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

1990–2020



Seasonal GLKN GIS technician Alejandra Rios checks a disturbance (forest harvesting) at St. Croix National Scenic Riverway.

NPS / A. KIRSCHBAUM

Landsat-based monitoring of landscape dynamics at Saint Croix National Scenic Riverway: 1990–2020

Science Report NPS/SR—2024/155

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Contents

Page

Figures....iv
Tables....vi
Abstract....vii
Acknowledgements....viii
Introduction....1
Methods....2
Study Area....2
Ownership....6
Disturbance Detection Methodology....8
Patch Definition....8
Interpreter-based Validation and Attribution of Change Agents....8
Results....11
Disturbance Agent Summaries....11
Maps of disturbances....11
Inside vs. outside the park....14
Watershed....15
Ownership....18
Patch size....19
Comparison among GLKN parks....20
Literature Cited....22
Appendix A. Fields Available in the Full Landscape Disturbance Dataset....23
Appendix B. Map Series of Disturbances within the SACN Analysis Area....25

Figures

Page

Figure 1. Analysis area for monitoring landscape dynamics in the greater St. Croix National Scenic Riverway ecosystem. 3

Figure 2. Labeled watersheds included in this analysis, as defined by level 10 Hydrologic Unit Codes (HUCs). 4

Figure 3. Land cover and land use classes in the analysis area, as mapped by the National Land Cover Database. 5

Figure 4. Percent of each land cover and land use class in the analysis area, as mapped by the National Land Cover Database. 6

Figure 5. Ownership within the analysis area. 7

Figure 6. Spatial extent of disturbances within the analysis area for St. Croix National Scenic Riverway, by disturbance agent, with watershed boundaries overlaid. 12

Figure 7. Spatial extent of disturbances within the analysis area for St. Croix National Scenic Riverway, identified by year of onset, with watershed boundaries overlaid. 13

Figure 8. Percent of land disturbed inside and outside the park, by disturbance agent and year. 14

Figure 9. Percent of land disturbed within each watershed, by disturbance agent and year, 1990–2020. 16

Figure 10. Percent of land disturbed within each ownership category, by disturbance agent and year, 1990–2020. 19

Figure 11. Violin plot displaying the patch size distribution of disturbances by disturbance agent inside and outside the park, 1990–2020. 20

Figure 12. Yearly average percent of land disturbed inside and outside nine Great Lakes Network national parks, by disturbance agent, 1990–2020. 21

Figure 13. Disturbances in the headwaters area of the Namekagon River, near Clam Lake, Wisconsin. 26

Figure 14. Disturbances around the upper Namekagon River from Lake Namekagon to Hayward, Wisconsin. 27

Figure 15. Disturbances around the upper Namekagon River near Hayward, Wisconsin. 28

Figure 16. Disturbances around the Namekagon River near Trego, Wisconsin. 29

Figure 17. Disturbances around the confluence of the Namekagon and St. Croix Rivers. 30

Figure 18. Disturbances around the upper St. Croix River and Tamarack Rivers. 31

Figures (continued)

Page

Figure 19. Disturbances around the confluence of the Tamarack and St. Croix Rivers. 32

Figure 20. Disturbances around the upper St. Croix River near Danbury, Wisconsin. 33

Figure 21. Disturbances in the Clam Lake watershed near Siren, Wisconsin. 34

Figure 22. Disturbances in the upper Clam Lake watershed near Cumberland, Wisconsin. 35

Figure 23. Disturbances along the St. Croix River near St. Croix State Park (Minnesota). 36

Figure 24. Disturbances along the St. Croix River near Wild River State Park (Minnesota). 37

Figure 25. Disturbances in the North Branch of the Sunrise River near North Branch, Minnesota. 38

Figure 26. Disturbances in the upper part of the Sunrise River watershed near Chisago City, Minnesota. 39

Figure 27. Disturbances in the Sunrise River watershed and St. Croix River near St. Croix Falls, Wisconsin. 40

Figure 28. Disturbances along the St. Croix River near Stillwater, Minnesota. 41

Figure 29. Disturbances in the lower Willow River watershed near Boardman, Wisconsin. 42

Figure 30. Disturbances in the Willow River watershed near New Richmond, Wisconsin. 43

Figure 31. Disturbances in the upper Willow River watershed near Connorsville, Wisconsin. 44

Figure 32. Disturbances around the lower St. Croix River near the confluence to the Mississippi River. 45

Tables

Page

Table 1. Ownership within the analysis area. 8

Table 2. Disturbance agents identified during manual validation in a GIS environment and how interpreters identify each. 9

Table 3. Simplified disturbance agent groupings used in this report and the agents present in each group. 10

Table 4. Total percent and area (hectares) disturbed by disturbance agent during analysis period, inside and outside the park. 15

Table 5. Total area and percentage of watershed disturbed, 1990–2020. 17

Table 6. Total area and percentage of watershed disturbed by disturbance agent, 1990–2020. 17

Table 7. Total percent of land disturbed, by ownership, 1990-2020. 18

Table 8. Fields, and their descriptions, used to describe a disturbance during the validation process, but which are not reported on in this summary. 23

Abstract

Landscape disturbances such as forest harvest, blowdowns, fire, and development activities create patches on the landscape that modify the structure and function of ecosystems and watersheds. Understanding the timing, location, size, and intensity of these disturbances can assist resource managers in making decisions regarding management options. To provide information regarding these metrics, the Great Lakes Inventory and Monitoring Network implemented a long-term monitoring project to quantify landscape dynamics inside and surrounding St. Croix National Scenic Riverway using an automated, satellite-based, change detection program called LandTrendr (Landsat-based detection of trends in disturbance and recovery). This is the second report for the park and varies slightly from the original report published in 2013 in terms of the time period analyzed, which increased by 23 years, from 2005–2010 (six years) to 1990–2020 (31 years). Results of this extended analysis showed that inside the park, disturbances due to forest harvest activities affected the largest amount of land (3,389 ha, or 109 ha annually). Lands in the area outside the park experienced far greater levels of disturbance, with forest harvest accounting for 78% of the disturbances and affecting 9.25% of the land (29,148 ha, or 940 ha annually). Long-term monitoring of this analysis area will contribute to our understanding of how these disturbances may affect water quality, wildlife corridors, and pressures on the natural resources within the St. Croix watershed.

Acknowledgements

The author would like to acknowledge the work and contribution of Alejandra Rios, who validated 43,000 St. Croix National Scenic Riverway polygons during the summer of 2022. She worked diligently and tirelessly to accomplish this task. Katelynn Roberts created the bulk of the maps in the report. I would also like to thank the natural resource staff at St. Croix National Scenic Riverway for graciously hosting our Oregon State University collaborators in the summer of 2023 for a brown bag luncheon presentation of preliminary analysis and results.

Introduction

Reported here are disturbances for St. Croix National Scenic Riverway (SACN) and the surrounding area using change detection methodology described in the Great Lakes Inventory and Monitoring Network (GLKN) Landscape Dynamics monitoring protocol (Kennedy et al. 2010b). The first report for SACN was published in 2013 and summarized disturbances over a shorter time period (Kirschbaum and Gafvert 2013). Here, disturbances occurring between 1990 and 2020 (31 years) are summarized.

Methods

Study Area

The analysis was conducted inside and adjacent to St. Croix National Scenic Riverway (SACN), which begins in Wisconsin and then forms the boundary between Wisconsin and Minnesota before joining the Mississippi River. The analysis area extended into six sub-watersheds (Figures 1 and 2). The watersheds were chosen to represent the gradient in land cover types and ownerships within the SACN watershed. Monitoring encompassed 347,055 ha of land, of which 31,983 ha was land inside the riverway boundary. Included in the analysis area are six watersheds as defined by level 10 delineations of the National Hydrography Dataset's Hydrologic Unit Code (HUC) (nhd.usgs.gov) (Figure 2). Landcover within the analysis area was split among developed, agriculture, and forest, as classified in the U.S. by the 2019 National Land Cover Database (NLCD) (Dewitz and U. S. Geologic Survey 2021) (Figures 3 and 4).

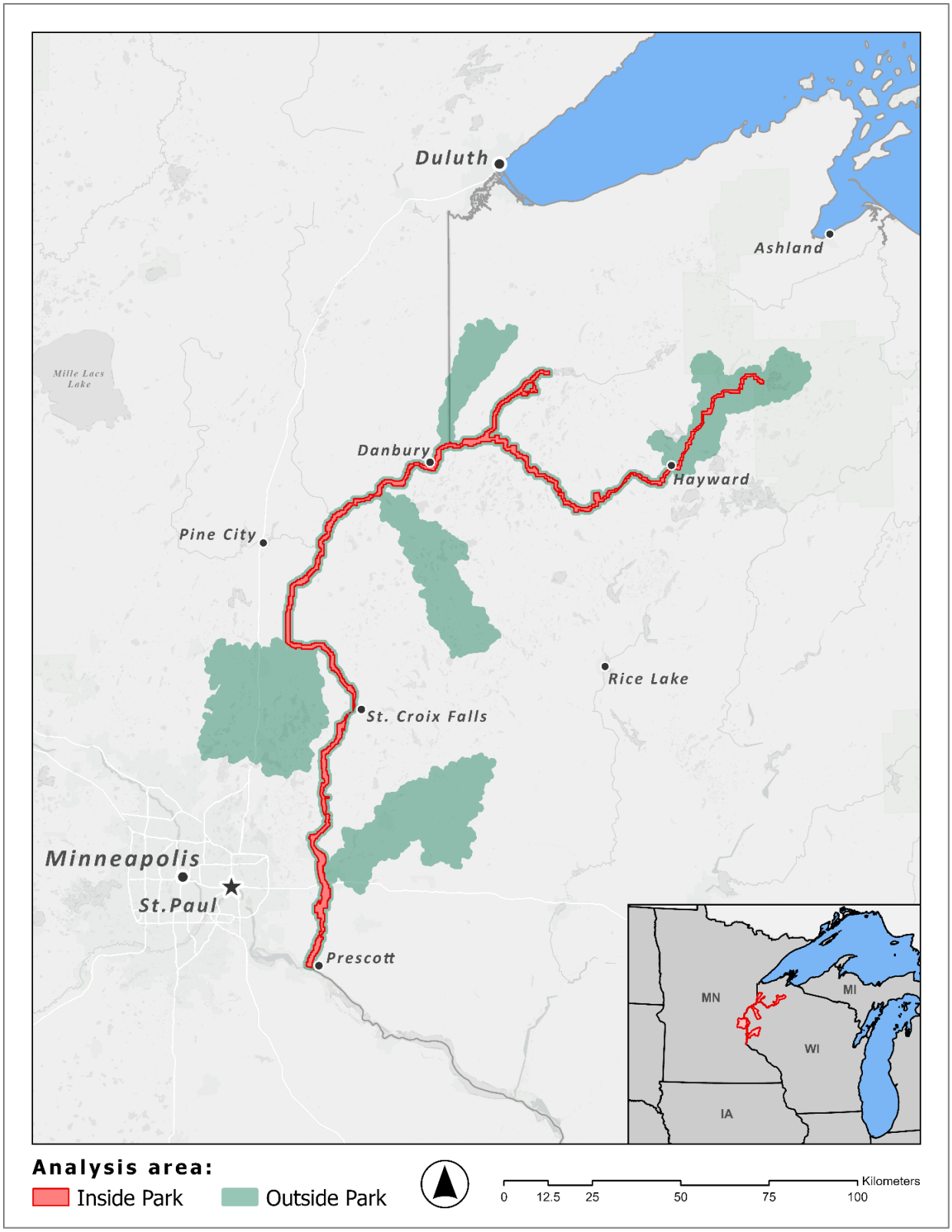


Figure 1. Analysis area for monitoring landscape dynamics in the greater St. Croix National Scenic Riverway ecosystem. Green indicates area monitored outside the park in additional watersheds.

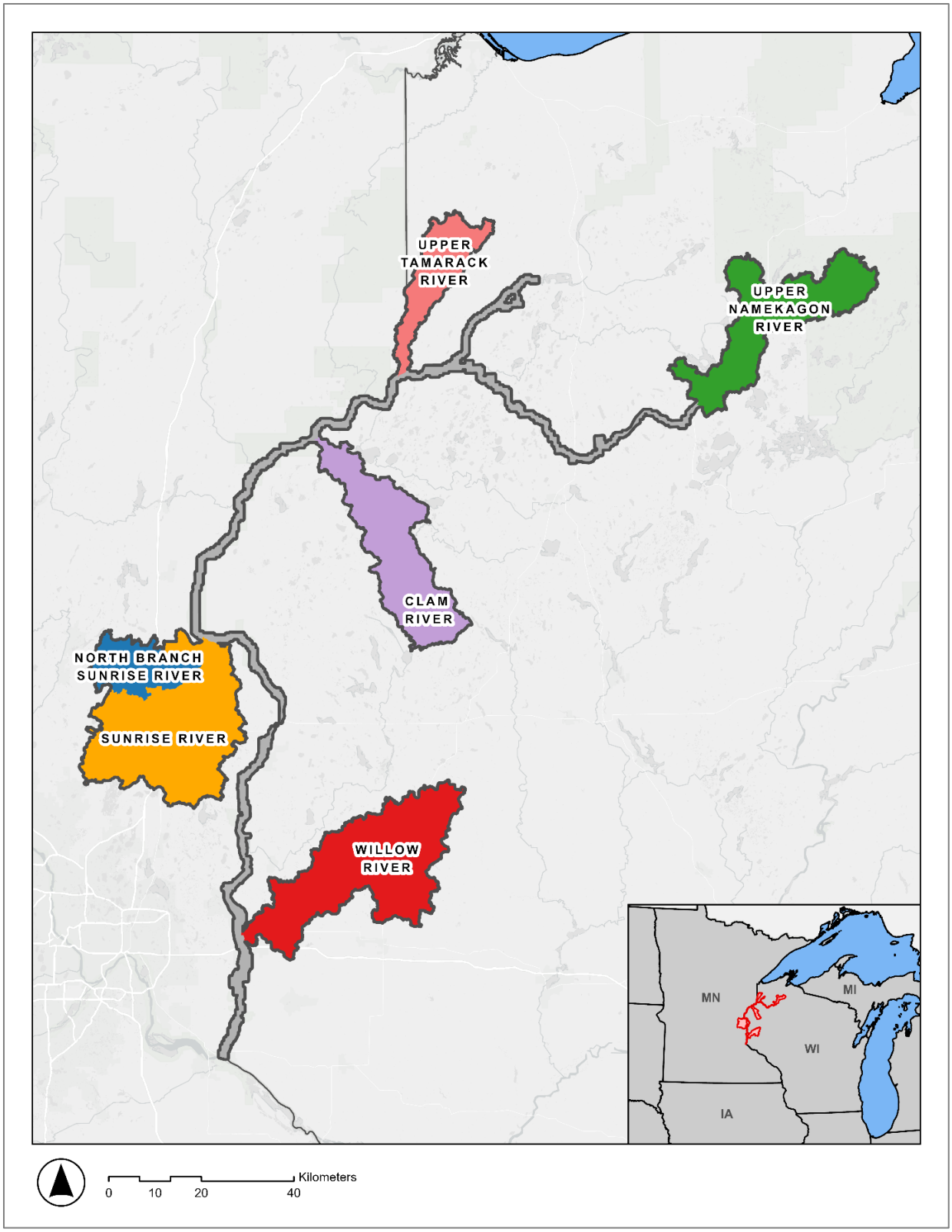


Figure 2. Labeled watersheds included in this analysis, as defined by level 10 Hydrologic Unit Codes (HUCs).

