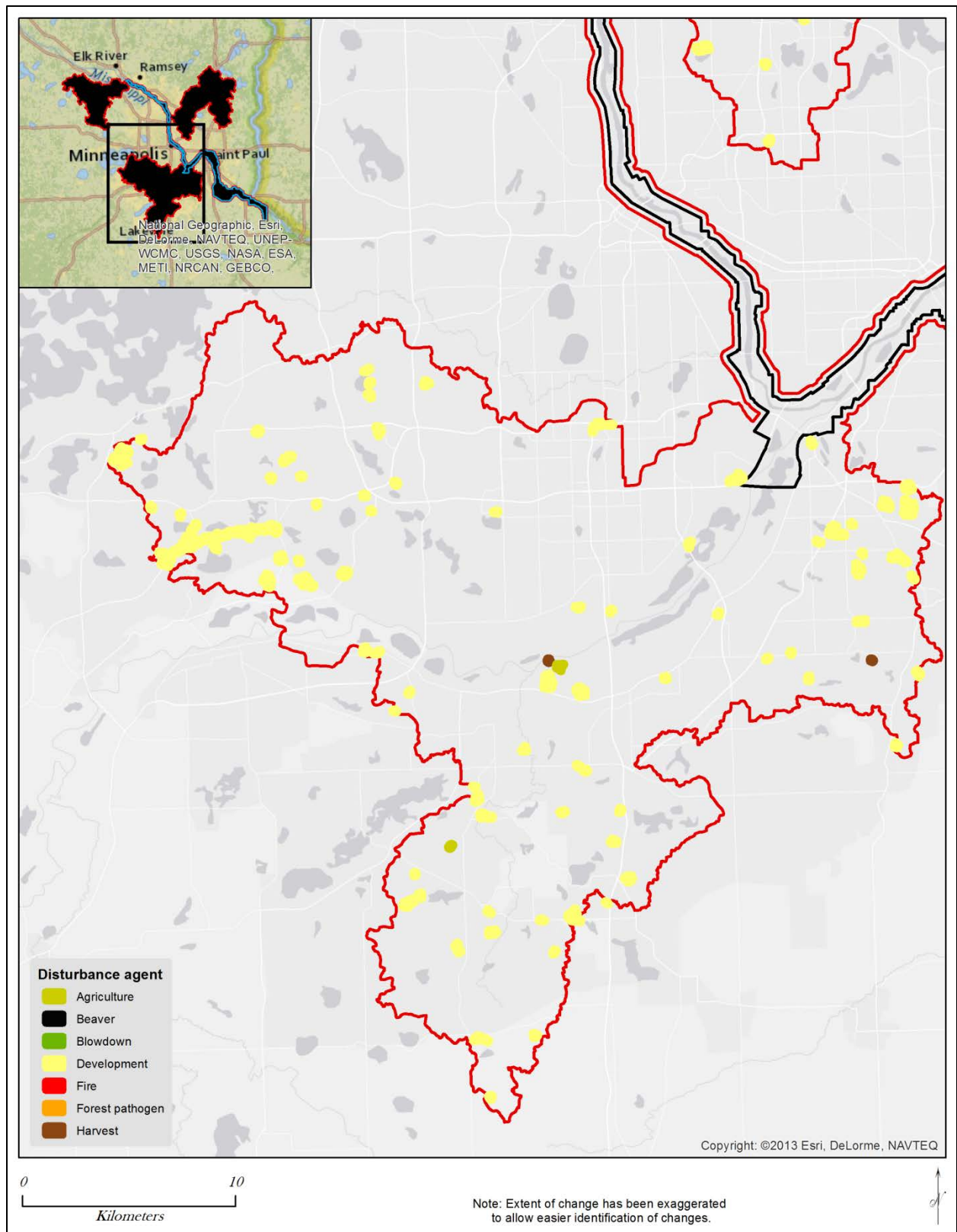


Figure B3. Spatial distribution of disturbances in the Minnesota River basin during the analysis period.

