

Are U.S. national parks in the Upper Midwest acting as refugia? Inside vs. outside park disturbance regimes

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Abstract. Landscape disturbances such as forest harvest, blowdowns, fire, and development activities create patches on the landscape that modify the structure and integrity of ecosystems. Understanding the agents of change, where they occur, and how much of the landscape they are affecting will assist resource managers in making difficult decisions. To fulfill this goal, the National Park Service implemented a long-term monitoring program to quantify landscape dynamics across 1.5 million ha within and adjacent to eight national parks in the Upper Midwest United States using an automated satellite-based change detection program called LandTrendr (Landsat-based detection of trends in disturbance and recovery). The disturbance agents detected inside parks included beaver, blowdown, development, fire, flooding, insect/disease, and forest harvest. Pictured Rocks National Lakeshore had the largest percentage of area affected inside a park (11.83%, 1.96% per yr), and Isle Royal National Park had the lowest percentage of land affected (0.03%, 0.05% per yr). Tree defoliation due to insect/disease affected the largest percentage of land inside parks (1.56%, or 0.26% per yr) but did not result in tree mortality. Adjacent to parks, disturbance agents detected included agriculture, beaver, blowdown, development, insect/disease, fire, flooding, and forest harvest. Lands adjacent to Pictured Rocks National Lakeshore experienced the highest rate of disturbance (8.75%, 1.45% per yr), largely due to forest harvests. The lands adjacent to the Mississippi National River and Recreation Area experienced the lowest percentage of change (0.62%, 0.10% per yr), with development activities being responsible for most of the change. Forest harvesting was the major change agent outside six of the eight parks, an indication of how important the wood products industry is in the region and the level to which this region is forested. These national parks are acting as integral buffers from adjacent lands that either do not have the ability or lack the capacity to allow the ecosystem to function without intensive management efforts.

Key words: blowdown; fire; forest harvest; Great Lakes Network; Landsat; landscape dynamics; National Park Service; Special Feature: Science for Our National Parks' Second Century.

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INTRODUCTION

The U.S. National Park System was established a century ago in an attempt to protect certain iconic landscapes from the threats of human exploitation. At the time, such preservation

efforts attended primarily to the static elements of nature such as physical land features and the endemic biota that inhabit them. Since then, we have come to appreciate the importance of national parks not only as passive refugia designed to preserve natural structure, but also

as places where large-scale ecosystem dynamics, even disruptive ones, are allowed to operate with minimal human interference (Vitousek et al. 1996, Hansen et al. 2014). Today, the U.S. National Park System serves dually as publically accessible nature reserves and as living laboratories for the study of natural processes, such as wildfire, and predator–prey dynamics that once dominated a wild North America (Peterson et al. 1984, McLaren and Peterson 1994, Ripple and Beschta 2003), but have since been excluded from most landscapes (Robinson and Wilcove 1994, Robinson et al. 1995, Sloan et al. 1998).

Knowledge gained in national parks by studying the resistance and resilience of ecosystems to natural disturbance has proven extremely valuable in the management of natural resources across a variety of public and private landscapes (Turner et al. 1989, Wolter and White 2002, Stueve et al. 2011a). However, differences between the habitats, land cover, and disturbance agents inside national parks and just outside their borders are often stark and broad-scale inventories of disturbances across these boundaries have been lacking (Cole and Landres 1996). To help fill this knowledge gap, the National Park Service implemented a long-term monitoring program to quantify landscape dynamics across 1.5 million ha within and adjacent to eight national parks in the Upper Midwest United States using an automated satellite-based change detection program called LandTrendr (Landsat-based detection of trends in disturbance and recovery) (Kennedy et al. 2010b).

Several different disturbance agents affect landscapes in the Upper Midwest, each of which can be quantified in space and time using LandTrendr. Forest harvest and building development are the dominant change agents on nonprotected forested land, typically creating a mosaic of disturbance patches (Mladenoff and Pastor 1993, Sturtevant et al. 2004). Forests in this region, both inside and outside national parks, are also subject to a variety of natural disturbances including high winds (referred to hereafter as blowdowns; Canham and Loucks 1984, Lorimer and White 2003, Moser et al. 2007, Nelson et al. 2009), flooding due to beaver activity (referred to hereafter as beaver; Smith et al. 1991, Johnston and Windels 2015), wildfires (referred to hereafter as fire; Heinselman 1973, Loope 1991, Scheller and Mladenoff 2005, Weyenberg and Pavlovic 2014), and tree mortality

and defoliation resulting from forest pathogens such as forest tent caterpillar, gypsy moth, beech bark disease, and emerald ash borer (referred to hereafter as insect/disease; Papaik et al. 2005, Wood et al. 2010, Pugh et al. 2011, DeSantis et al. 2013).

By providing a regional inventory of disturbance events over space and time, we aim to provide ecologists and land managers throughout the Upper Midwest a better understanding of how disturbance is shaping the region and how these endemic processes may themselves respond to external forces such as climate change, species invasions, and changing human pressures. Specifically, we set out to answer the following questions: (1) What disturbance agents were present during our analysis period in and adjacent to national parks? (2) How did disturbance patch characteristics vary among agents? (3) How did disturbance patch characteristics vary across park boundaries? (4) How is the land cover mosaic responding to various disturbance types?

METHODS

Study area

The climate in the study area region is mid-continental with mean annual precipitation ranging from 645 to 907 mm and temperatures that vary from minus 40°C in winter to over 32°C in summer. Due to lake effects near the Great Lakes, annual snowfall varies widely from 711 to 346 mm. Vegetation diversity is high as parks in the study intersect portions of seven Environmental Protection Agency (EPA) Level III North American Ecoregions (Woods et al. 1996). The northern portion of the study area consists of forests dominated by *Populus tremuloides* (trembling aspen), *Abies balsamea* (balsam fir), *Pinus banksiana* (jack pine), and *Pinus resinosa* (red pine). The central part of the study area is comprised of north central hardwood forests dominated by *Quercus* spp. (oak), *Carya* spp. (hickory), and *Fraxinus* spp. (ash) and agricultural land use, typically row crops such as corn and soybeans. In the southern part of the region, the landscape is dominated by corn belt plains which were originally tallgrass and short-grass prairies.