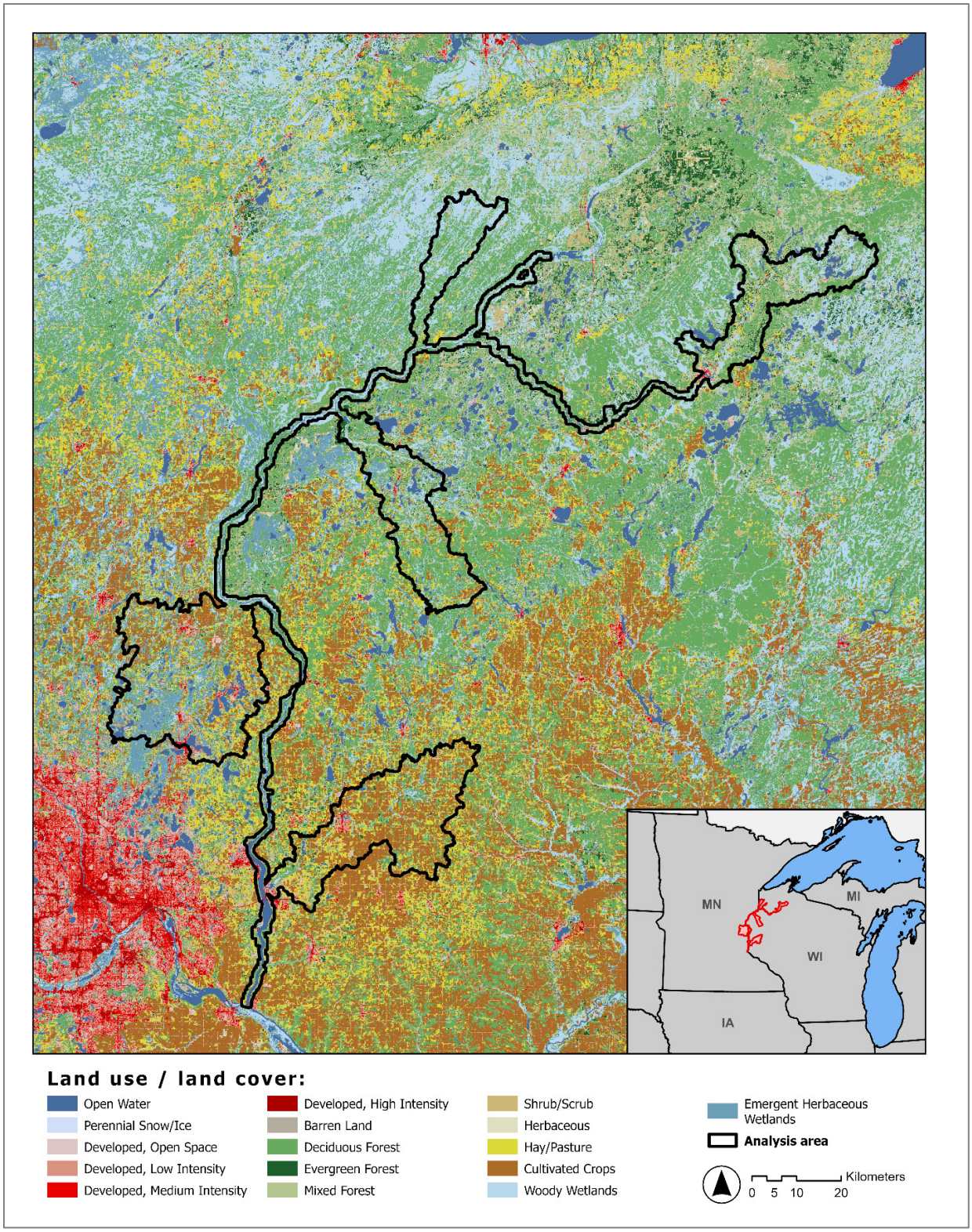


Figure 3. Land cover and land use classes in the analysis area, as mapped by the National Land Cover Database. Source: Dewitz and U. S. Geologic Survey 2021.

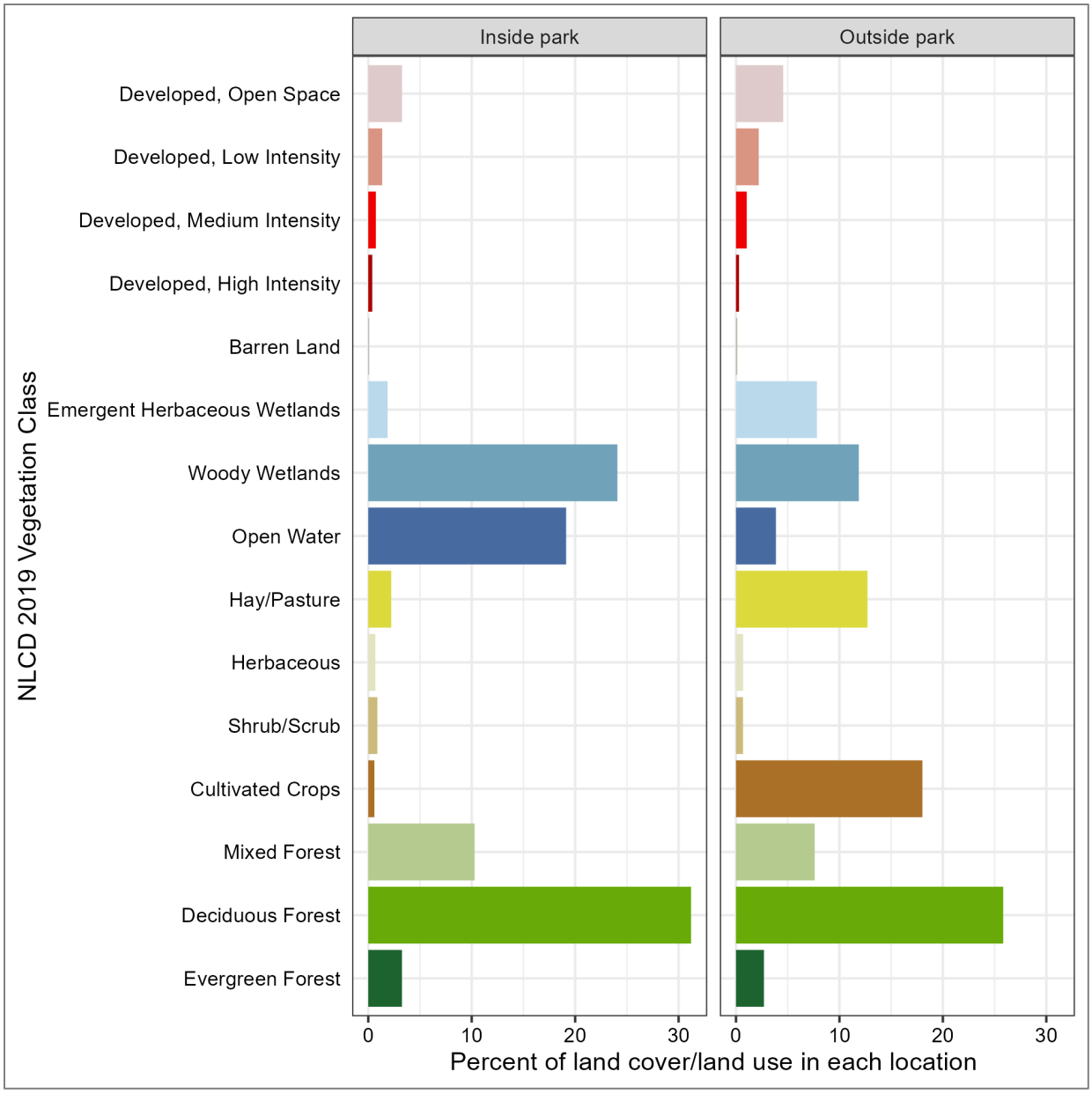


Figure 4. Percent of each land cover and land use class in the analysis area, as mapped by the National Land Cover Database. Source: Dewitz and U. S. Geologic Survey 2021.

Ownership

Ownership within the analysis area was obtained from the Wisconsin Statewide Parcel Initiative (https://www.sco.wisc.edu/parcels/data/) and from the Minnesota Gap Analysis Program (https://gdrs.dnr.state.mn.us/gdrs/data/pub/us_mn_state_dnr/plan_gap_stewardship_2008.zip) (Figure 5). Most land was privately held (80%), followed by county (11%), state (6%) and federal (1%) (Table 1).

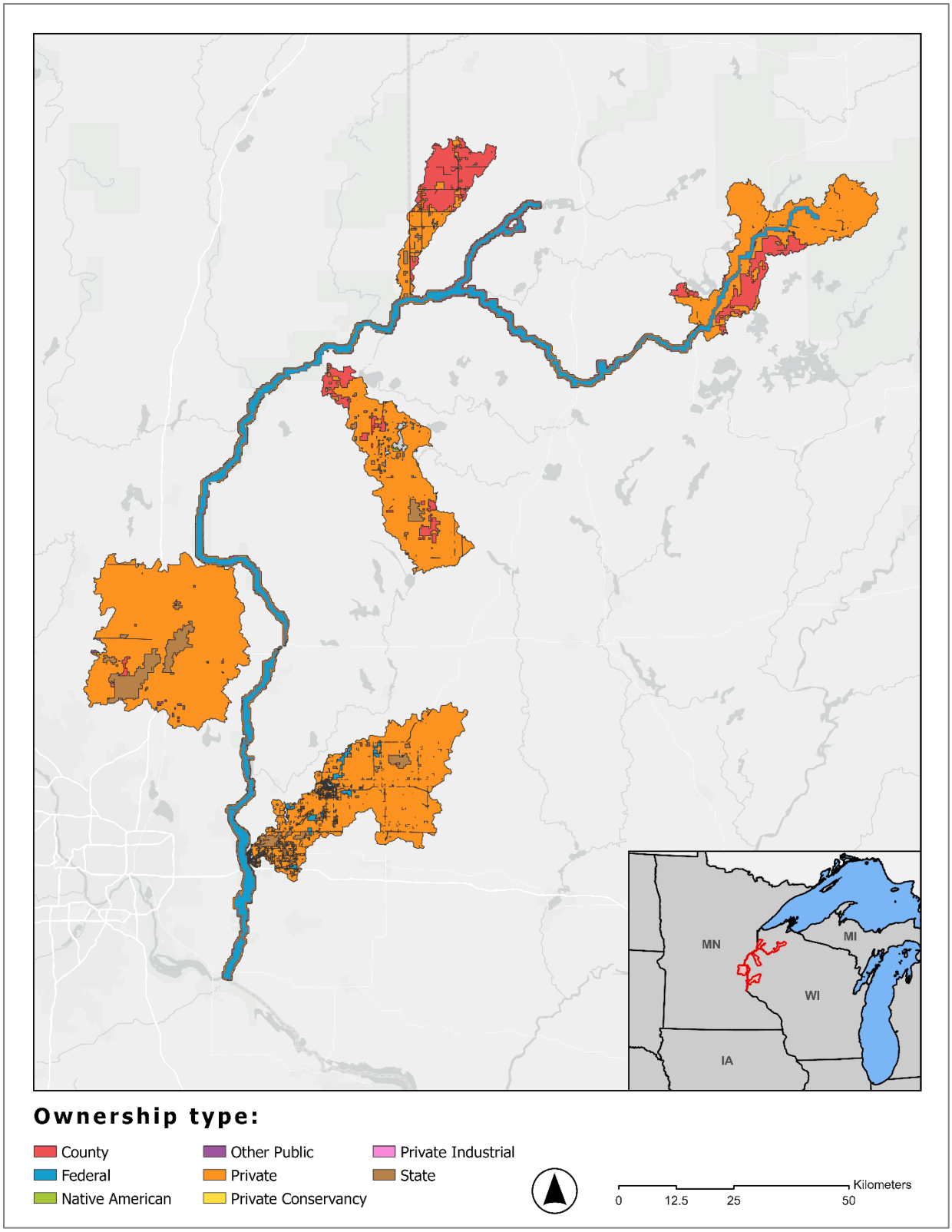


Figure 5. Ownership within the analysis area. Ownership data was obtained from the Wisconsin Statewide Parcel Initiative (version 6) and the Minnesota Gap Analysis Program.

Table 1. Ownership within the analysis area. Ownership data from the Wisconsin Statewide Parcel Initiative and Minnesota Gap Analysis Program.

Ownership	Area (ha)	Percent of land
County	4,0479.3	11.27
Federal	4,387.7	1.22
Native American	198.0	0.06
Other Public	326.6	0.09
Private	29,0158.5	80.81
Private Conservancy	33.9	0.01
Private Industrial	15.1	<0.01
State	23,464.9	6.54

Disturbance Detection Methodology

A set of processing and analysis steps collectively known as LandTrendr (Kennedy et al. 2010a, 2010b) were used. 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). Only changes are reported in this analysis, where and when they occurred.

To minimize effects of phenological variation, Landsat images between July and September of each year (1985–2021) were selected. Atmospheric correction, cloud and cloud shadow masking, and segmentation (disturbance detection) were performed using LandTrendr algorithms implemented through Google Earth Engine (Kennedy et al. 2018). Although Landsat has multiple reflectance bands, LandTrendr can only be run on one band or index for disturbance detection. Therefore, an ensemble composite index (ENC) was used, which incorporates the average of the six highest ranked disturbance indices in Cohen et al. (2018). This index balances the omission and commission error rates and allows the detection of short abrupt changes as well as more subtle disturbances.

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 (ca. 1 ha, 2.5 ac) were removed from the dataset to avoid small, often unverifiable disturbance events. This size is small enough to capture most forest harvests in addition to other disturbance agents such as beavers, some development activities, and blowdowns.

Interpreter-based Validation and Attribution of Change Agents

Every (census) disturbance polygon that was generated by LandTrendr was validated to remove commission errors (false positives) and, at the same time, determine the change agent. If a polygon spanned boundaries (watershed, ownership), the attribute with the majority of the polygon

represented was chosen. Validation of possible disturbances followed details given in Kirschbaum and Gafvert (2013) and are 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 2). Up to ten change agents can be confidently distinguished during the validation process, but those ten were grouped into six for ease of reporting (Table 3). Disturbances known to have occurred but for which a change agent could not be attributed were classified as "unknown." See Table A1 in Appendix A to view all fields filled out during the validation process.

Table 2. Disturbance agents identified during manual validation in a GIS environment and how interpreters identify each.

Disturbance agent	Description and means of identification
Agriculture	Conversion of a non-agricultural 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 air photos and are usually oriented in the direction of the wind event.
Development	Permanent conversion of vegetated surface to non-vegetated surface such as mines, paved roads, parking lots, 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.
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	This category is used when the interpreter is unable to determine the causal agent.

Table 3. Simplified disturbance agent groupings used in this report and the agents present in each group.

Disturbance agent grouping	Disturbance agents present in group
Development	Agriculture, development
Beaver	Beaver
Blowdown	Blowdown
Fire	Fire
Forest harvest	Forest harvest categories light, moderate, and heavy
Forest pathogen	Insect/disease defoliation and mortality
Other	Other

High resolution (≤5 m) imagery (air photo and satellite) was used to determine whether changes had occurred. Much of the imagery used was from the National Agriculture Imagery Program (NAIP), with a pixel resolution of 1 m. Contextual information such as forest type, ownership, and drainage patterns were important for determining the disturbance agent and land cover classes. The entire Landsat image stack (1985–2021) for each prospective disturbance was also viewed, along with a graph of the reflectance values through time (1985–2021) of said disturbance.

In a GIS environment, utilizing high resolution imagery, ancillary datasets, and the Landsat imagery itself, a total of 43,016 LandTrendr-delineated disturbance polygons were validated, removing all false positive (commission) polygons from the summary analysis. Since the analysis area contains a significant amount of water, disturbance area was computed as percentage of land area, excluding bodies of water as classified by the 2019 National Land Cover Database (Dewitz and U.S. Geological Survey 2021).