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	9.94	17457.48
Developed, open space	9.95	17463.24
Developed, low intensity	15.54	27273.24
Developed, medium intensity	9.86	17317.80
Developed, high intensity	5.63	9875.97
Barren land	0.22	386.01
Deciduous forest	13.67	24006.78
Evergreen forest	0.67	1181.88
Mixed forest	0.05	79.83
Shrub	1.34	2353.14
Grassland/herbaceous	2.01	3527.73
Pasture	11.63	20423.88
Cultivated crops	10.58	18571.14
Woody wetlands	2.09	3663.18
Emergent herbaceous wetlands	6.82	11974.86

Table C2. Percent of each vegetation class within each subwatershed in the analysis area. Data summarized from the 2006 NLCD.

Class name	Minnesota River	Rice Creek	Crow River
Open water	5.76	9.69	9.70
Developed, open space	13.71	8.51	7.39
Developed, low intensity	22.73	13.99	5.59
Developed, medium intensity	15.02	7.46	2.91
Developed, high intensity	8.54	3.41	0.72
Barren land	0.03	0.12	0.07
Deciduous forest	15.49	13.37	10.60
Evergreen forest	0.50	1.29	0.41
Mixed forest	0.04	0.06	0.04
Shrub	1.28	0.87	2.14
Grassland/herbaceous	1.11	3.29	2.68
Pasture	6.84	15.35	21.87
Cultivated crops	3.47	8.09	31.00
Woody wetlands	1.18	0.77	0.16
Emergent herbaceous wetlands	4.28	13.74	4.73

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

Year	MISS (ha)	MISS (%)	Non-MISS (ha)	Non-MISS (%)
2005	10.58	0.05	215.71	0.14
2006	16.33	0.07	342.44	0.22
2007	23.84	0.11	207.77	0.14
2008	4.68	0.02	64.52	0.04
2009	5.53	0.03	30.91	0.02
2010	0.43	0.00	22.60	0.01
Total	61.39	0.28	883.94	0.57

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

Analysis area	Year	Area of land disturbed (ha)			Total
		<i>Agriculture</i>	<i>Development</i>	<i>Forest harvest</i>	
MISS	2005	0	10.58	0	10.58
	2006	0	16.33	0	16.33
	2007	0	23.84	0	23.84
	2008	0	4.68	0	4.68
	2009	0	5.53	0	5.53
	2010	0	0.43	0	0.43
	Total	0	61.39	0	61.39
Non-MISS	2005	5.80	209.04	0.86	215.71
	2006	9.59	330.17	2.67	342.44
	2007	7.60	196.40	3.77	207.77
	2008	0	64.52	0	64.52
	2009	0	30.91	0	30.91
	2010	0	22.60	0	22.60
	Total	22.99	853.64	7.31	883.94

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

Analysis area	Year	Percent of land disturbed			Total
		<i>Agriculture</i>	<i>Development</i>	<i>Forest harvest</i>	
MISS	2005	0	0.05	0	0.05
	2006	0	0.07	0	0.07
	2007	0	0.11	0	0.11
	2008	0	0.02	0	0.02
	2009	0	0.03	0	0.03
	2010	0	0.00	0	0.00
	Total	0	0.28	0	0.28
Non-MISS	2005	<0.01	0.14	<0.01	0.14
	2006	0.01	0.21	<0.01	0.22
	2007	<0.01	0.13	<0.01	0.14
	2008	0	0.04	0	0.04
	2009	0	0.02	0	0.02
	2010	0	0.01	0	0.01
	Total	0.01	0.56	0.00	0.57