Eight national parks within the National Park Service Great Lakes Inventory and Monitoring Network (GLKN) were monitored as part of this analysis (Fig. 1). Five of the parks, Isle Royale

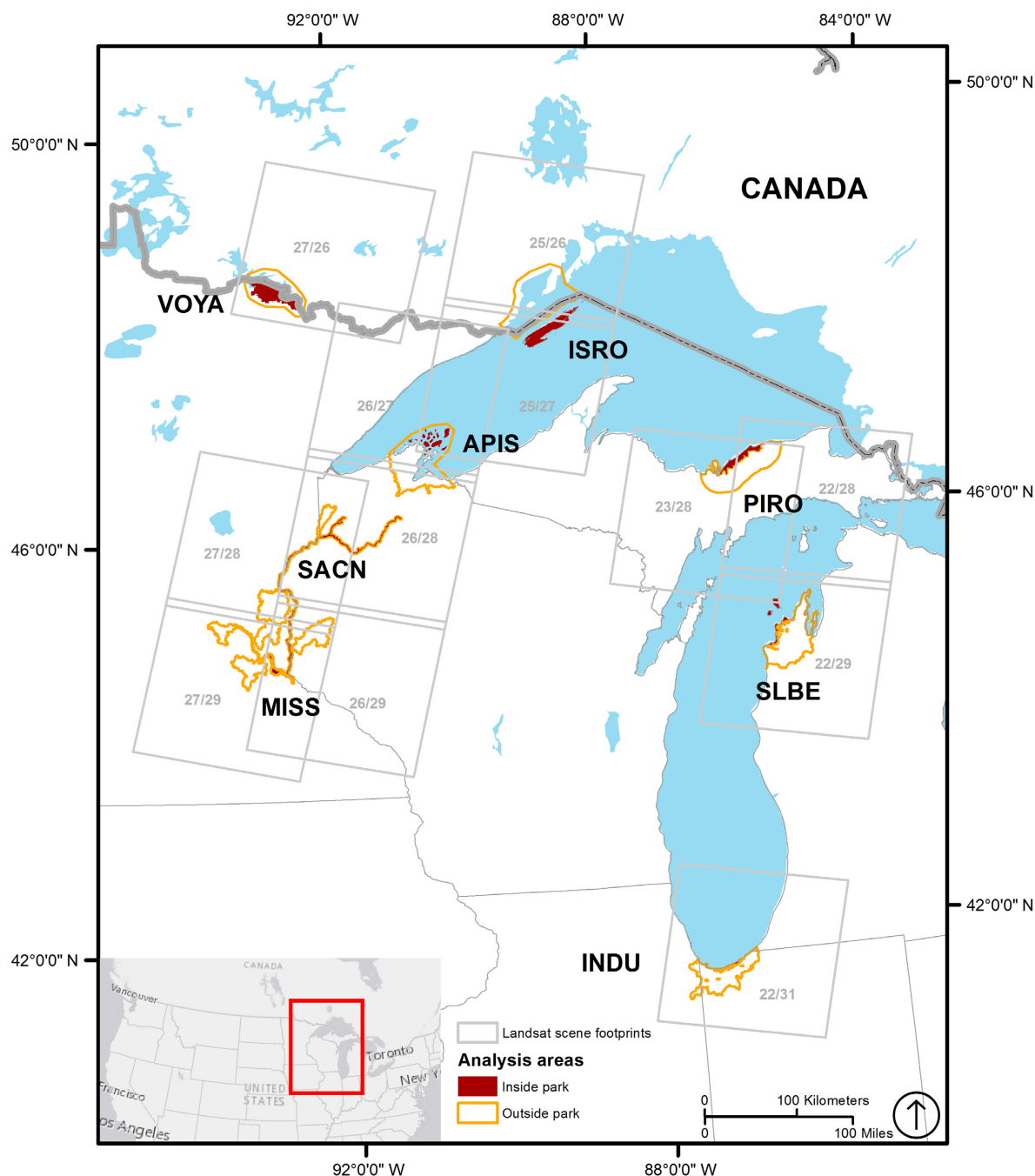


Fig. 1. Location of the eight parks and areas outside the parks analyzed for this study.

National Park (ISRO), Pictured Rocks National Lakeshore (PIRO), Apostle Islands National Lakeshore (APIS), Sleeping Bear Dunes National Lakeshore (SLBE), and Indiana Dunes National Lakeshore (INDU), are located on either

Lake Superior or Lake Michigan. The remaining three parks, St. Croix National Scenic Riverway (SACN), Mississippi National Recreation River Area (MISS), and Voyageurs National Park (VOYA), are located on large river systems or

lakes inland from the Great Lakes. The parks range in size and shape from the 28.5 ha serpentine corridor surrounding MISS to the large 231,396 ha island of ISRO. Lastly, Voyageurs National Park includes portions of the United States and Canadian border lake complex with a mosaic of freshwater lakes, ponds, and streams.

As part of this study, the entire park area was analyzed, and in addition to the parks, lands adjacent to the parks were also analyzed. At five parks (APIS, INDU, MISS, SACN, and SLBE), the areas outside the parks were defined by level 10 delineations of the National Hydrography Dataset's Hydrologic Unit Code (nhd.usgs.gov). At the remaining three parks (ISRO, PIRO, and VOYA), a 5-km minimum buffer around the park was used to define the analysis area. In total, 1.5 million ha was monitored, of which 86% were outside the parks (Table 1).

Image analysis

Although the entire Landsat archive (1984–2014) was used for disturbance detection at each park, we were limited to validating disturbances for a 6-yr span at each park. The exact years summarized vary slightly among parks due to the order in which the parks were analyzed (Table 1). For example, in 2008, we analyzed and summarized VOYA, choosing the most recent 6-yr time period, 2002–2007. Then, the following year (2009) we analyzed ISRO and reported on disturbances from 2003 to 2008. There were also years in which we processed two parks in the same year, that is, MISS and SACN (Table 1). Lastly, 612 Level 1T Landsat Thematic Mapper and Enhanced Thematic Mapper + images from 11 scenes were selected and downloaded from the

United States Geological Survey Global Visualization Viewer archive (glovis.usgs.gov) (Table 2). Images selected were from the mid-summer season (1 July–31 August).

Disturbance detection methodology

We used a set of processing and analysis steps collectively known as LandTrendr (Kennedy et al. 2010a, b, 2012). Using statistical fitting algorithms, LandTrendr works on a per pixel (30 m resolution) basis to describe a time series of spectral reflectance values, capturing the shape of the time series curve, while smoothing undesired random noise, such as phenological condition or sun angle at the time of image acquisition. LandTrendr identifies periods of spectral stability (no change) and instability (change). For this analysis, we only report on changes, where and when they occur.

To minimize effects of phenological variation, we selected Landsat images between July and August of each year (1984–2014). We preprocessed Landsat images following standard procedures for atmospheric correction and cloud/shadow screening. We atmospherically corrected images using the Landsat Ecosystem Disturbance Adaptive Processing System (Vermote et al. 1997, Masek et al. 2006). Clouds, associated shadows, and missing pixel data were masked using the Fmask algorithm developed by Zhu and Woodcock (2012). These processed images served as the base on which LandTrendr algorithms were run. We used the normalized burn ratio (Deering 1989, Key and Benson 2006) and band 5 (short-wave infrared) with LandTrendr because it has been shown that band 5 is more effective at detecting short duration (<2 yr),

Table 1. Analysis years and land area monitored for each park (inside and outside).

Park	Year established	Analysis years	Inside park land area (ha)	Outside park land area (ha)	Total land area (ha)
Voyageurs NP (VOYA)	1971	2002–2007	53,036	93,526	146,562
Isle Royale NP (ISRO)	1940	2003–2008	54,067	102,574	156,641
Apostle Islands NL (APIS)	1970	2004–2009	16,563	169,443	186,006
Mississippi NRR (MISS)	1988	2005–2010	16,107	141,996	158,103
St. Croix NSR (SACN)	1968	2005–2010	32,108	220,461	252,569
Picture Rocks NL (PIRO)	1966	2006–2011	26,435	203,675	230,110
Sleeping Bear Dunes NL (SLBE)	1970	2006–2011	24,096	191,884	215,980
Indiana Dunes NL (INDU)	1966	2007–2012	6195	155,159	161,354
Total			228,607	1,278,718	1,507,325

Table 2. Landsat images used in the study.