This validation workflow corroborates what has been shown in past studies (Antonova et al. 2011, Cohen et al. 2018), that on-screen validation of polygons with the aid of high spatial resolution imagery, 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 clearcuts (forest harvest) 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 on private land) or because the evidence (e.g., insect/disease, low level forest harvests) has been masked by time (Antonova et al. 2011, Cohen et al. 2018).

Results

Disturbance Agent Summaries

Maps of disturbances

Maps presented below show the location of disturbances in the analysis area by disturbance agent (Figure 6) and by year (Figure 7). The most widespread and ubiquitous change agent was forest harvest, found nearly everywhere in the analysis area, but most prominently in the northern half of the study area (Figure 6). Inside the park, two years (2010 and 2011) had notably higher levels of forest harvest than the rest of the time series, while outside the park, forest harvest was relatively stable during the entire time series (Figures 7 and 8). In the southern half of the study area disturbances due to the development were more common (Figure 6).

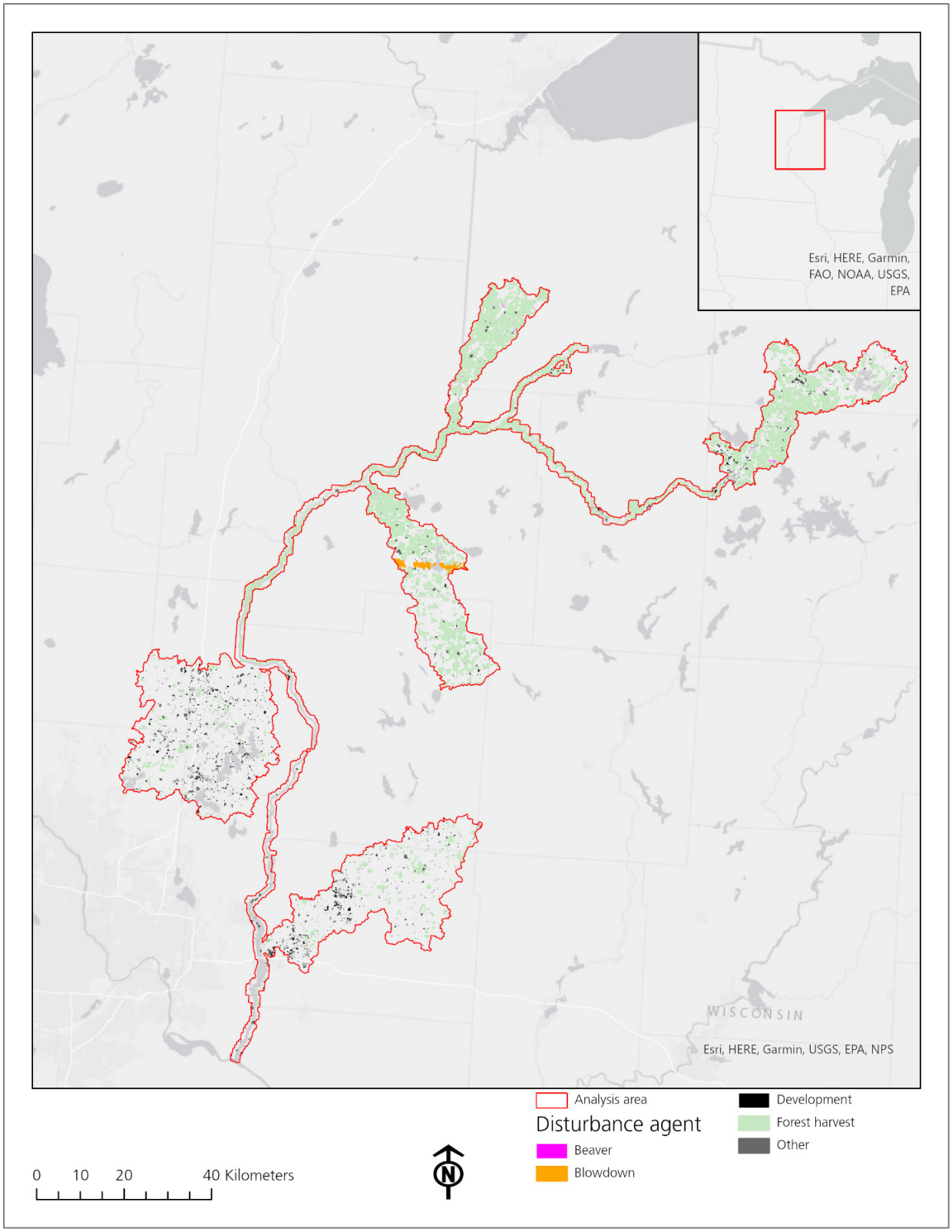


Figure 6. Spatial extent of disturbances within the analysis area for St. Croix National Scenic Riverway, by disturbance agent, with watershed boundaries overlaid.

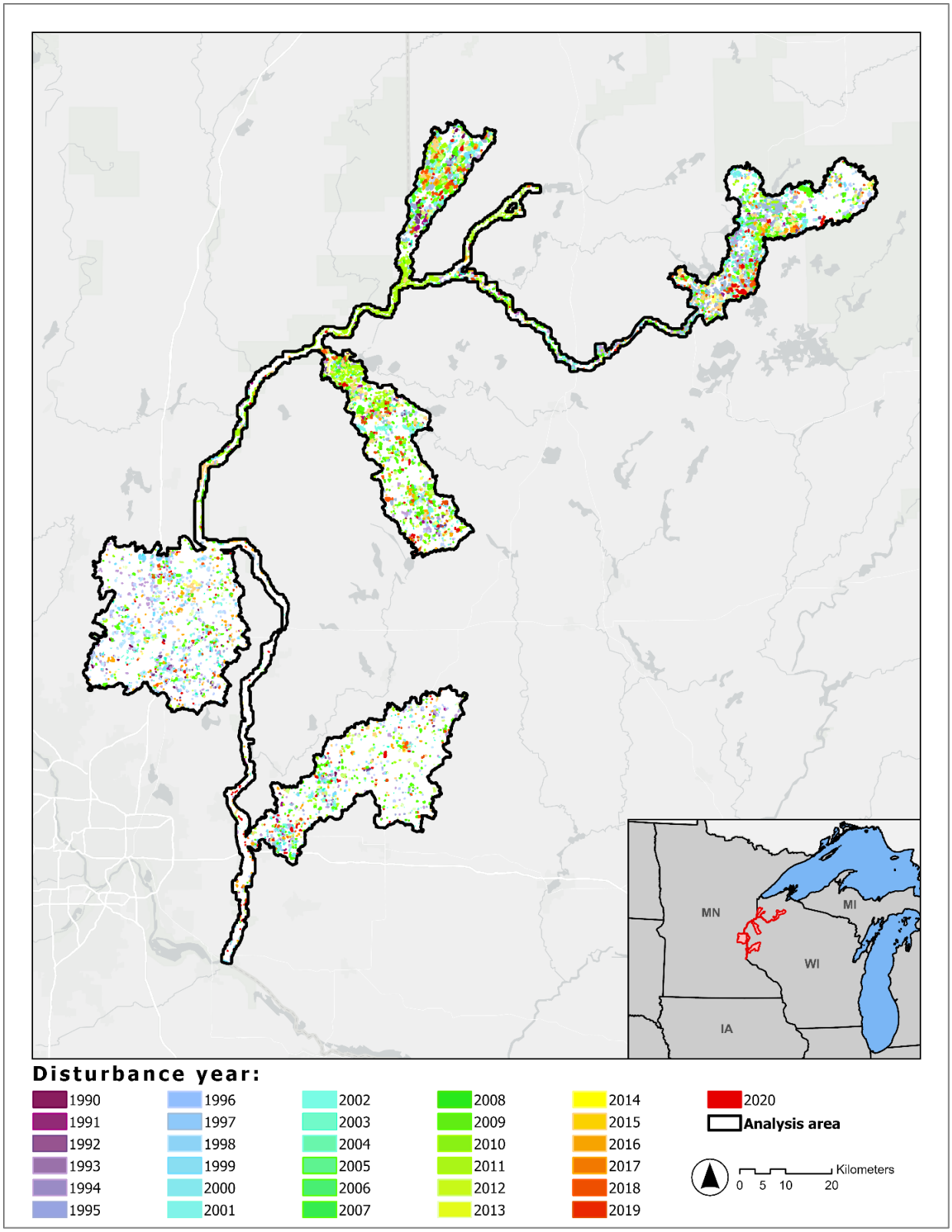


Figure 7. Spatial extent of disturbances within the analysis area for St. Croix National Scenic Riverway, identified by year of onset, with watershed boundaries overlaid.

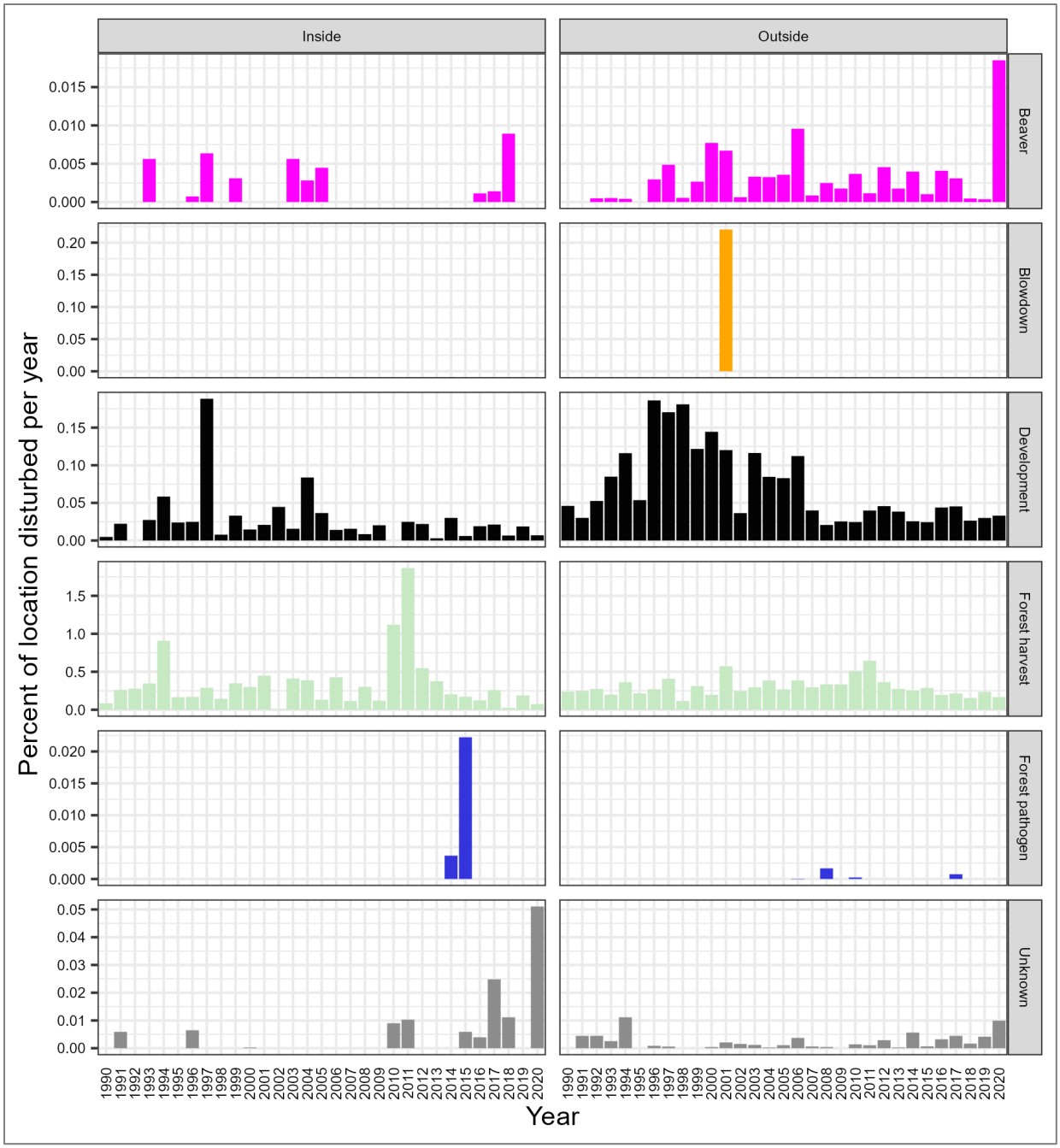


Figure 8. Percent of land disturbed inside and outside the park, by disturbance agent and year. Note: Y axis scale varies by disturbance agent.

Inside vs. outside the park

Inside the park boundary, disturbances due to forest harvest activities represented the largest amount of land affected over the period (10.60%, 3,389.29 ha), followed by development disturbances (0.82%, 263.20 ha) (Figure 8 and Table 4).

Outside the park, disturbances due to forest harvest were the most prevalent, occurring every year of the analysis (Figure 8) and averaged 940.27 ha/year during the analysis period (Table 4). The next most prevalent disturbance agent outside the park was development, which affected 2.2% of land, or 6,937.85 ha. Lastly, a blowdown event occurred in 2001 near Siren, Wisconsin, which was an F3 tornado that traveled 27 miles in an west-east path.

Table 4. Total percent and area (hectares) disturbed by disturbance agent during analysis period, inside and outside the park.

Disturbance agent	Inside park Area (ha)	Inside park Percent land disturbed	Outside park Area (ha)	Outside park Percent land disturbed
Beaver	12.85	0.04	298.88	0.09
Blowdown	0	0	694.35	0.22
Development	263.20	0.82	6,937.85	2.20
Fire	0	0	0	0
Forest harvest	3,389.29	10.60	29,148.60	9.25
Forest pathogen	8.28	0.03	8.52	<0.01
Unknown	41.20	0.13	222.82	0.07

Watershed

There were six watersheds located within the study area (see Figure 2). Of the watersheds, Upper Tamarack River had the highest disturbance rates during the analysis period (32.87% of land in the watershed disturbed) (Figure 9 and Table 5). The Upper Namekagon River watershed experienced the next highest level of disturbance (18.13% of the land in the watershed disturbed), with nearly all disturbance the result of forest harvesting (Figure 9 and Table 6). These two watersheds also have the largest percentages of county-owned lands (see Figure 5). Spatially, most development occurred in the three watersheds located closest to the Minneapolis area (see Figure 6). Although the watersheds closer to the metro area experience lower amounts of disturbance, the prevalent disturbance agent is development, which could have a greater impact on ecosystem function.

