



Landsat-based Monitoring of Landscape Dynamics at Saint Croix National Scenic Riverway

2005-2010

Natural Resource Technical Report NPS/GLKN/NRTR—2013/715



ON THE COVER

Prescribed fire at Farmington Bottoms, April 2006.

Photograph by: Ted Gostomski

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Abstract

Saint Croix National Scenic Riverway (SACN) is a long, narrow corridor starting in northwestern Wisconsin and ending in west central Wisconsin/east central Minnesota. Disturbances, or distinct changes in vegetation cover, are important drivers shaping ecosystem structure and function. 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 SACN 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 for photo interpretation to substantiate evidence of a disturbance, and hence, validate whether the disturbance occurred. For each validated disturbance, we identified the agent of change (fire, forest harvest, development, flooding due to beaver activity, and blowdowns) in addition to the year of occurrence, and starting and ending vegetation classes. Summary analyses showed that disturbances outside the park were dominated by forest harvest and development, while inside the park disturbances were caused primarily by forest harvest, fire, forest pathogens, and to a lesser degree, development.

Acknowledgments

We would like to acknowledge staff at Saint Croix National Scenic Riverway for assistance in aerial photo acquisition, providing on-the-ground knowledge of land cover changes, logistical support, and in helping to design the land cover monitoring program's scope and extent for the 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 the three reviewers; Byron Karns, Jill Medlund, and Jim Almendinger 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
BLM	Bureau of Land Management
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.
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.
NASS	National Agricultural Statistics Service. http://www.nass.usda.gov/
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 1 March 1984. http://landsat.usgs.gov/about_landsat5.php
USGS	United States Geological Survey
VOYA	Voyageurs National Park
WISCLAND	Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data. http://dnr.wi.gov/maps/gis/datalandcover.html
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 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% (0.25%/yr) 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 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 4.0% (0.26%/yr) of the land was disturbed in the lower Lake Superior basin from 1985-1999 and 2.9% (0.32%/yr) of the land was disturbed from 2000-2008. 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 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 WI and MI, 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 (fires, hurricanes, extreme wind events).

More localized to the St. Croix river, there have been studies modeling the effects of land cover use and water quality parameters, more specifically, how do ongoing changes in population growth, urbanization, and land cover/land use changes affect non-point source pollution and phosphorous loading for two tributaries of the St. Croix River, the Willow and the Sunrise (Almendinger and Murphy 2007, Almendinger and Ulrich 2012). In the Sunrise River report they modeled the effects of four separate changing scenarios, including projected populated growth, agricultural practices, urban development, and wetland mitigation (Almendinger and Ulrich 2012). Lastly, Almendinger and Murphy (2005) used WISCLAND and National Agricultural Statistics Service (NASS) data to summarize changes in land cover use and agricultural practices in the Willow watershed. Among the results they found that from 1992 to 1999, cropland in the watershed declined by ca. 8.5-12%, with nearly 80% of the cropland loss occurring in the lower watershed due to residential development.

Importance of Disturbance Monitoring

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

Because landscape disturbances can affect a broad range of natural resources, being cognizant of what is happening in parts of the Saint Croix 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 landowners surrounding the park (Hansen and Rotella 2002, Wiersma et al. 2004, DeFries et al. 2007). The loss of roadless areas and increased fragmentation in the northern portions of the park may affect the abundance and movement patterns of species of interest within the park, and may contribute to the spread of both aquatic and terrestrial invasive species. Forest harvests adjacent to the St. Croix corridor may contribute to blowdown events (Stueve et al. 2011b), and abandoned logging roads may provide greater access to the park via motorized vehicles such as four-wheelers and snowmobiles.

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

Great Lakes Network Approach to Disturbance Monitoring at SACN

Given the choices in disturbance monitoring, the Great Lakes Network (GLKN) spent three years working with various collaborators to evaluate the advantages and disadvantages of various techniques. For our purpose, we define ‘disturbance’ as a distinct change in vegetation type. In addition to being accurate, the method chosen by GLKN needed to be cost-efficient to allow other GLKN 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 (Table 1). Another approach under consideration included the use of high resolution aerial photos with object-oriented software to delineate land cover classes which would then be monitored through time. This approach was not chosen due to the lack of a consistent source of high spatiotemporal resolution airphotos, and lack of repeatability. In the end, a consistent, unbiased approach was chosen that relies on freely available, moderate resolution (30m) satellite imagery (Landsat) (Table 1). 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 GGLN in terms of cost per hectare. The cost of implementing the protocol at SACN was only 3¢ 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 need to be undertaken, very similar to those of Almendinger et al. mentioned in the previous section.

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 four subwatersheds of the St. Croix river, totaling ca. 250,000 hectares (Figure 1). The size of the analysis area was limited by the amount of time the Network

could spend validating disturbances. It should be noted the ability to monitor large areas of land outside the park is due to the fact that Landsat imagery is being utilized as the foundation of the monitoring process.

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)
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)

Study Area

The study was conducted using four Landsat scenes (rows 28 and 29 in paths 26 and 27), to include SACN and four adjacent subwatersheds in western Wisconsin and eastern Minnesota (Figure 1). The administrative boundary of the park comprises an area of almost 40,000 ha (32,000 and 8,000 ha of land and water, respectively) and includes lands owned by the National Park Service (NPS), State and local governments, and lands in private ownership and encompassing over 400 km of river (Saint Croix and Namekagon). The Namekagon River is located wholly within the state of Wisconsin and the St. Croix River forms the boundary between Wisconsin and Minnesota from near the confluence of the Upper Tamarack to the St. Croix's confluence with the Mississippi River. In addition to the park administrative boundary, we analyzed a 300 meter buffer adjacent to the park, as well as four subwatersheds (Figure 2), totaling ca. 250,000 ha of land (Table 2). The four 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 77% of the total analysis area (Table 3).

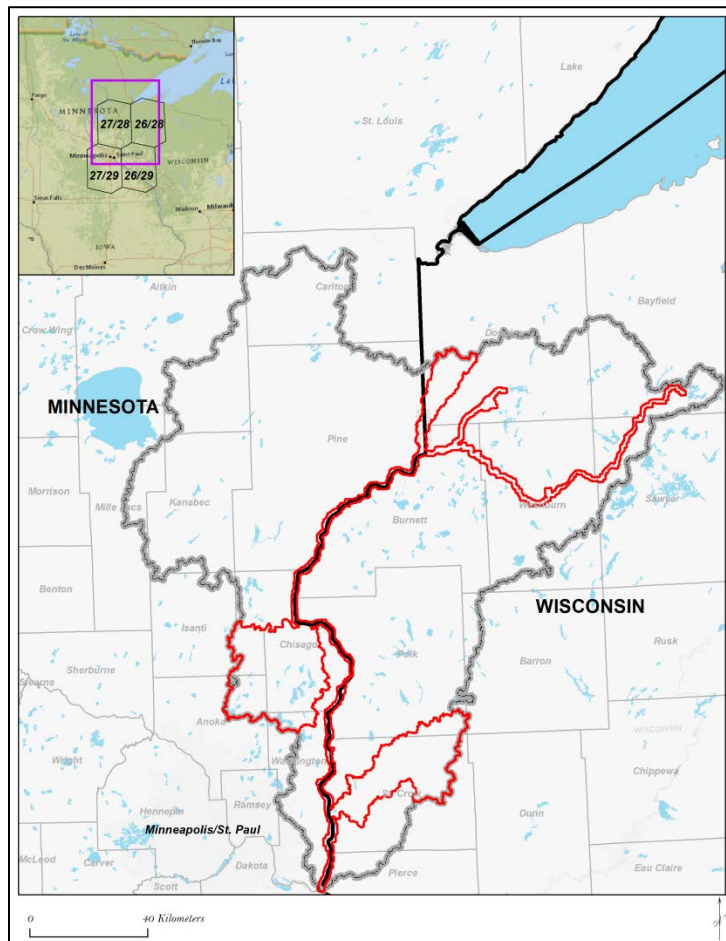


Figure 1. Study area for long-term monitoring of landscape-scale disturbances in and around St. Croix National Scenic Riverway. The inset shows extent (black lines) of the four Landsat scenes analyzed for this report. The larger map shows the extent of the analysis area (red line) inside the St. Croix river watershed (thick gray line).

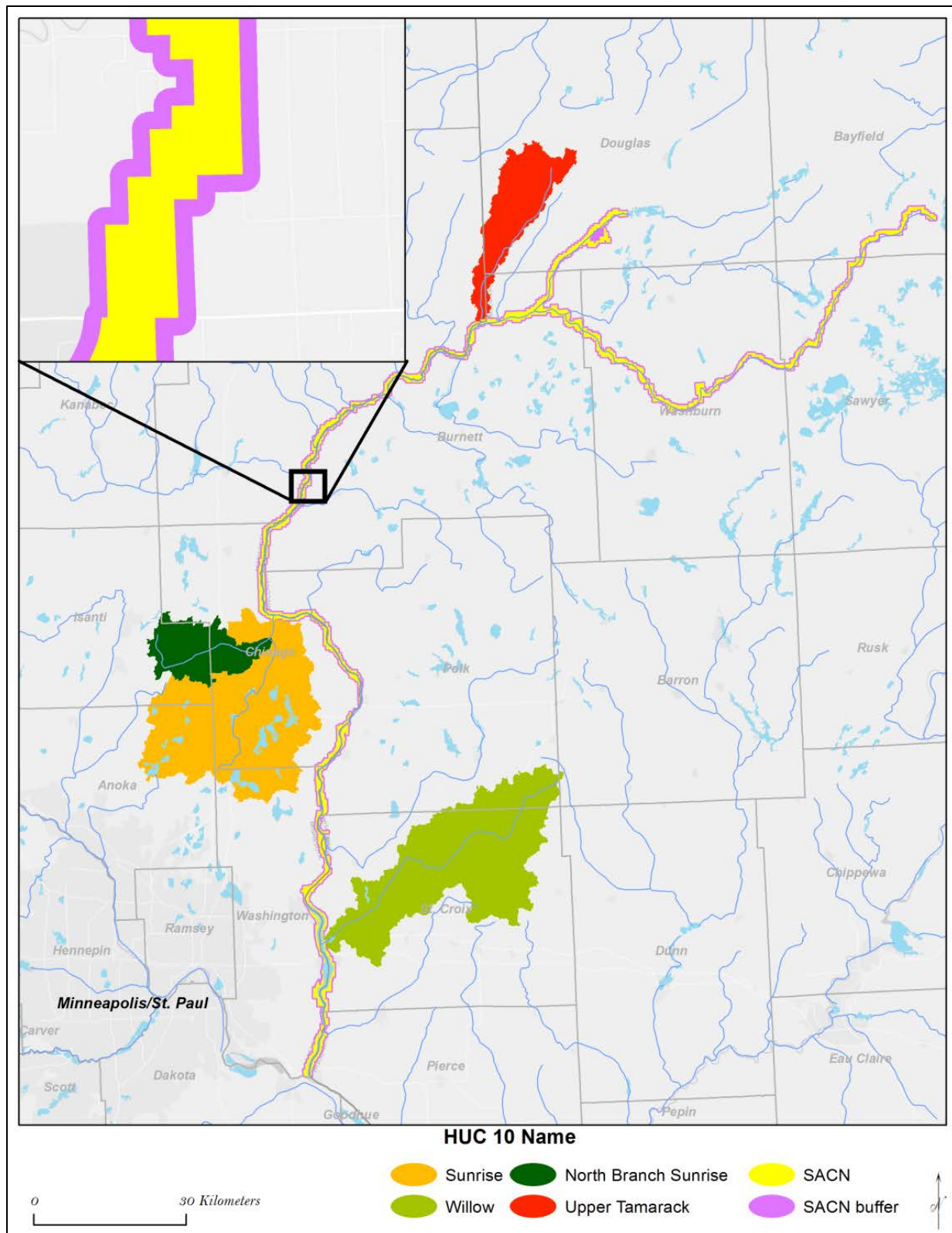


Figure 2. Location of the four subwatersheds (Sunrise, North Branch Sunrise, Willow, and Tamarack rivers) within the analysis area. The inset shows an example of the park administrative boundary (yellow) and the 300 m buffer (purple) adjacent to the park.

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

Analysis area	Size (ha)	Percent of analysis area
SACN	32,152	13
Non-SACN	220,502	87
Total	252,655	100

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

Watershed	Size (ha)	Percent of analysis area
Sunrise	73,020	29
North Branch Sunrise	19,906	8
Upper Tamarack	25,534	10
Willow	76,665	30
Total	195,126	77

Vegetation

The upper portion of the analysis area (north of the Sunrise river watershed) is dominated by a forested landscape consisting of northern boreal forest, bogs, and peatlands (Curtis 1959) (Figure 3). Conversely, the southern portion of the analysis area was originally vegetated by prairie and northern mixed hardwoods, but has since been converted to developed land and agricultural use (Curtis 1959). Overall, forests (deciduous, evergreen, and mixed) and agricultural land (pasture and agriculture) comprise 34 and 36%, respectively, of the analysis area (Appendix C, Table C1).

The northernmost watershed in the analysis area, the Upper Tamarack, has the largest proportion of forested area, with the remaining watersheds each having approximately the same proportion of forested area (Figures 4 and 5). The Willow watershed contains the largest proportion of agriculture/pasture lands, while the Upper Tamarack has the lowest proportion of agriculture/pasture land use, reflecting the forested landscape of northern Wisconsin (Figures 4 and 5). Lastly, the Upper Tamarack has the largest proportion of wetlands (woody and herbaceous), while the Willow has the lowest proportion (Table C2).

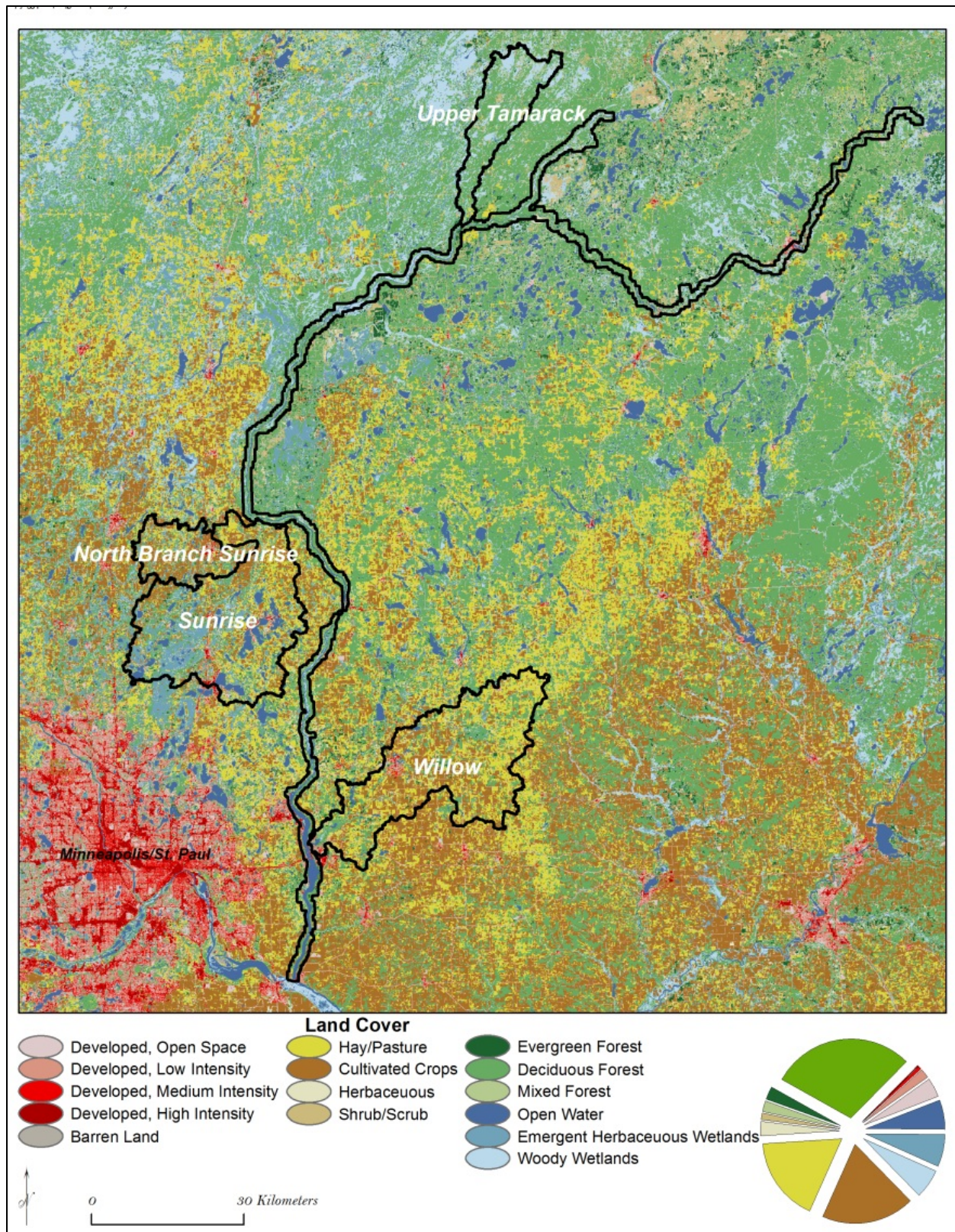


Figure 3. Vegetation classes within the analysis area (black line) and a pie chart showing the relative abundance of each class within the analysis area. Data from 2006 NLCD.

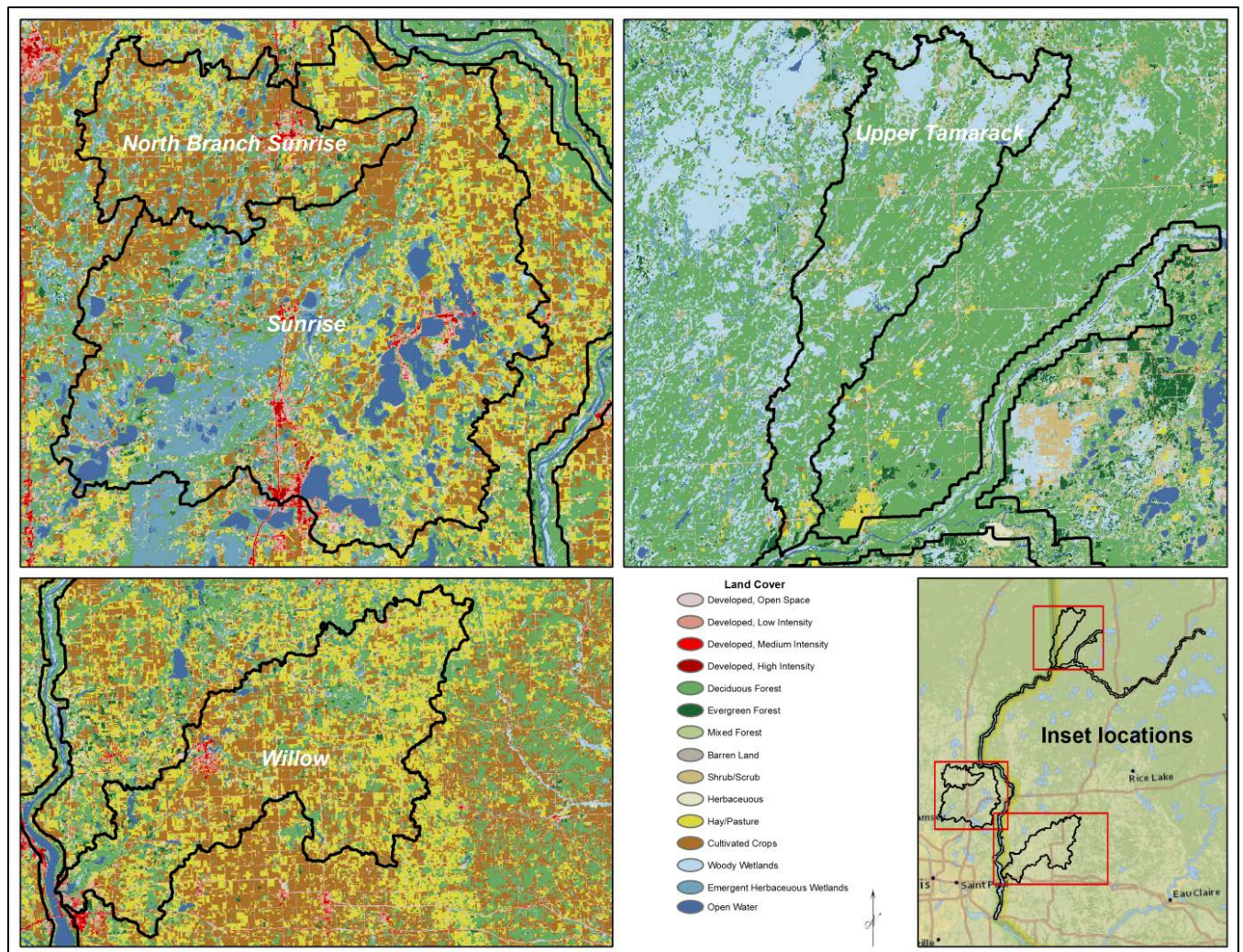


Figure 4. Vegetation within each of the four subwatersheds in the analysis area (black line). Data from 2006 NLCD.

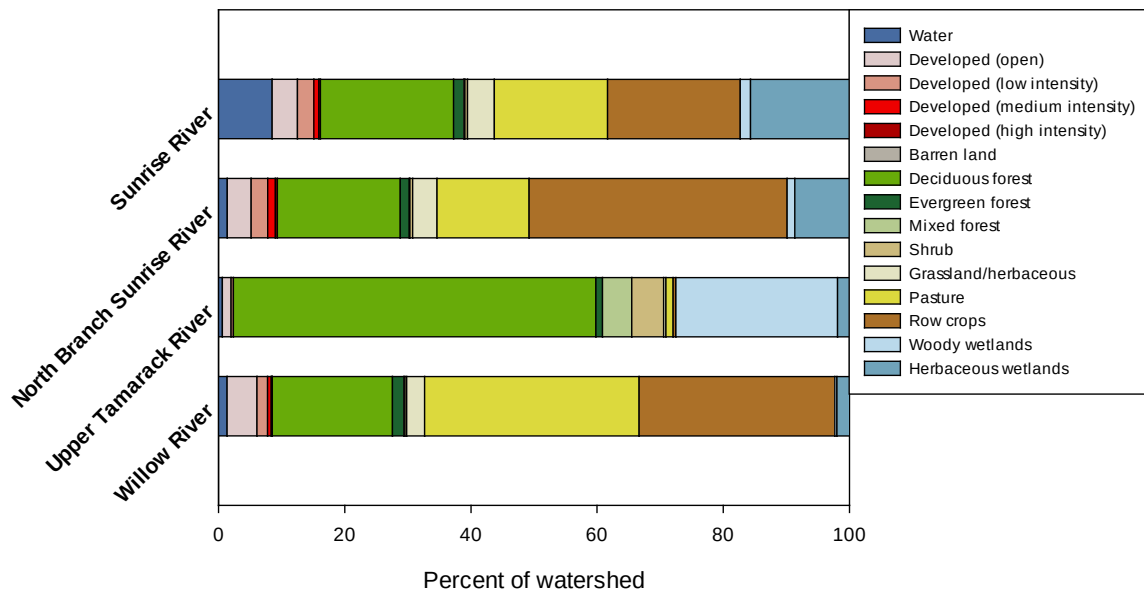


Figure 5. Relative abundance of vegetation classes within each of the four subwatersheds included in the analysis. Data from 2006 NLCD.

Ownership

We also summarized disturbances by ownership description and owner name as denoted by WI and MN GAP ownership layers. Ownership description is grouped into six categories: tribal, state, private, other public, federal, and county (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	Minnesota: Anoka, Chisago, Pine, Washington Wisconsin: Bayfield, Burnett, Polk, Douglas, Polk, Sawyer, Washburn
Federal	U.S. Army Corps of Engineers, Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service
Private	Carlson Farms Incorporated, Conservation Reserve Program (CRP) lands, Private, The Nature Conservancy
Other public	City of Forest Lake, City of Marine on St. Croix, University of Minnesota
State	Department of Corrections, Department of Military Affairs, Department of Transportation, Minnesota DNR, State of Minnesota, State of Wisconsin, Town of Somerset, Wisconsin DNR
Tribal	St. Croix Chippewa Indians of Wisconsin

The analysis area is largely held in private ownership, accounting for nearly 80% of the ownership (Figure 6). There were only four other ownerships which accounted for >2% of the land inside the analysis area: Douglas county, Minnesota DNR, National Park Service, and the Wisconsin DNR. These ownership patterns are also reflected in the six grouped categories, where private ownership outpaced all other grouped ownership types (Figure 7). County, state, and federal ownership were the remaining dominant owner types (Figure 7).