Scene path/row	No. of images	Missing years?
22/28	85	
22/29	69	1991
22/31	53	1985, 1989, 1992
23/28	86	
25/26	48	1985, 1992, 1994, 1997, 2001
25/27	34	1985, 1990, 1992, 1994, 1997, 2001
26/27	34	1987, 1989, 1991, 1994
26/28	49	1987, 1994, 1996, 1997
26/29	48	
27/26	56	1985, 1999
27/29	50	2001

abrupt changes such as forest harvest clear-cuts (Schroeder et al. 2011), while NBR is more sensitive to subtle disturbances such as partial forest harvests (Kennedy et al. 2012).

Patch definition

To delineate patches, adjacent pixels experiencing disturbances in the same year were assumed to have experienced the same event and were grouped together using an 8-neighbor adjacency rule. Patches with 10 or fewer pixels were removed from the data set to avoid small, often-unverifiable disturbance events. This size was small enough to capture most forest harvests in addition to other disturbance agents such as beavers, some development activities, and blow-downs. We merged the outputs from NBR and band 5 using a patch agglomeration script that evaluated each individual patch from the NBR output and determined whether any part of a patch in the band 5 output overlapped geographically and occurred in the same year. If so, the pixels in the two patches were merged into one disturbance patch.

Assessment of LandTrendr segmentation

At 1000 individual plots distributed randomly across all lands in the study area, we assessed the accuracy of the LandTrendr pixel-resolution change detection using TimeSync (Cohen et al. 2010). We chose to use TimeSync because Cohen et al. (2010) showed that interpretations made using this technique agree strongly with independent reference data and is consistent across years and ownerships. We labeled each plot as stable or disturbed and for each disturbance

assigned a confidence level (high, medium, low) and change agent (agriculture, beaver, development, fire, forest harvest, or insect).

To assess the accuracy of LandTrendr algorithms, the 3 x 3 pixel plot was intersected with the disturbance polygons, and a match was counted if the polygon and interpreter agreed on the disturbance within 1 yr of each other.

Interpreter-based validation and attribution of change

We chose to validate every (census) disturbance polygon that was generated by LandTrendr to remove commission errors (false positives) and at the same time determine the change agent. If a polygon spanned boundaries (inside/outside park), we attributed the polygon with the majority of the polygon represented. Validation of possible disturbances followed details given in Kirschbaum and Gafvert (2010) and is briefly summarized here. After disturbance polygons were created by LandTrendr, the next step was to validate whether a change occurred in the polygon and document the agent of change (Table 3). To determine whether changes had occurred, we used high-resolution (≤ 1 m) imagery (airphoto and satellite). The majority of the imagery used was from the National Agriculture Imagery Program (NAIP) with a pixel resolution of 1 m. When validating disturbances in Canada where NAIP imagery was not available, we relied on satellite imagery from various satellites such as WorldView-1, WorldView-2, Quickbird, and GeoEye-1 with pixel resolutions ranging from 0.3 to 1 m. In addition to imagery, we also used spatial information from the U.S. Forest Service Insect and Disease surveys (<http://foresthealth.fs.usda.gov/portal/Flex/IDS>). Contextual information such as forest type, ownership, and drainage boundaries was important for determining the disturbance agent. Lastly, we also viewed the entire Landsat image stack (1985–2014) for each prospective disturbance and a graph of the reflectance values through time (1985–2014) of said disturbance. By viewing high-resolution imagery, ancillary data, Landsat imagery, and reflectance values, our interpretation eliminated false positives, while preserving more subtle disturbances such as defoliation or slow vegetation declines. In a GIS environment utilizing high-resolution imagery, ancillary data

Table 3. Disturbance agents identified in this study and how interpreters identify each.

Disturbance agent	Description and means of identification
Agriculture	Conversion of a nonagricultural land use/land cover type (e.g., forest, wetland) to an agricultural land use (row crops, pasture, hay).
Beaver	Landscape changes caused by beaver dams. Identified by flooding (i.e., presence of water) of wooded wetlands and the subsequent killing of trees.
Blowdown	The uprooting and tipping over of trees by wind. Blown down trees are evident in high-resolution airphotos and are usually oriented in the direction of the wind event.
Development	Permanent conversion of vegetated surface to nonvegetated surface such as mines, paved roads, parking lots, buildings, and houses.
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.
Flooding	Detection of flooding is distinguished from a beaver disturbance due to the lack of beaver ponds proximal to disturbance.
Forest harvest (light)	Most easily identified by the proximal presence of pervious roads and very linear features outlining the extent of the disturbance. This category of forest harvest has 60–90% of the overstory remaining.
Forest harvest (moderate)	Same contextual information as forest harvest (light) however, this harvest category has 30–59% of the overstory remaining.
Forest harvest (heavy)	Same contextual information as forest harvest (light); however, this harvest category has 0–29% of the overstory remaining.
Insect/disease (defoliation)	Disturbances in the overstory due to insects or diseases that result in tree defoliation.
Insect/disease (mortality)	Disturbances in the overstory due to insects or diseases that result in tree mortality.
Other	When the interpreter is unable to determine the causal agent, this category is used.

sets, and the Landsat imagery itself, we validated a total of 24,563 LandTrendr-delineated disturbance polygons among the eight parks, removing all false-positive (commission) polygons from the summary analysis. As all of our analysis areas differ in size, disturbance area was computed as percentage of land area, excluding bodies of water as delineated by the 2006 National Land Cover Database (Fry et al. 2011).

Our work corroborated what has been shown in past studies (Cohen et al. 2010, Antonova et al. 2011) that on-screen validation of polygons with the aid of high spatial resolution imagery, in addition to high temporal resolution (yearly) Landsat imagery and Landsat reflectance values, is as good as any ancillary or ground-based validation method. The most obvious disturbances such as forest clear-cuts and development are the two main disturbances that can be field-validated; however, they are also the disturbances most easily validated with high-resolution imagery and/or Landsat imagery. More subtle or older disturbances are largely not possible to validate in the field due to logistical constraints (too remote to access) or because the evidence (e.g., insect/disease, low level forest harvests) has been masked by time (Cohen et al. 2010, Antonova et al. 2011).

RESULTS

Assessment of LandTrendr segmentation

Based on point-level comparison with human interpretation, the LandTrendr segmentation had commission and omission rates of 24.7% and 7.3%, respectively (Table 4). On just over half (515) of the plots, the human interpreter and LandTrendr agreed that no disturbance occurred. Lastly, there were 165 plots (16.5%) that the interpreter and LandTrendr agreed there was a disturbance (Table 4).

Disturbance agents inside park boundaries

There were very few tree-killing disturbances detected inside the eight parks during the analysis period (Fig. 2). The three parks with the highest percentage of land disturbed were APIS, PIRO, and SLBE, with the bulk of the disturbances at APIS and SLBE the result of a tree defoliation event that did not kill any trees (Fig. 2). The defoliation events at APIS and SLBE affected 7.68% and 4.80% of the land, respectively, and did not result in any tree mortality. At PIRO, the majority (72%) of the disturbances were due to forest harvest activities that are allowed inside the inland buffer zone of the park and collectively disturbed 8.56% of the land (Fig. 2). The

Table 4. Agreement between point-based interpretation of disturbance using TimeSync and LandTrendr segmentation results.