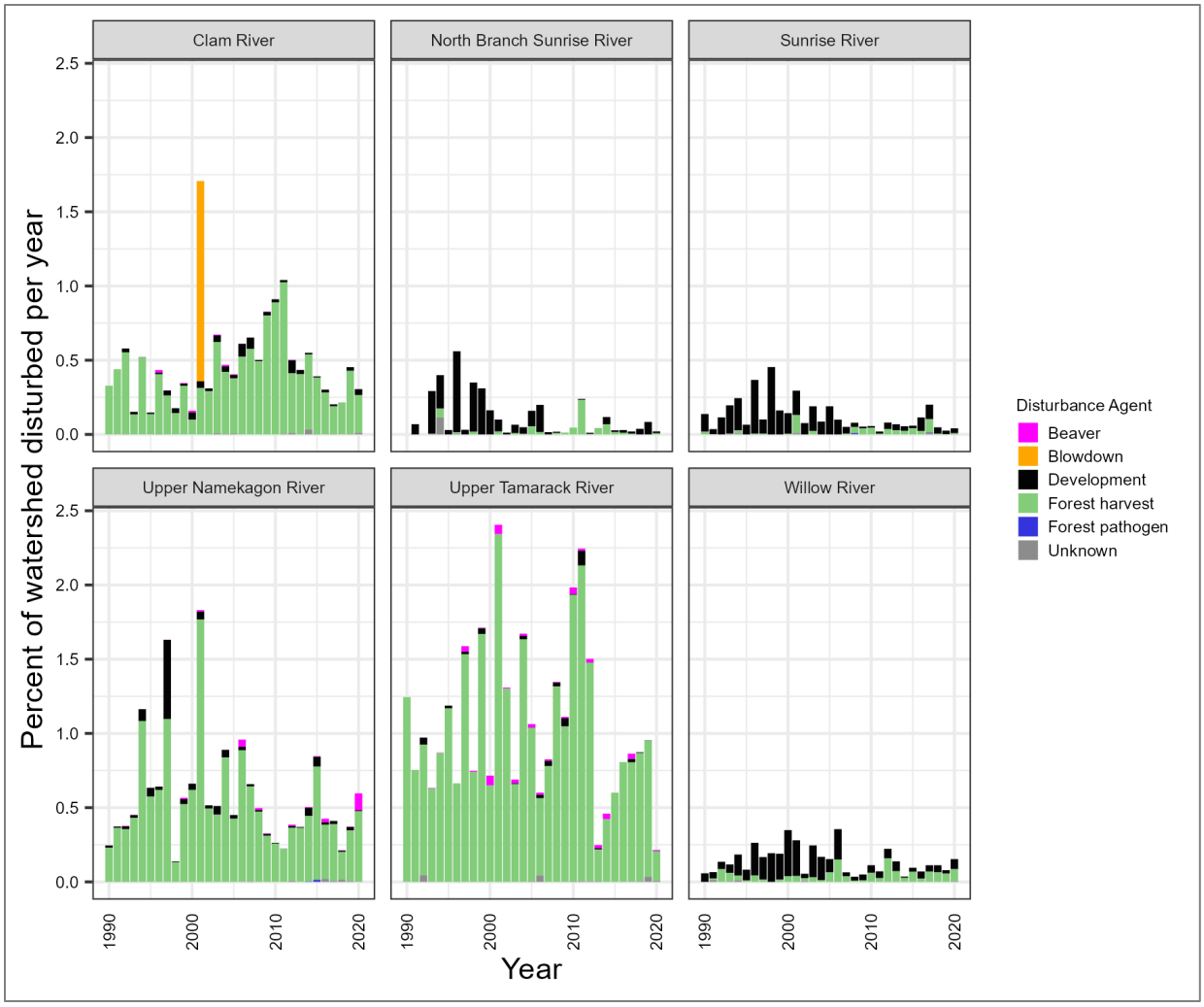


Figure 9. Percent of land disturbed within each watershed, by disturbance agent and year, 1990–2020.

Table 5. Total area and percentage of watershed disturbed, 1990–2020.

Watershed	Area (ha)	Percent
Clam River	7,746.06	15.05
North Branch Sunrise River	701.08	3.51
Sunrise River	2,843.69	3.91
Upper Namekagon River	9,023.09	18.13
Upper Tamarack River	8,432.35	32.87
Willow River	3,381.64	4.41

Table 6. Total area and percentage of watershed disturbed by disturbance agent, 1990–2020.

Watershed	Disturbance agent	Land disturbed (ha)	Percent land disturbed
Clam River	Beaver	33.35	0.06
Clam River	Blowdown	694.35	1.35
Clam River	Development	429.44	0.83
Clam River	Forest harvest	6,545.95	12.72
Clam River	Unknown	42.97	0.08
North Branch Sunrise River	Development	547.80	2.74
North Branch Sunrise River	Forest harvest	128.76	0.65
North Branch Sunrise River	Unknown	24.53	0.12
Sunrise River	Beaver	0.81	<0.01
Sunrise River	Development	2,378.13	3.27
Sunrise River	Forest harvest	429.29	0.59
Sunrise River	Forest pathogen	7.60	0.01
Sunrise River	Unknown	27.86	0.04
Upper Namekagon River	Beaver	126.54	0.25
Upper Namekagon River	Development	668.50	1.34
Upper Namekagon River	Forest harvest	8,188.26	16.45
Upper Namekagon River	Forest pathogen	8.28	0.02
Upper Namekagon River	Unknown	31.50	0.06
Upper Tamarack River	Beaver	122.59	0.48
Upper Tamarack River	Development	112.84	0.44
Upper Tamarack River	Forest harvest	8,157.62	31.79
Upper Tamarack River	Unknown	39.30	0.15
Willow River	Development	2,294.11	2.99
Willow River	Forest harvest	1,059.46	1.38
Willow River	Forest pathogen	0.16	<0.01
Willow River	Unknown	27.90	0.04

Ownership

The ownership category experiencing the greatest percent of land disturbed was county, with 33.74% of land in county ownership being disturbed during the analysis period (Table 7 and Figure 10). Most of the disturbance in this ownership category was from forest harvest. Federal land experienced the next highest amount of disturbance, with a total of 14.81% of its land being disturbed during the analysis period, largely due to forest harvest (Table 7 and Figure 10). Native American and state-owned categories also experienced similar disturbance rates (Table 7 and Figure 10), although there was less than 1% of land disturbed within the Native American category (see Table 1).

Table 7. Total percent of land disturbed, by ownership, 1990-2020.

Ownership	Percent land disturbed
County	33.74
Federal	14.81
Native American	11.86
Other public	2.25
Private	8.87
State	10.92

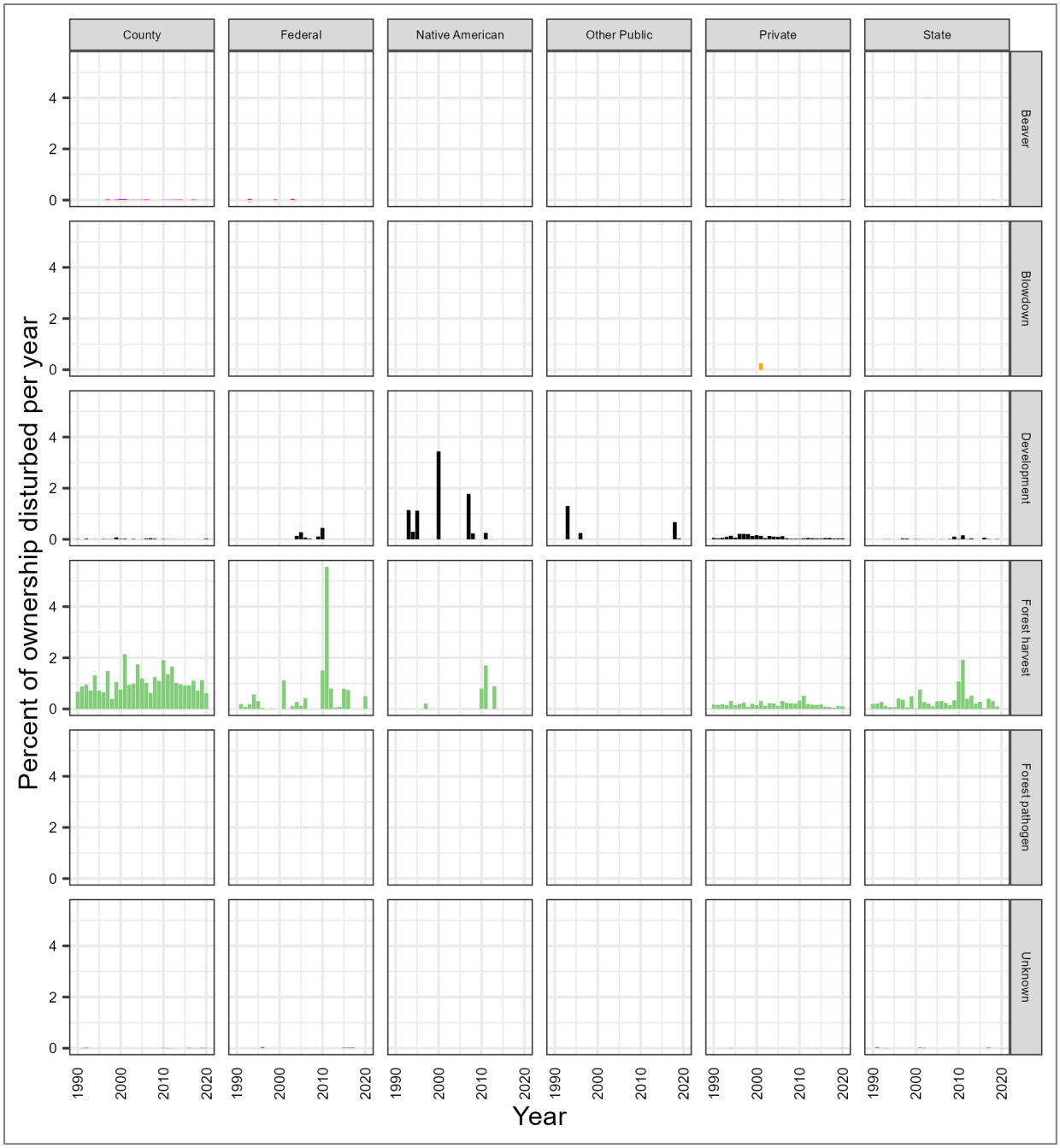


Figure 10. Percent of land disturbed within each ownership category, by disturbance agent and year, 1990–2020.

Patch size

The disturbances due to blowdown were the largest in size (Figure 11). However, this was only one event, which was a tornado near Siren. Forest harvests, which were the most prevalent disturbance agent, exhibited similar patch size characteristics both inside and outside the park boundary (Figure 11).

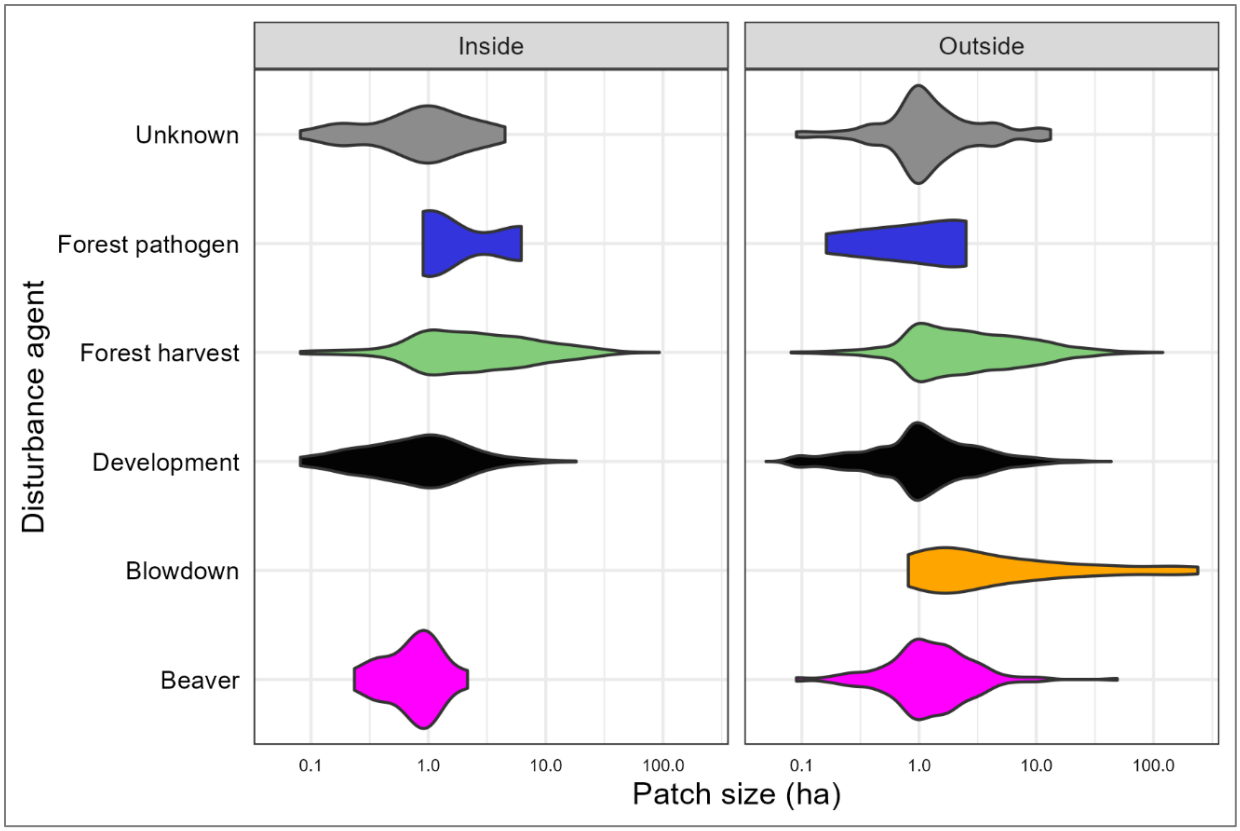


Figure 11. Violin plot displaying the patch size distribution of disturbances by disturbance agent inside and outside the park, 1990–2020. The height of the violin indicates larger numbers of patches at a given size, and the ends of the violin indicate the minimum and maximum patch size. Note: X axis is on log10 scale.

Comparison among GLKN parks

Compared to other network parks, the disturbance regime inside and outside SACN is unique (Figure 12). The length of this park spans a latitudinal gradient from suburban/agricultural in the south to forested in the north. Half of the watersheds are dominated by development and the other half are experiencing steady rates of forest harvest on public and private lands. Thus, the northern part of the SACN analysis area reflects disturbance regimes common to our more northern parks (Voyageurs, Grand Portage, Apostle Islands, Pictured Rocks, and Isle Royale) and the southern portion of the analysis area is more similar to our southern parks (Mississippi River, Indiana Dunes, and Sleeping Bear Dunes) (Figure 12).

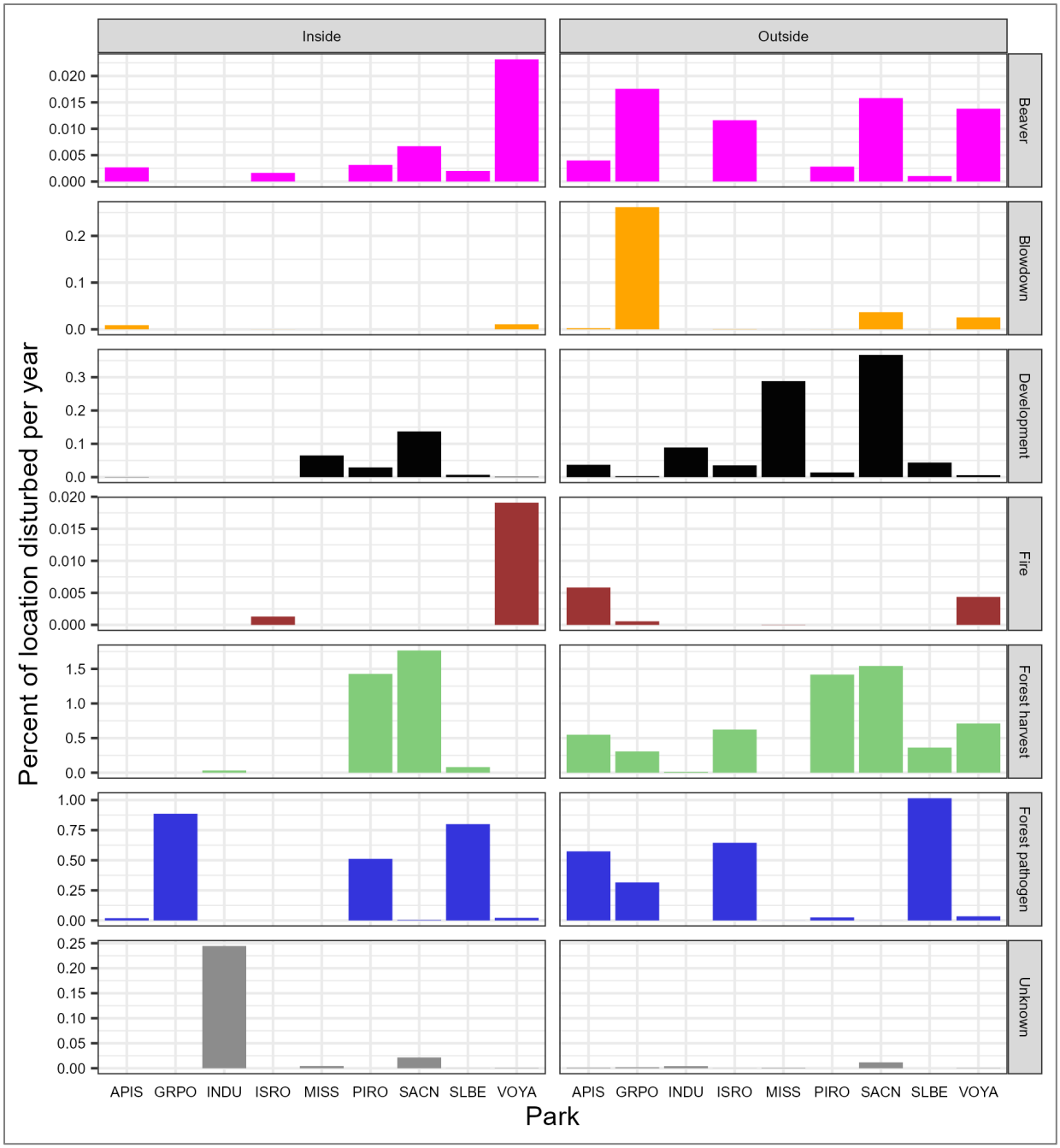


Figure 12. Yearly average percent of land disturbed inside and outside nine Great Lakes Network national parks, by disturbance agent, 1990–2020. Note: Y axis scale varies by disturbance agent. APIS=Apostle Islands, INDU=Indiana Dunes, ISRO=Isle Royale, MISS=Mississippi National River and Recreation Area, PIRO=Pictured Rocks, SACN=St. Croix National Scenic Riverway, SLBE=Sleeping Bear Dunes, VOYA=Voyageurs.