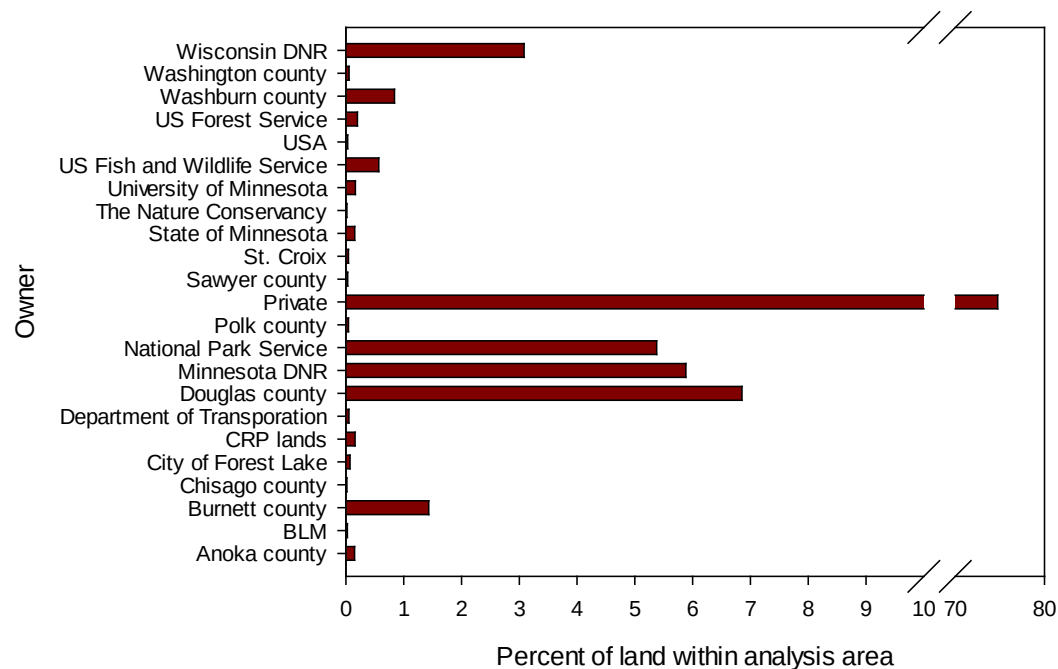


Figure 6. Percent of land within the analysis summarized by owner name. Owner names which represented <0.01% of the analysis area are not displayed on the bar graph. Data from the MN and WI GAP analysis datasets.

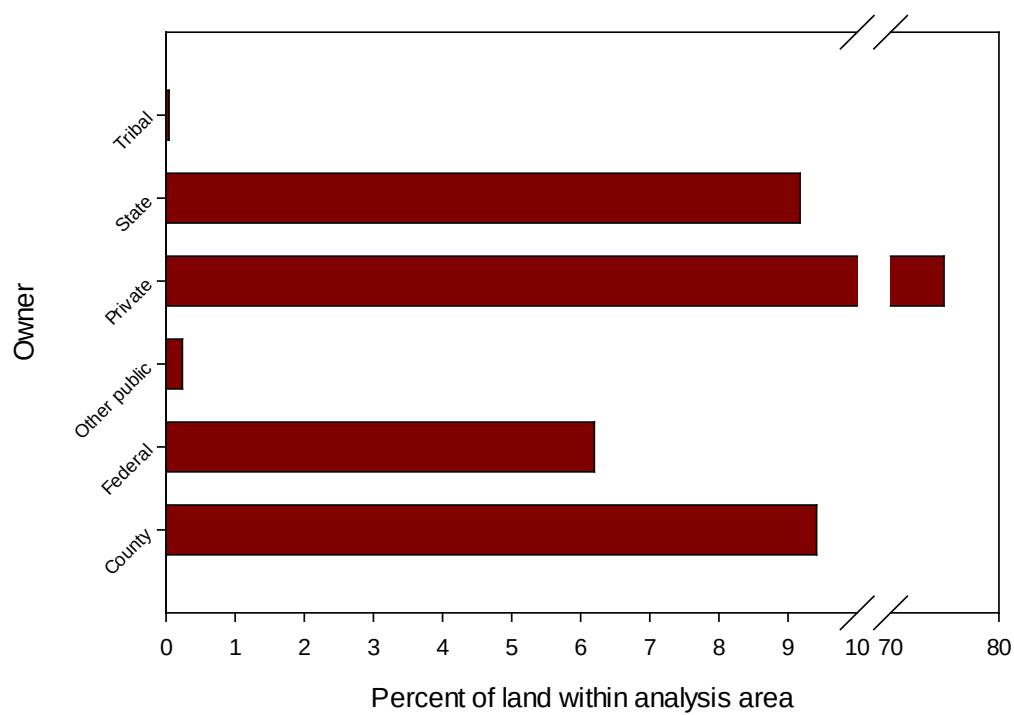


Figure 7. Percent of land within the analysis summarized by owner description. Data from the MN and WI GAP analysis datasets.

Methods

Image Data and Processing

Due to the location of Landsat scenes in reference to the analysis area, four scenes (paths 27 and 26, rows 28 and 29) were acquired for analysis (see Figure 1). [NOTE: the word “scene” refers to the path/row address that is recorded every 16 days by the Landsat satellite; data recorded on a specific date is referred to as an “image”] Landsat imagery was downloaded from the Landsat data archive via the U.S. Geological Survey’s (USGS) GLOVIS website (<http://glovis.usgs.gov/>). To minimize the effect of phenology, imagery was selected in a two month window (July and August) during the peak growing season (Figure 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. In total, nearly 200 images were downloaded and processed for analysis. Each collection of images by scene will be referred to as a Landsat time-series (LTS).

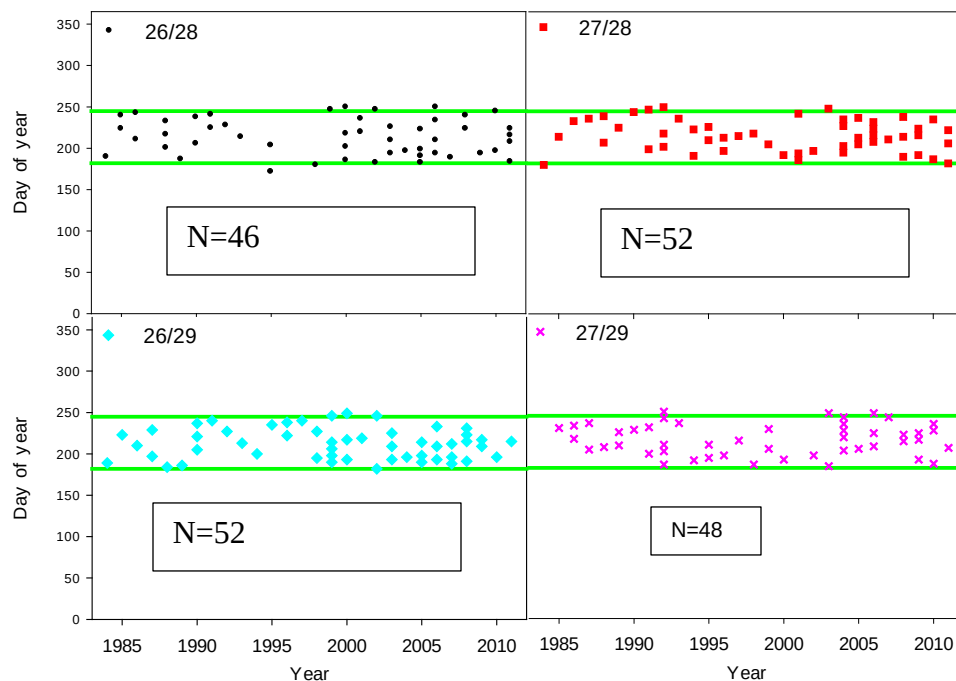


Figure 8. Day and year of Landsat images used for analysis for the four scenes with green lines delineating the time period between 1 July and 31 August.

Preprocessing of images (atmospheric correction, cloud screening, relative normalization) within each LTS followed details given in Kennedy et al. (2010b), and are briefly summarized here. Atmospheric correction was performed for a single reference image within each LTS using the COST model (Chavez 1996). All remaining images in the LTS were normalized using the MADCAL (Canty et al. 2004) approach to match the radiometric properties of the reference image. No effort was made to normalize each LTS to one another. We used an automated cloud

masking algorithm that incorporates the thermal band, a digital elevation model (DEM), a forest mask, and sun illumination geometry to automatically detect and remove clouds and associated shadows (Huang et al. 2010b). For images from the ETM+ sensor after the onset of scan line errors (2003 and later), missing pixel data were also masked. The normalized, cloud-screened images in the LTS served as the foundation for subsequent processing.

Next we applied the LandTrendr segmentation algorithms to every pixel in each scene's processing area. For details regarding any part of the LandTrendr process, see Kennedy et al. (2010b). LandTrendr algorithms operate on a single detection index; a detection index can be any single band of information. For this analysis we used the normalized burn ratio (NBR), which contrasts the short-wave infrared with the near-infrared bands (Key and Benson 2006). The segmentation process then proceeds as follows. 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 5). 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.

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 6 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 5 for parameters). This filtering is an effective means of reducing false changes from overfitting of anomalous or ephemeral spectral features in the times-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 less than four years 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 5. Parameters used in the LandTrendr process. Details found in Kennedy et al. (2010b).

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)

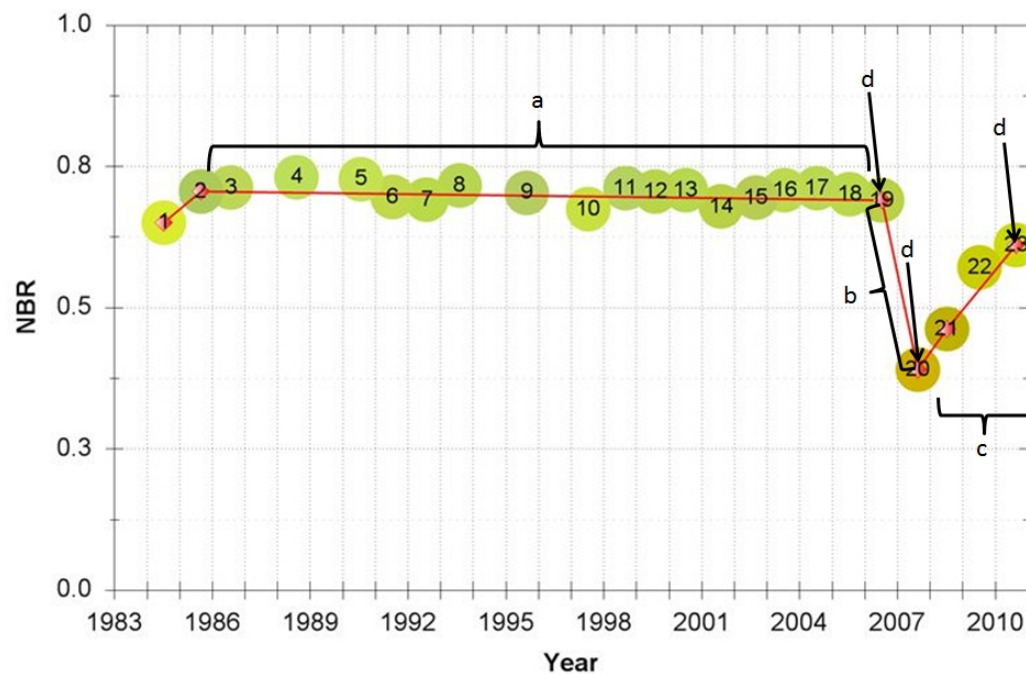


Figure 9. Diagram of how the LandTrendr segmentation algorithm processes a single pixel. The x-axis is the year of image acquisition and the y-axis is defined by the NBR value. Generally, NBR values range from low to high dependent on the amount of vegetation present. This graph shows a single pixel's 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.

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

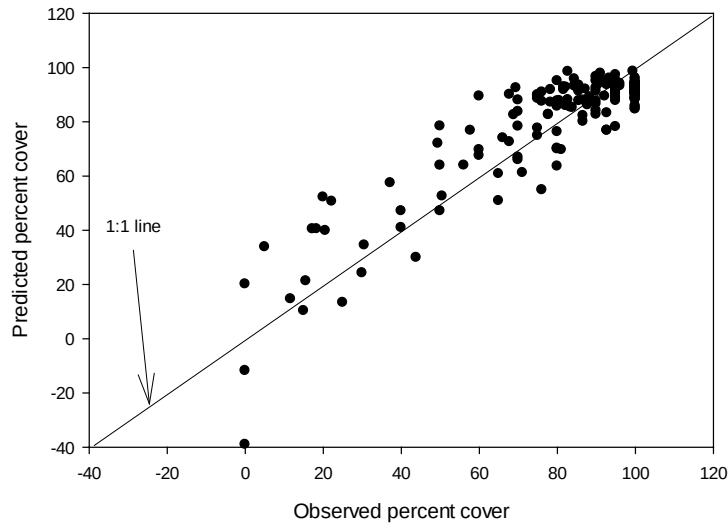


Figure 10. Predicted versus observed percent cover results from model predictions.

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 starting and ending vegetation classes (Table 7) and agent of change (Table 8) were added during the validation process. Using high resolution imagery (Table 9), 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 the starting and ending 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 the wind. Strong wind events, sometimes termed 'straight-line winds,' can create varying patch sizes of downed trees. These blown down trees are evident in high resolution airphotos and are usually oriented in the direction of the wind event. If this event occurs on private lands and a salvage harvest occurs before it is seen, it is classified as a harvest.
Development	Permanent conversion of vegetated surface to non-vegetated surface such as mines, paved roads, parking lots, and buildings.
Fire	Detection is limited to instances where there is mortality in the overstory. Thus, areas in which fires only burn the understory are not delineated.
Harvest	Forest harvests, including clearcuts and thinnings, new logging roads, and post-harvest prescriptions such as herbicide application or scarification.
Forest pathogen	Disturbances (mortality) in the overstory due to insects (e.g., forest tent caterpillar, spruce budworm) or diseases (e.g., oak wilt).

Table 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	1	B&W	APFO-NAPP	Airphoto	Entire
1998	1	B&W	APFO-NAPP	Airphoto	Entire
Summer 2003	1	RGB	APFO-NAIP	Airphoto	Partial
Summer 2004	2	RGB	APFO-NAIP	Airphoto	Entire
Summer 2005	0.3	RGB	APFO-NAIP	Airphoto	Entire
Fall 2005	0.18	CIR	GLKN	Airphoto	SACN
Spring 2006	0.15	RGB	GLKN	Airphoto	SACN – partial
Spring 2007	0.15	RGB	GLKN	Airphoto	SACN – partial
Summer 2006	2	RGB	APFO-NAIP	Airphoto	Entire
Summer 2008	1	RGB	APFO-NAIP	Airphoto	Entire
Summer 2009	1	RGB	APFO-NAIP	Airphoto	Partial
Spring 2010	0.45	RGB	WROC	Airphoto	Partial
Summer 2010	1	RGB	APFO-NAIP	Airphoto	Entire

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

Field	Definition
Location	SACN or Non-SACN
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 (<20% tree cover remaining), 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 SACN. To investigate the possible effects of multiple interpreters such as systematic bias, 10% of each users' 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 used to create the graphs presented in the results section.

Percent of Land Disturbed

SACN

During the six-year study period, a total of 1.1% (358 ha) of the land inside the park administrative boundary was disturbed (Appendix C, Table C3). The largest percentage of land disturbed in any single year was 2007, in which a fire in the northern reaches of the Namekagon River was detected (Appendix A, Figure A1). The percent of disturbed land varied through the analysis time period, ranging from a low of 0.04% in 2009 to a high of 0.36% in 2007 (Figure 11).

Non-SACN

Collectively, 0.85% (1876 ha) of the land outside the park was disturbed during the six-year period (Appendix C, Table C3). The amount of land disturbed each year was generally stable, averaging ca. 300 ha/yr. In half of the years, the percent of land disturbed outside the park was greater than that inside the park boundary (Figure 11).

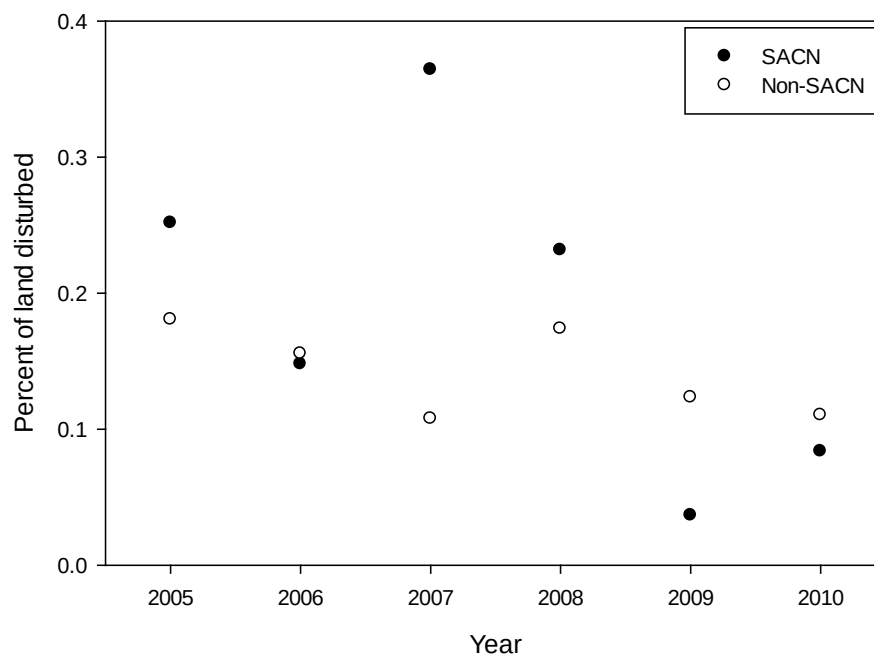


Figure 11. Percent of land disturbed within each analysis area, by year.

Disturbance Agents

SACN

During the six year analysis period, all possible disturbance agents were detected, with forest harvest being the most prevalent, detected in each year (Figure 12). The administrative boundary

of the park includes non-NPS ownership (ca. 40%) which accounts for (most of) the forest harvest disturbances. Disturbances by forest pathogens were found in years 2005 and 2010, with blowdown events occurring in 2006 and 2010. The only year with appreciable ($>0.01\%$) disturbance by development was 2005, when ca. 10 ha of land was developed inside the administrative boundary (Figure 12 and Appendix C, Table C4). One disturbance event which may be of interest to SACN, was the blowdown event in 2011. However, because our analysis period is from 2005-2010, this event was not delineated by LandTrendr. This event was mapped by the WI DNR shortly after it occurred and their data is presented in Appendix E.

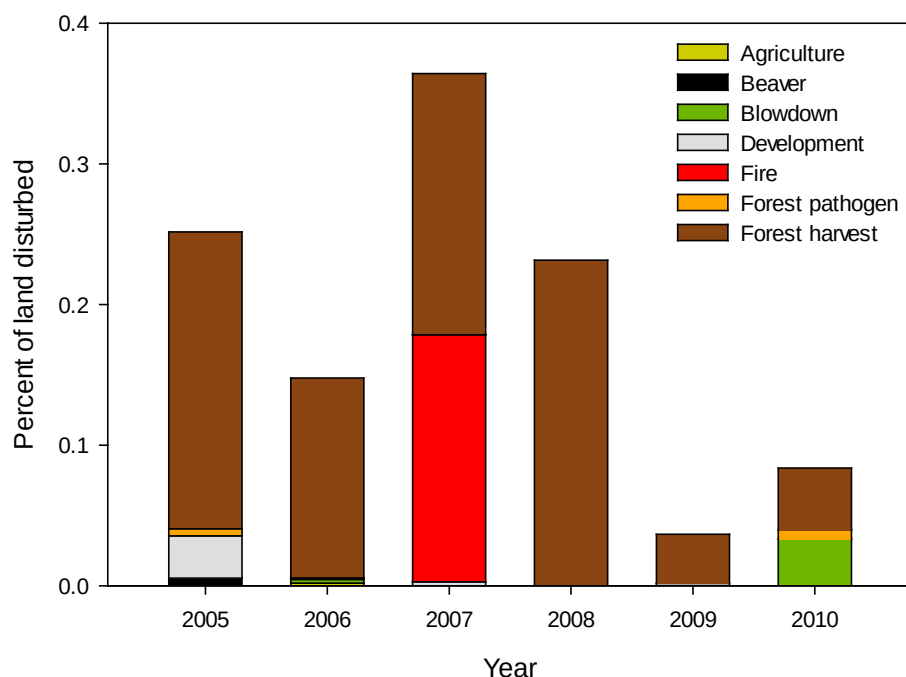


Figure 12. Percent of land disturbed by causal agent and year inside SACN during the analysis period.

Non-SACN

On lands outside the park administrative boundary, forest harvest was the largest contributor to disturbances in each of the analysis years (Figure 13). Forest harvesting peaked in 2008, when 0.15% (339 ha) of the land was disturbed. Development was also present in each year of the analysis, with the largest amount of disturbance in 2005 and the least amount in 2009 (Figure 13 and Appendix C, Table C4). There were also disturbances by beaver in five of the six years, although, in total, affected only 0.01% (14.7 ha) of the land outside the park (Appendix C, Table C4). Agricultural disturbances, where land was converted to agricultural row crops, were also present outside the park, but totaled $<0.01\%$ of the land, or 6 ha (Appendix C, Table C4).

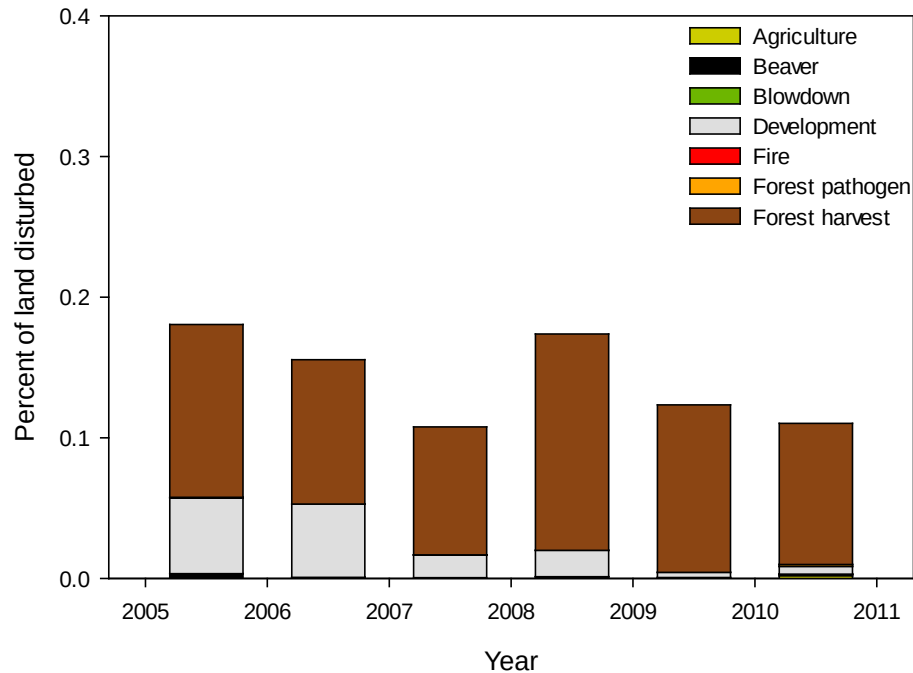


Figure 13. Percent of land disturbed by causal agent and year outside SACN during the analysis period.

Land Cover Dynamics

It is possible to identify up to three separate starting and ending classes for polygons that encompass multiple cover types. For more details on how starting and ending classes are defined and chosen, see Kirschbaum and Gafvert (2010a). To facilitate displaying data in this report, starting and ending classes have been combined into generalized groupings (Table 11).

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

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

SACN

The fire in 2007 converted some upland forest to upland shrub, the result of a canopy fire which killed the overstory trees. Nearly half of the lowland forest disturbed in 2005 was converted to lowland shrub, in addition, some of the land was converted to pervious surface (Figure 14). In all remaining years (2006, 2008-2010), the majority of the conversion was from upland forest to upland woodland and shrub as a result of forest harvests, blowdown and forest pathogens (Figure 14).