Methodology	Disturbance agent	Interpreter confidence			LandTrendr commission nondisturbed
		High	Medium	Low	
Matched segment	Agriculture	1			247
	Beaver	6	1		
	Development	28	2		
	Fire	1	2		
	Forest harvest	84	3	1	
	Insect/disease (mortality)	18	14	5	
	None	515			
LandTrendr omission	Nondisturbed	55	14	4	

Notes: Any pixel within a 3×3 pixel window with agreement is considered a match. A total of 1000 random plots were chosen for this accuracy assessment.

remaining disturbances at PIRO were due to insect/disease mortality (beech bark disease) that disturbed 3.10% of the land and 0.17% of the land due to development (Fig. 2). At VOYA, disturbance due to fire affected 0.34% of the land, followed by beaver (0.18%) and blowdown (0.15%) (Fig. 2). Fire was also detected at SACN affecting 0.16% of the land. Similar to PIRO, this park also allows forest harvests inside the park boundary, and like PIRO, these forest harvests disturbed the largest percentage of land (0.87%) (Fig. 2). At MISS, only disturbances due to development were present, affecting 0.38% of the land (Fig. 2). Lastly, ISRO had the lowest amount of disturbance inside the park, with a mere 0.027% of land affected by beaver, blowdown, and insect/disease mortality combined.

Disturbance agents outside park boundaries

Disturbance regimes outside the eight parks can be grouped into three general categories. The northern parks (VOYA, ISRO, APIS, and PIRO) were dominated by forest harvest disturbances outside the park boundaries, with little development activity. The next disturbance regime category includes parks in the rural/metro intersection (SLBE and SACN) where disturbances are split among agricultural, development, and forest harvests. Lastly, MISS and INDU were dominated by development outside their boundaries.

Among the parks dominated by forest harvests, the park with the highest percentage of forest harvest was PIRO, with 8.50% of the land disturbed followed by 5.96% at VOYA (Fig. 2). All

of VOYA's forest harvest was due to clear-cuts, whereas two-thirds of PIRO's forest harvests left between 30% and 60% of the forest canopy (Fig. 2). APIS and ISRO followed behind VOYA with 3.83% and 2.48%, respectively. Forest harvests around APIS were nearly evenly divided between the three harvest intensities (light, moderate, and heavy), while those adjacent ISRO were all clear-cuts (heavy) (Fig. 2). Forest harvests around SLBE and SACN affected 2.17% and 0.69% of the lands and were split among the different harvest intensities (Fig. 2). Each area adjacent to a park experienced some disturbance due to development, with those located near a major metropolitan area experiencing the greatest amounts. These parks were MISS, INDU, and SLBE with 0.60%, 0.52%, and 0.20% of land disturbed. The parks with the three lowest amounts of development disturbance were VOYA (0.02%), PIRO (0.08%), and APIS (0.11%). The only natural disturbances (nonanthropogenic) occurring outside the parks that affected >0.02% of the land were beaver and blowdown that both occurred outside VOYA.

Patch size characteristics inside park boundaries

Median patch sizes inside parks due to natural disturbance agents were largely below 4 ha in size with notable exceptions at PIRO, SLBE, and APIS (Fig. 3). There were six patches over 30 ha in size at APIS and SLBE due to defoliation events and four at PIRO that were the result of insect/disease mortality (Fig. 3). Remaining disturbances with median patch sizes over 4 ha in size were the result of anthropogenic disturbances, more specifically,

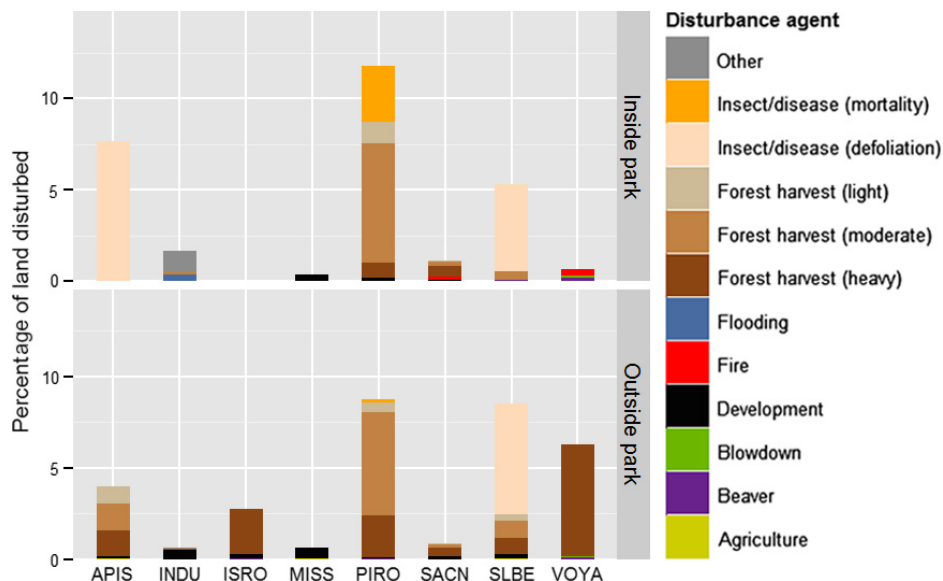


Fig. 2. Percentage of land disturbed inside the park (top) and outside the park (bottom) and disturbance agent.

forest harvests. At PIRO, median patch sizes for the three levels of forest harvests, light, moderate, and heavy, were 8.80, 6.17, and 8.98 ha, respectively (Fig. 3). Disturbances due to natural processes, such as beaver, blowdown, and fire, were much smaller. At VOYA, the median patch sizes for blowdown, fire, and beaver were 2.29, 1.65, and 1.41 ha, respectively (Fig. 3).

Patch size characteristics outside park boundaries

Outside the parks, disturbance patches were larger in size. PIRO had some of the largest patches among all parks, the result of forest harvesting. The three levels of forest harvest at PIRO, light, moderate, and heavy, had median patch sizes of 6.57, 4.41, and 8.79 ha, respectively (Fig. 4). PIRO also had the largest single patch size (945 ha) among all parks, the result of a forest harvest (Fig. 4). Outside VOYA, the median patch size of forest harvest (heavy) was 5.72 ha with an average patch size of 16.08 ha and a maximum patch size of 332 ha (Fig. 4). Other agents present outside VOYA were beaver, blowdown, and development with median patch sizes of 2.51, 3.29, and 0.93 ha, respectively. Outside APIS, the median patch sizes of forest harvest light, moderate, and heavy were 3.32, 3.69, and 2.88 ha, similar to the forest harvest patch sizes

outside ISRO at 3.60 ha. At MISS and INDU, patch size among disturbance agents was smaller. The median patch size at MISS for all agents was below 2 ha, and at INDU, the median patch size for all agents except development, flooding, and forest harvest (moderate) was below 3 ha.