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>Upland forest</i>	<i>Upland woodland</i>	<i>Upland shrub/herb</i>	<i>Lowland forest</i>	<i>Lowland shrub/herb</i>	<i>Water</i>	<i>Impervious surface</i>	<i>Pervious surface</i>	<i>Impervious/vegetated</i>
MISS	2005	-3.87	0	-5.64	-1.08	0	0	0	0	0
	2006	-5.38	0	-6.53	-3.83	0	0	0	0	-0.32
	2007	-5.23	0	-1.99	-15.44	-1.01	0	0	0	-0.18
	2008	-2.96	0	-0.31	-1.19	0	0	0	0	-0.23
	2009	-3.87	0	-0.59	-0.62	-0.10	0	0	0	-0.35
	2010	-0.22	0	0	-0.22	0	0	0	0	0
	Total	-21.51	0	-15.06	-22.38	-1.11	0	0	0	-1.07
Non-MISS	2005	-61.70	0	-127.74	-4.36	-18.76	0	-0.21	-0.14	-2.81
	2006	-99.53	-0.14	-209.09	-20.49	-5.16	0	0	0	-7.18
	2007	-63.81	-8.01	-105.55	-13.28	-8.33	0	0	0	-8.88
	2008	-23.08	-0.61	-26.59	-0.44	-2.55	0	-1.14	0	-10.11
	2009	-6.88	0	-19.63	-0.86	-0.15	0	0	0	-3.39
	2010	-4.79	0	-14.15	-0.31	-0.92	0	0	0	-2.43
	Total	-259.79	-8.76	-502.73	-39.74	-35.88	0	-1.35	-0.14	-34.79

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>Upland forest</i>	<i>Upland woodland</i>	<i>Upland shrub/herb</i>	<i>Lowland forest</i>	<i>Lowland shrub/herb</i>	<i>Water</i>	<i>Impervious surface</i>	<i>Pervious surface</i>	<i>Impervious/vegetated</i>
MISS	2005	0	0	2.43	0	0	0.73	6.56	0.27	0.59
	2006	0	0	5.04	0	0	0	0	8.06	3.22
	2007	0	0	20.12	0	1.26	0	0.38	2.09	0
	2008	0	1.44	1.37	0	0	0.15	0.23	1.49	0
	2009	0	0	1.19	0.10	0	0	0	4.24	0
	2010	0	0	0	0	0	0	0	0.43	0
	Total	0	1.44	30.15	0.10	1.26	0.88	7.17	16.58	3.81
Non-MISS	2005	0	0	37.14	0	0	0.29	7.90	35.22	135.15
	2006	0	0	56.30	0	7.48	5.08	71.88	30.35	171.35
	2007	0	0	65.31	0	1.55	5.06	73.67	18.26	44.12
	2008	0	0.495	12.96	0	0.61	0.99	20.48	5.68	23.30
	2009	0	0	2.08	0	0	0	11.58	3.58	13.66
	2010	0	0	2.27	0	0	0.51	4.40	4.98	10.44
	Total	0	0.495	176.06	0	9.65	11.93	189.92	98.06	398.02

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

Owner	Agriculture	Development	Forest harvest
County	2.81	18.89	0.86
Federal	0	2.86	0
Other public	0	37.86	0
Private	19.43	841.97	3.77
Private industrial	0	9.72	2.67
State	0.76	3.73	0

Table C9. Area (ha) of land disturbed inside the analysis area by owner, grouped into more specific ownership classes.

Owner	Agriculture	Development	Forest harvest
Anoka County	0	3.62	0
City of Blaine	0	4.95	0
City of Forest Lake	0	32.91	0
Dakota County	0	11.54	0.86
Hennepin County	0	3.73	0
Metro Airports Com	0	9.72	2.67
Minnesota DNR	0	1.44	0
Private	19.43	841.97	3.77
Ramsey County	2.81	0	0
State of Minnesota	0.76	2.29	0
US Fish and Wildlife Service	0	2.86	0

Table C10. Total area (ha) of land disturbed by disturbance agent inside each of three subwatersheds.

HUC 10 name	Agriculture	Development	Forest harvest
Crow River	0	164.97	0
Minnesota River	4.95	334.05	2.12
Rice Creek	17.35	335.42	5.18

Table C11. Total area (ha) of land disturbed inside the park administrative boundary by owner.

Owner	Development
Dakota County	1.30
Private	60.09

Table C12. Percent of land by owner within the MISS administrative boundary.