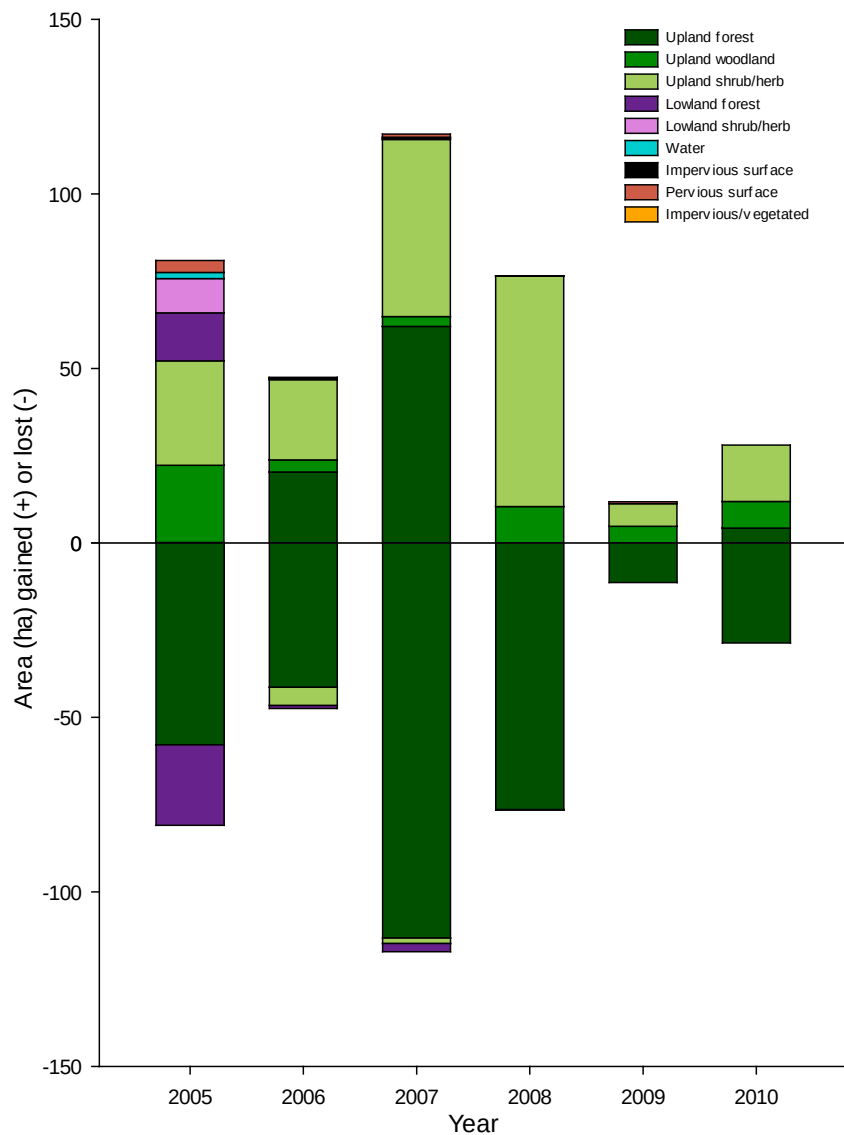


Figure 14. Area (ha) of vegetation cover type lost (-) and gained (+) at SACN during the analysis period (2005-2010). In some cases (year 2006) the vegetation lost is the same amount and type as vegetation gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to alter the vegetation type. One such example is a forest thinning which removes a portion of the tree cover, but is still classified as forest because it did not meet the lower percent cover threshold for woodland.

Non-SACN

Outside the SACN administrative boundary, there was much more land conversion to ‘developed’ classes, i.e., impervious, pervious, and impervious/vegetated (Figure 15). The majority of the pervious surface gained during the analysis period occurred in 2005 and 2006, with a small amount gained in 2008 as well (Figure 15 and Table C7). Upland forest was the most common land cover class disturbed during the analysis period, with the majority of it being converted to upland woodland and shrub/herb (Figure 15).

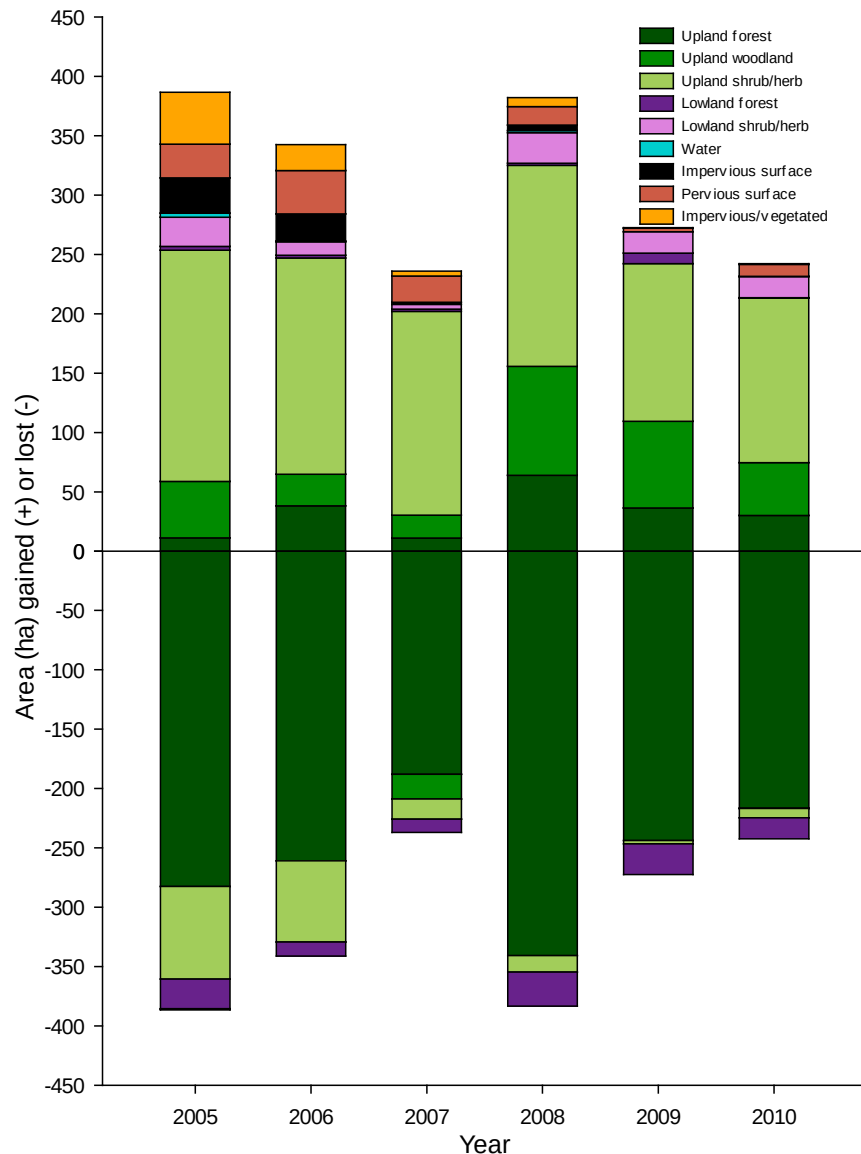


Figure 15. Area (ha) of vegetation cover type lost (-) and gained (+) outside the SACN administrative boundary during the analysis period (2005-2010). In some cases (year 2006) the vegetation lost is the same amount and type as vegetation gained. This occurs when a vegetation type has been affected, but the disturbance was not severe enough to alter the vegetation type. One such example is a forest thinning which removes a portion of the tree cover, but is still classified as forest because it did not meet the lower percent cover threshold for woodland.

Disturbance Agents by Ownership Type

If an owner name or owner description category is not represented on the graph, there were no disturbances in the respective ownership. Ownership data for lands in MN were obtained from the complete MN GAP stewardship database available at the MN DNR data deli (<http://deli.dnr.state.mn.us/>). Similarly, ownership data for WI was obtained from the complete WI GAP stewardship database available at the WI DNR public ftp site (<ftp://dnrftp01.wi.gov/geodata/>).

Owner description

As a percent of the analysis area, lands owned by counties were disturbed at a higher rate than all others, including private ownership (Figure 16). Forest harvesting was the largest disturbance agent in county ownership, with disturbances by beaver and development contributing much smaller amounts (Table C8). Federally owned lands had blowdown, development, fire, and forest harvests occur on their land, with forest harvests being the largest proportion of the disturbances (Figure 16). Lands within tribal ownership had almost no disturbance, except for a very small amount (<1ha or 0.00035%) of development (Table C8). The major disturbance types within privately-owned lands were development and forest harvest, which were nearly equal, with additional disturbances by everything else except fire (Table C8). Lastly, state-owned lands were predominantly disturbed due to forest harvest, yet small amounts disturbance by beaver, development, and forest pathogens were detected (Figure 16).

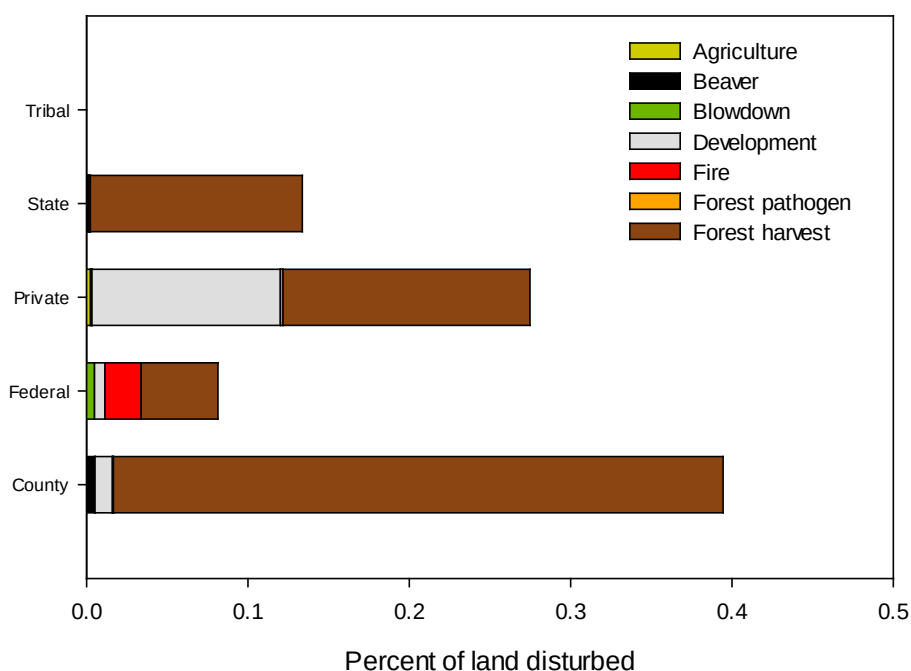


Figure 16. Percent of land disturbed inside the entire analysis area, totaled for the six year analysis period, in five broad ownership types (owner description). There were no disturbances in the 'other public' ownership category.

Owner name

If ownership is looked at we can see that the two major owners with disturbances were Douglas county and private (Figure 17). Nearly half of the disturbances in private ownership were of development, with the remainder mainly forest harvesting. This contrasts the disturbances within Douglas county land, where nearly all of the disturbances were due to forest harvests (Figure 17). All remaining ownerships had disturbances totaling less than 0.1% of the entire analysis area. In addition, we summarized the amount of land within the analysis area by the owner and overlaid this on each owner's contribution to the percent of land disturbed. This revealed that, although Douglas county and Private ownership both contributed equally to the amount of land disturbed within the analysis area, Douglas county owned only 7% of the land within the analysis area. On the other hand, privately owned land accounted for nearly 80% of the land within the analysis area.

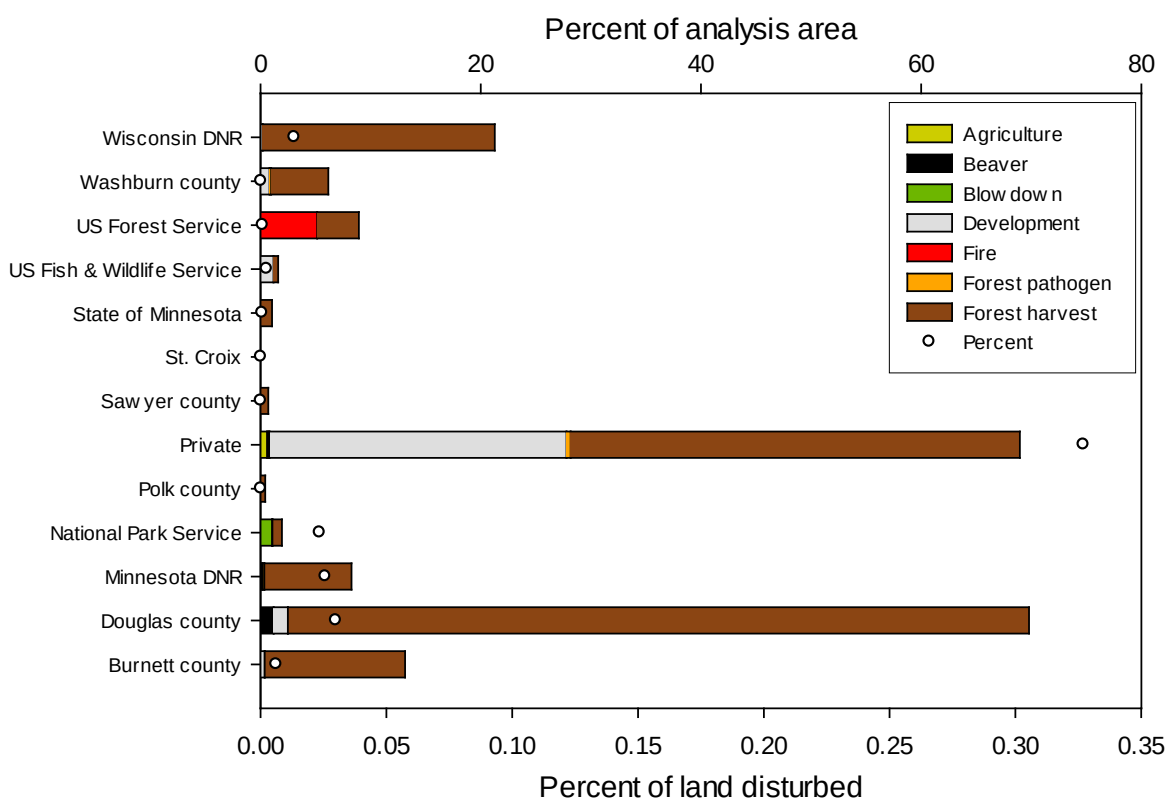


Figure 17. Percent of land disturbed within the entire analysis area by owner name, overlaid by percent of analysis area occupied (hollow circles). If an owner name is missing, there were no disturbances in the category.

Disturbance Agents by Subwatershed

Disturbance agents can also be summarized by the four subwatersheds (HUC 10) in the analysis area. The Upper Tamarack experienced the largest amount of land disturbed amongst the watersheds, with just over 3% of its land disturbed during the analysis period. Most of the disturbance was due to forest harvest (2.9%), with much smaller disturbances by beaver and development (Figure 18). In the remaining subwatersheds, development outpaced all other disturbance agents.

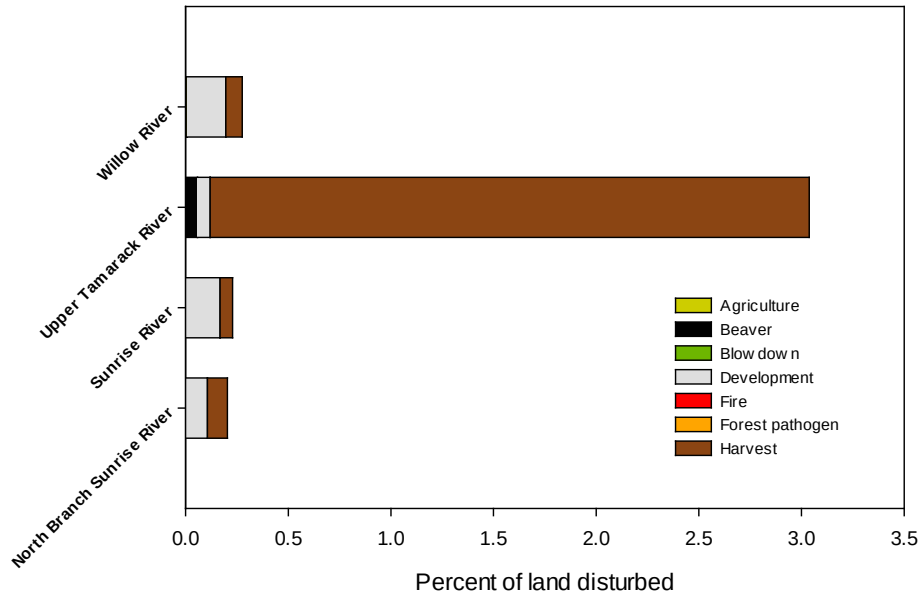


Figure 18. Percent of each subwatershed (HUC 10), by disturbance agent, affected during the analysis period. For example, 3% of the land area within the Upper Tamarack was disturbed.

Discussion

Contrary to all other parks we have analyzed thus far (VOYA, ISRO, and APIS); SACN actually had a larger percent of the land within the park administrative boundary disturbed than outside (Figure 11). This is due to the fact that the National Park Service does not own all of the land within the SACN administrative boundary. In fact, the park only owns 60% of the land area within the administrative boundary (Figure 19). The remaining land is owned and managed by others, including state and private entities (Table C12).

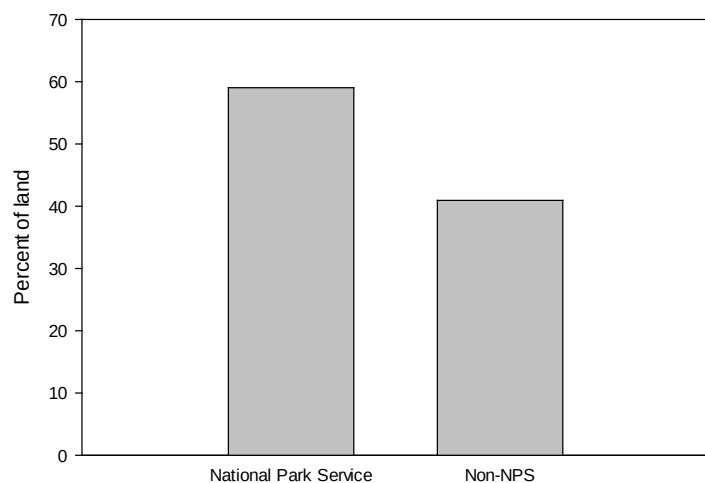


Figure 19. Percent of land (not including water) owned by the NPS and non-NPS, within the SACN administrative boundary.

When viewing the disturbances by ownership type within the administrative boundary, one can see there is nearly five-times as much disturbance by non-NPS ownership. Slightly over half of the disturbance in NPS ownership was due to a blowdown event totaling only 11.5 ha, while the forest harvest that occurred on NPS-owned land, totaled 9.5 ha (Appendix C, Table C11). It should be noted that the ownership information was derived from MN and WI GAP ownership GIS layers. These data may not always accurately describe the ownership levels, particularly if the parcels are small (<1 ha) or have recently (post-2010) changed ownership. The disturbances on non-NPS owned lands inside the boundary were mainly results of forest harvesting with additional disturbances by fire, development, forest pathogen and beaver (Figure 20 and Appendix C, Table C11).

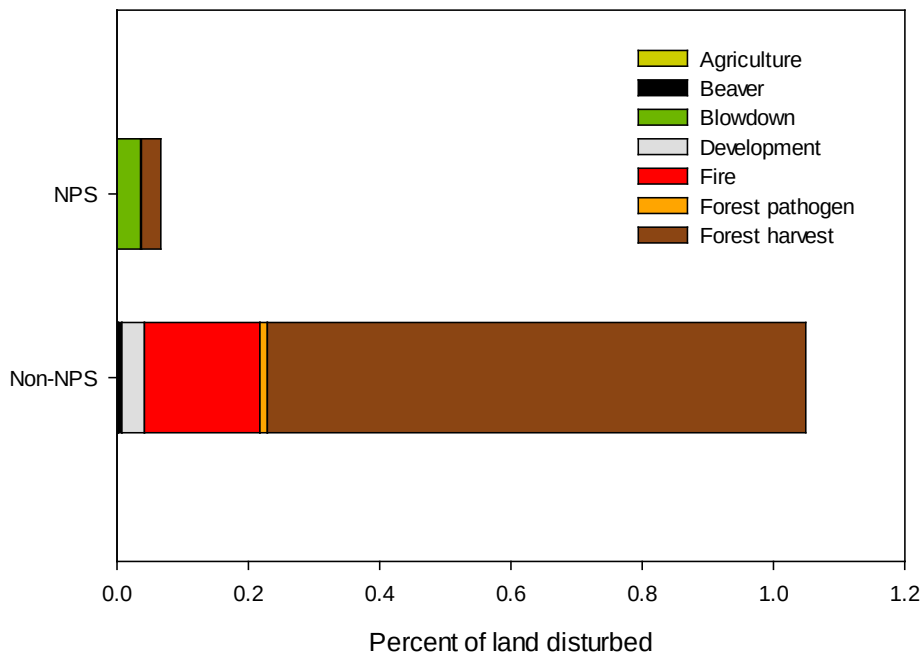


Figure 20. Percent of land disturbed inside the SACN administrative boundary by disturbance agent and NPS versus non-NPS-owned lands.

Inside the park boundary most of the land conversion was from forested land classes (upland and lowland) to shrub/herbaceous or woodland classes. The amount of land converted to a more ‘developed’ class (impervious, pervious, or impervious/vegetated) was quite small and only an appreciable amount was seen in 2005, when there was a total of ca. 3.5 ha of pervious surface gained (Figure 14 and Appendix C, Table C7). The nearly total absence of gains in ‘developed’ classes within the boundary indicates that the majority of the lands have not actually experienced land use changes, instead, this land is still being utilized for the same land use type. While this is encouraging for the river corridor proper, in itself it cannot be used to indicate a completely healthy (ecologically) river.

Outside the administrative boundary, forest harvesting was the most prevalent agent of change each year of the analysis period. Spatially, these harvests largely occurred in the Upper Tamarack watershed, in the northern part of the analysis area (Appendix B, Figure B1). As a percent of the total analysis area, the Upper Tamarack accounted for slightly over a third of the land disturbed in the analysis area, dominated by forest harvests (Figure 21). However, as a percent of the total analysis area, the Upper Tamarack only comprised 10% of the analysis area. By comparison, the Sunrise and Willow comprised nearly 30% each of the analysis area, but had much lower rates of disturbance. The river corridor (park boundary plus 300 m buffer) experienced the highest rate of disturbance, but also comprised nearly a quarter of the analysis area.

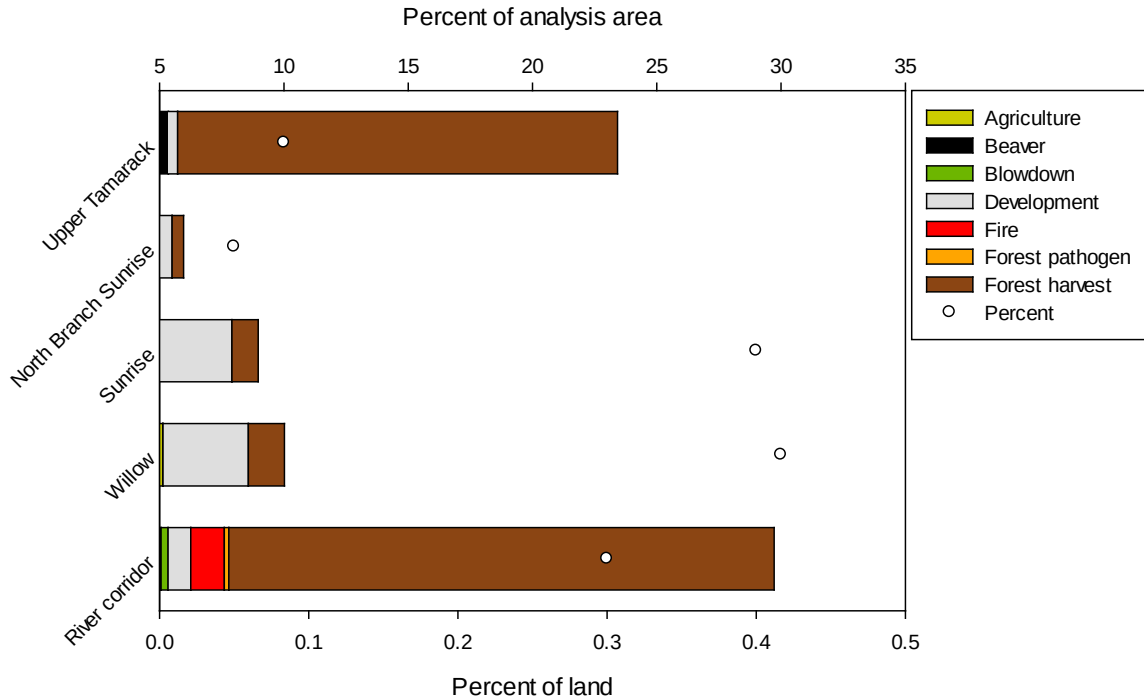


Figure 21. Percent of land disturbed inside the entire analysis area by subwatershed and all other land (river corridor), overlaid by the percent of analysis area occupied (hollow circle).

To investigate if management could be driving the amount of forest harvest within the Upper Tamarack and the river corridor areas, we summarized ownership within each area (Figure 22). Within the Upper Tamarack, county ownership represented the majority of land (60%) with private ownership the second largest owner. In contrast to the subwatersheds, the river corridor had the most diversified collection of ownership types, with private ownership representing the largest percentage. Federal, state, county, other public, and tribal ownership were the remaining owners within the corridor (Figure 22). The remaining subwatersheds (North Branch Sunrise, Sunrise, and Willow) were all heavily dominated by private ownership and having less diverse ownership patterns than the river corridor which contained six different owners.

We can also see the role of land use in influencing the disturbance agents. The subwatersheds dominated by non-forest land classes; Willow, Sunrise, and the North Branch of Sunrise, were dominated by development (see Figures 5 and 21). Not surprisingly, the same three subwatersheds also have the highest population and road density (Figure 23).