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Kirschbaum, A. A., and U. B. Gafvert. 2013. Landsat-based monitoring of landscape dynamics at Saint Croix National Scenic Riverway, 2005–2010. Natural Resource Technical Report. NPS/GLKN/NRTR—2013/715. National Park Service, Fort Collins, Colorado. Available at: https://irma.nps.gov/DataStore/DownloadFile/466840

Appendix A. Fields Available in the Full Landscape Disturbance Dataset.

During validation, we fill out numerous fields that are not necessarily reflected in the data summary report series. Table 8 identifies additional fields filled in during the validation process and a brief description of each. The more detailed dataset is available upon request.

Table 8. Fields, and their descriptions, used to describe a disturbance during the validation process, but which are not reported on in this summary.

Field	Description
Year	Year of disturbance onset.
Percent of polygon affected	Percent of polygon affected by any disturbance.
Disturbance agent 1	A polygon could be comprised of multiple disturbance agents. We use this field to identify the first (and maybe only) disturbance agent.
Percent of polygon in disturbance agent 1	Percent of disturbed (affected) area due to disturbance agent one.
Percent cover remaining for disturbance agent 1	If the disturbance agent is forest harvest, this field is filled in. We estimate the percent cover (in 10% increments) of overstory remaining after the disturbance for disturbance agent one.
Disturbance agent 2	If multiple disturbance agents are present in the polygon, we identify the second disturbance agent.
Percent of polygon in disturbance agent 2	Percent of disturbed (affected) area due to disturbance agent two.
Percent cover remaining for disturbance agent 2	If the disturbance agent is forest harvest, this field is filled in. We estimate the percent cover (in 10% increments) of overstory remaining after the disturbance for disturbance agent two.
Disturbance agent 3	If multiple disturbance agents are present in the polygon, we identify the third disturbance agent.
Percent of polygon in disturbance agent 3	Percent of disturbed (affected) area due to disturbance agent three.
Percent cover remaining for disturbance agent 3	If the disturbance agent is forest harvest, this field is filled in. We estimate the percent cover (in 10% increments) of overstory remaining after the disturbance for disturbance agent three.
Start class 1	The starting land cover/land use class of the disturbed area. We allow up to three unique starting classes for each disturbed polygon. Class options are forest closed, forest semi-closed, forest open, shrub, herbaceous, pervious, impervious/vegetated, impervious, and water.
Start class 1 percent	Percent of the disturbed (affected) area in starting class one.
Start class 2	If multiple classes were disturbed, we identify the second class.
Start class 2 percent	Percent of the disturbed (affected) area in starting class two (if needed).
Start class 3	Same as start class 2.
Start class 3 percent	Same as start class 2 percent.

Table 8 (continued). Fields, and their descriptions, used to describe a disturbance during the validation process, but which are not reported on in this summary.

Field	Description
End class 1	The ending land cover/land use class of the disturbed area. This should reflect the immediate result of the disturbance and not the future condition of the area. Class options are the same as in the starting class options.
End class 1 percent	Percent of the disturbed (affected) area in ending class one.
End class 2	Same as end class 1.
End class 2 percent	Same as end class 1 percent.
End class 3	Same as end class 1.
End class 3 percent	Same as end class 1 percent.
Owner type	During validation we add ownership data from the best available source. Owner type is a higher-level ownership classification such as federal, county, state, and private.
Owner name	Owner name is a more detailed level of ownership such as National Park Service, Bayfield County, or Wisconsin Department of Natural Resources.
Watershed identifier	During validation we add the unique 12-digit watershed identifier, referred to as the Hydrologic Unit Code 12 (HUC12) from the USGS database.

Appendix B. Map Series of Disturbances within the SACN Analysis Area.

Figures 13 through 32 are detailed maps of disturbances in the SACN study area.

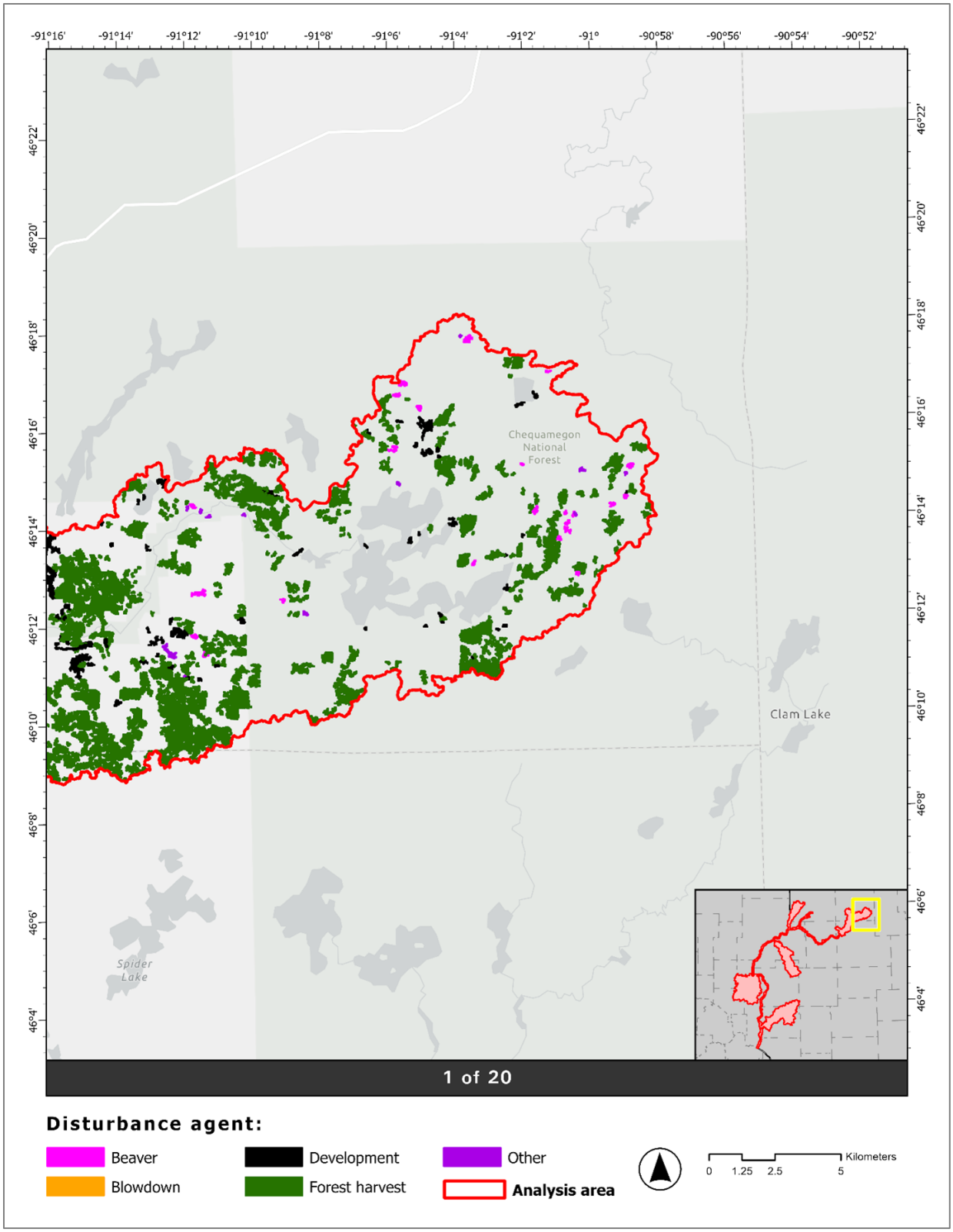


Figure 13. Disturbances in the headwaters area of the Namekagon River, near Clam Lake, Wisconsin.

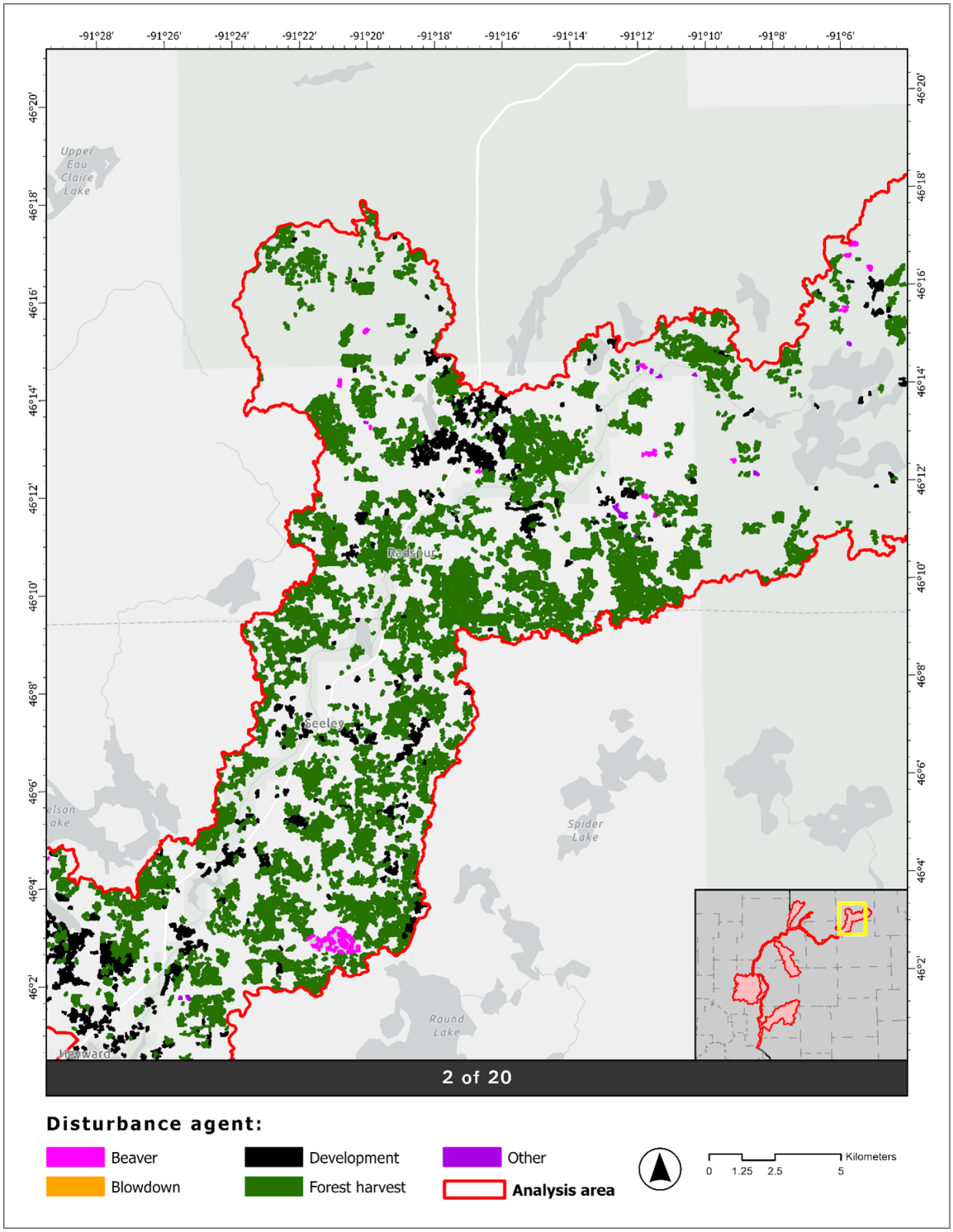


Figure 14. Disturbances around the upper Namekagon River from Lake Namekagon to Hayward, Wisconsin.

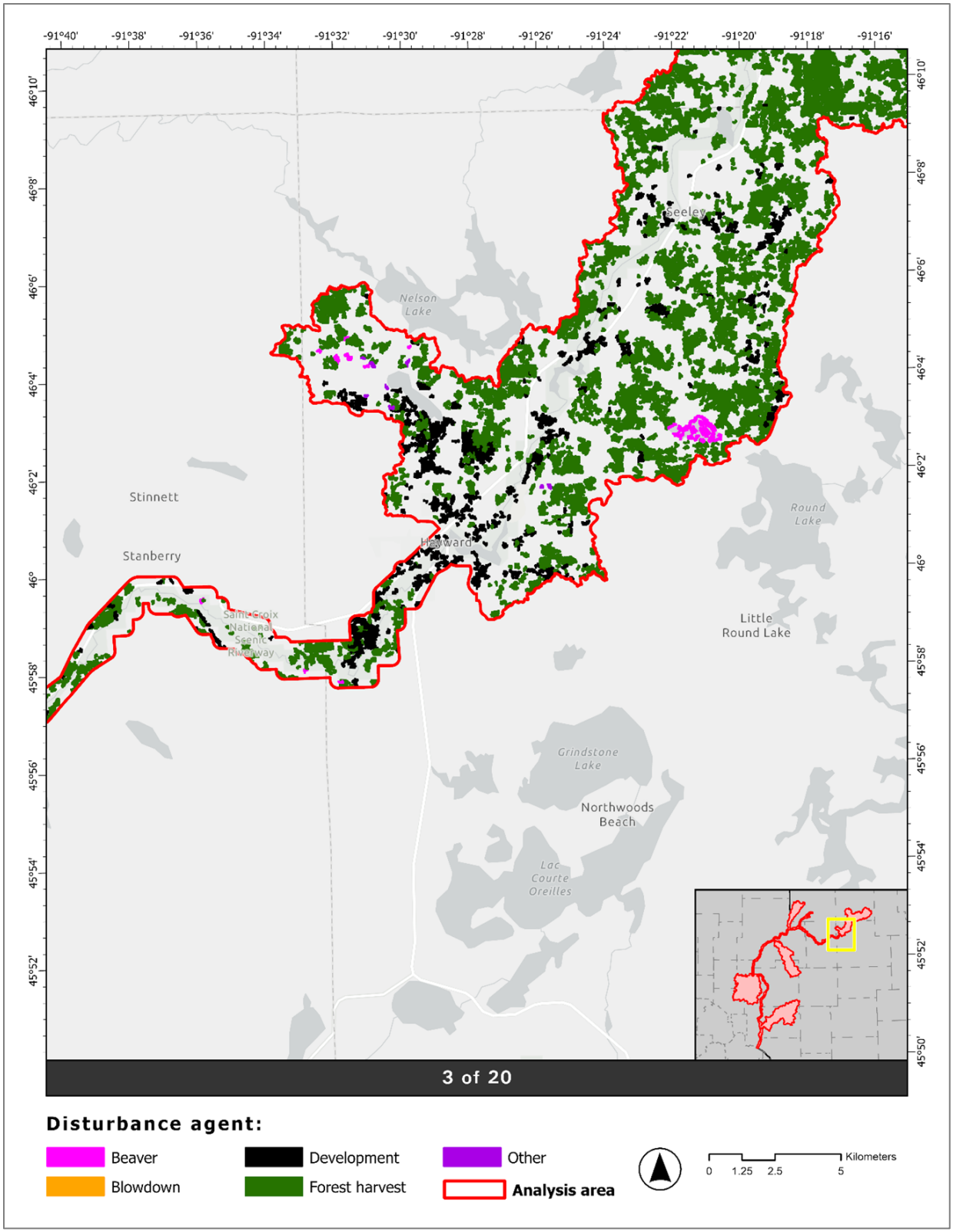


Figure 15. Disturbances around the upper Namekagon River near Hayward, Wisconsin.