DISCUSSION

Inside the parks

After analysis, it appears that the parks are serving largely as refugia as evidenced by the relative lack of anthropogenic disturbances inside park boundaries. The disturbance agents we detected inside the parks were dominated by natural disturbance agents such as beaver, blowdown, fire, and insect/disease. These drivers of change are important in many ways. For example, inside VOYA, there were four times as many disturbances due to beaver (on a per area basis) compared to lands adjacent to the park. Beavers have been shown to be important ecological driver of change due to their ability to modify ecosystems by changing the geomorphology and ultimately the hydrologic and biotic properties of the landscape (Collen and Gibson 2000, Rosell et al. 2005). Various cover types occur within beaver impoundments, first with the creation of new

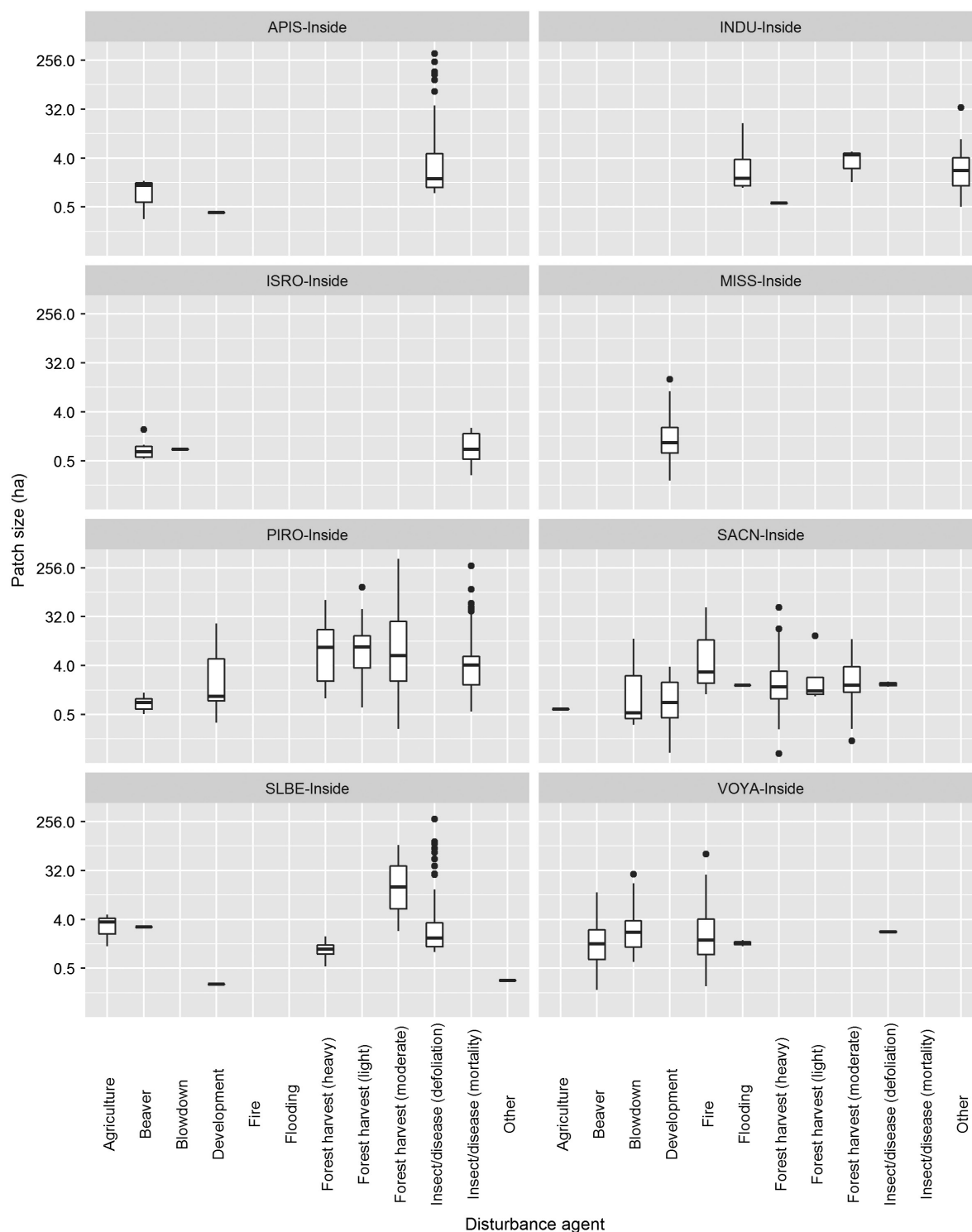


Fig. 3. Estimated disturbance patch size (ha) inside parks. Box represents upper and lower quartiles, solid vertical line is the median, horizontal line represents minimum and maximum values (excluding outliers), and dots represent outliers (more or less than one and half times the upper and lower quartiles). The y-axis is on a log base 2 scale.