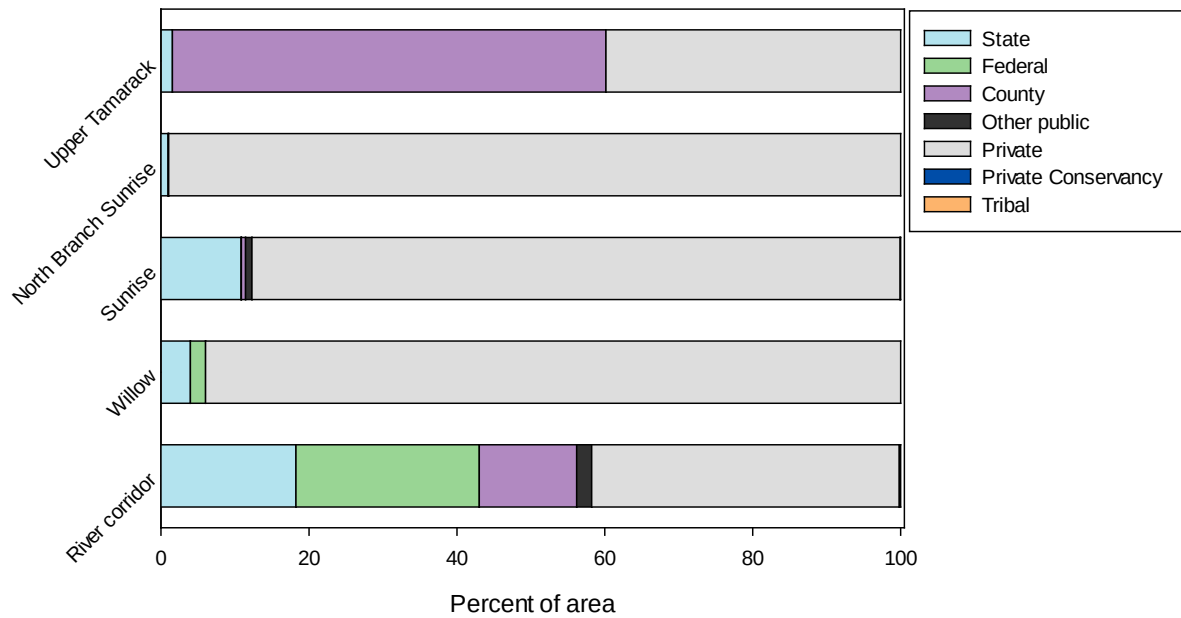


Figure 22. Ownership categories within each of the subwatersheds and the river corridor.

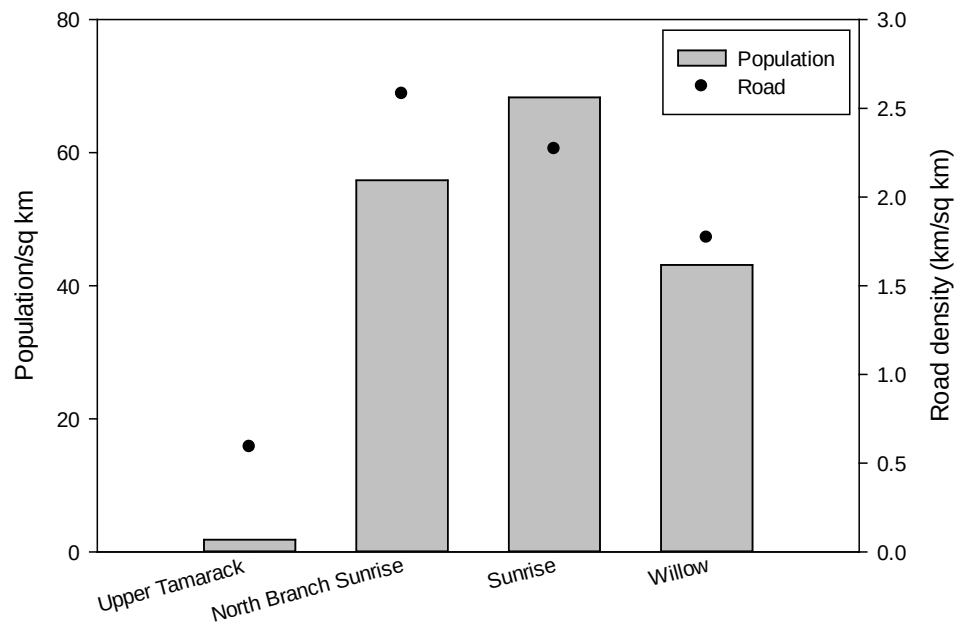


Figure 23. Population (per square km) and road (km/sq km) density within each of the subwatersheds in the analysis area. Census and road data from 2010.

Comparison Across Park Units

This is the fourth park analyzed in the series of parks, with Voyageurs NP, (VOYA), Isle Royale NP (ISRO), and Apostle Islands NL (APIS), being analyzed in 2009, 2010, and 2011, respectively (Kirschbaum and Gafvert 2010b, 2012, Kirschbaum et al. 2012). The specific years analyzed for each park varied, each containing a total of six years (Table 12). If the APIS forest pathogen is excluded, SACN had the highest percent of land inside the park disturbed across the four parks. The forest pathogen disturbance at APIS did not result in any forest mortality, only deciduous defoliation. As was mentioned earlier, this is due to the fact that the park does not own all land inside its boundary. Outside the park boundary, SACN had the lowest percentage of land disturbed, with ISRO having the next highest disturbance rate outside the park (Figure 24).

Table 12. The years contained within each analysis period by park unit.

Park	Years analyzed
VOYA	2002-2007
ISRO	2003-2008
APIS	2004-2009
SACN	2005-2010

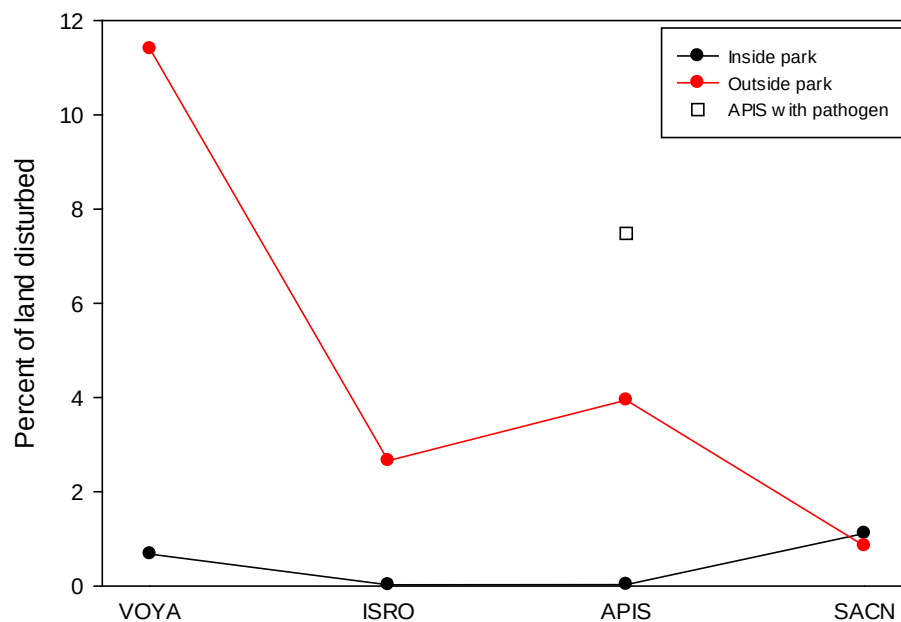


Figure 24. Percent of land disturbed inside the park (black line and circle) versus outside the parks (red line and circle). The hollow square symbol includes a large forest pathogen event inside APIS, while the black circle does not incorporate this disturbance

While viewing the disturbance agents present inside park boundaries across the four parks, one agent present at SACN and in no other parks, was forest harvest. As mentioned previously, this

is because not all the land within the administrative boundary is managed by the park service. In addition, SACN also had disturbances due to development activities (Figure 25).

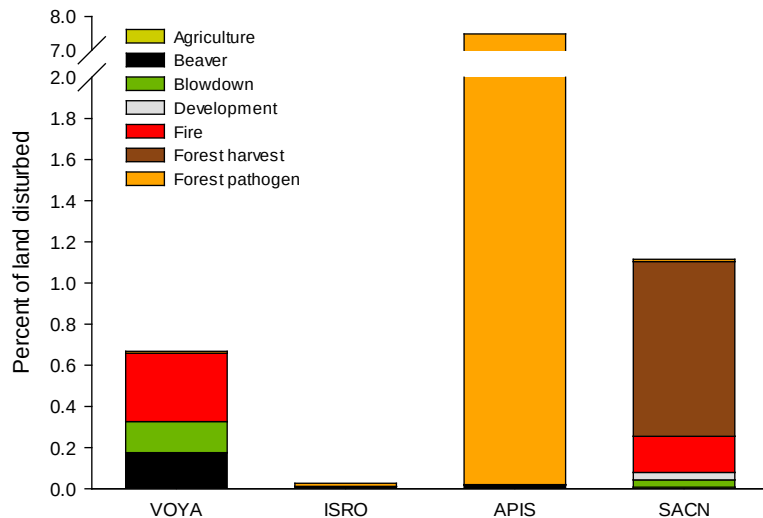


Figure 25. Percent of disturbed land at ISRO, VOYA, and APIS by causal agent.

Outside the parks, forest harvest continues to be the dominant disturbance agent; however the lands surrounding SACN experienced less forest harvest than any park to date. SACN also had the lowest overall percent of land disturbed, nearly ten times less than lands surrounding VOYA (Figure 26). The lands surrounding VOYA are heavily managed for large scale timber production, versus the smaller tracts of land surrounding the SACN boundary.

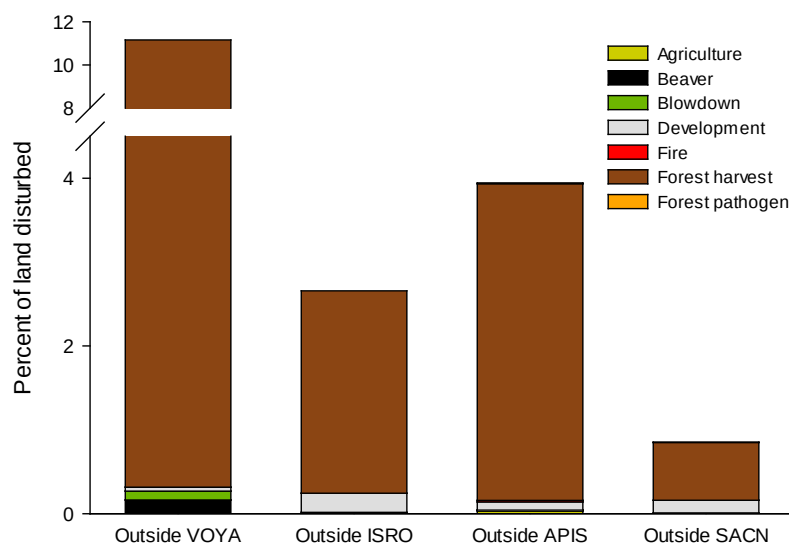


Figure 26. Percent of land disturbed by disturbance agent outside each of the respective parks.

Conclusions

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

- 1) SACN experienced the 2nd highest amount of land disturbed within the administrative boundary of all parks analyzed thus far.
- 2) Privately owned lands experienced the greatest percentage of land disturbed, nearly equally distributed among forest harvest and development.
- 3) Of the four subwatersheds studied, the Upper Tamarack had the highest disturbance rate (0.5%/yr). The vast majority of the disturbance was due to forest harvesting on lands owned by Douglas County. Although this watershed only represented 10% of the total analysis area, it was the second largest contributor to disturbances within the analysis area.
- 4) Among the four parks, SACN had the lowest percentage of land disturbed outside the park. The level of disturbance at SACN was low largely because forestry practices, which affect large tracts of land, were limited because of the prominence of agriculture and development in the lower half of the basin.
- 5) The river corridor contributed the largest percentage of disturbances, mainly the result of forest harvesting.
- 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', however 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 on which we will continue to monitor the same types of activities and develop a long-term record of disturbance. Over a longer term, this program may help reveal a change in the disturbance regime (size, location, frequency) due to climate change, with increased high intensity storm events, or outbreaks of insect or disease due to higher mean annual temperatures. Information gleaned from these reports will become increasingly emergent.

Literature Cited

- Aldrich, R. C. 1975. Detecting disturbances in a forest environment. *Photogrammetric Engineering and Remote Sensing* 41:39-48.
- Almendinger, J. E., and M. Murphy. 2005. Land-use change and agricultural practices in the Willow River watershed, western Wisconsin, 1992-2004. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota.
- Almendinger, J. E., and M. Murphy. 2007. Constructing a SWAT model of the Willow River watershed, western Wisconsin. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota.
- Almendinger, J. E., and J. Ulrich. 2012. Applying a SWAT model of the Sunrise River watershed, eastern Minnesota, to predict water-quality impacts from land-use changes. St. Croix Watershed Research Station, Science of Museum of Minnesota, Marine on St. Croix, Minnesota.
- Benz, U. C., P. Hofmann, G. Willhauck, I. Lingenfelder, and M. Heynen. 2004. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. *ISPRS Journal of Photogrammetry and Remote Sensing* 58:239-258.
- Brown, D. G. 2003. Land use and forest cover on private parcels in the upper Midwest USA, 1970 to 1990. *Landscape Ecology* 18:777-790.
- Canty, M. J., A. A. Nielsen, and M. Schmidt. 2004. Automatic radiometric normalization of multitemporal satellite imagery. *Remote Sensing of Environment* 91:441-451.
- Chavez, P. S. 1996. Image-based atmospheric corrections revisited and improved. *Photogrammetric Engineering and Remote Sensing* 62:1025-1036.
- Chen, X. X., J. E. Vogelmann, M. Rollins, D. Ohlen, C. H. Key, L. M. Yang, C. Q. Huang, and H. Shi. 2011. Detecting post-fire burn severity and vegetation recovery using multitemporal remote sensing spectral indices and field-collected composite burn index data in a ponderosa pine forest. *International Journal of Remote Sensing* 32:7905-7927.
- Cihlar, J. 2000. Land cover mapping of large areas from satellites: Status and research priorities. *International Journal of Remote Sensing* 21:1093-1114.
- Cohen, W. B., M. Fiorella, J. Gray, E. Helmer, and K. Anderson. 1998. An efficient and accurate method for mapping forest clearcuts in the Pacific Northwest using Landsat imagery. *Photogrammetric Engineering and Remote Sensing* 64:293-300.
- Cohen, W. B., and S. N. Goward. 2004. Landsat's role in ecological applications of remote sensing. *BioScience* 54:535-545.

- Cohen, W. B., Z. Yang, and R. E. Kennedy. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync - Tools for calibration and validation. *Remote Sensing of Environment* 114:2911-2924.
- Coppin, P., I. Jonckheere, K. Nackaerts, B. Muys, and E. Lambin. 2004. Digital change detection methods in ecosystem monitoring: A review. *International Journal of Remote Sensing* 25:1565-1596.
- Coppin, P. R., and M. E. Bauer. 1995. The potential contribution of pixel-based canopy change information to stand-based forest management in the northern U.S. *Journal of Environmental Management* 44:69-82.
- Curtis, J. T. 1959. The Vegetation of Wisconsin. University of Wisconsin Press, Madison, Wisconsin.
- Deel, L. N., B. E. McNeil, P. G. Curtis, S. P. Serbin, A. Singh, K. N. Eshleman, and P. A. Townsend. 2012. Relationship of a Landsat cumulative disturbance index to canopy nitrogen and forest structure. *Remote Sensing of Environment* 118:40-49.
- DeFries, R., A. Hansen, B. L. Turner, R. Reid, and J. Liu. 2007. Land use change around protected areas: Management to balance human needs and ecological function. *Ecological Applications* 17:1031-1038.
- Desclee, B., P. Bogaert, and P. Defourny. 2006. Forest change detection by statistical object-based method. *Remote Sensing of Environment* 102:1-11.
- Eshleman, K. N., B. E. McNeil, and P. A. Townsend. 2009. Validation of a remote sensing based index of forest disturbance using streamwater nitrogen data. *Ecological Indicators* 9:476-484.
- Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution and Systematics* 34:487-515.
- Fitzpatrick, F. A., J. C. Knox, and H. E. Whitman. 1999. Effects of historical land-cover changes on flooding and segmentation, North Fish Creek, Wisconsin. USGS Water-Resources Investigations Report 99-4083.
- Hansen, A. J., and J. J. Rotella. 2002. Biophysical factors, land use, and species viability in and around nature reserves. *Conservation Biology* 16:1112-1122.
- Harvey, K. R., and G. J. E. Hill. 2001. Vegetation mapping of a tropical freshwater swamp in the Northern Territory, Australia: A comparison of aerial photography, Landsat TM and SPOT satellite imagery. *International Journal of Remote Sensing* 22:2911-2925.
- Hay, G. J., T. Blaschke, D. J. Marceau, and A. Bouchard. 2003. A comparison of three image-object methods for the multiscale analysis of landscape structure. *ISPRS Journal of Photogrammetry and Remote Sensing* 57:327-345.

- Healey, S. P., W. B. Cohen, Z. Q. Yang, and O. N. Krankina. 2005. Comparison of tasseled cap-based Landsat data structures for use in forest disturbance detection. *Remote Sensing of Environment* 97:301-310.
- Heurich, M., T. Ochs, T. Andresen, and T. Schneider. 2010. Object-orientated image analysis for the semi-automatic detection of dead trees following a spruce bark beetle (*Ips typographus*) outbreak. *European Journal of Forest Research* 129:313-324.
- Homer, C., C. Q. Huang, L. M. Yang, B. Wylie, and M. Coan. 2004. Development of a 2001 national land-cover database for the United States. *Photogrammetric Engineering and Remote Sensing* 70:829-840.
- Huang, C., S. N. Goward, J. G. Masek, N. Thomas, Z. Zhu, and J. E. Vogelmann. 2010a. An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment* 114:183-198.
- Huang, C., S. N. Goward, K. Schleeweis, N. Thomas, J. G. Masek, and Z. Zhu. 2009. Dynamics of national forests assessed using the Landsat record: Case studies in eastern United States. *Remote Sensing of Environment* 113:1430-1442.
- Huang, C., N. Thomas, S. N. Goward, J. G. Masek, Z. Zhiliang, J. R. G. Townshend, and J. E. Vogelmann. 2010b. Automated masking of cloud and cloud shadow for forest change analysis using Landsat images. *International Journal of Remote Sensing* 31:5449-5464.
- Kennedy, R., A. Kirschbaum, U. Gafvert, P. Nelson, Z. Yang, W. Cohen, E. Pfaff, and B. Gholson. 2010a. Landsat-based monitoring of landscape dynamics in the national parks of the Great Lakes Inventory and Monitoring Network (Version 1.0). National Resource Report NPS/GLKN/NRR—2010/221. National Park Service, Fort Collins, Colorado.
- Kennedy, R. E., W. B. Cohen, A. A. Kirschbaum, and E. Haunreiter. 2007a. Protocol for Landsat-based monitoring of landscape dynamics at North Coast and Cascades Network parks. U.S. Geological Survey Techniques and Methods 2-G1. USGS Biological Resources Division, Reston, Virginia.
- Kennedy, R. E., W. B. Cohen, and T. A. Schroeder. 2007b. Trajectory-based change detection for automated characterization of forest disturbance dynamics. *Remote Sensing of Environment* 110:370-386.
- Kennedy, R. E., Z. Yang, and W. B. Cohen. 2010b. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms. *Remote Sensing of Environment* 114:2897-2910.
- Kennedy, R. E., Z. Yang, W. B. Cohen, E. Pfaff, J. Braaten, and P. Nelson. 2012. Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment*.
- Key, C. H., and N. C. Benson. 2006. Landscape assessment: Remote sensing measure of severity, the Normalized Burn Ratio. Pages LA1-LA51 In D. C. Lutes, editor.

- FIREMON: Fire effects monitoring and inventory system. USDA Forest Service, Rocky Mountain Research Station, Ogden, Utah.
- Kirschbaum, A., and U. Gafvert. 2010a. Standard operating procedure #6: Lab validation of LandTrendr outputs. In R. Kennedy, A. Kirschbaum, U. Gafvert, P. Nelson, Z. Yang, W. Cohen, E. Pfaff, and B. Gholson, editors. Landsat-based monitoring of landscape dynamics in the national parks of the Great Lakes Inventory and Monitoring Network (version 1.0). National Resource Report NPS/GLKN/NRR—2010/221. National Park Service, Fort Collins, Colorado.
- Kirschbaum, A. A., and U. B. Gafvert. 2010b. Landsat-based monitoring of landscape dynamics at Voyageurs National Park, 2002-2007. Natural Resources Technical Report NPS/GLKN/NRTR—2010/356. National Park Service, Fort Collins, Colorado.
- Kirschbaum, A. A., and U. B. Gafvert. 2012. Landsat-based monitoring of landscape dynamics at Isle Royale National Park, 2003-2008. Natural Resources Technical Report NPS/GLKN/NRTR—2012/535. National Park Service, Fort Collins, Colorado.
- Kirschbaum, A. A., U. B. Gafvert, and W. B. Monahan. 2012. Landsat-based monitoring of landscape dynamics at Apostle Islands National Lakeshore, 2004-2009. Natural Resources Technical Report NPS/GLKN/NRTR—2012/608. National Park Service, Fort Collins, Colorado.
- Laliberte, A. S., A. Rango, K. M. Havstad, J. F. Paris, R. F. Beck, R. McNeely, and A. L. Gonzalez. 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. *Remote Sensing of Environment* 93:198-210.
- Law, B. E., D. Turner, J. Campbell, O. J. Sun, S. Van Tuyl, W. D. Ritts, and W. B. Cohen. 2004. Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. *Global Change Biology* 10:1429-1444.
- Lillesand, T. M., and R. W. Kiefer. 2000. Remote Sensing and Image Interpretation, 4th edition. John Wiley & Sons Inc., New York.
- Lu, D., P. Mausel, E. Brondízio, and E. Moran. 2004. Change detection techniques. *International Journal of Remote Sensing* 25:2365-2401.
- Lu, P., A. Stumpf, N. Kerle, and N. Casagli. 2011. Object-oriented change detection for landslide rapid mapping. *Ieee Geoscience and Remote Sensing Letters* 8:701-705.
- Maheu-Giroux, M., and S. de Blois. 2005. Mapping the invasive species *Phragmites australis* in linear wetland corridors. *Aquatic Botany* 83:310-320.
- Meigs, G. W., R. E. Kennedy, and W. B. Cohen. 2011. A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. *Remote Sensing of Environment* 115:3707-3718.

- Morgan, J. L., S. E. Gergel, and N. C. Coops. 2010. Aerial photography: A rapidly evolving tool for ecological management. *BioScience* 60:47-59.
- Potapov, P., M. C. Hansen, S. V. Stehman, K. Pittman, and S. Turubanova. 2009. Gross forest cover loss in temperate forests: Biome-wide monitoring results using MODIS and Landsat data. *Journal of Applied Remote Sensing* 3:1-23.
- Powell, S. L., W. B. Cohen, S. P. Healey, R. E. Kennedy, G. G. Moisen, K. B. Pierce, and J. L. Ohmann. 2010. Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: A comparison of empirical modeling approaches. *Remote Sensing of Environment* 114:1053-1068.
- Radke, R. J., S. Andra, O. Al-Kofahi, and B. Roysam. 2005. Image change detection algorithms: A systematic survey. *Image Processing, IEEE Transactions on* 14:294-307.
- Rutchev, K., and L. Vilchek. 1999. Airphoto interpretation and satellite imagery analysis techniques for mapping cattail coverage in a northern Everglades impoundment. *Photogrammetric Engineering and Remote Sensing* 65:185-191.
- Schroeder, T. A., M. A. Wulder, S. P. Healey, and G. G. Moisen. 2011. Mapping wildfire and clearcut harvest disturbances in boreal forests with Landsat time series data. *Remote Sensing of Environment* 115:1421-1433.
- Sonnenschein, R., T. Kuemmerle, T. Udelhoven, M. Stellmes, and P. Hostert. 2011. Differences in Landsat-based trend analyses in drylands due to the choice of vegetation estimate. *Remote Sensing of Environment* 115:1408-1420.
- Stueve, K. M., I. W. Housman, P. L. Zimmerman, M. D. Nelson, J. B. Webb, C. H. Perry, R. A. Chastain, D. D. Gormanson, C. Huang, S. P. Healey, and W. B. Cohen. 2011a. Snow-covered Landsat time series stacks improve automated disturbance mapping accuracy in forested landscapes. *Remote Sensing of Environment* 115:3203-3219.
- Stueve, K. M., C. H. Perry, M. D. Nelson, S. P. Healey, A. D. Hill, G. G. Moisen, W. B. Cohen, D. D. Gormanson, and C. Huang. 2011b. Ecological importance of intermediate windstorms rivals large, infrequent disturbances in the northern Great Lakes. *Ecosphere* 2: 2. Available at <http://dx.doi.org/10.1890/ES10-00062.1> (accessed 15 March 2013).
- Turner, D. P., W. D. Ritts, J. M. Styles, Z. Yang, W. B. Cohen, B. E. Law, and P. E. Thornton. 2006. A diagnostic carbon flux model to monitor the effects of disturbance and interannual variation in climate on regional NEP. *Tellus Series B-Chemical and Physical Meteorology* 58:476-490.
- Veraverbeke, S., W. W. Verstraeten, S. Lhermitte, and R. Goossens. 2010. Illumination effects on the differenced Normalized Burn Ratio's optimality for assessing fire severity. *International Journal of Applied Earth Observation and Geoinformation* 12:60-70.