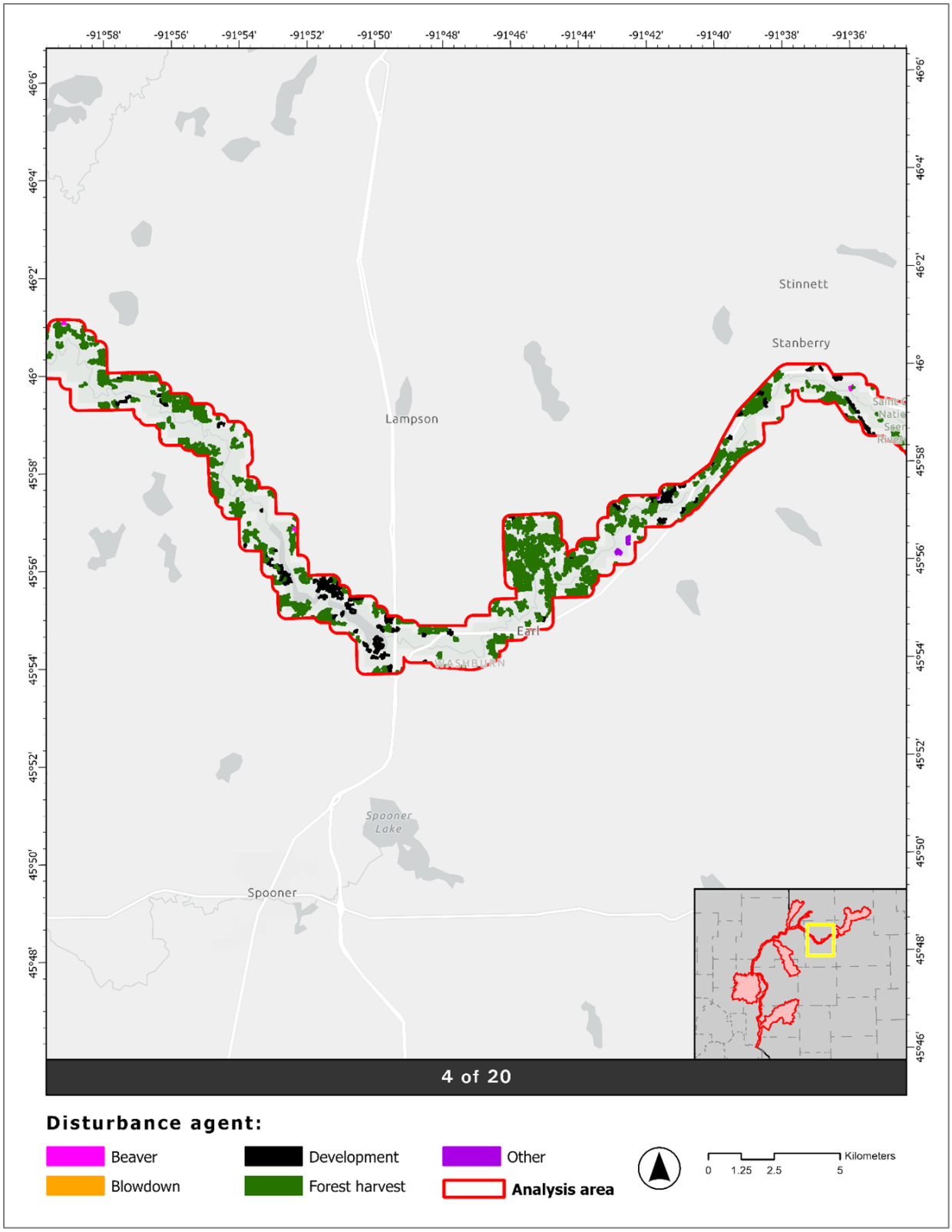


Figure 16. Disturbances around the Namekagon River near Trego, Wisconsin.

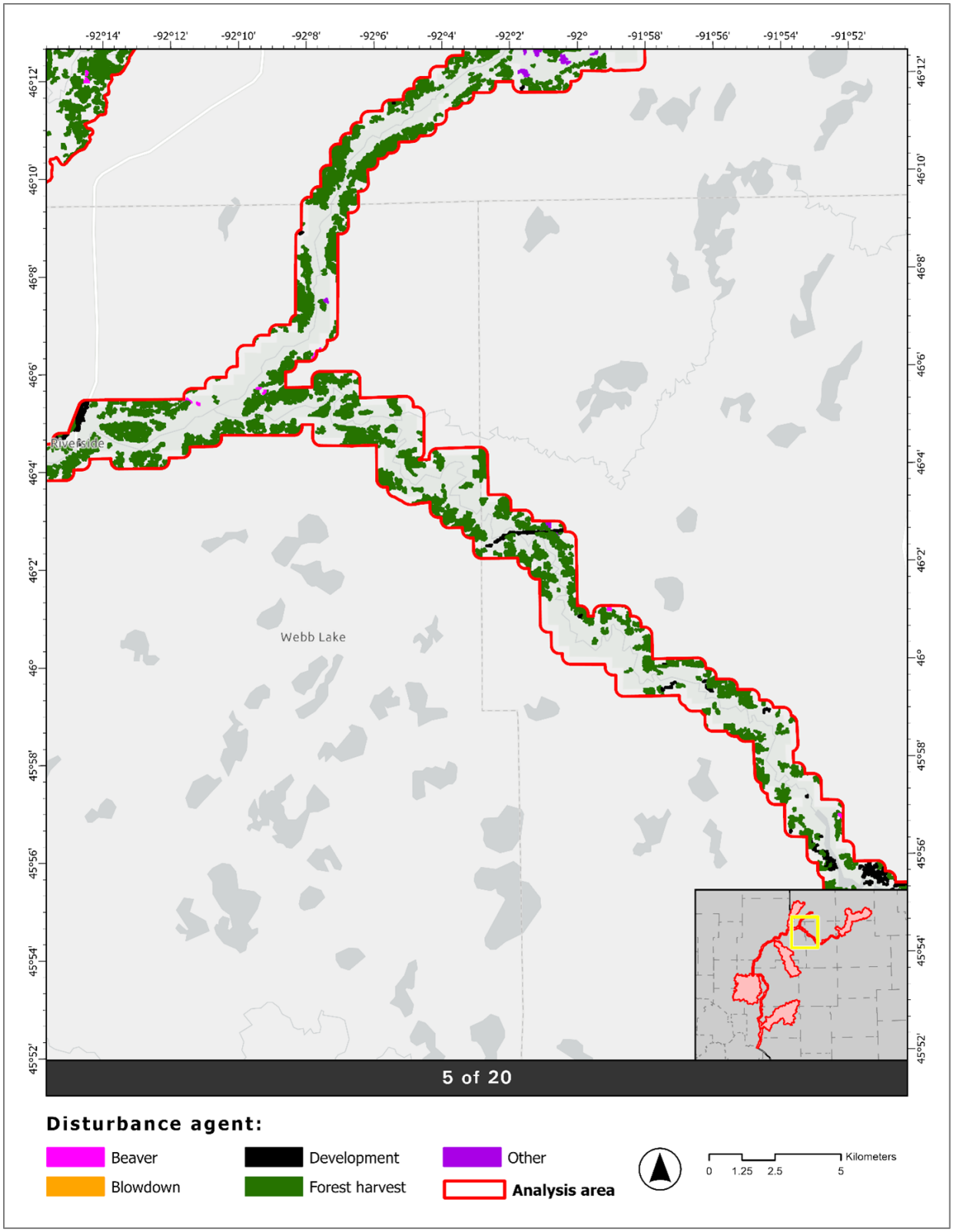


Figure 17. Disturbances around the confluence of the Namekagon and St. Croix Rivers.

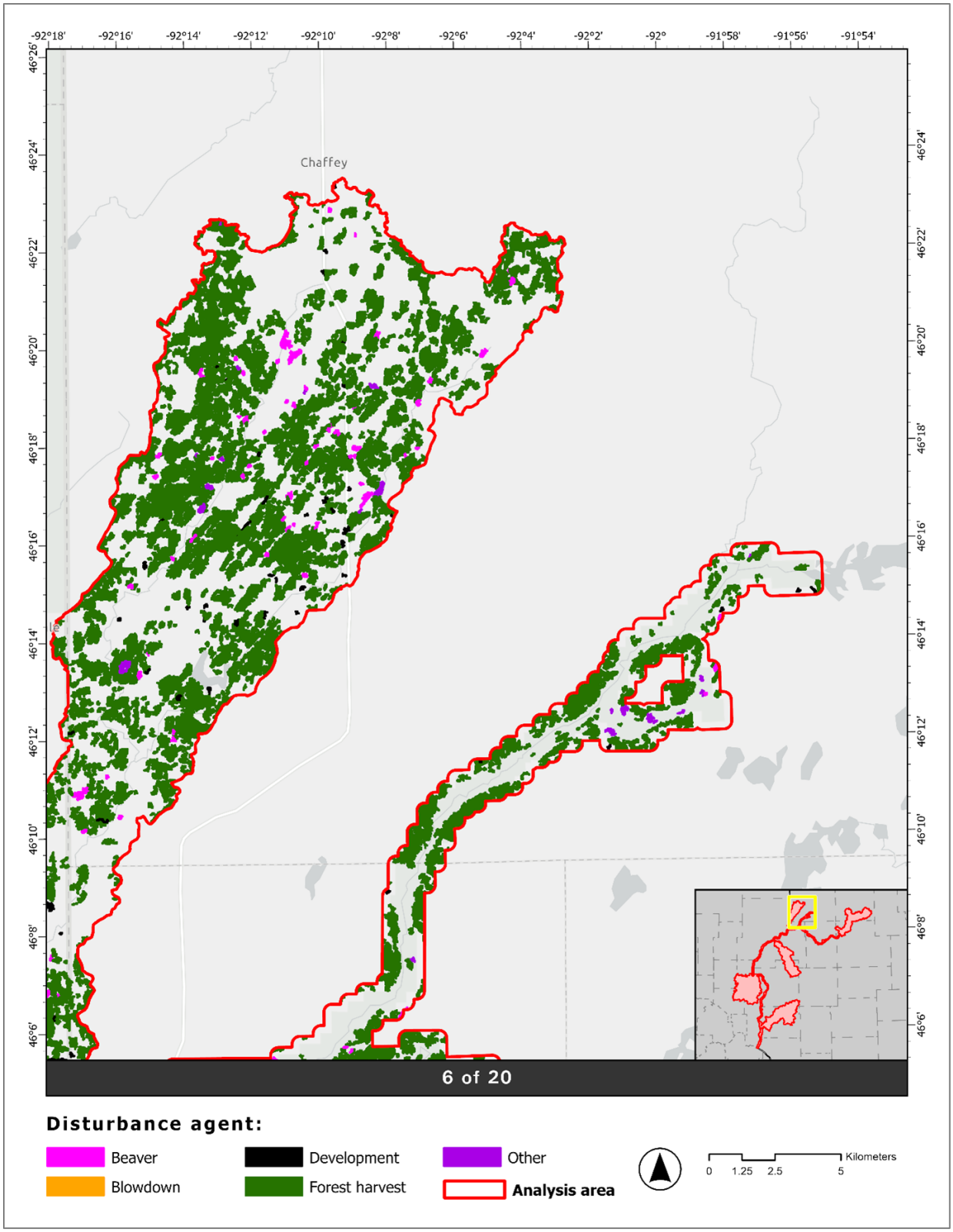


Figure 18. Disturbances around the upper St. Croix River and Tamarack Rivers.

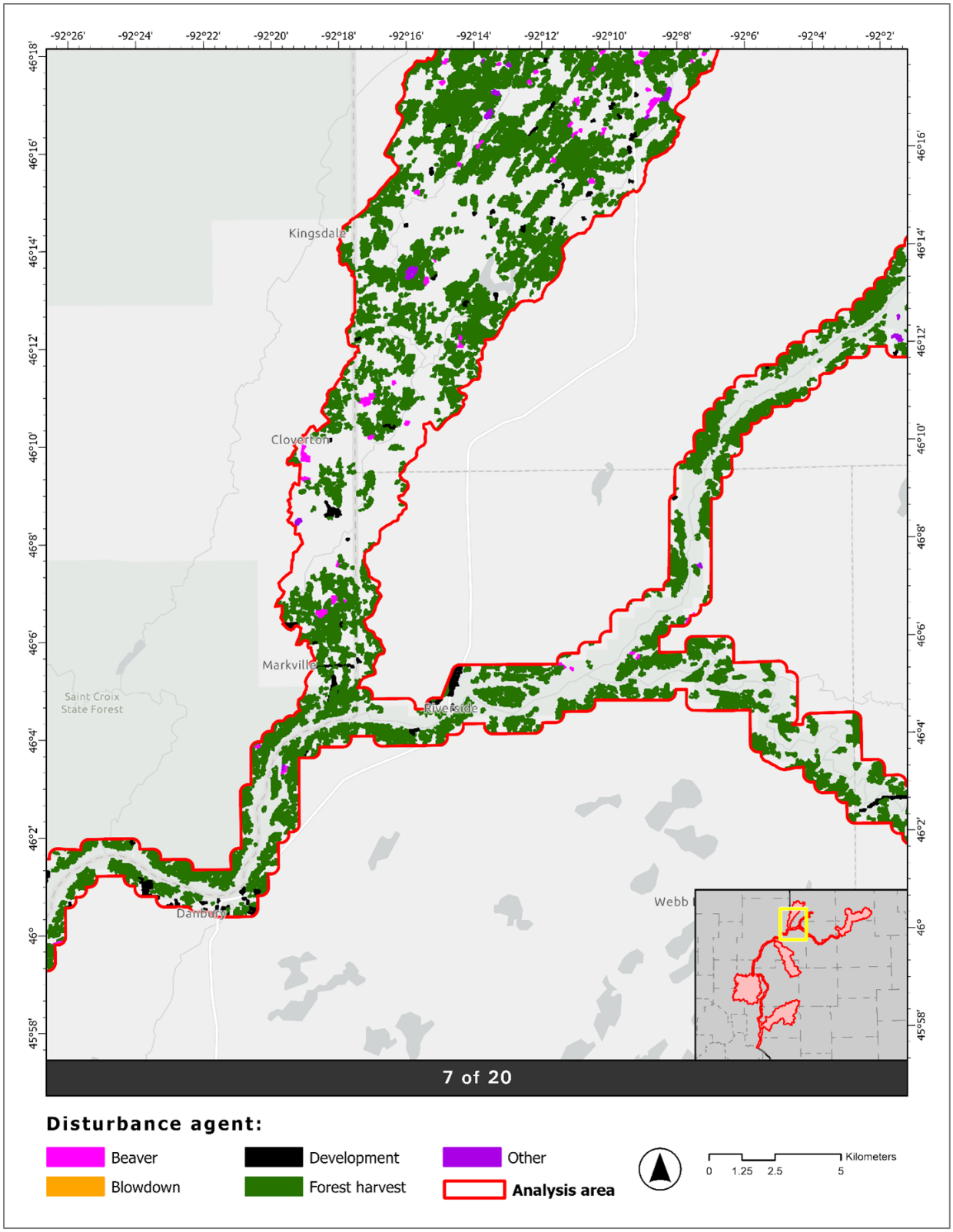


Figure 19. Disturbances around the confluence of the Tamarack and St. Croix Rivers.