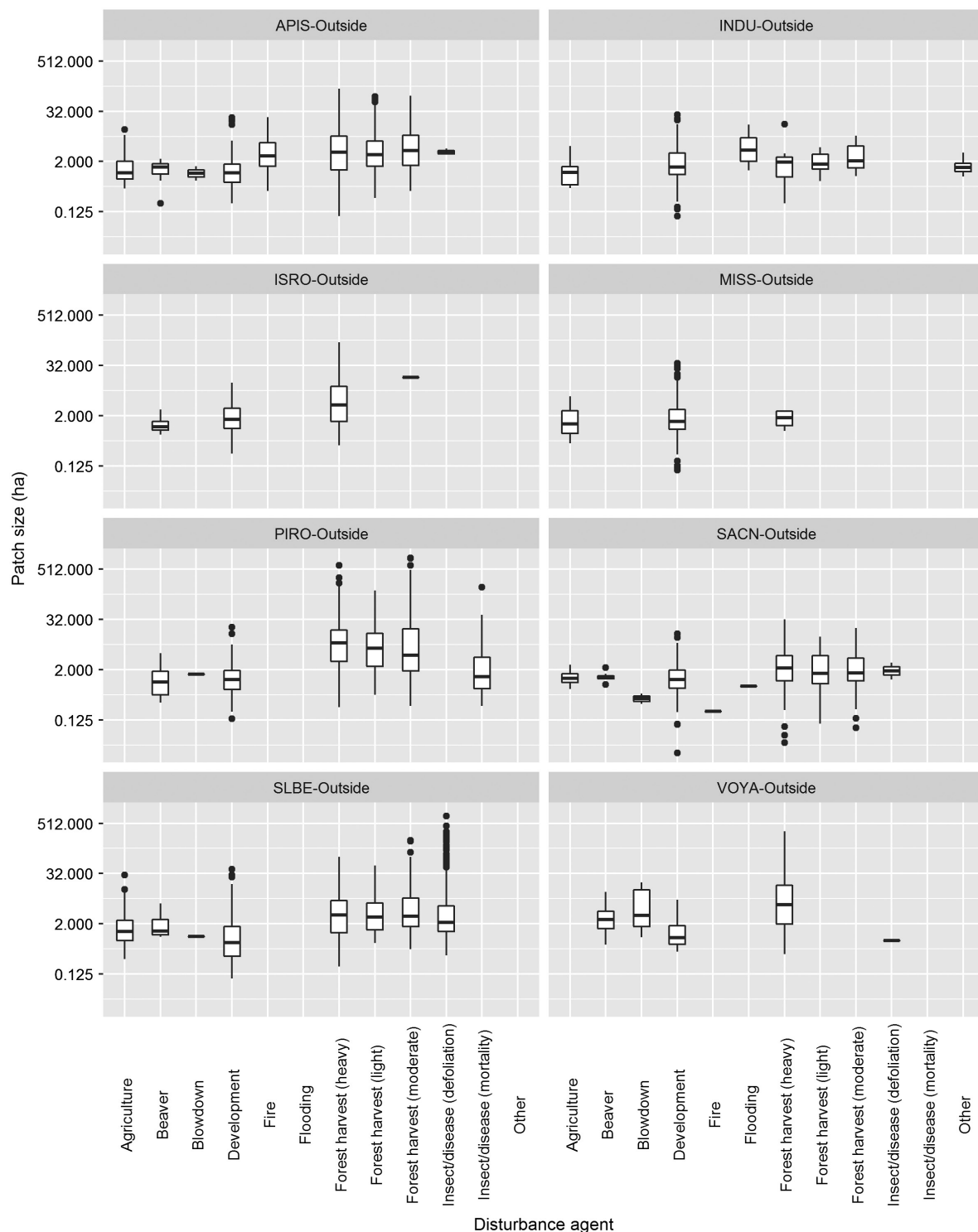


Fig. 4. Estimated disturbance patch size (ha) outside parks. Box represents upper and lower quartiles, solid vertical line is the median, horizontal line represents minimum and maximum values (excluding outliers), and dots represent outliers (more or less than one and half times the upper and lower quartiles). The y-axis is on a log base 2 scale.

ponds that contain flood-tolerant trees or shrubs or standing dead trees that have been killed by deeper, longer inundation (Hyvönen and Nummi 2008). After a beaver leaves an area, the dam eventually fails, sometimes draining a large area in which a saturated wetland inhabited by grasses and sedges exists (Wright et al. 2003, Little et al. 2012). If left long enough, this wetland meadow will eventually be inhabited by shrubs (Remillard et al. 1987). Johnston and Naiman (1990) documented a 43% decline in tree density and basal area after beaver activity, showing the level to which these mammals can affect the forest composition due to their browse preference for trembling aspen. Thus, the lower rate of disturbance due to beaver outside VOYA may point to an aggressive removal of beavers by trapping, removal of beaver dams, or simply the lack of appropriate habitat.

Also of note is the overall lack of fire inside the parks. VOYA was the only park with a considerable amount of land affected by fire. The fire within VOYA affected 180 ha, creating a mosaic of forest burned at varying intensities. Possible contributing factors to the low amounts of fire could be due to the parks' prior history, as many of the parks were formed after changes in the vegetation had already occurred through prior land use. Paulson et al. (2016, this issue) documented the shift in forest community composition since the 19th century toward early-successional species (aspen and maple) and declines in fire-dependent species (jack pine, red pine, bur oak) and species present during the early 20th-century cutover (white pine and hemlock). At ISRO, fire was the major disturbance agent between 1843 and 1900 when much of the forest was burned by mining companies to accommodate prospectors (Snyder and Janke 1976). Since then, there have been two large stand replacing fires, one in 1904 on the southwest end of the park (Cooper 1928) and another fire in 1936 which severely burned over 20% of the land on the island (Snyder and Janke 1976). The current lack of wildfires at ISRO could suppress regeneration of vegetative browse utilized by moose, negatively impacting ecosystem engineers such as moose and beaver (Jordan et al. 2000, Scarpino 2011). In the Upper Midwest, wildfires have been greatly suppressed, leaving straight-line wind the predominant natural

disturbance in the region (Frelich and Lorimer 1991, Schulte and Mladenoff 2005, Stueve et al. 2011b).

Outside the parks

Outside the parks, anthropogenic activities in the forms of agriculture, development, and forest harvest were the dominant disturbance agents (Fig. 2). At the two northernmost parks (VOYA and ISRO), the majority of forest harvests were clear-cuts (forest harvest—heavy) indicating even-aged management of forested areas. Keller et al. (2003) showed that breeding bird species richness in northeastern U.S. forests was highest in 2- to 6-yr-old clear-cuts, declining rapidly after year 10. If the forests outside these parks continue to be managed in such a way as to maximize stand heterogeneity through rotation techniques, there should be a high diversity of breeding birds outside the park. Arguably, there could be a greater diversity of breeding birds outside parks than inside parks due to the higher levels of habitat creation in the form of age diversity. Outside SLBE, PIRO, APIS, and SACN, forest harvests were spread among the three different harvest levels, creating a much more diverse mosaic of forest vegetation, age, and, ultimately, structure (Carleton and MacLellan 1994, Spies et al. 1994, Edenius and Elmberg 1996, Gauthier et al. 1996, Schulte and Niemi 1998). However, the large amounts of forest harvest we detected around four parks (VOYA, ISRO, APIS, and PIRO) may be disrupting migration corridors for small mammals and ungulates, potentially isolating populations inside the park and causing genetic bottlenecks (Wayne et al. 1991, Machtans et al. 1996, Schmiegelow et al. 1997, Russell et al. 2004).

Although forest harvest can have a negative impact on the landscape in the form of additional runoff, fragmentation, and loss of cover, it continues to be vegetated and will regrow into a forest again. Conversely, disturbances due to development will, in most cases, permanently change the landscape from a vegetated class to a nonvegetated class such as impervious surface (parking lots, buildings, etc.) or at the very least, an herbaceous class (lawns). The dominance of forest harvest as a disturbance agent outside these parks corresponds to the low population density in lands adjacent to the parks with these regions depending on resource extraction

for their livelihood. Although we saw low levels of disturbance by development adjacent to these parks, this is a trend we should continue to monitor as there have been studies that show an increase in anthropogenic pressure adjacent to natural areas due to the desirability of living next to them (Radeloff et al. 2010, Gimmi et al. 2011, Hansen et al. 2014).

Large natural perturbations can be ecologically beneficial by resetting the successional process and adding to an area's biodiversity (Dale et al. 1998, Turner et al. 1998). In the Great Lakes region, the most dominant disturbance agents have historically been fire and wind, with return intervals of 100 and 2000 years, respectively (Heinselman 1973, Canham and Loucks 1984, Frelich and Lorimer 1991). Unfortunately, forest harvests cannot serve as a surrogate for natural disturbances due to the differences in processes and the resulting changes in forest structure (Franklin et al. 2002).

To mitigate the effects of these anthropogenic disturbances, park managers may need to create more protected areas or work cooperatively with landowners outside the parks to provide useable corridors between the parks, especially due to migrations related to climate change (Halpin 1997, Frelich and Reich 2009). Currently, areas outside the park are much more fragmented than the parks due to high levels of harvest and development. Hence, these areas cannot be used or navigated through by certain species.

In conclusion, continuing to monitor the lands inside and outside the parks to fully understand change over time will become increasingly important as further development fragments the landscape and stresses from climate change put increased pressure on the parks. If we value these ever more rare pockets of refugia, land managers will need to have information to understand the continuing life history of the parks to help them react to future changes and challenges.