- Verry, E. S. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. *Water Resources Bulletin*, American Water Resources Association. Volume 19, Number 1.
- Vogelmann, J. E., T. L. Sohl, P. V. Campbell, and D. M. Shaw. 1998. Regional land cover characterization using Landsat thematic mapper data and ancillary data sources. *Environmental Monitoring and Assessment* 51:415-428.
- Walter, V. 2004. Object-based classification of remote sensing data for change detection. *ISPRS Journal of Photogrammetry and Remote Sensing* 58:225-238.
- Wang, L., W. P. Sousa, and P. Gong. 2004. Integration of object-based and pixel-based classification for mapping mangroves with IKONOS imagery. *International Journal of Remote Sensing* 25:5655-5668.
- Ward, J. V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation* 83:269-278.
- White, M. A., and G. E. Host. 2003. Changes in disturbance frequency, age and patch structure from pre-Euro-American to settlement to present in northcentral and northeastern Minnesota. Minnesota Forest Resources Council Report LT-1203a, St. Paul, Minnesota.
- White, M. A., and G. E. Host. 2008. Forest disturbance frequency and patch structure from pre-European settlement to present in the mixed forest province of Minnesota, USA. *Canadian Journal of Forest Research* 38:2212-2226.
- Wiersma, Y. F., T. D. Nudds, and D. H. Rivard. 2004. Models to distinguish effects of landscape patterns and human population pressures associated with species loss in Canadian national parks. *Landscape Ecology* 19:773-786.
- With, K. A. 2002. The landscape ecology of invasive spread. *Conservation Biology* 16:1192-1203.
- Wolter, P. T., C. A. Johnston, and G. J. Niemi. 2006. Land use land cover change in the U.S. Great Lakes basin 1992 to 2001. *Journal of Great Lakes Research* 32:607-628.
- Wolter, P. T., and M. A. White. 2002. Recent forest cover type transitions and landscape structural changes in northeast Minnesota. *Landscape Ecology* 17:133-155.
- Wulder, M. A., and S. E. Franklin. 2007. *Understanding Forest Disturbance and Spatial Pattern, Remote Sensing and GIS Approaches*. CRC Press Boca Raton, Florida.
- Yu, X., J. Hyypä, H. Kaartinen, and M. Maltamo. 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning. *Remote Sensing of Environment* 90:451-462.