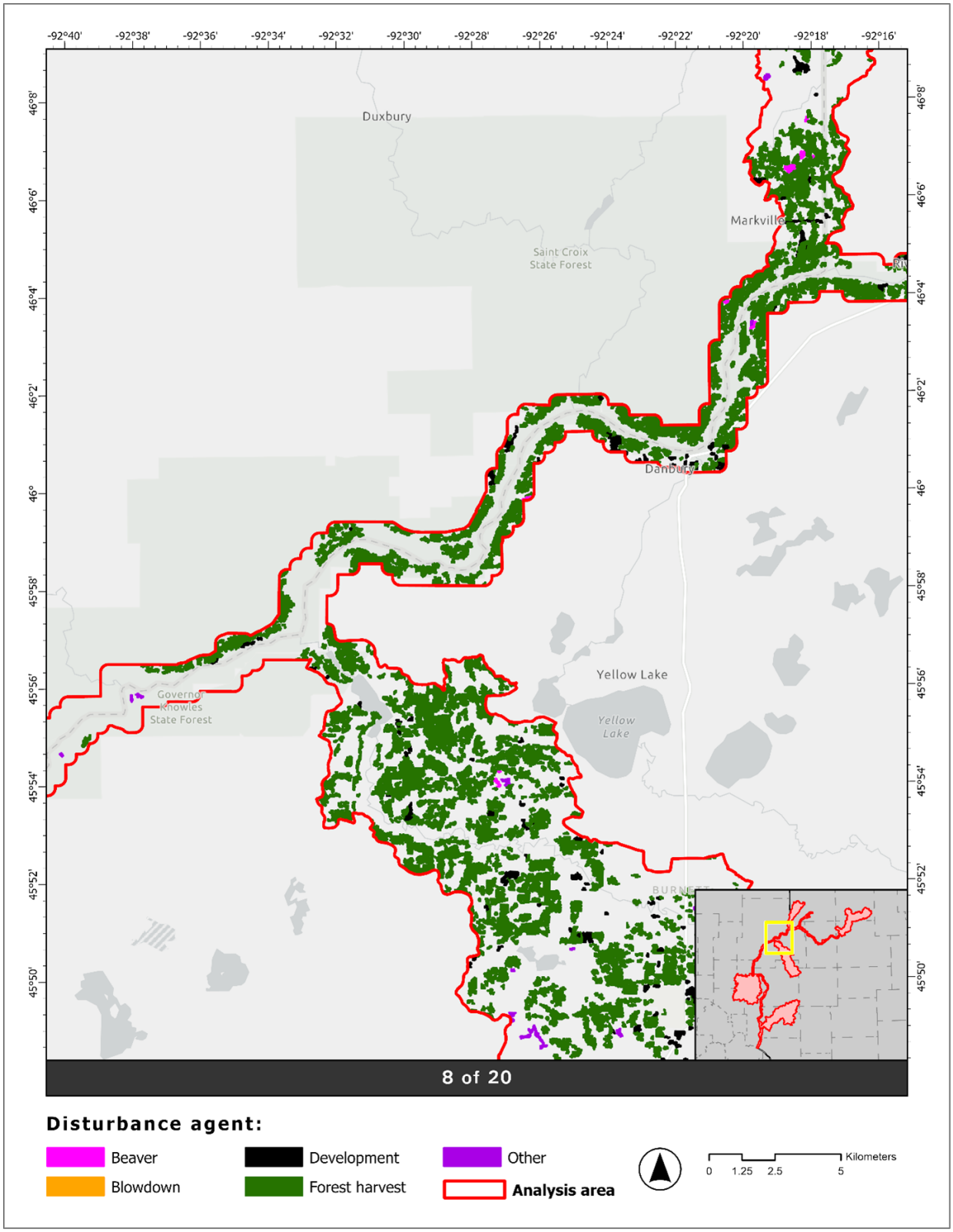


Figure 20. Disturbances around the upper St. Croix River near Danbury, Wisconsin.

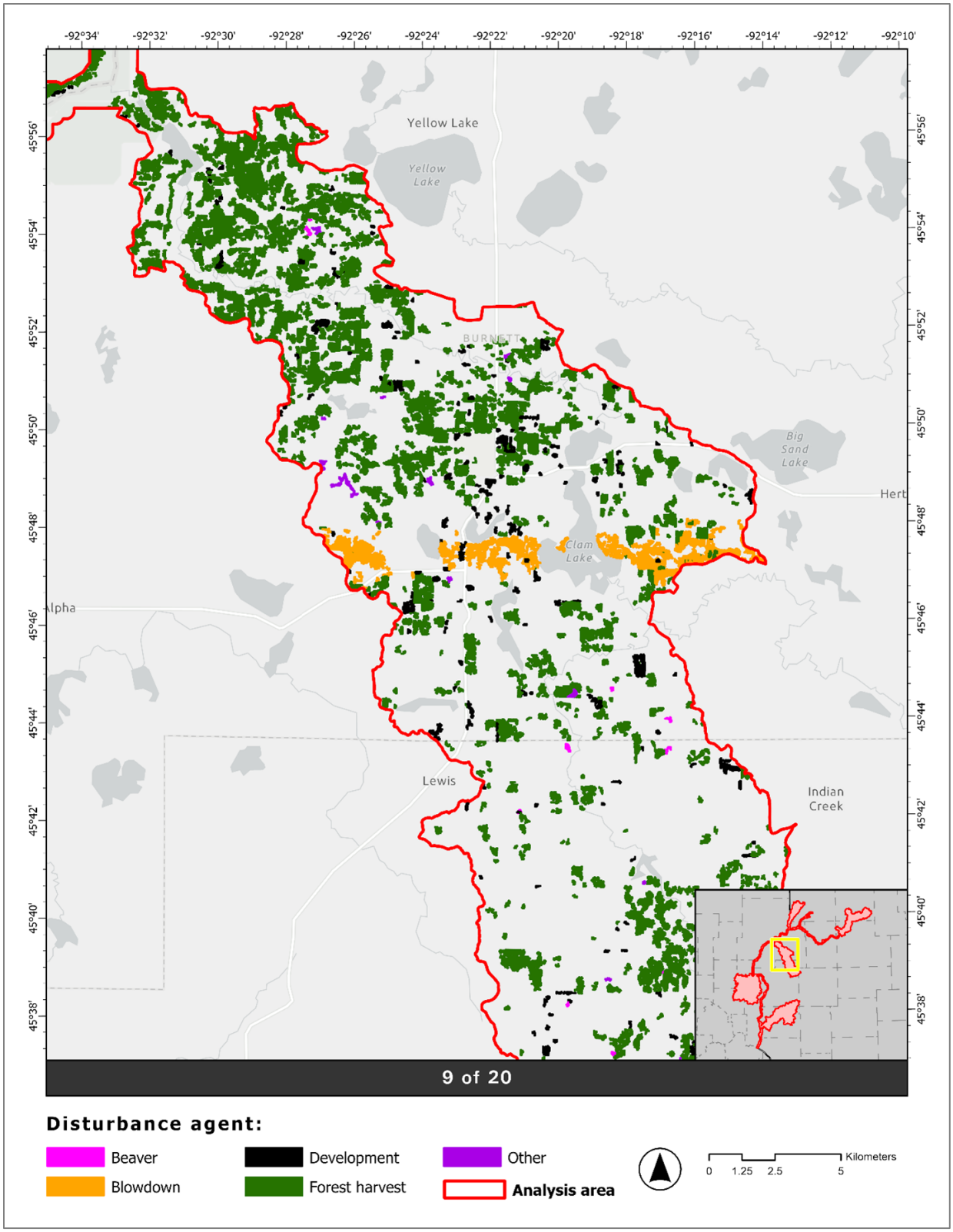


Figure 21. Disturbances in the Clam Lake watershed near Siren, Wisconsin.

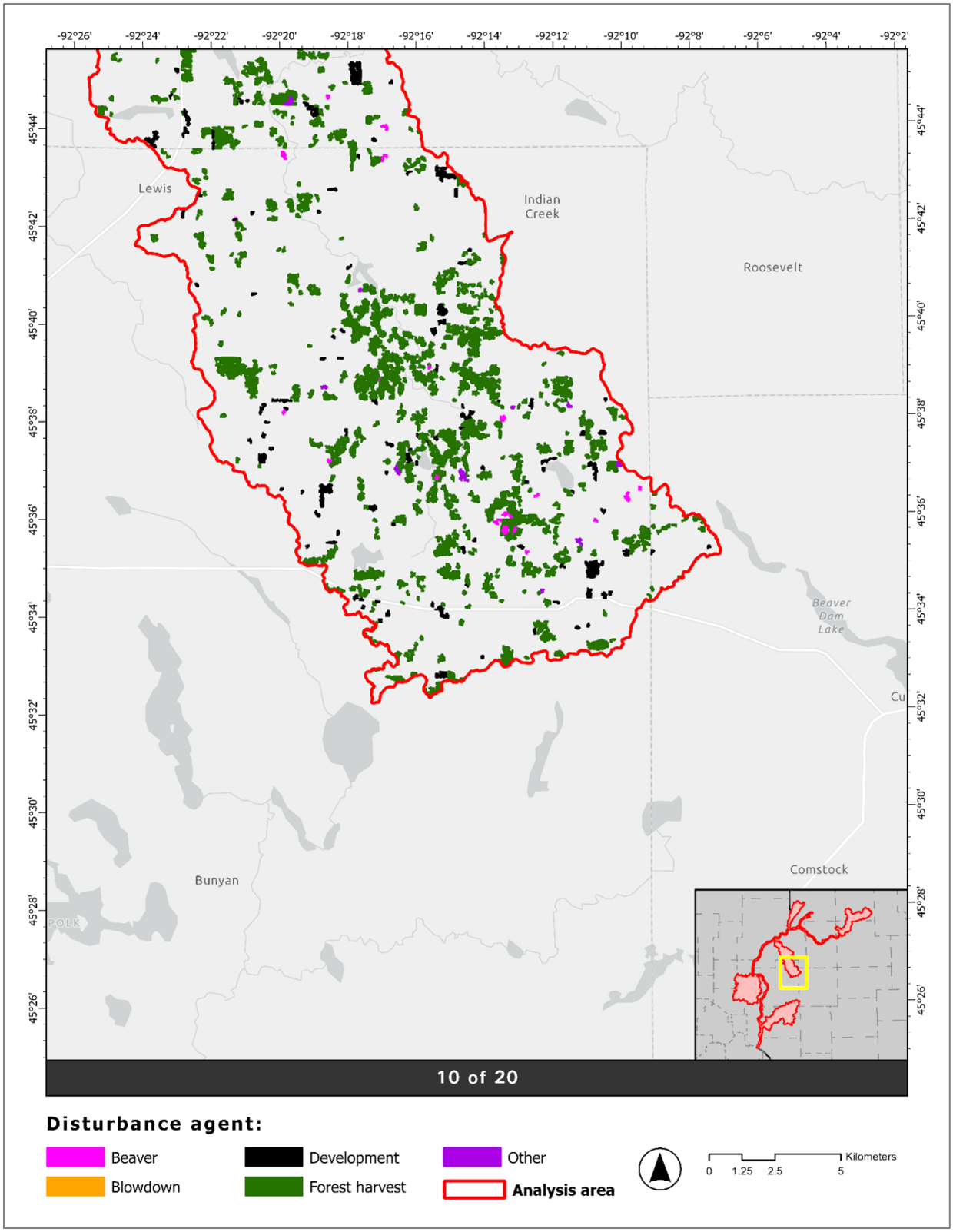


Figure 22. Disturbances in the upper Clam Lake watershed near Cumberland, Wisconsin.

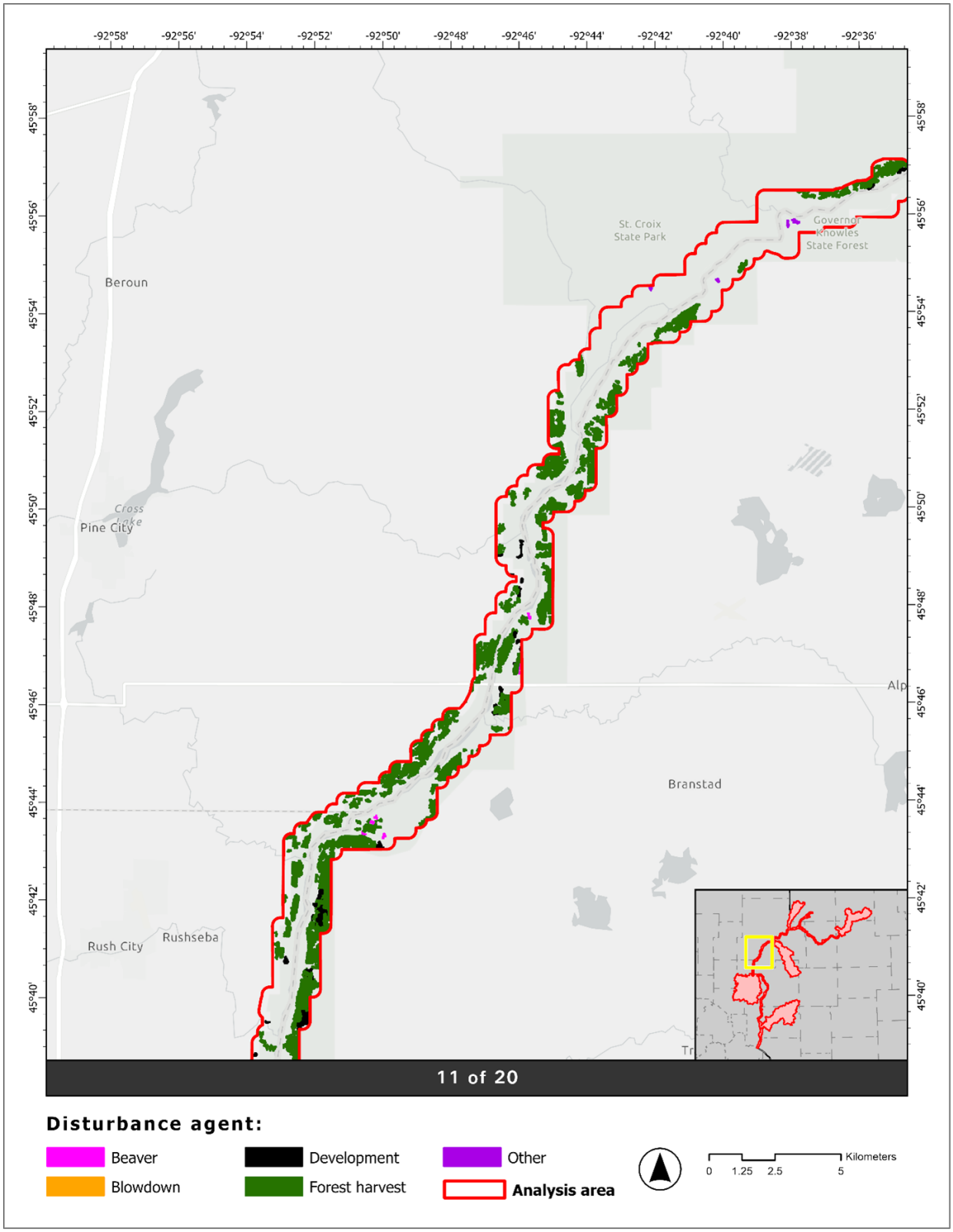


Figure 23. Disturbances along the St. Croix River near St. Croix State Park (Minnesota).