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LITERATURE CITED

- Antonova, N. V., C. Thompson, D. Wallin, R. Bryson, S. Clary, A. Hayes, I. Oehler, B. Pickard, M. Ponce-McDermott, and N. Schaller. 2011. Identifying the Causes of Landscape Change in the North Coast and Cascade Network parks. Published Report-2184853, Task Agreement J8W07110003; PNW CESU Agreement H8W07110001. North Coast and Cascades Network, National Park Service, Sedro-Woolley, Washington, USA.
- Canham, C. D., and O. L. Loucks. 1984. Catastrophic windthrow in the presettlement forests of Wisconsin. *Ecology* 65:803–809.
- Carleton, T. J., and P. MacLellan. 1994. Woody vegetation responses to fire versus clear-cutting logging: a comparative survey in the central Canadian boreal forest. *Ecoscience* 1:141–152.
- 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.
- Cole, D. N., and P. B. Landres. 1996. Threats to wilderness ecosystems: impacts and research needs. *Ecological Applications* 6:168–184.
- Collen, P., and R. Gibson. 2000. The general ecology of beavers (*Castor* spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. *Reviews in Fish Biology and Fisheries* 10:439–461.
- Cooper, W. S. 1928. Seventeen years of successional change upon Isle Royale, Lake Superior. *Ecology* 9:1–5.
- Dale, V. H., A. E. Lugo, J. A. MacMahon, and S. T. A. Pickett. 1998. Ecosystem management in the context of large, infrequent disturbances. *Ecosystems* 1:546–557.
- Deering, D. W. 1989. Field measurements of bidirectional reflectance. Pages 14–65 in G. Asrar, editor. *Theory and applications of optical remote sensing*. Wiley & Sons, New York, New York, USA.
- DeSantis, R. D., W. K. Moser, D. D. Gormanson, M. G. Bartlett, and B. Vermunt. 2013. Effects of climate on emerald ash borer mortality and the potential for ash survival in North America. *Agricultural and Forest Meteorology* 178–179:120–128.
- Edenius, L., and J. Elmberg. 1996. Landscape level effects of modern forestry on bird communities in

- North Swedish boreal forests. *Landscape Ecology* 11:325–338.
- Franklin, J. F., et al. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management* 155:399–423.
- Frelich, L. E., and C. G. Lorimer. 1991. Natural disturbance regimes in hemlock-hardwood forests of the Upper Great Lakes Region. *Ecological Monographs* 61:145–164.
- Frelich, L. E., and P. B. Reich. 2009. Wilderness conservation in an era of global warming and invasive species: a case study from Minnesota's Boundary Waters Canoe Area Wilderness. *Natural Areas Journal* 29:385–393.
- Fry, J., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold, and J. Wickham. 2011. Completion of the 2006 National Land Cover Database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing* 77: 858–864.
- Gauthier, S., A. Leduc, and Y. Bergeron. 1996. Forest dynamics modelling under natural fire cycles: a tool to define natural mosaic diversity for forest management. *Environmental Monitoring and Assessment* 39:417–434.
- Gimmi, U., S. L. Schmidt, T. J. Hawbaker, C. Alcántara, U. Gafvert, and V. C. Radeloff. 2011. Increasing development in the surroundings of U.S. National Park Service holdings jeopardizes park effectiveness. *Journal of Environmental Management* 92:229–239.
- Halpin, P. N. 1997. Global climate change and natural-area protection: management responses and research directions. *Ecological Applications* 7:828–843.
- Hansen, A. J., N. Piekielek, C. Davis, J. Haas, D. M. Theobald, J. E. Gross, W. B. Monahan, T. Olliff, and S. W. Running. 2014. Exposure of U.S. National Parks to land use and climate change 1900–2100. *Ecological Applications* 24:484–502.
- Heinselman, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research* 3:329–382.
- Hyvönen, T., and P. Nummi. 2008. Habitat dynamics of beaver *Castor canadensis* at two spatial scales. *Wildlife Biology* 14:302–308.
- Johnston, C. A., and R. J. Naiman. 1990. Browse selection by beaver: effects on riparian forest composition. *Canadian Journal of Forest Research* 20: 1036–1043.
- Johnston, C. A., and S. K. Windels. 2015. Using beaver works to estimate colony activity in boreal landscapes. *Journal of Wildlife Management* 79: 1072–1080.
- Jordan, P. A., B. E. McLaren, and S. M. Sell. 2000. A summary of research on moose and related ecological topics at Isle Royale, U.S.A. *Alces* 36:233–267.
- Keller, J., M. Richmond, and C. Smith. 2003. An explanation of patterns of breeding bird species richness and density following clearcutting in northeastern USA forests. *Forest Ecology and Management* 174:541–564.
- 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, USA.
- Kennedy, R. E., Z. Yang, and W. B. Cohen. 2010b. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr – temporal segmentation algorithms. *Remote Sensing of Environment* 114:2897–2910.
- Kennedy, R. E., Z. Yang, W. B. Cohen, E. Pfaff, J. Braaten, and P. Nelson. 2012. Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment* 122:117–133.
- 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, USA.
- Kirschbaum, A., and U. Gafvert. 2010. Standard operating procedure #6: lab validation of LandTrendr outputs. Pages 1–31 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, USA.
- Little, A. M., G. R. Guntenspergen, and T. F. Allen. 2012. Wetland vegetation dynamics in response to beaver (*Castor canadensis*) activity at multiple scales. *Ecoscience* 19:246–257.
- Loope, W. L. 1991. Interrelationships of fire history, land use history, and landscape pattern within Pictured Rocks National Lakeshore, Michigan. *Canadian Field-Naturalist* 105:18–28.
- Lorimer, C. G., and A. S. White. 2003. Scale and frequency of natural disturbances in the northeastern US: implications for early successional forest habitats and regional age distributions. *Forest Ecology and Management* 185:41–64.