Appendix A: Spatial Distribution of Disturbances at SACN and 300 meter buffer

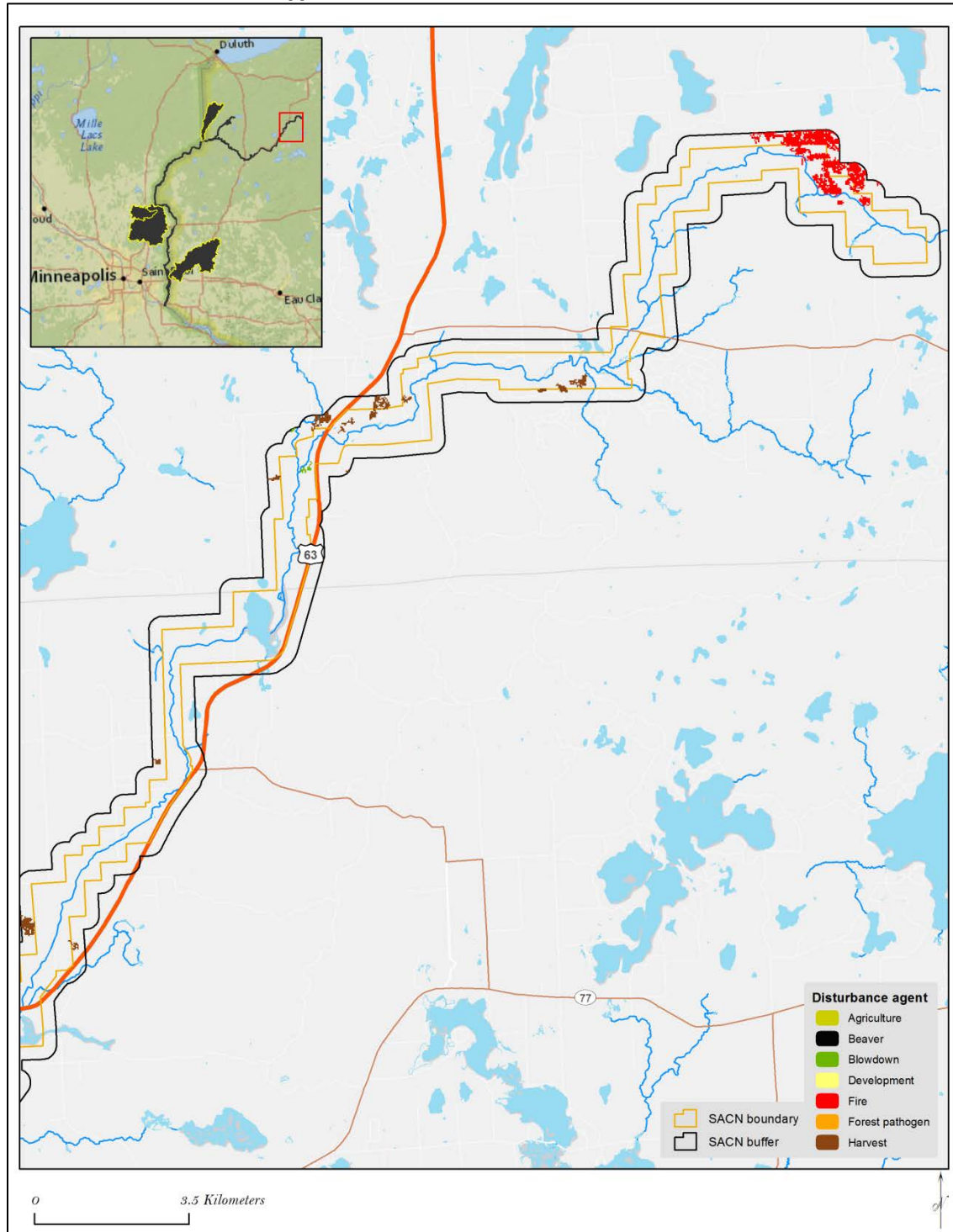


Figure A1. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

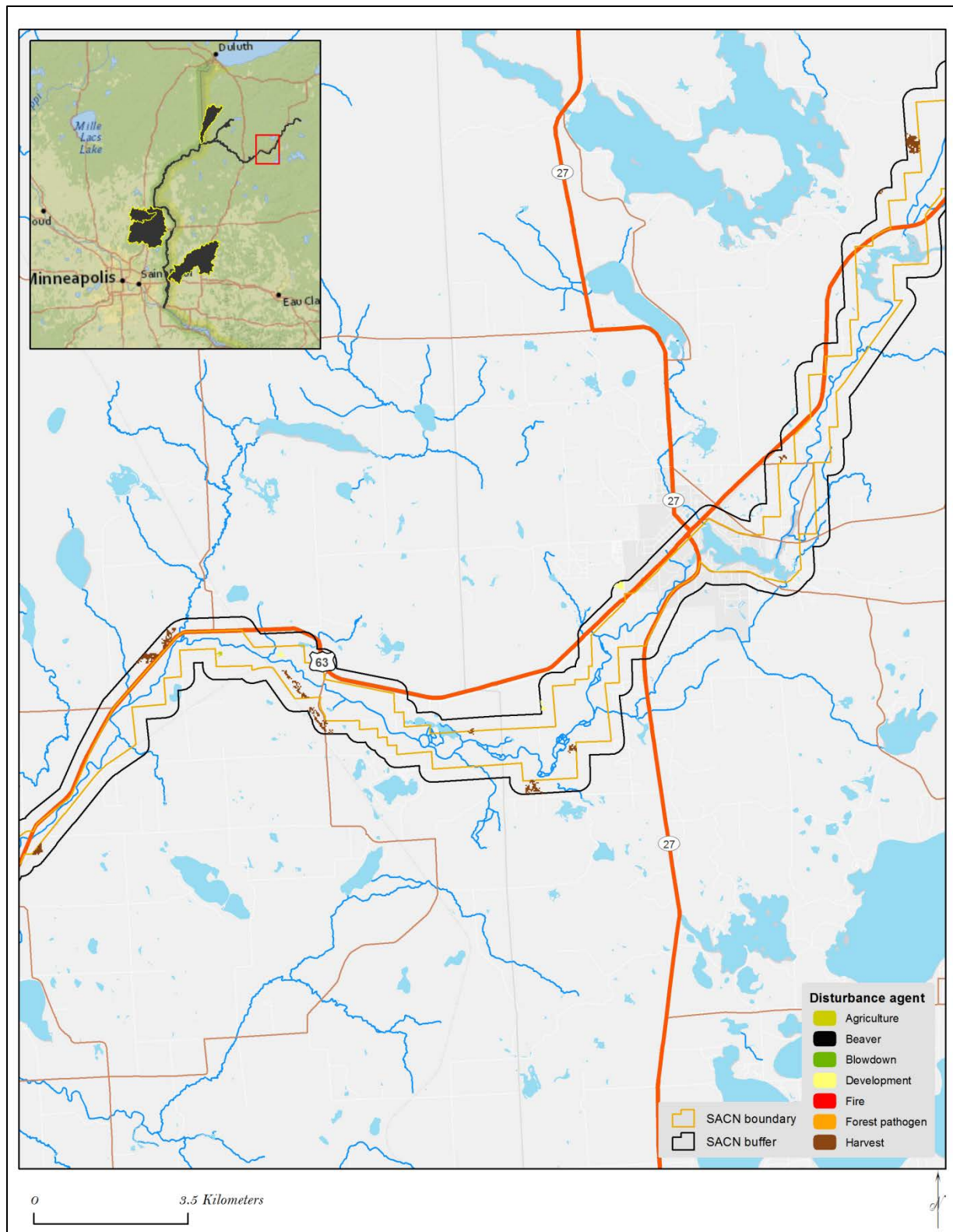


Figure A2. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

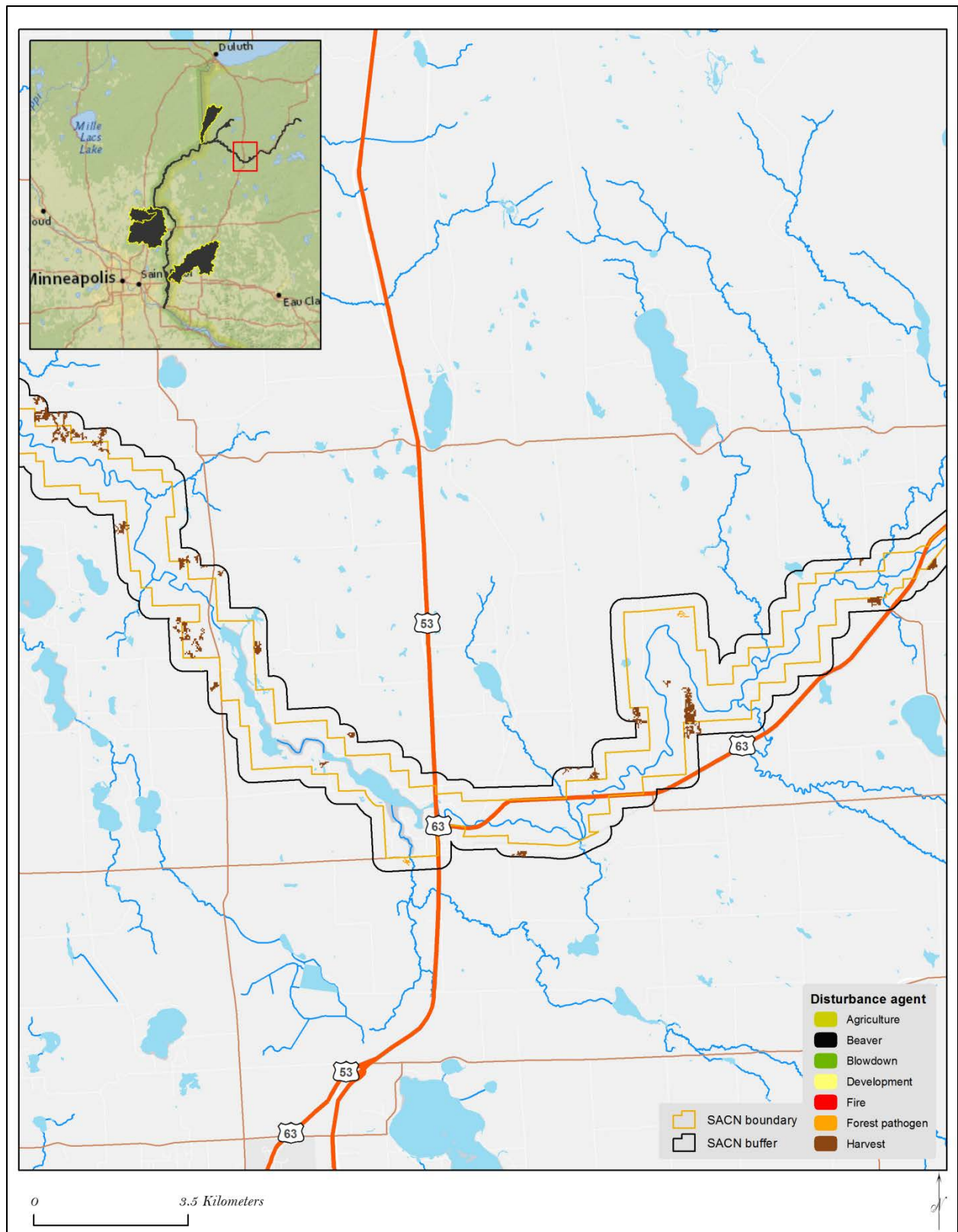


Figure A3. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

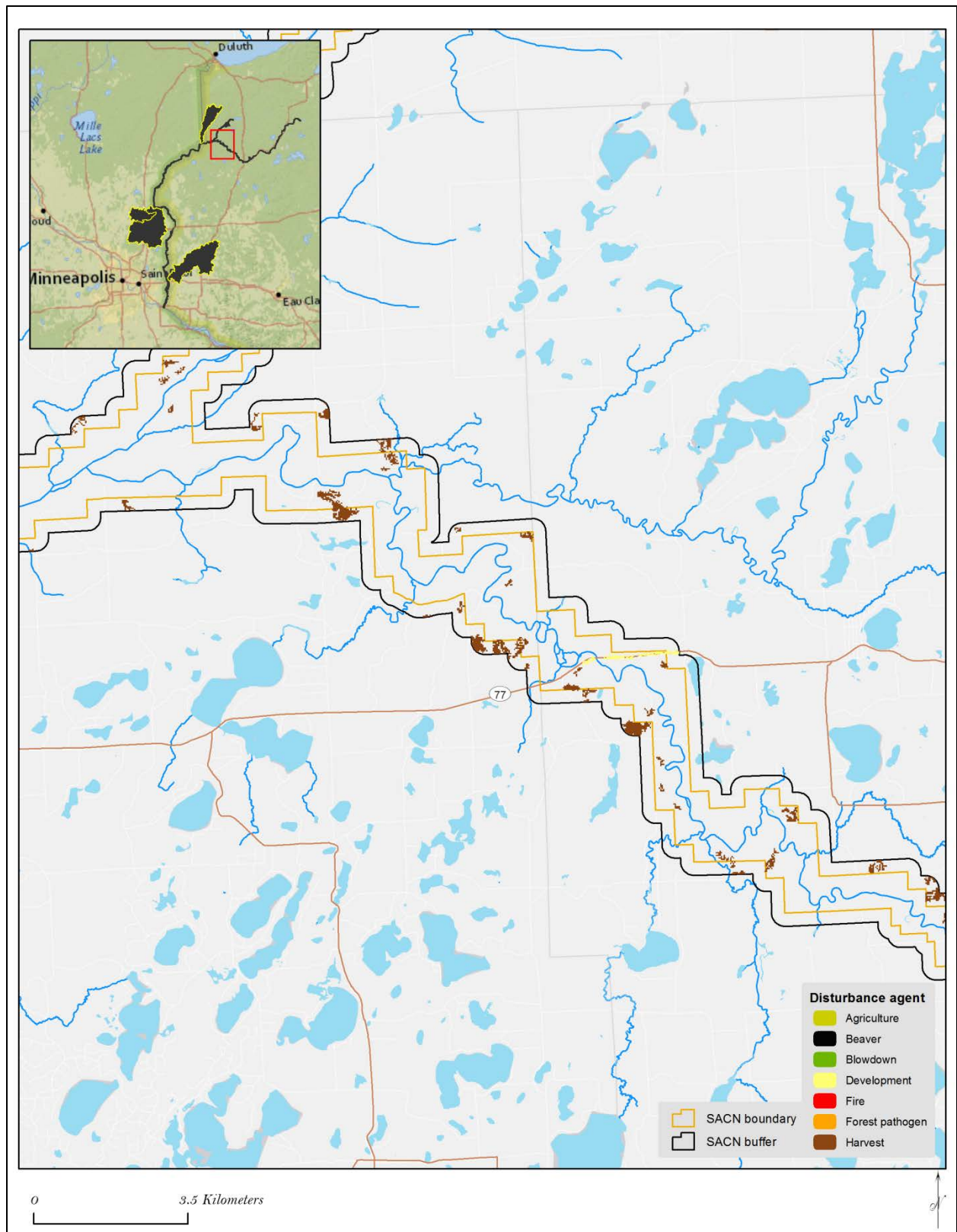


Figure A4. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

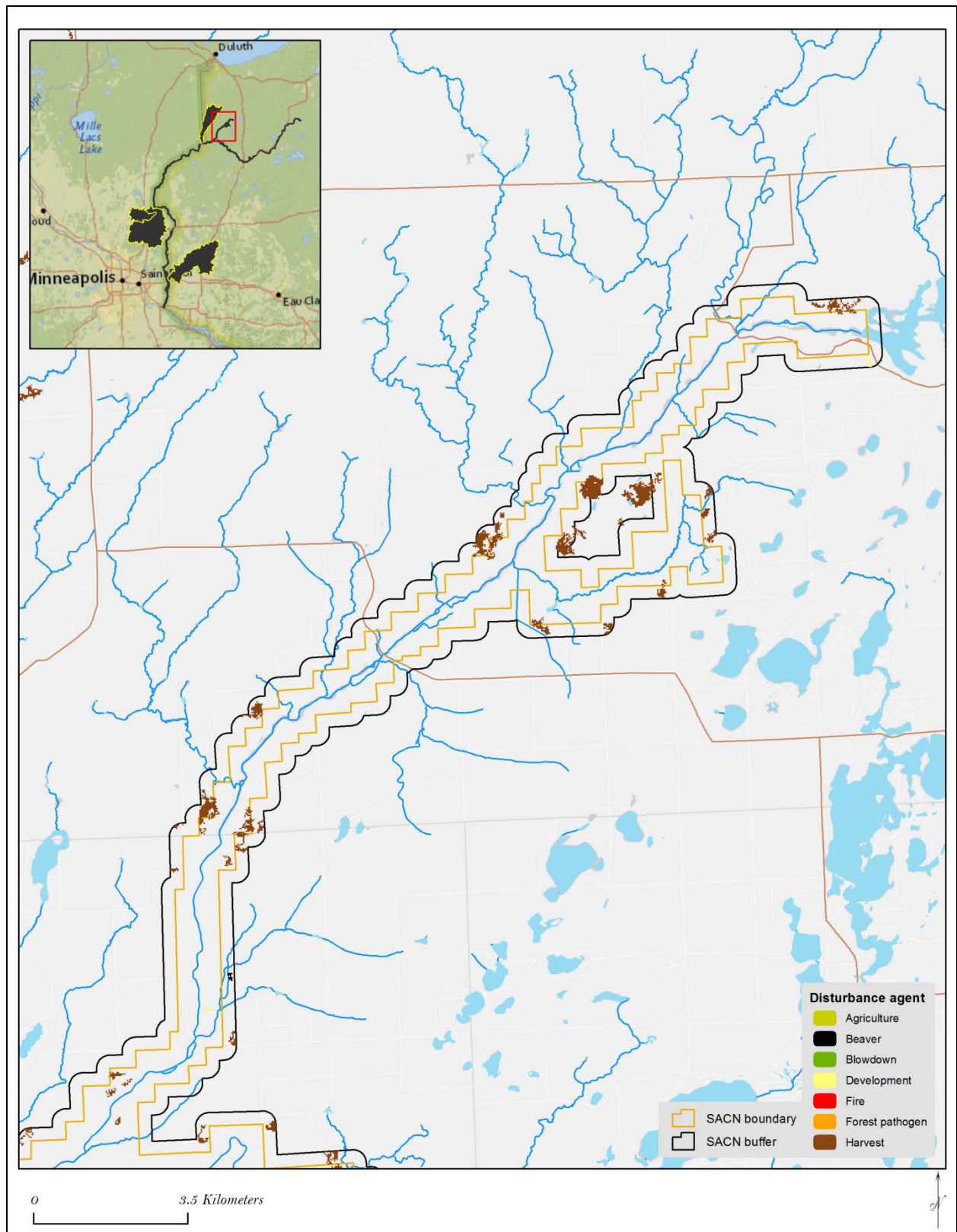


Figure A5. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

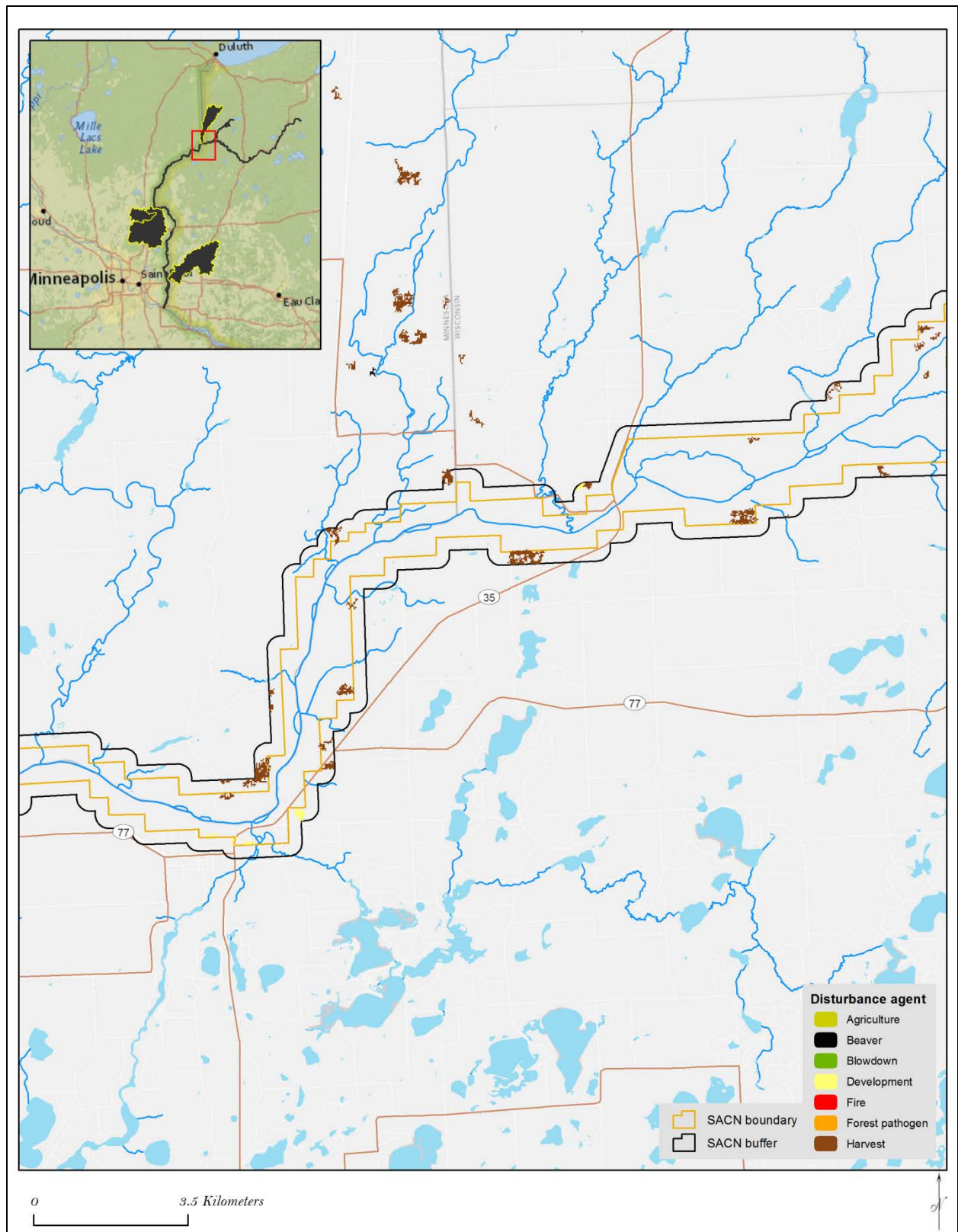


Figure A6. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

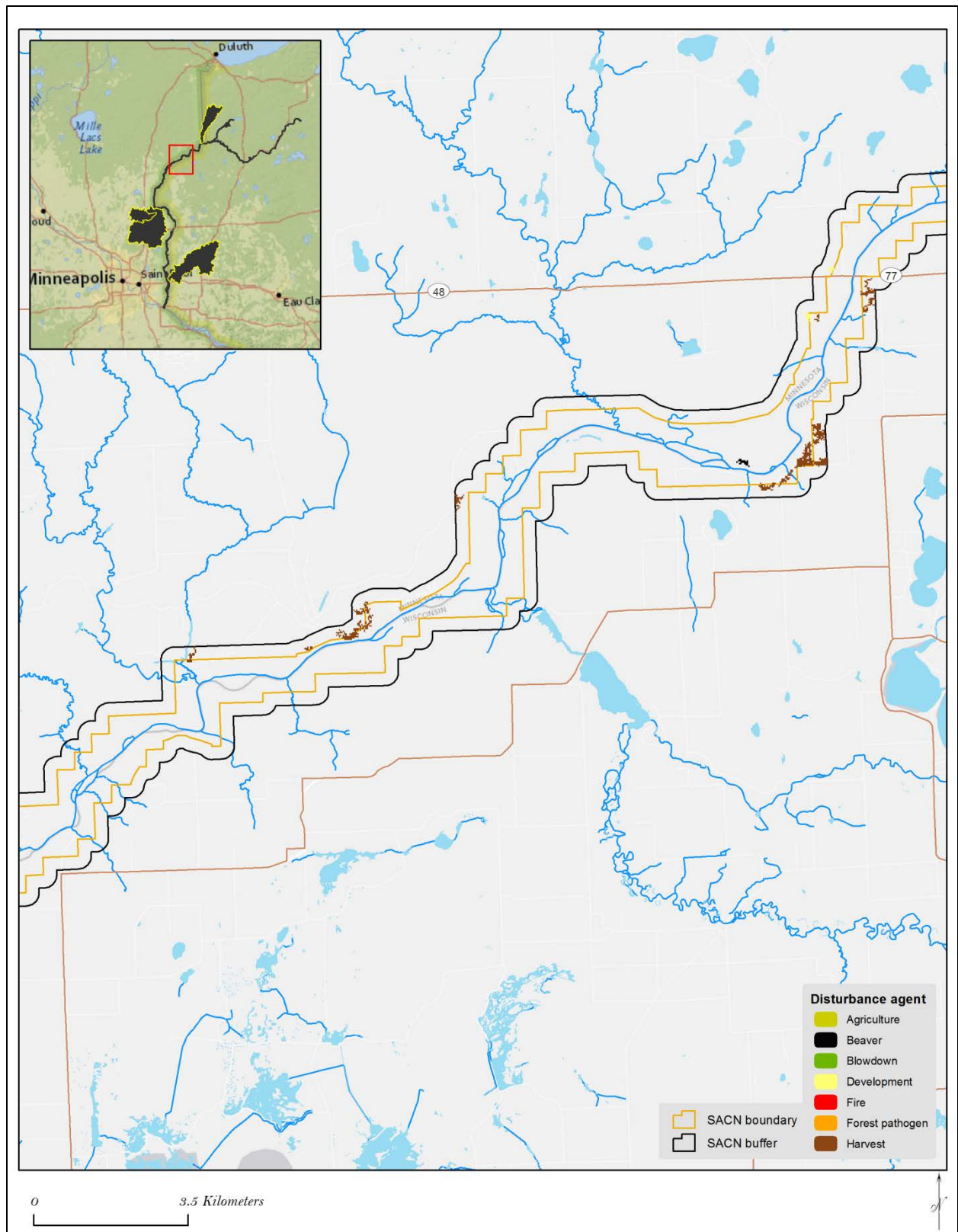


Figure A7. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

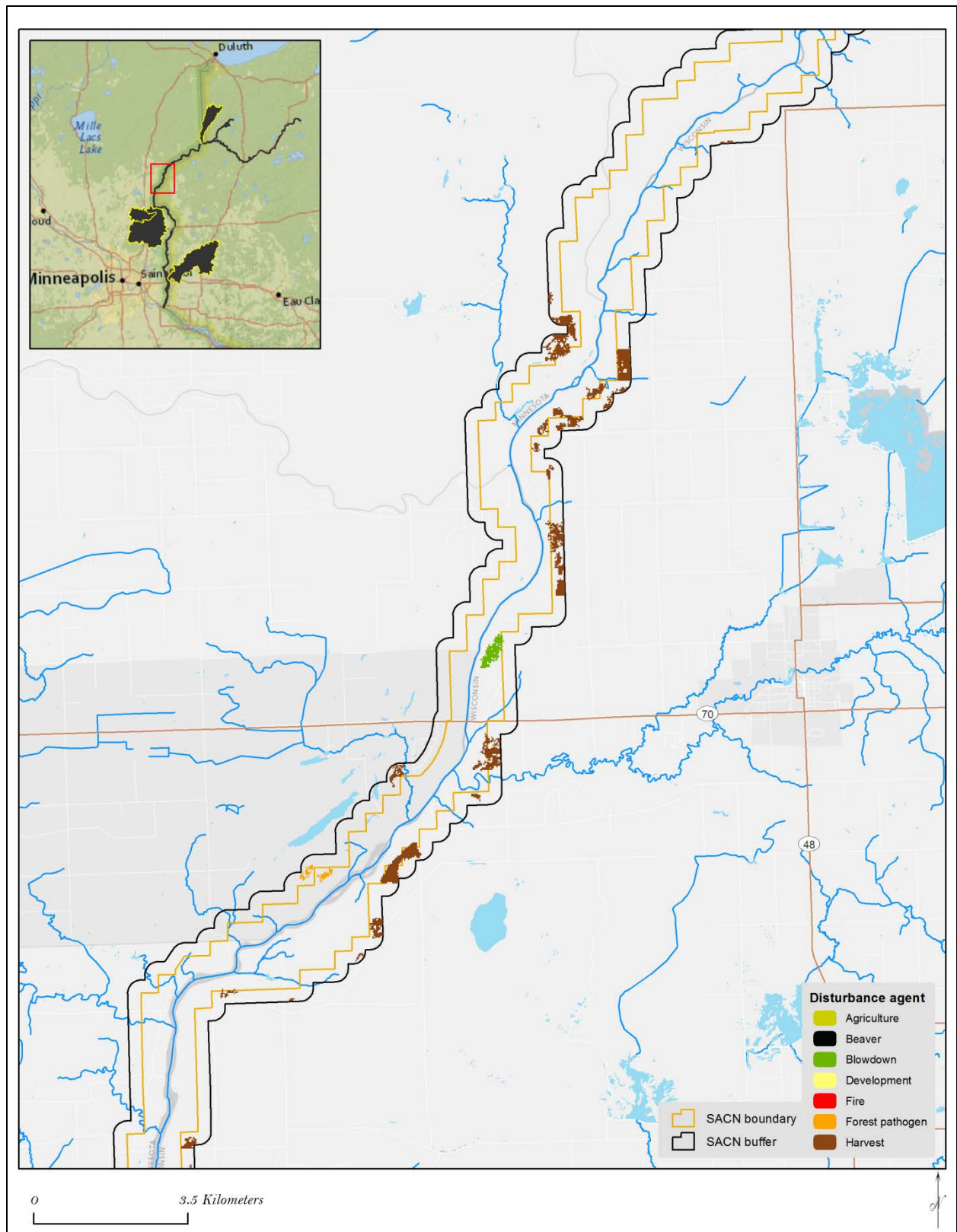


Figure A8. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

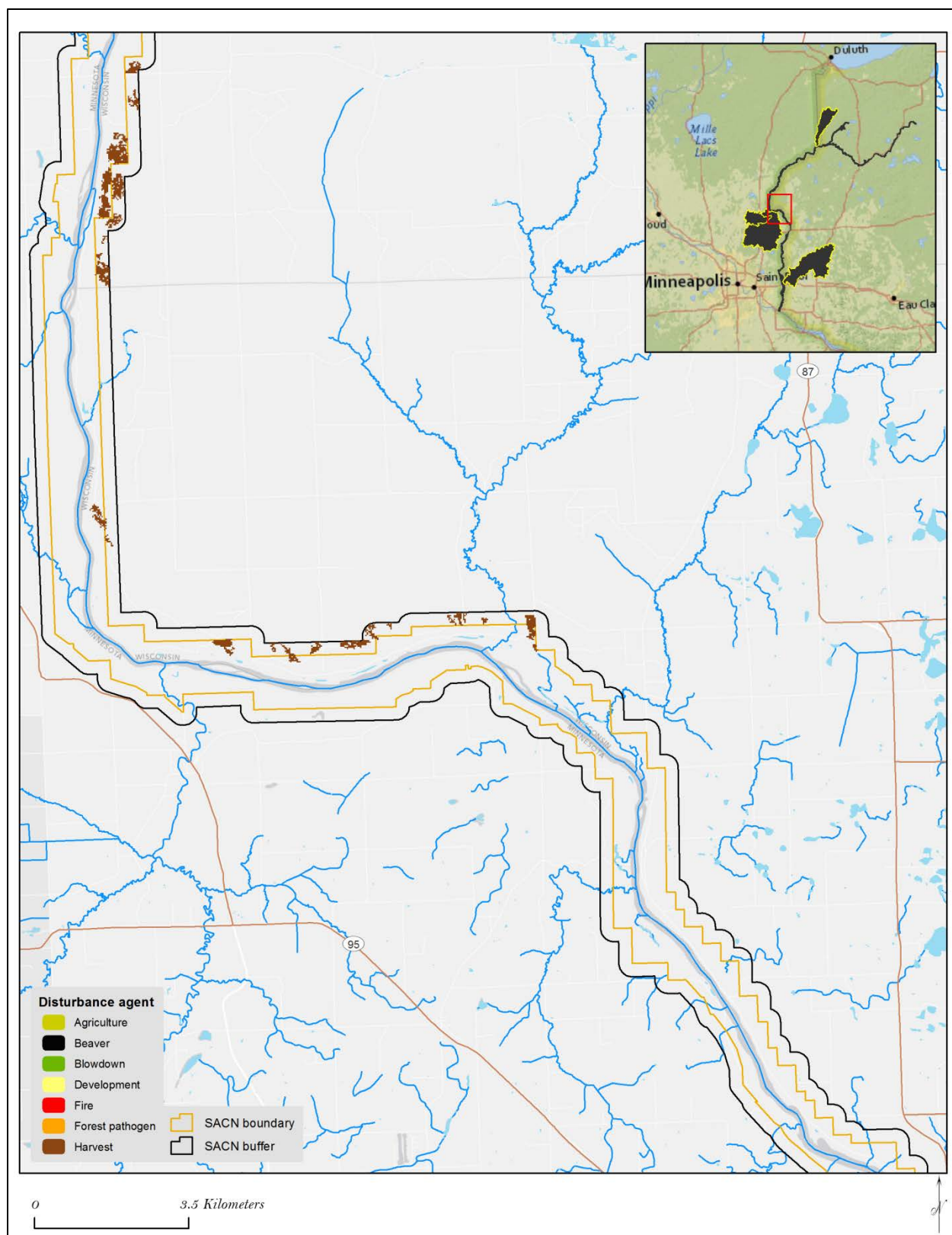


Figure A9. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

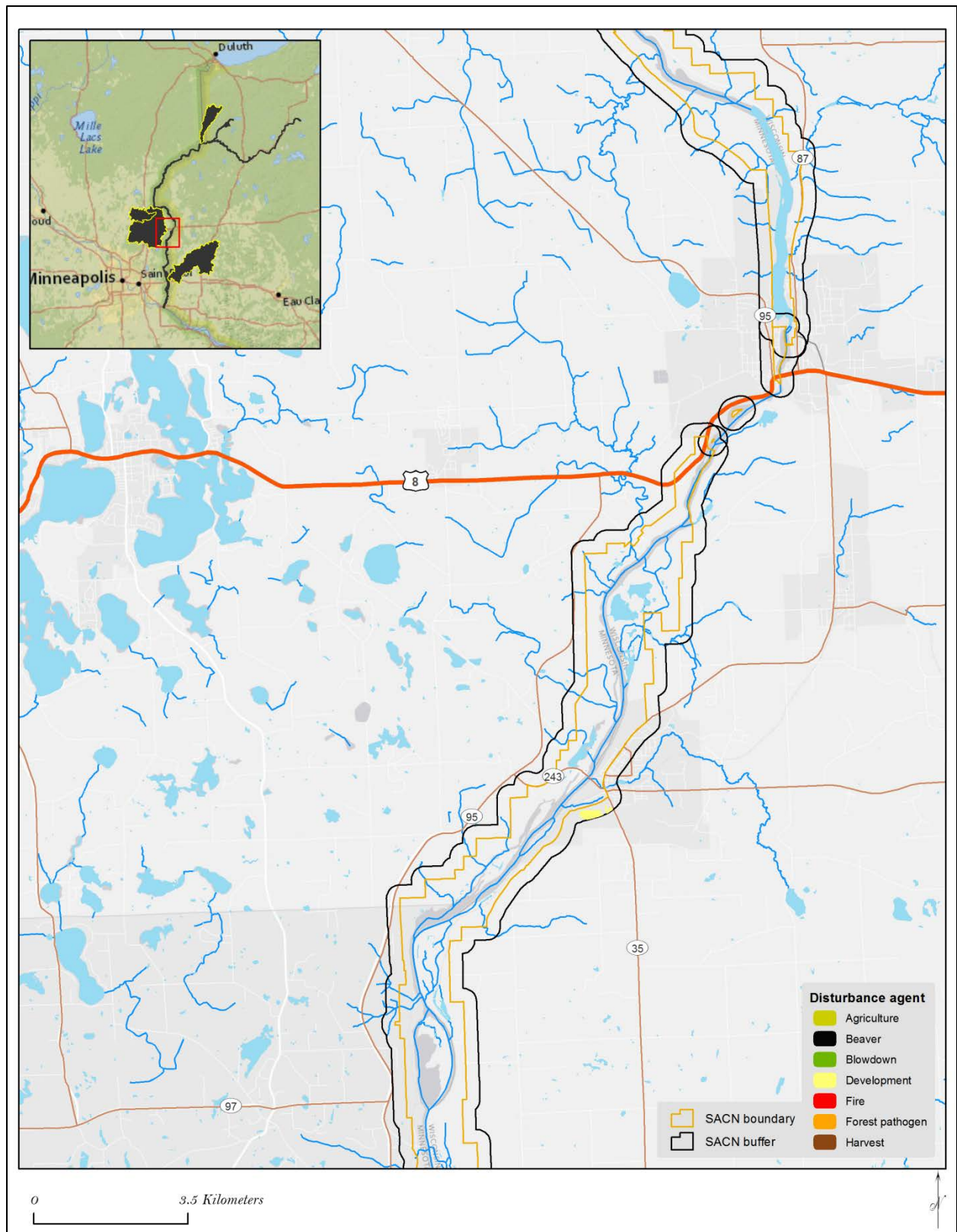


Figure A10. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

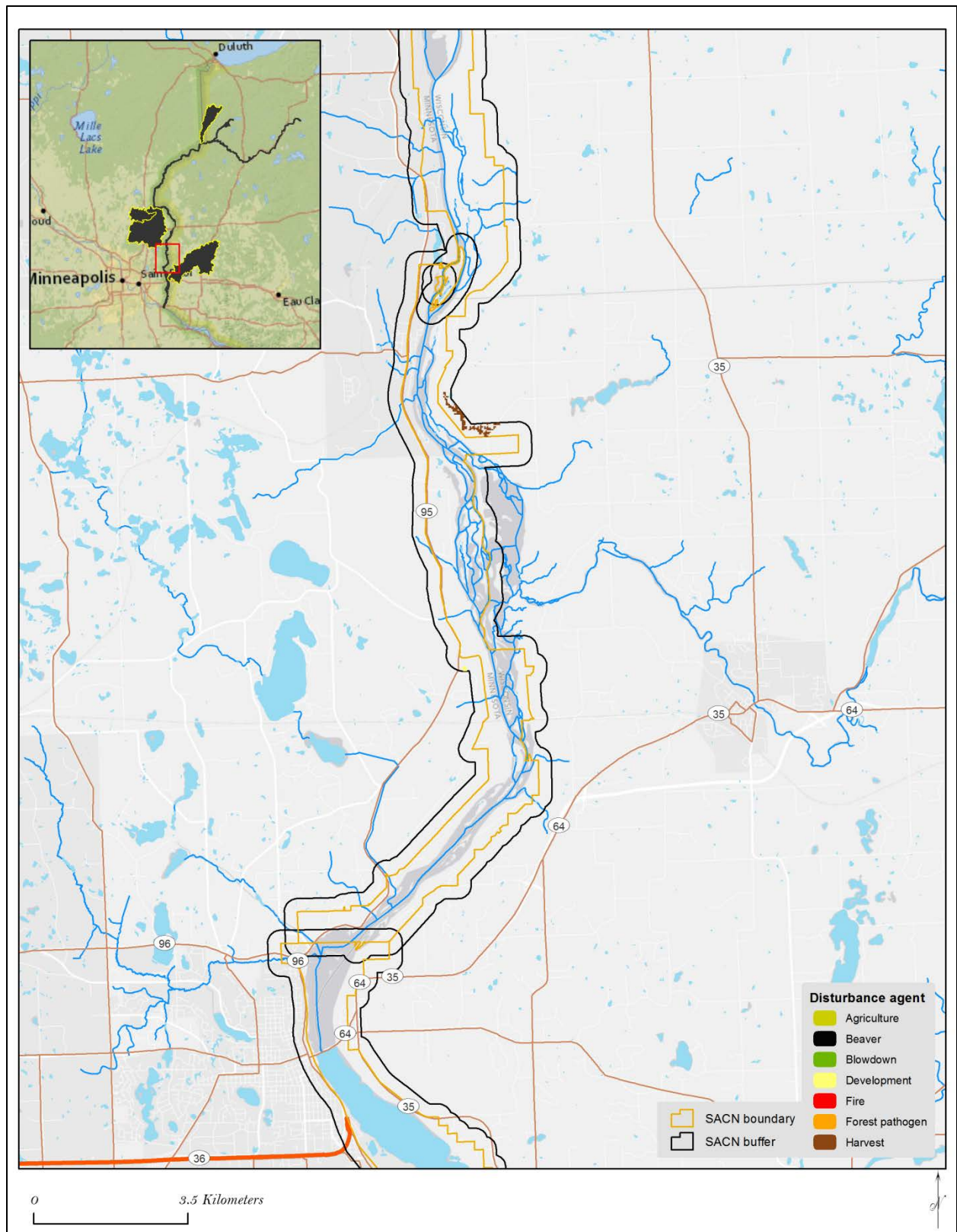


Figure A11. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

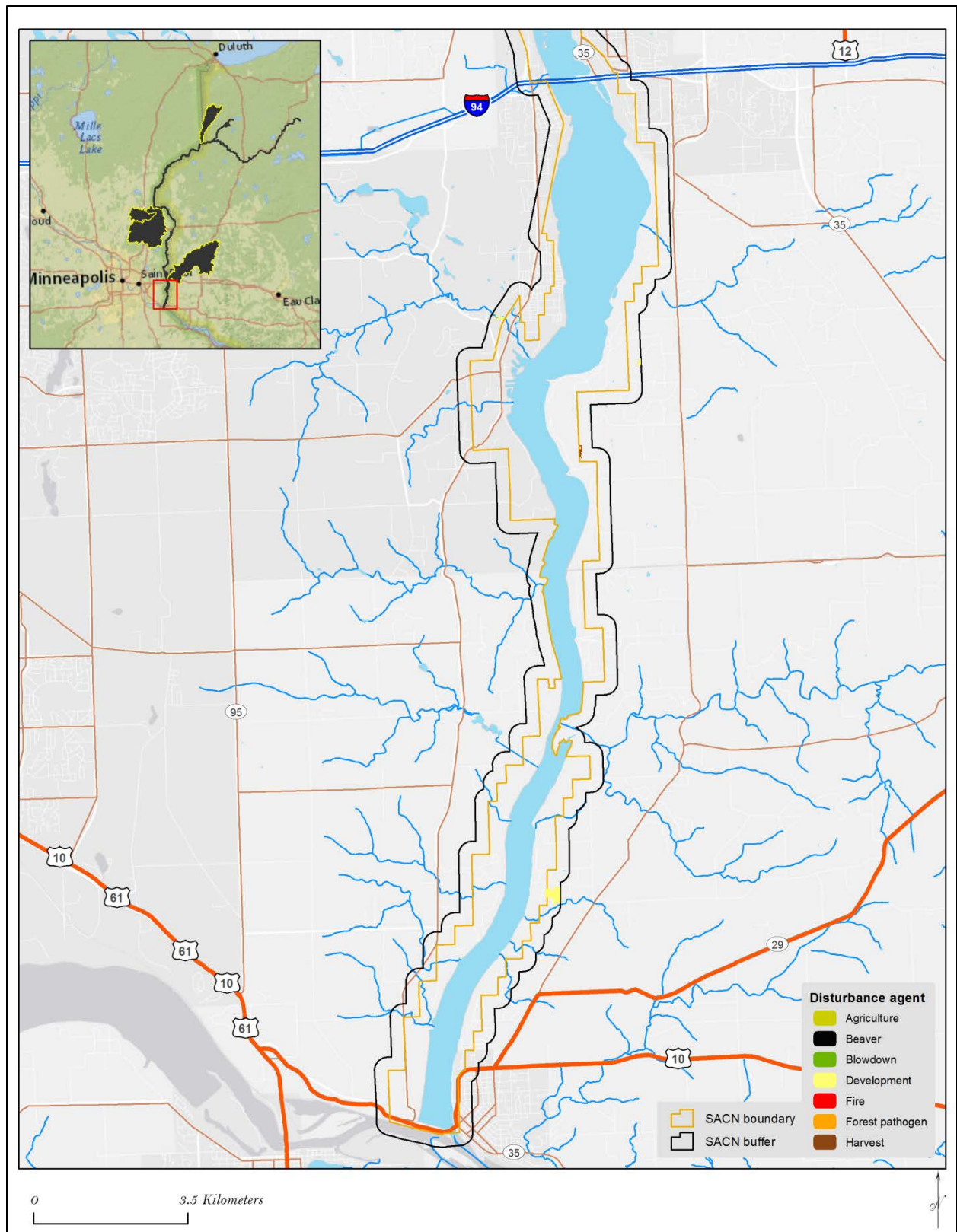


Figure A12. Close-up of disturbances inside SACN boundary and within the 300 meter buffer area during the analysis period.

Appendix B: Spatial Distribution of Disturbances in Subwatersheds

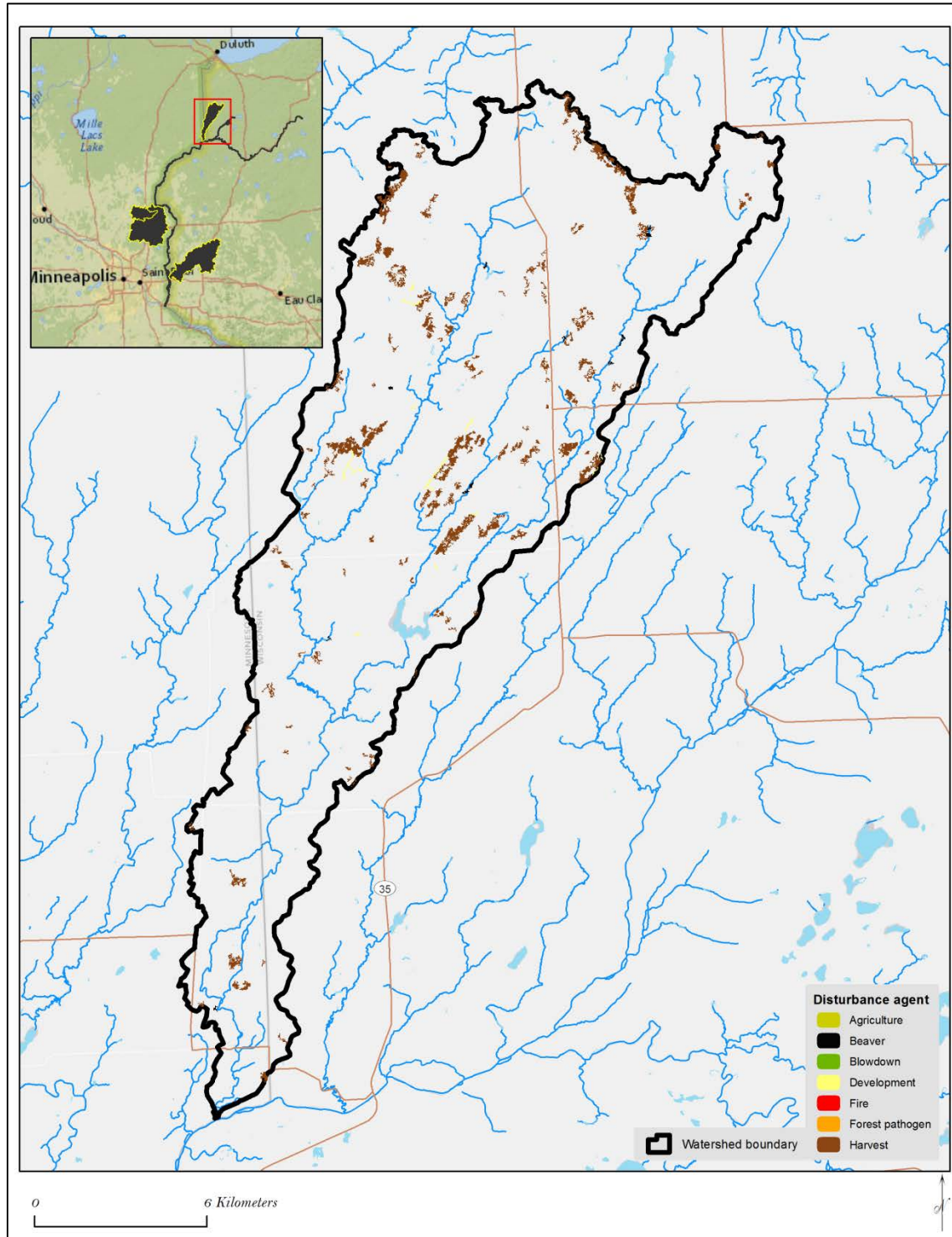


Figure B1. Spatial distribution of disturbances during the analysis period in the Upper Tamarack river basin.