Owner	Percent
State of Minnesota	2.86
Private	72.11
Minnesota DNR	9.08
Anoka County	1.26
City of Anoka	0.53
Ramsey County	4.55
Army Corps of Engineers	2.10
Hennepin County	1.29
Washington County	0.20
First Trust Co of St. Paul	2.17
Minnesota Mining & Manufacturing Company	1.25
Northwestern Refining Company	0.11
Dakota County	2.49

Appendix D: Results from Interpreter Cross Validation.

Two interpreters made independent decisions regarding the veracity of each disturbance polygon, and if it was determined to be “true,” remaining attributes were filled in by the interpreter. Although every effort was made to reduce the amount of user bias that could be introduced into the validation process, we tested this assumption by randomly selecting 10% of each validator’s polygons and having the other interpreter validate each one. 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 14 none-matching values can be interpreted as follows: interpreter 1 called something false 14 times when interpreter called it true.

		Interpreter 2		Total interpreted	Proportion unambiguous
		FALSE	TRUE		
Interpreter 1	FALSE	50	3	53	0.94
	TRUE	1	27	28	0.96

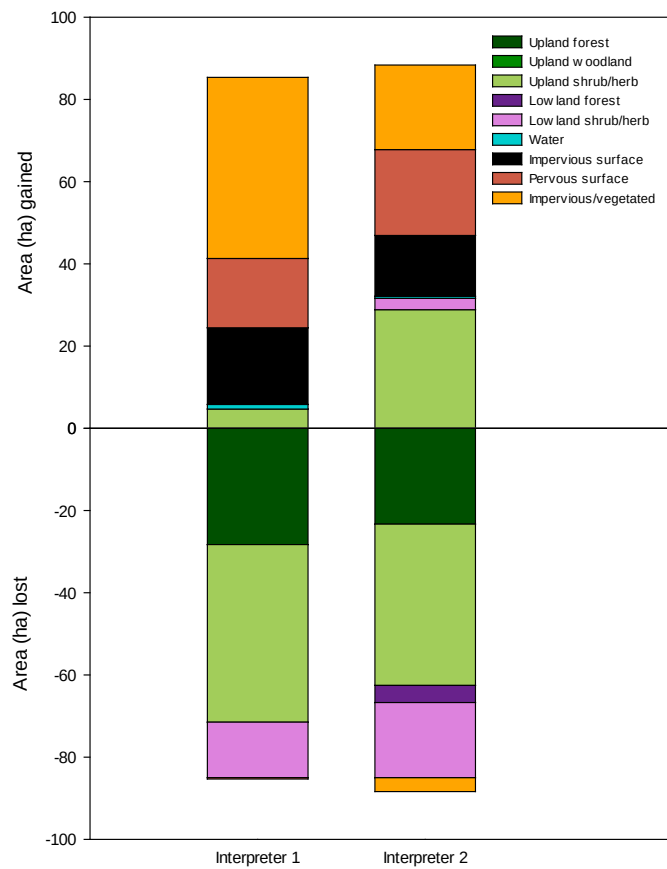


Figure D1. Area (ha) of vegetation gained and lost as indicated by each interpreter.