- Machtans, C. S., M. A. Villard, and S. J. Hannon. 1996. Use of riparian buffer strips as movement corridors by forest birds. *Conservation Biology* 10:1366–1379.
- Masek, J. G., E. F. Vermote, N. E. Saleous, R. Wolfe, F. G. Hall, K. F. Huemmrich, F. Gao, J. Kutler, and T. K. Lim. 2006. A Landsat surface reflectance dataset for North America, 1990–2000. *IEEE Geoscience and Remote Sensing Letters* 3:68–72.
- McLaren, B. E., and R. O. Peterson. 1994. Wolves, moose, and tree rings on Isle Royale. *Science* 266:1555–1558.
- Mladenoff, D. J., and J. Pastor. 1993. Sustainable forest ecosystems in the northern hardwood and conifer forest region: concepts and management. Pages 145–180 in G. H. Aplet, N. Johnson, J. T. Olson, and V. A. Sample, editors. *Defining sustainable forestry*. Island Press, Washington, D.C., USA.
- Moser, K. W., M. H. Hansen, M. D. Nelson, S. J. Crocker, C. H. Perry, B. Schulz, and C. W. Woodall. 2007. After the blowdown: a resource assessment of the Boundary Waters Canoe Area Wilderness, 1999–2003. General Technical Report NRS-7, USDA Forest Service, Northern Research Station, Newton Square, Pennsylvania, USA.
- Nelson, M. D., S. P. Healey, W. K. Moser, and M. H. Hansen. 2009. Combining satellite imagery with forest inventory data to assess damage severity following a major blowdown event in northern Minnesota, USA. *International Journal of Remote Sensing* 30:5089–5108.
- Papaik, M. J., C. D. Canham, E. F. Latty, and K. D. Woods. 2005. Effects of an introduced pathogen on resistance to natural disturbance: beech bark disease and windthrow. *Canadian Journal of Forest Research* 35:1832–1843.
- Paulson, A. K., S. Sanders, J. Kirschbaum, and D. A. Waller. 2016. Using history to inform our understanding of ecological changes in the forests of the Great Lakes National Parks. *Ecosphere*, in press.
- Peterson, R. O., J. D. Woolington, and T. N. Bailey. 1984. Wolves of the Kenai Peninsula, Alaska. *Wildlife Monographs* 88:3–52.
- Pugh, S. A., A. M. Liebhold, and R. S. Morin. 2011. Changes in ash tree demography associated with emerald ash borer invasion, indicated by regional forest inventory data from the Great Lakes States. *Canadian Journal of Forest Research* 41: 2165–2175.
- Radeloff, V. C., S. I. Stewart, T. J. Hawbaker, U. Gimmi, A. M. Pidgeon, C. H. Flather, R. B. Hammer, and D. P. Helmers. 2010. Housing growth in and near United States protected areas limits their conservation value. *Proceedings of the National Academy of Sciences USA* 107:940–945.
- Remillard, M. M., G. K. Gruendling, and D. J. Bogucki. 1987. Disturbance by beaver (*Castor canadensis* Kuhl) and increased landscape heterogeneity. Pages 103–122 in M. G. Turner, editor. *Landscape heterogeneity and disturbance*. Springer-Verlag, New York, New York, USA.
- Ripple, W. J., and R. L. Beschta. 2003. Wolf reintroduction, predation risk, and cottonwood recovery in Yellowstone National Park. *Forest Ecology and Management* 184:299–313.
- Robinson, S. K., F. R. Thompson III, T. M. Donovan, D. R. Whitehead, and J. Faaborg. 1995. Regional forest fragmentation and the nesting success of migratory birds. *Science* 267:1987–1990.
- Robinson, S. K., and D. S. Wilcove. 1994. Forest fragmentation in the temperate zone and its effects on migratory songbirds. *Bird Conservation International* 4:233–249.
- Rosell, F., O. Bozser, P. Collen, and H. Parker. 2005. Ecological impact of beavers *Castor fiber* and *Castor canadensis* and their ability to modify ecosystems. *Mammal Review* 35:248–276.
- Russell, K. R., T. B. Wigley, W. M. Baughman, H. G. Hanlin, and W. M. Ford. 2004. Responses of southeastern amphibians and reptiles to forest management: a review. Pages 319–334 in H. M. Rauscher and K. Johnsen, editors. *Southern forest science: past, present, and future*. USDA Forest Service, Southern Research Station, Asheville, North Carolina, USA.
- Scarpino, P. V. 2011. Isle Royale National Park: balancing human and natural history in a maritime park. *George Wright Forum* 28:182–198.
- Scheller, R. M., and D. J. Mladenoff. 2005. A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. *Global Change Biology* 11:307–321.
- Schmiegelow, F. K., C. S. Machtans, and S. J. Hannon. 1997. Are boreal birds resilient to forest fragmentation? An experimental study of short-term community responses. *Ecology* 78:1914–1932.
- 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.
- Schulte, L. A., and D. J. Mladenoff. 2005. Severe wind and fire regimes in northern forests: historical variability at the regional scale. *Ecology* 86: 431–445.
- Schulte, L. A., and G. J. Niemi. 1998. Bird communities of early-successional burned and logged forest. *Journal of Wildlife Management* 62:1418–1429.

- Sloan, S. S., R. T. Holmes, and T. W. Sherry. 1998. Depredation rates and predators at artificial bird nests in an unfragmented northern hardwoods forest. *Journal of Wildlife Management* 62: 529–539.
- Smith, D. W., R. O. Peterson, T. D. Drummer, and D. S. Sheputis. 1991. Over-winter activity and body temperature patterns in northern beavers. *Canadian Journal of Zoology* 69:2178–2182.
- Snyder, J. D., and R. A. Janke. 1976. Impact of moose browsing on boreal-type forests of Isle Royale National Park. *American Midland Naturalist* 95: 79–92.
- Spies, T. A., W. J. Ripley, and G. A. Bradshaw. 1994. Dynamics and pattern of a managed coniferous forest landscape in Oregon. *Ecological Applications* 4:555–568.
- 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. 2011*a*. Ecological importance of intermediate windstorms rivals large, infrequent disturbances in the northern Great Lakes. *Ecosphere* 2:1–21.
- Stueve, K. M., et al. 2011*a*. Snow-covered Landsat time series stacks improve automated disturbance mapping accuracy in forested landscapes. *Remote Sensing of Environment* 115:3203–3219.
- Sturtevant, B. R., P. A. Zollner, E. J. Gustafson, and D. T. Cleland. 2004. Human influence on the abundance and connectivity of high-risk fuels in mixed forests of northern Wisconsin, USA. *Landscape Ecology* 19:235–253.
- Turner, M. G., W. L. Baker, C. J. Peterson, and R. K. Peet. 1998. Factors influencing succession: lessons from large, infrequent natural disturbances. *Ecosystems* 1:511–523.
- Turner, M. G., R. V. O'Neill, R. H. Gardner, and B. T. Milne. 1989. Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Ecology* 3:153–162.
- Vermote, E. F., N. El Saleous, C. O. Justice, Y. J. Kaufman, J. L. Privette, L. Remer, J. C. Roger, and D. Tanre. 1997. Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: background, operational algorithm and validation. *Journal of Geophysical Research: Atmospheres* 102:17131–17141.
- Vitousek, P. M., C. M. Antonio, L. L. Loope, and R. Westbrooks. 1996. Biological invasions as global environmental change. *American Scientist* 84:468.
- Wayne, R., N. Lehman, D. Girman, P. Gogan, D. Gilbert, K. Hansen, R. Peterson, U. Seal, A. Eisenhower, and L. Mech. 1991. Conservation genetics of the endangered Isle Royale gray wolf. *Conservation Biology* 5:41–51.
- Weyenberg, S. A., and N. B. Pavlovic. 2014. Vegetation dynamics after spring and summer fires in red and white pine stands at Voyageurs National Park. *Natural Areas Journal* 34:443–458.
- 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.
- Wood, D. M., D. Parry, R. D. Yanai, and N. E. Pitel. 2010. Forest fragmentation and duration of forest tent caterpillar (*Malacosoma disstria* Hübner) outbreaks in northern hardwood forests. *Forest Ecology and Management* 260:1193–1197.
- Woods, A., J. Omernik, D. Brown, and C. Kiilsgaard. 1996. Level III ecoregions of the continental United States. Environmental Protection Agency, EPA/600/R-96/077, Digital Coverage.
- Wright, J. P., A. S. Flecker, and C. G. Jones. 2003. Local vs. landscape controls on plant species richness in beaver meadows. *Ecology* 84:3162–3173.
- Zhu, Z., and C. E. Woodcock. 2012. Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment* 118: 83–94.