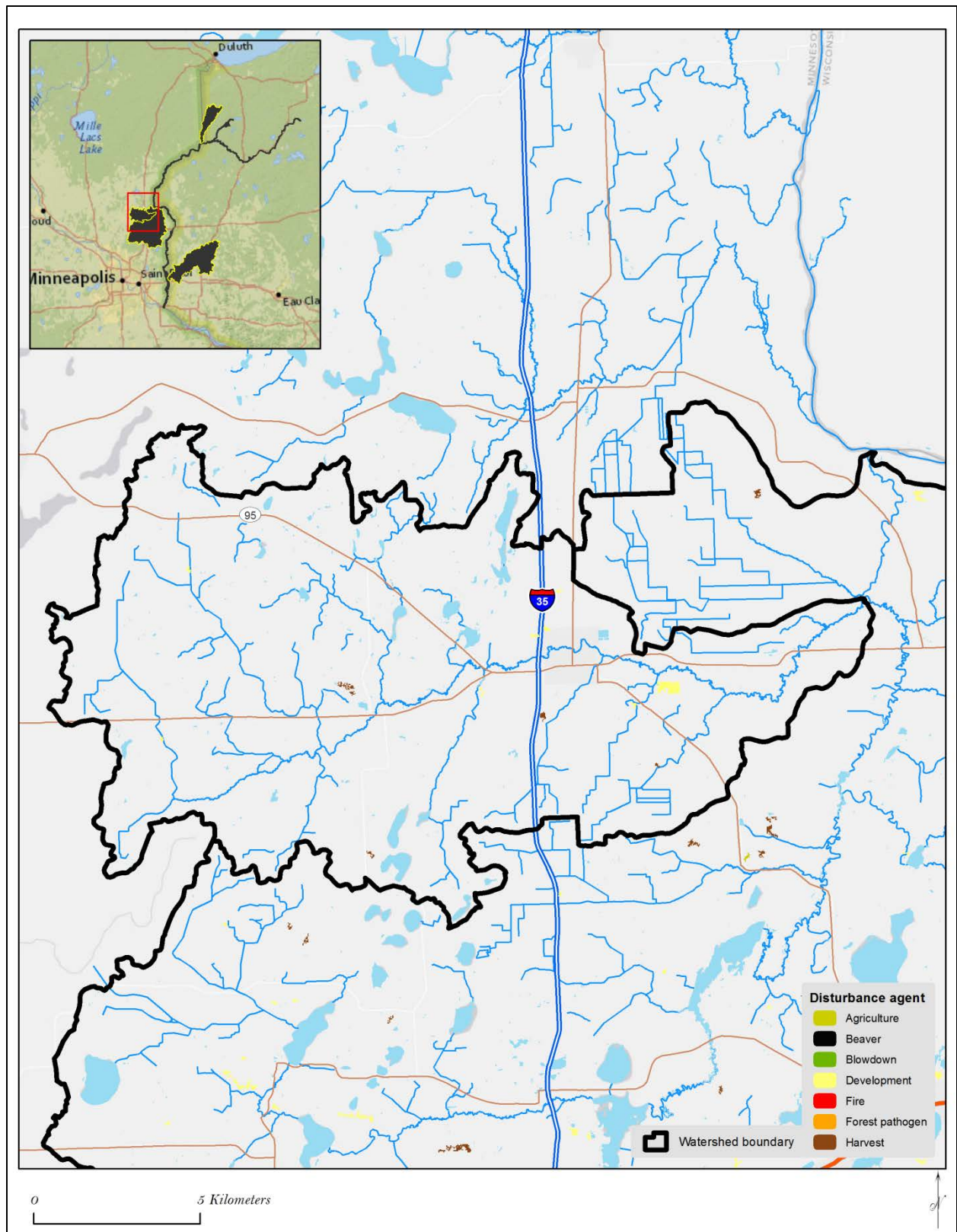


Figure B2. Spatial distribution of disturbances during the analysis period in the North Branch of the Sunrise river basin.

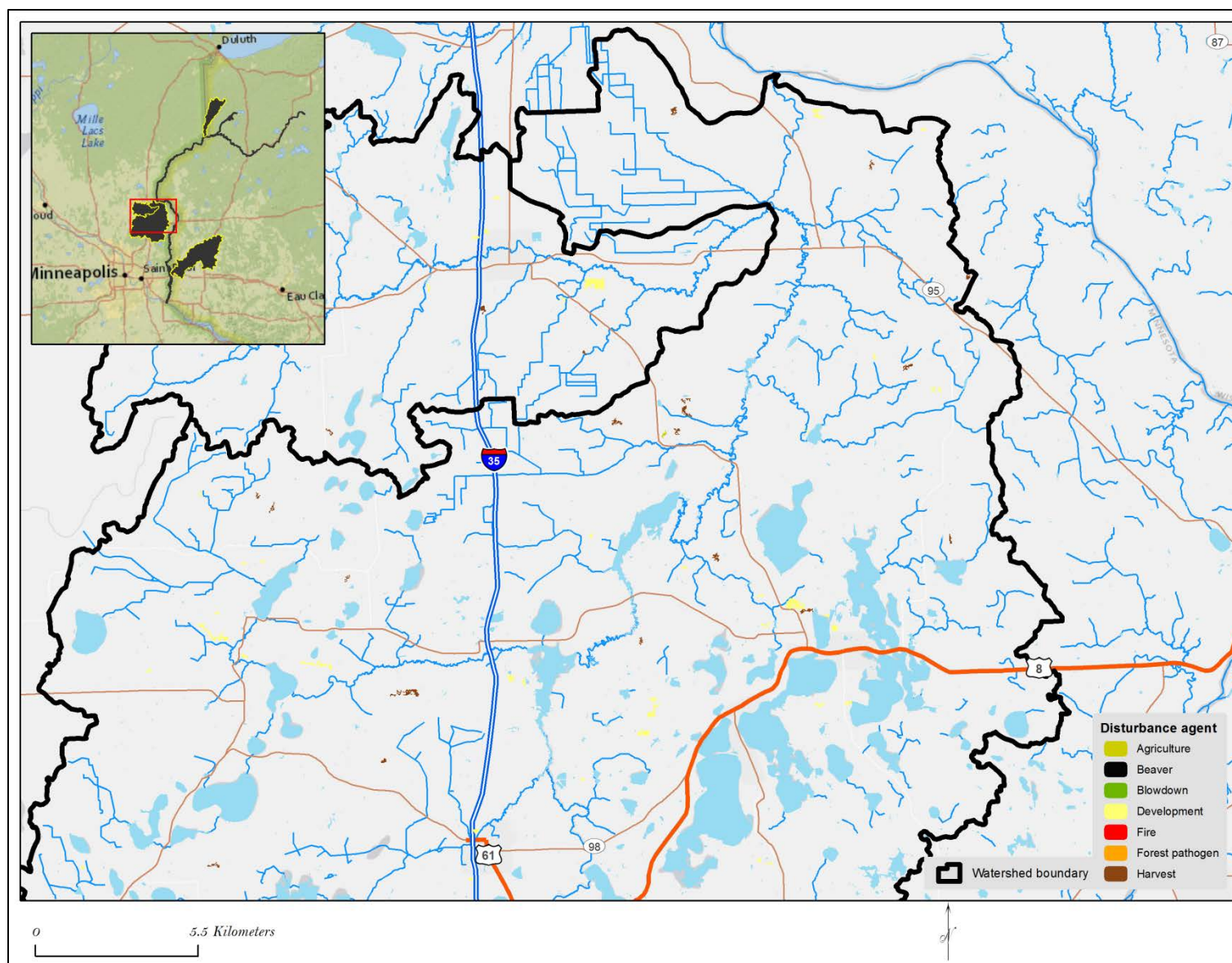


Figure B3. Spatial distribution of disturbances during the analysis period in the Sunrise river basin (1 of 2).

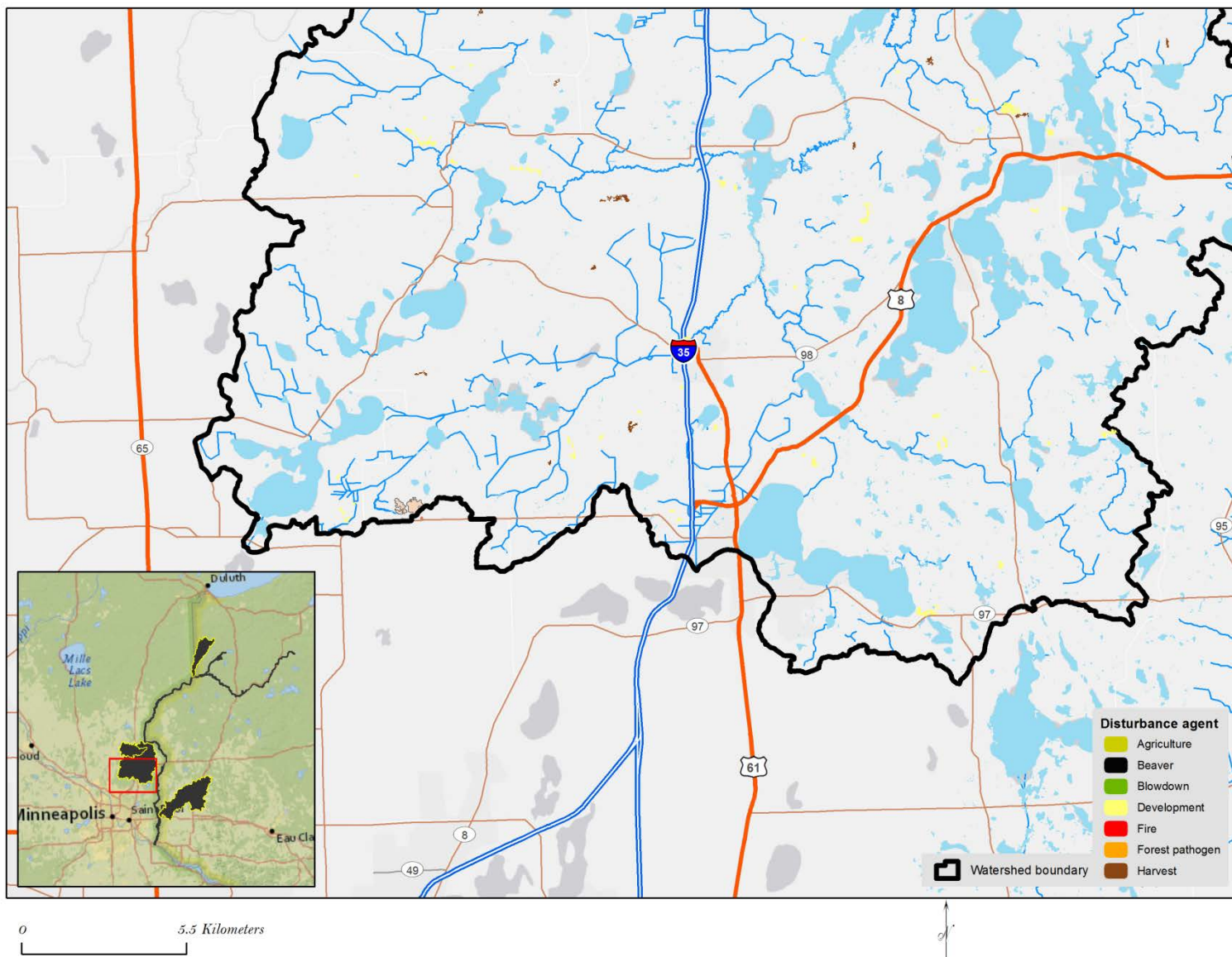


Figure B4. Spatial distribution of disturbances during the analysis period in the Sunrise river basin (2 of 2).

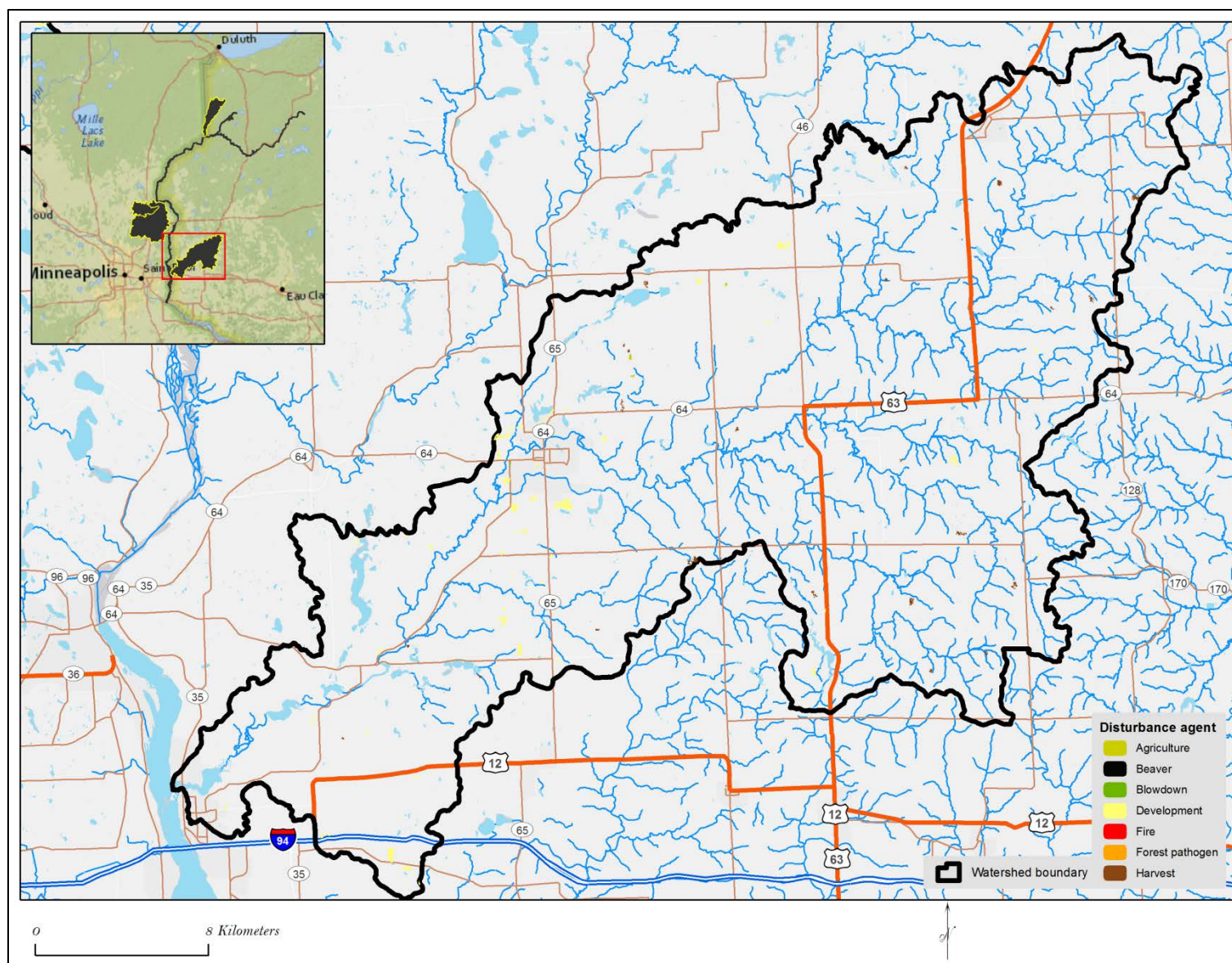


Figure B5. Spatial distribution of disturbances during the analysis period in the Willow river basin.

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	5.95	15981.39
Developed, open space	3.92	10529.73
Developed, low intensity	1.91	5134.05
Developed, medium intensity	0.67	1801.44
Developed, high intensity	0.22	585.81
Barren land	0.01	22.86
Deciduous forest	29.18	78330.87
Evergreen forest	2.64	7079.85
Mixed forest	2.2	5895.63
Shrub	1.35	3624.03
Grassland/herbaceous	2.91	7816.59
Pasture	17.29	46424.16
Cultivated crops	19.07	51185.07
Woody wetlands	6	16104.33
Emergent herbaceous wetlands	6.68	17922.06

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

Class name	Willow River	Upper Tamarack River	North Branch Sunrise River	Sunrise River
Open water	1.34	0.59	1.38	8.49
Developed, open space	4.74	1.39	3.78	4.01
Developed, low intensity	1.69	0.36	2.63	2.6
Developed, medium intensity	0.57	0	1.21	0.8
Developed, high intensity	0.15	0	0.31	0.23
Barren land	0.01	0	0	0.01
Deciduous forest	19.05	57.49	19.49	21.11
Evergreen forest	1.79	1.04	1.43	1.62
Mixed forest	0.21	4.64	0.09	0.16
Shrub	0.27	5.04	0.43	0.42
Grassland/herbaceous	2.83	0.36	3.86	4.26
Pasture	34.03	1.15	14.61	17.95
Cultivated crops	30.99	0.43	40.91	21.05
Woody wetlands	0.36	25.63	1.21	1.61
Emergent herbaceous wetlands	1.96	1.89	8.66	15.66

Table C3. Percent of each analysis area (SACN and Non-SACN) disturbed and area (ha) disturbed.

Year	SACN (ha)	SACN (%)	Non-SACN (ha)	Non-SACN (%)
2005	80.95	0.25	398.19	0.18
2006	47.48	0.15	342.89	0.16
2007	117.14	0.36	237.58	0.11
2008	74.47	0.23	383.05	0.17
2009	11.80	0.04	271.95	0.12
2010	26.91	0.08	243.10	0.11
Total	358.74	1.12	1876.76	0.85

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

Analysis area	Hectares of land disturbed								Total
	Year	Agriculture	Beaver	Blowdown	Development	Fire	Forest pathogen	Forest harvest	
SACN	2005	0	1.73	0	9.67	0	1.62	67.93	80.95
	2006	0.59	0	0.86	0.33	0	0	45.69	47.48
	2007	0	0	0	0.88	56.54	0	59.72	117.14
	2008	0	0	0	0	0	0	74.47	74.47
	2009	0	0	0	0.54	0	0	11.26	11.80
	2010	0	0	10.69	0	0	2.03	14.19	26.91
	Total	0.59	1.73	11.56	11.43	56.54	3.65	273.25	358.74
Non-SACN	2005	0	7.52	0	118.35	0	1.17	271.15	398.19
	2006	0	1.44	0.30	114.72	0	0	226.42	342.89
	2007	1.13	0	0	35.55	0.20	0	200.70	237.58
	2008	0.68	2.07	0	41.35	0	0	338.95	383.05
	2009	0	1.44	0	8.11	0	0	262.40	271.95
	2010	3.96	2.27	0.54	12.10	0	2.95	221.28	243.10
	Total	5.78	14.73	0.84	330.18	0.20	4.12	1520.90	1876.76

Table C5. Percent of land disturbed in each analysis area (SACN and non-SACN) by disturbance agent and year.

Analysis area	Percent of land disturbed								
	Year	Agriculture	Beaver	Blowdown	Development	Fire	Forest pathogen	Forest harvest	Total
SACN	2005	0	0.01	0	0.03	0	0.01	0.21	0.25
	2006	<0.01	0	<0.01	<0.01	0	0	0.14	0.15
	2007	0	0	0	<0.01	0.18	0	0.19	0.36
	2008	0	0	0	0	0	0	0.23	0.23
	2009	0	0	0	<0.01	0	0	0.04	0.04
	2010	0	0	0.03	0	0	0.01	0.04	0.08
	Total	<0.01	0.01	0.04	0.04	0.18	0.01	0.85	1.12
Non-SACN	2005	0	<0.01	0	0.05	0	<0.01	0.12	0.18
	2006	0	<0.01	0	0.05	0	0	0.10	0.16
	2007	<0.01	0	0	0.02	0	0	0.09	0.11
	2008	0	<0.01	0	0.02	0	0	0.15	0.17
	2009	0	<0.01	0	<0.01	0	0	0.12	0.12
	2010	<0.01	<0.01	0	0.01	0	<0.01	0.10	0.11
	Total	<0.01	0.01	0	0.15	0	<0.01	0.69	0.85

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	Area (ha) of land cover types disturbed in the analysis period (starting class)									
	Year	Upland forest	Upland woodland	Upland shrub/herb	Lowland forest	Lowland shrub/herb	Water	Impervious surface	Pervious surface	Impervious/vegetated
SACN	2005	-57.88	0	0	-23.07	0	0	0	0	0
	2006	-41.38	0	-5.22	-0.88	0	0	0	0	0
	2007	-113.27	0	-1.51	-2.36	0	0	0	0	0
	2008	-76.44	0	0	-0.11	0	0	0	0	0
	2009	-11.36	0	0	0	0	0	0	0	0
	2010	-28.69	0	0	0	0	0	0	0	0
	Total	-329.02	0	-6.73	-26.42	0	0	0	0	0
Non-SACN	2005	-282.56	0	-78.07	-24.94	-0.32	0	0	0	-0.63
	2006	-260.99	0	-68.28	-11.88	0	0	0	0	0
	2007	-187.99	-20.88	-17.02	-11.16	0	0	0	0	0
	2008	-340.72	0	-13.98	-28.58	0	0	0	0	0
	2009	-243.80	0	-2.93	-25.77	0	0	0	0	0
	2010	-216.69	-0.14	-7.89	-17.71	0	0	0	0	0
	Total	-1532.74	-21.02	-188.16	-120.03	-0.32	0	0	0	-0.63

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	Area (ha) of land cover types disturbed in the analysis period (ending class)									
	Year	Upland forest	Upland woodland	Upland shrub/herb	Lowland forest	Lowland shrub/herb	Water	Impervious surface	Pervious surface	Impervious/vegetated
SACN	2005	0.16	22.10	29.89	13.79	9.82	1.73	0	3.46	0
	2006	20.31	3.51	22.96	0.31	0.13	0	0	0.26	0
	2007	62.04	2.84	50.71	0.32	0.35	0	0	0.88	0
	2008	0	10.44	66.00	0	0.11	0	0	0	0
	2009	0	4.77	6.49	0	0	0	0	0.54	0
	2010	4.28	7.61	16.15	0	0	0	0	0	0
	Total	86.79	51.27	192.20	14.42	10.41	1.73	0	5.14	0
Non-SACN	2005	11.26	47.60	194.81	3.11	24.61	3.40	29.76	28.38	43.75
	2006	38.25	26.58	182.21	2.35	11.34	0.64	22.86	36.49	21.91
	2007	11.10	19.32	171.57	2.02	3.92	0	1.83	22.12	4.16
	2008	63.93	91.82	169.35	1.84	25.67	1.82	4.66	15.46	7.61
	2009	36.45	73.00	132.80	8.96	17.95	0	0	2.99	0.54
	2010	30.18	44.51	138.54	0.45	17.71	0.23	0	10.09	0.57
	Total	191.17	302.83	989.27	18.74	101.20	6.09	59.11	115.53	78.53

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

Owner	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen
County	0	13.03	0	27.22	0	954.98	1.62
Federal	0	0	11.56	13.29	56.74	56.08	0
Private	6.37	1.70	0.84	298.19	0	451.10	4.12
State	0	1.73	0	2.02	0	331.99	2.03
Tribal	0	0	0	0.88	0	0	0

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

Owner	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen
Burnett County, WI	0	0	0	4.04	0	141.05	0
Douglas County, WI	0	13.03	0	14.30	0	744.24	0
Minnesota DNR	0	1.73	0	0	0	87.51	2.03
National Park Service	0	0	11.56	0.33	0	9.52	0
Polk County, WI	0	0	0	0	0	4.53	0
Private	6.37	1.70	0.84	298.19	0	451.10	4.12
Sawyer County, WI	0	0	0	0	0	7.68	0
St. Croix Chippewa Indians of Wisconsin	0	0	0	0.88	0	0	0
State of Minnesota	0	0	0	0	0	11.43	0
US Fish and Wildlife Service	0	0	0	12.96	0	4.68	0
USDA Forest Service	0	0	0	0	56.74	41.88	0
Washburn County, WI	0	0	0	8.88	0	57.49	1.62
Wisconsin DNR	0	0	0	2.02	0	233.05	0

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

HUC 10 name	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen
North Branch Sunrise River	0	0	0	21.13	0	19.37	0
Sunrise River	0.68	0	0	121.72	0	44.48	0
Upper Tamarack River	0	14.73	0	15.74	0	745.20	0
Willow River	5.09	0	0.54	144.47	0	61.17	0

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

Owner	Agriculture	Beaver	Blowdown	Development	Fire	Forest harvest	Forest pathogen
Burnett County, WI	0	0	0	0	0	56.88	0
Minnesota DNR	0	1.73	0	0	0	15.55	2.03
National Park Service	0	0	11.56	0.33	0	9.52	0
Private	0.59	0	0	1.33	0	46.05	0
St. Croix Chippewa Indians of Wisconsin	0	0	0	0.88	0	0	0
USDA Forest Service	0	0	0	0	56.54	41.88	0
Washburn County, WI	0	0	0	8.88	0	20.50	1.62
Wisconsin DNR	0	0	0	0	0	82.87	0

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

Owner	Percent
Burnett County, WI	6.39
Douglas County, WI	4.27
National Park Service	59.04
Polk County, WI	0.08
Private	10.98
Sawyer County, WI	<0.01
St. Croix Chippewa Indians of Wisconsin	0.29
State of Wisconsin	0.02
Town of Somerset, WI	0.01
USDA Forest Service	1.10
Washburn County, WI	5.38
Wisconsin DNR	12.44

Appendix D. Results from Interpreter Cross Validation

As mentioned in the introduction, two interpreters were used for making 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 considerable thought has been given 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 validators’ polygon 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 non-matching values can be interpreted as follows: interpreter 1 called something false 14 times when interpreter 2 called it true.