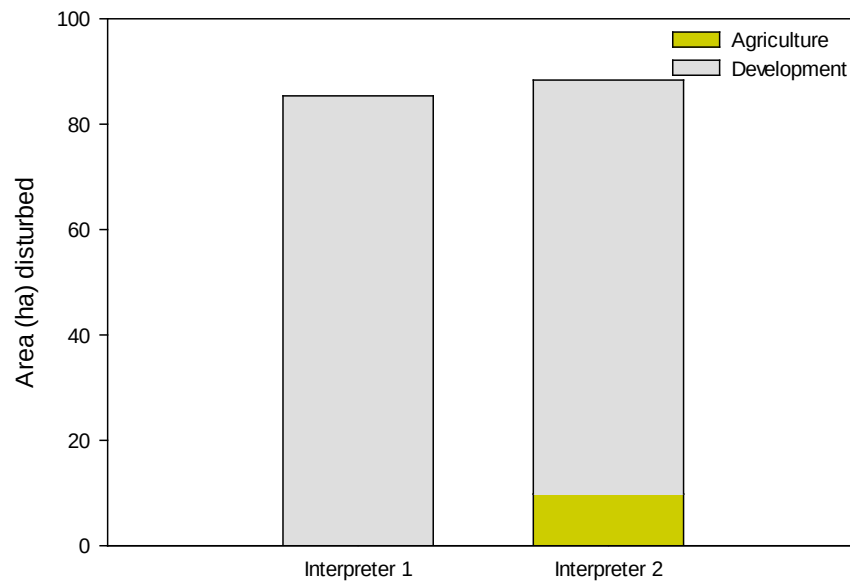


Figure D2. Area (ha) of land disturbed by disturbance agent as indicated by each interpreter.

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 D2. Generalized pre- and post-disturbance vegetation classes (level 2) used for summary.

Generalized class	Groups in this general class
Upland forest	Upland evergreen forest, upland deciduous forest, upland mixed forest
Upland woodland	Upland evergreen woodland, upland deciduous woodland, upland mixed woodland
Upland shrub/herb	Upland shrub, upland herbaceous
Lowland forest	Lowland evergreen forest, lowland deciduous forest, lowland mixed forest
Lowland shrub/herb	Lowland shrub, lowland herbaceous
Water	Water
Bare ground	Impervious surface, pervious surface, impervious/vegetated

Table D3. Generalized pre- and post-disturbance vegetation classes (level 3) used for summary.

Generalized class	Groups in this general class
Forest	Upland evergreen forest, upland deciduous forest, upland mixed forest, lowland evergreen forest, lowland deciduous forest, lowland mixed forest
Woodland	Upland evergreen woodland, upland deciduous woodland, upland mixed woodland
Shrub/herb	Upland shrub, upland herbaceous, lowland shrub, lowland herbaceous
Water	Water
Bare ground	Impervious surface, pervious surface, impervious/vegetated

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

Disturbance agent	Interpreter 2											Proportion unambiguous
	Agriculture	Beaver	Blowdown	Development	Fire	Flooding	Harvest (clearcut)	Harvest (partial)	Forest pathogen	None	Total interpreted	
Agriculture	0	0	0	0	0	0	0	0	0	0	0	0
Beaver	0	0	0	0	0	0	0	0	0	0	0	0
Blowdown	0	0	0	0	0	0	0	0	0	0	0	0
Development	5	0	0	22	0	0	0	0	0	0	27	0.81
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	0	0	0	0	0	0
Harvest (partial)	0	0	0	0	0	0	0	0	0	0	0	0
Forest pathogen	0	0	0	0	0	0	0	0	0	0	0	0
None	0	0	0	0	0	0	0	0	0	54	54	1.00

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 compares the starting classes at the most detailed level (Level 1).

		Interpreter 2																			
		Upland								Lowland											
Starting class		Evergreen forest	Deciduous forest	Mixed forest	Evergreen woodland	Deciduous woodland	Mixed woodland	Shrub	Herbaceous	Evergreen forest	Deciduous forest	Mixed forest	Shrub	Herbaceous	Water	Impervious surface	Pervious surface	Impervious/vegetated	None	Total interpreted	Proportion unambiguous
Interpreter 1	Upland																				
	Evergreen forest	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1.00
	Deciduous forest	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	13	0.92
	Mixed forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Evergreen woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deciduous woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mixed woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Shrub	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Herbaceous	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	15	1.00
	Lowland																				
	Evergreen forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deciduous forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mixed forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1.00
	Shrub	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Herbaceous	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2	0.50
		Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Impervious surface	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pervious surface	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
		Impervious/vegetated	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		None	0	2	0	0	0	3	2	0	0	3	0	1	0	0	0	6	32	49	0.65

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 compares the ending classes at the most detailed level (Level 1).

Ending class		Interpreter 2																			
		Upland								Lowland											
		Evergreen forest	Deciduous forest	Mixed forest	Evergreen woodland	Deciduous woodland	Mixed woodland	Shrub	Herbaceous	Evergreen forest	Deciduous forest	Mixed forest	Shrub	Herbaceous	Water	Impervious surface	Pervious surface	Impervious/vegetated	None	Total interpreted	Proportion unambiguous
Interpreter 1	Upland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deciduous forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mixed forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Evergreen woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deciduous woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mixed woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Shrub	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Herbaceous	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	4	1.00
	Lowland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Evergreen forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Deciduous forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mixed forest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Shrub	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Herbaceous	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Water		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2	0.5
Impervious surface		0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	1	0	10	0.90	
Pervious surface		0	0	0	0	0	0	1	1	0	0	0	0	0	0	4	2	0	8	0.50	
Impervious/vegetated		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	4	0	5	0.80	
None		0	0	0	0	0	0	0	5	0	0	0	3	0	2	3	3	0	36	54	0.69

Table D7. 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 summarized to level 2.

		Interpreter 2									
Interpreter 1	Starting vegetation class	Upland forest	Upland woodland	Upland shrub/herbaceous	Lowland forest	Lowland shrub/herbaceous	Water	Bare ground	None	Total interpreted	Proportion unambiguous
	Upland forest	13	0	0	0	0	0	1	0	14	0.93
	Upland woodland	0	0	0	0	0	0	0	0	0	0
	Upland shrub/ herbaceous	0	0	16	0	0	0	0	0	16	1.00
	Lowland forest	0	0	0	0	0	0	0	0	0	0
	Lowland shrub/herbaceous	0	0	0	1	1	0	0	0	2	0.50
	Water	0	0	0	0	0	0	0	0	0	0
	Bare ground	0	0	0	0	1	0	0	0	1	0
	None	2	0	5	1	1	0	3	32	44	0.73

Table D8. 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 summarized to level 2.

	Ending vegetation class	Interpreter 2								Total interpreted	Proportion unambiguous
		Upland forest	Upland woodland	Upland shrub/herbaceous	Lowland forest	Lowland shrub/herbaceous	Water	Bare ground	None		
Interpreter 1	Upland forest	0	0	0	0	0	0	0	0	0	0
	Upland woodland	0	0	0	0	0	0	0	0	0	0
	Upland shrub/ herbaceous	0	0	4	0	0	0	0	0	4	1.00
	Lowland forest	0	0	0	0	0	0	0	0	0	0
	Lowland shrub/herbaceous	0	0	0	0	0	0	0	0	0	0
	Water	0	0	0	0	0	1	0	1	2	0.50
	Bare ground	0	0	2	0	0	0	21	0	23	0.91
	None	0	0	6	0	3	2	2	39	52	0.75

Table D9. 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 summarized to level 3.

		Interpreter 2							
Interpreter 1	Starting vegetation class	Forest	Woodland	Shrub-herbaceous	Water	Bare ground	None	Total interpreted	Proportion unambiguous
	Forest	13	0	0	0	1	0	14	0.93
	Woodland	0	0	0	0	0	0	0	0
	Shrub-herbaceous	1	0	12	0	0	0	13	0.92
	Water	0	0	0	0	0	0	0	0
	Bare ground	0	0	1	0	0	0	1	0
	None	2	0	3	0	6	37	48	0.77

Table D10. 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 summarized to level 3.

		Interpreter 2							
Interpreter 1	Ending vegetation class	Forest	Woodland	Shrub-herbaceous	Water	Bare ground	None	Total interpreted	Proportion unambiguous
	Forest	0	0	0	0	0	0	0	0
	Woodland	0	0	0	0	0	0	0	0
	Shrub-herbaceous	0	0	4	0	0	0	4	1
	Water	0	0	0	1	0	1	2	0.50
	Bare ground	0	0	2	0	21	0	23	0.91
	None	0	0	6	2	3	41	52	0.79

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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