		Interpreter 2		Total interpreted	Proportion unambiguous
		FALSE	TRUE		
Interpreter 1	FALSE	222	14	236	0.94
	TRUE	3	58	61	0.95

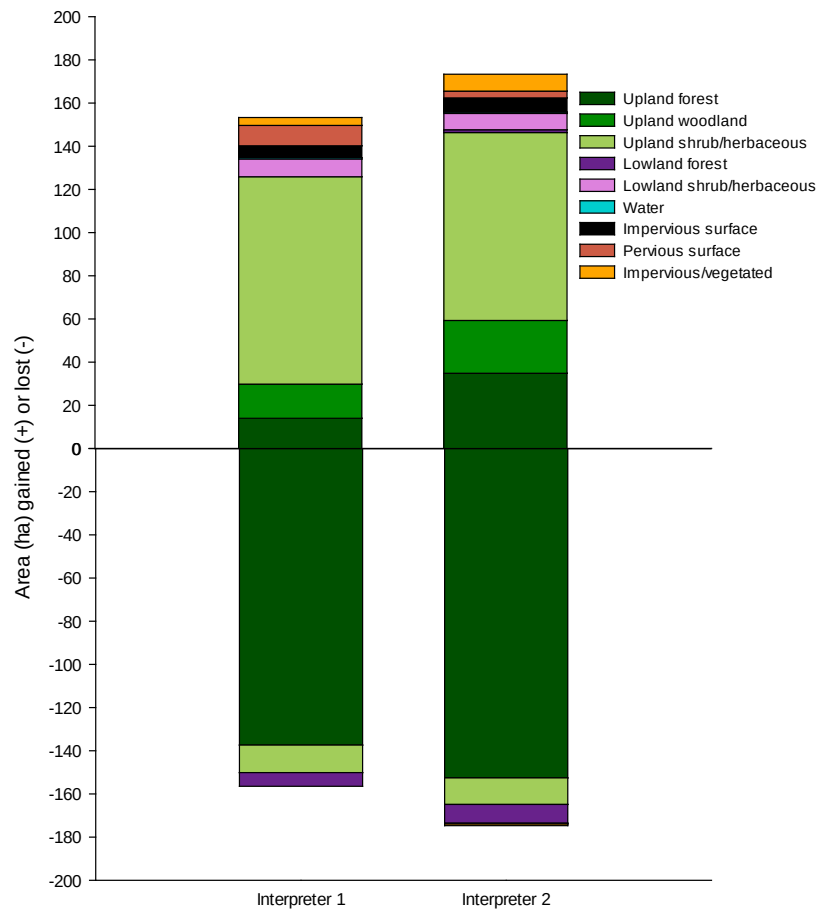


Figure D1. Area (ha) of vegetation gained and lost as indicated by each interpreter.

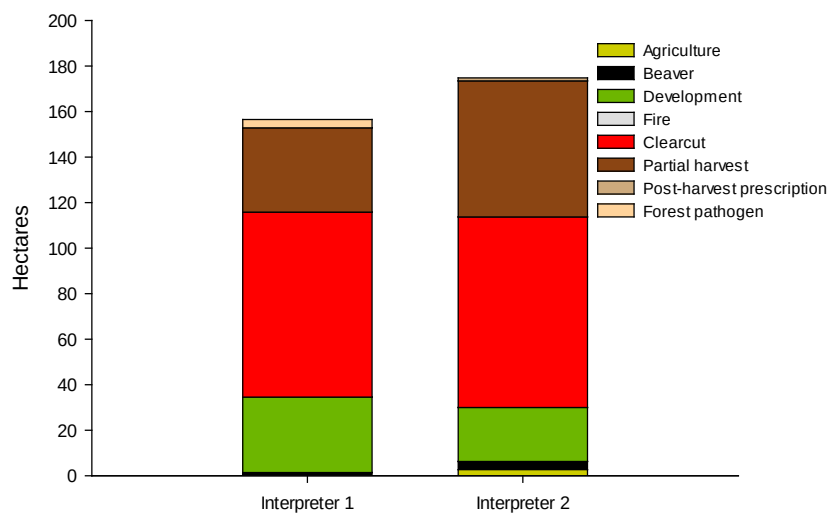


Figure D2. Area (ha) of land disturbed by disturbance agent as indicated by each interpreter.

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 where interpreter 2, classified it as partial harvest.

Table D2. Generalized starting and ending 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 starting and ending 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										Total interpreted	Proportion unambiguous
		Agriculture	Beaver	Blowdown	Development	Fire	Flooding	Harvest (clearcut)	Harvest (partial)	Forest pathogen	None		
Interpreter 1	Agriculture	0	0	0	0	0	0	0	0	0	0	0	0.00
	Beaver	0	1	0	0	0	0	0	0	0	0	1	1.00
	Blowdown	0	0	0	0	0	0	0	0	0	0	0	0.00
	Development	0	0	0	14	0	0	2	1	0	0	17	0.82
	Fire	0	0	0	0	0	0	0	0	0	0	0	0.00
	Flooding	0	0	0	0	0	0	0	0	0	0	0	0.00
	Harvest (clearcut)	0	0	0	1	0	0	27	2	0	1	31	0.87
	Harvest (partial)	0	0	0	1	0	0	0	8	0	0	9	0.89
	Forest pathogen	0	0	0	0	0	0	0	1	0	0	1	0.00
	None	1	0	0	0	0	0	1	3	0	110	115	0.96

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	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1.00
		Deciduous forest	1	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0.98
		Mixed forest	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	1.00
		Evergreen woodland	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
		Mixed woodland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Lowland	Shrub	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1.00
		Herbaceous	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	8	1.00
		Evergreen forest	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
		Mixed forest	0	0	0	0	0	0	0	0	0	0	7	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
		Herbaceous	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	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	0	0	0	0	0	0	0	0	0	0	0	0	0
		Impervious/vegetated	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		None	4	6	2	0	0	1	2	0	0	3	0	0	0	0	0	1	87	106	0.82

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).

			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	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	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1.00
		Mixed forest	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		Evergreen woodland	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		Deciduous woodland	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0.33
		Mixed woodland	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0.50
		Shrub	0	0	0	0	3	0	24	0	0	0	0	0	0	0	0	0	0	0	27	0.89
		Herbaceous	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	1	5	0.40
	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	0	0
		Shrub	0	1	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	7	0.86
		Herbaceous	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	2	0
		Water	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
		Impervious surface	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	0	4	0.75
		Pervious surface	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	3	0	1	7	0.43
Impervious/vegetated	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	3	0.33		
None	0	1	1	0	1	0	5	1	0	0	2	0	0	1	2	2	1	91	108	0.84		

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	48	0	0	0	0	0	0	0	48	1.00
	Upland woodland	0	0	0	0	0	0	0	0	0	0
	Upland shrub/ herbaceous	0	0	9	0	0	0	0	0	9	1.00
	Lowland forest	0	0	0	7	0	0	0	0	7	1.00
	Lowland shrub/herbaceous	0	0	0	0	0	0	0	0	0	0
	Water	0	0	0	0	0	0	0	0	0	0
	Bare ground	0	0	0	0	0	0	0	0	0	0
	None	4	0	3	4	0	0	1	98	110	0.89

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.

		Interpreter 2									
Interpreter 1	Ending vegetation class	Upland forest	Upland woodland	Upland shrub/herbaceous	Lowland forest	Lowland shrub/herbaceous	Water	Bare ground	None	Total interpreted	Proportion unambiguous
	Upland forest	2	1	0	0	0	0	0	0	3	0.67
	Upland woodland	2	2	0	0	0	0	1	0	5	0.40
	Upland shrub/ herbaceous	0	2	28	0	0	0	0	1	31	0.90
	Lowland forest	0	0	0	0	0	0	0	0	0	0
	Lowland shrub/herbaceous	0	0	1	0	7	0	0	0	8	0.88
	Water	0	0	0	0	0	0	0	1	1	0
	Bare ground	1	0	0	0	0	0	12	0	13	0.92
	None	2	1	6	2	0	0	2	97	110	0.88

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
Interpreter 1	Forest	52	0	0	0	0	0	52
	Woodland	0	0	0	0	0	0	0
	Shrub-herbaceous	0	0	9	0	0	0	9
	Water	0	0	0	0	0	0	0
	Bare ground	0	0	0	0	0	0	0
	None	2	0	3	0	1	107	113

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
Interpreter 1	Forest	4	0	0	0	0	0	4
	Woodland	2	2	0	0	1	0	5
	Shrub-herbaceous	0	3	33	0	0	2	38
	Water	0	0	0	0	0	1	1
	Bare ground	1	0	0	0	12	0	13
	None	2	2	3	0	2	104	113

Appendix E: 2011 Storm damage (blowdown) maps

Overview

During the summer of 2011 (July 1st), a large blowdown event occurred on the MN-WI border in northwestern WI. There was also an EF2 tornado associated with this extreme wind event near Solon Springs. Using ground information and overflights of the area, the WI DNR produced wind damage maps, to help prioritize salvage areas and risk assessment. In this appendix we have provided one of the maps from the WI DNR (Figure E2) and have produced additional maps (Figures E1 and E3-5) pertinent to the SACN analysis area.

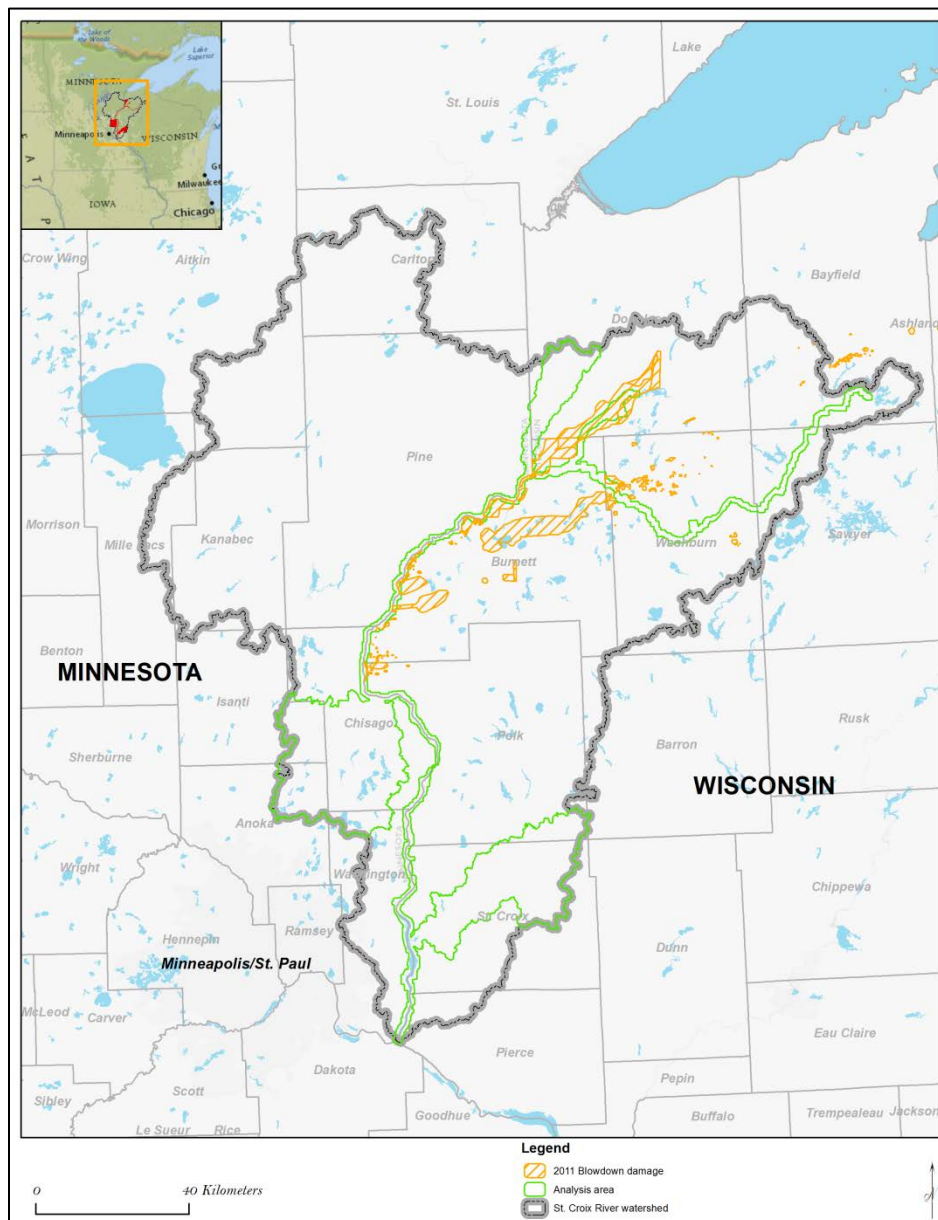


Figure E1. Overview of the 2011 blowdown extent within the analysis area. Geospatial data regarding the extent of the damage was provided by the WI DNR.

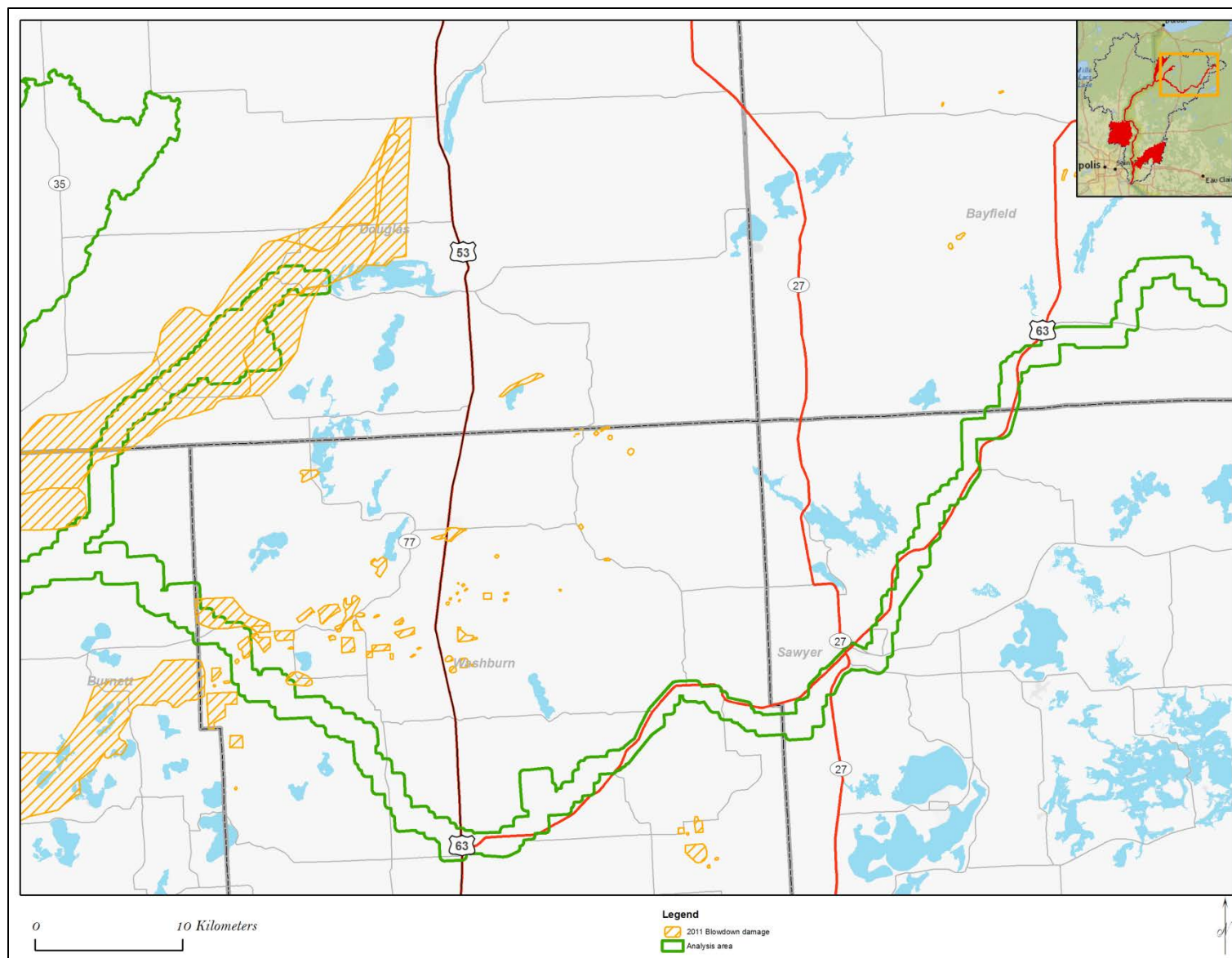


Figure E3. Close-up (1of 3) of the blowdown event in and around SACN. Spatial data from the WI DNR.

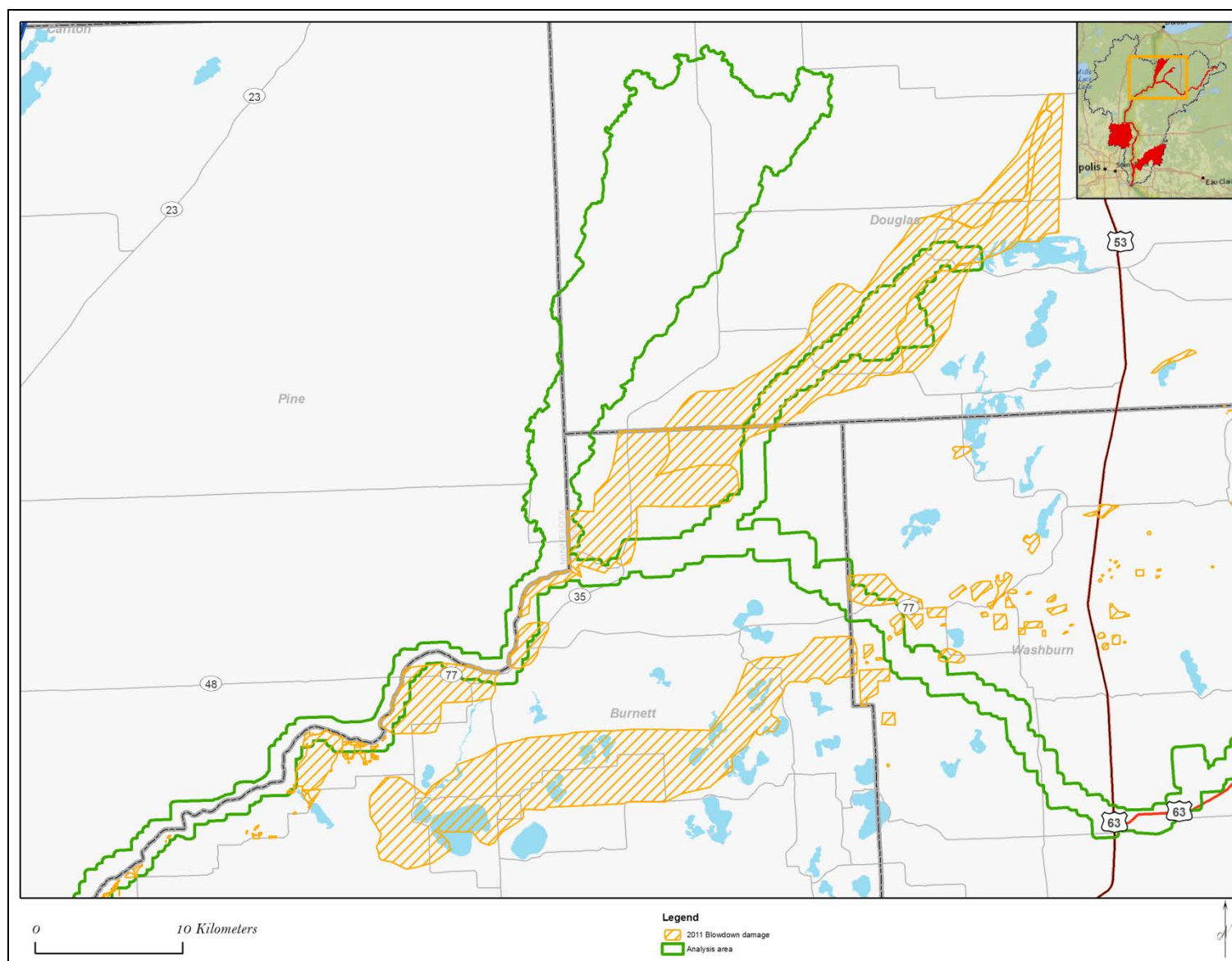


Figure E4. Close-up (2 of 3) of the blowdown event in and around SACN. Spatial data from the WI DNR.

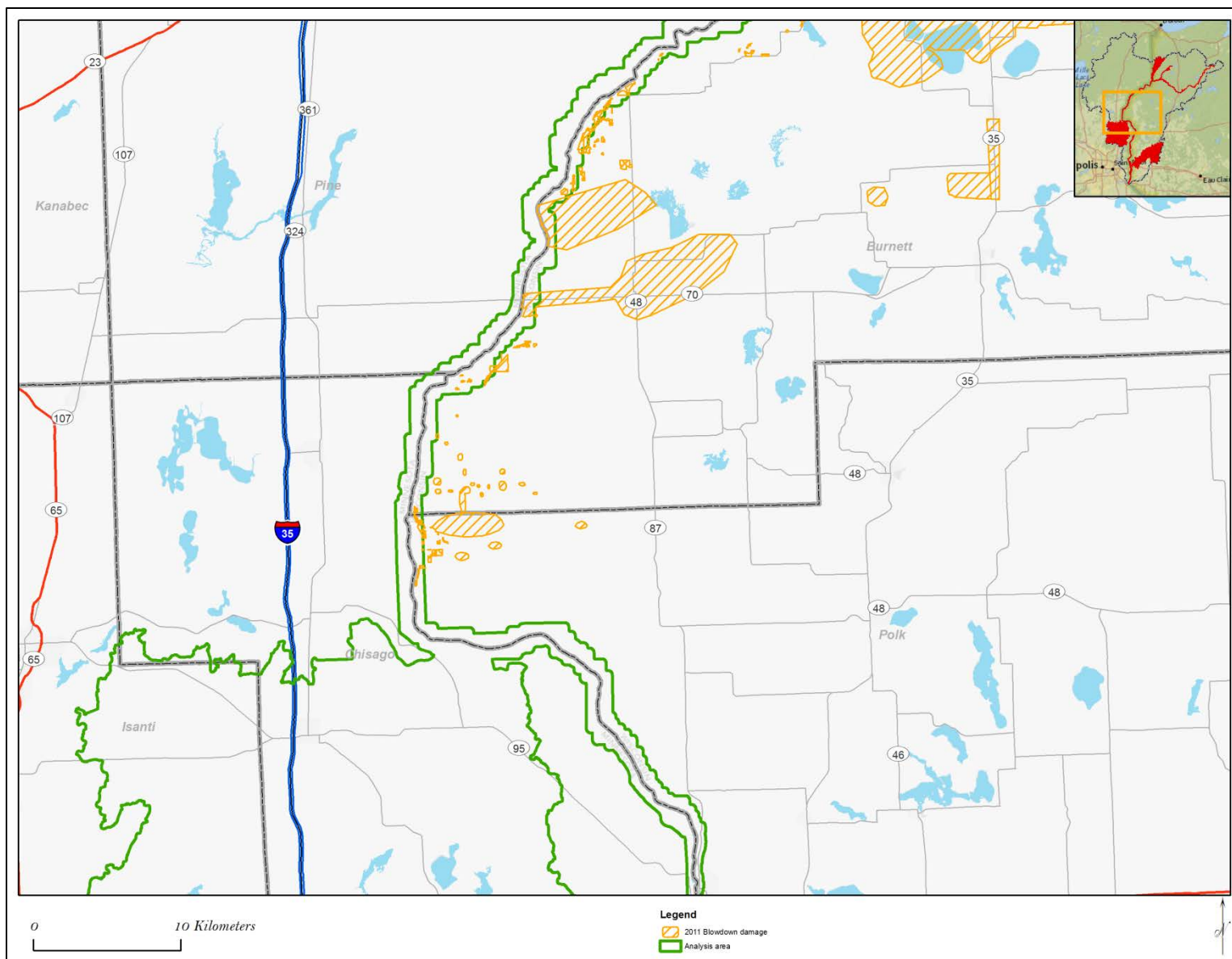


Figure E5. Close-up (3 of 3) of the blowdown event in and around SACN. Spatial data from the WI DNR.

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