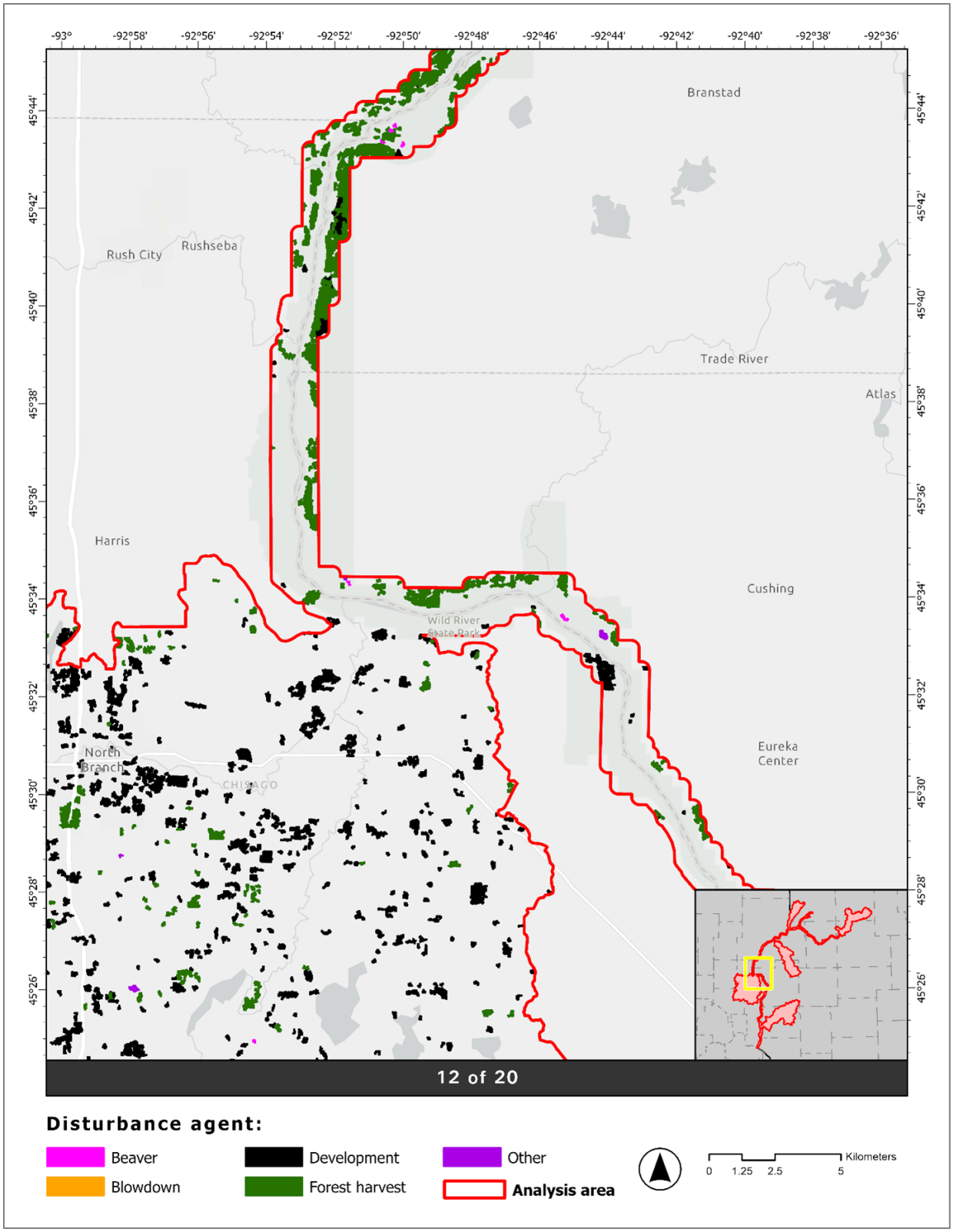


Figure 24. Disturbances along the St. Croix River near Wild River State Park (Minnesota).

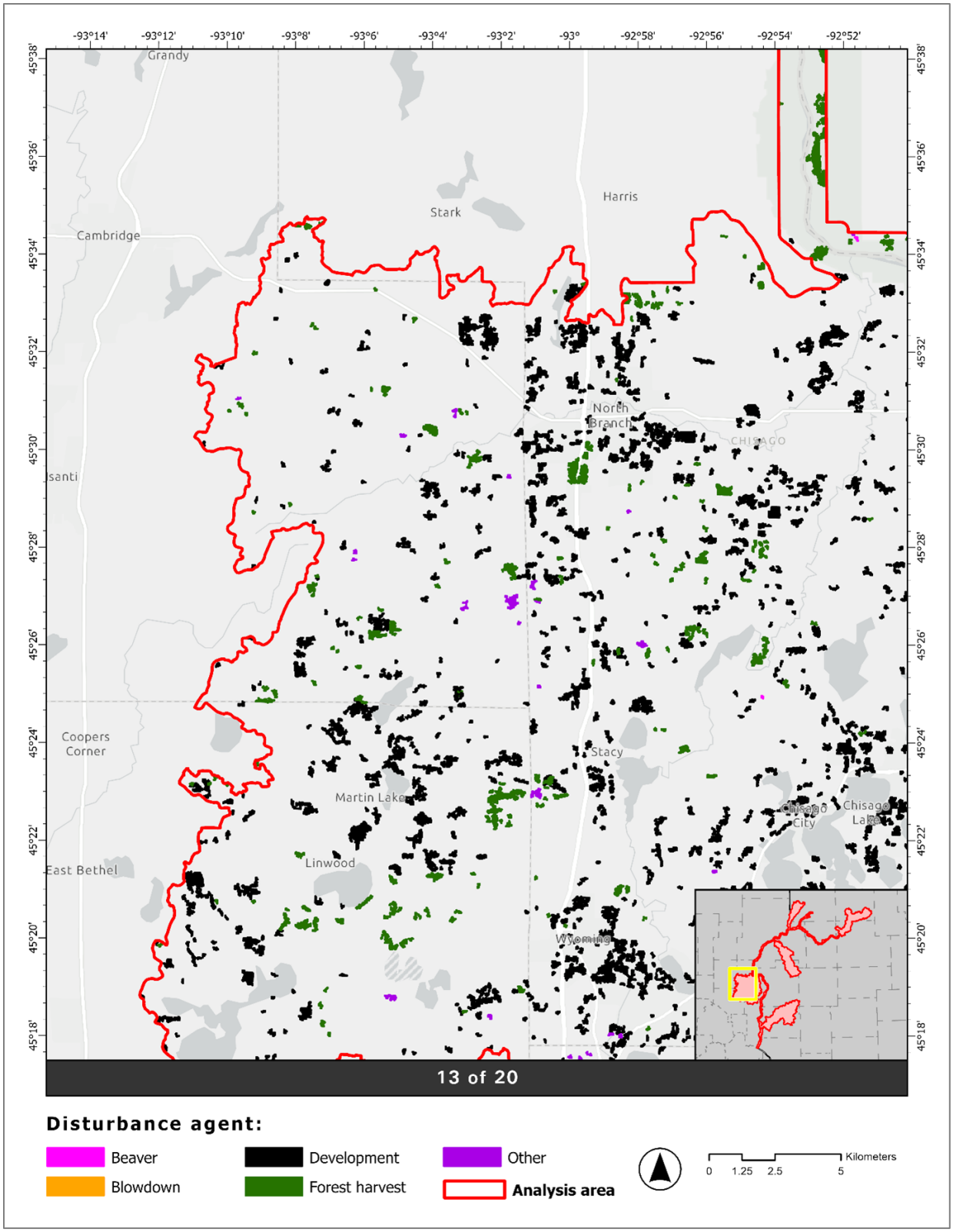


Figure 25. Disturbances in the North Branch of the Sunrise River near North Branch, Minnesota.

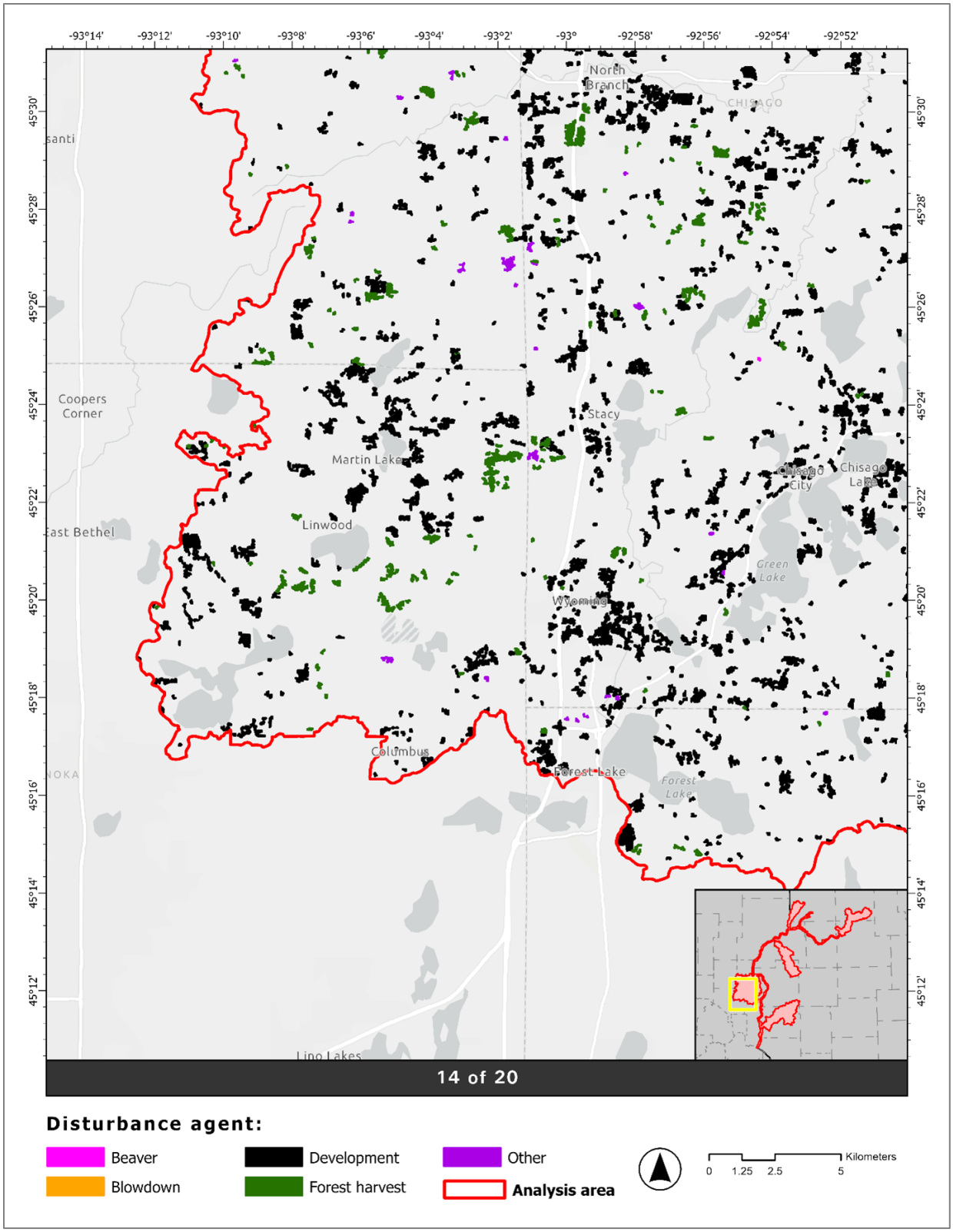


Figure 26. Disturbances in the upper part of the Sunrise River watershed near Chisago City, Minnesota.

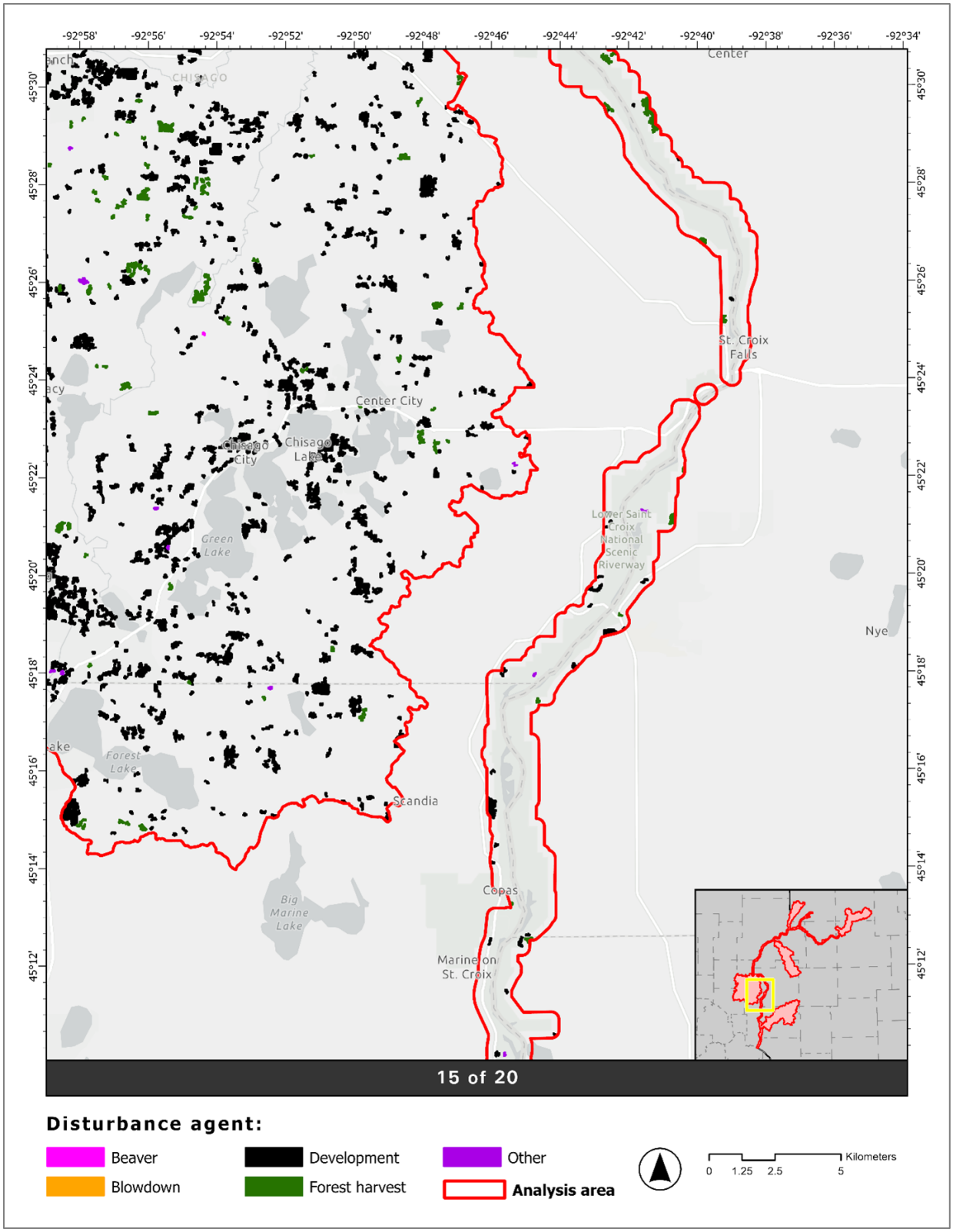


Figure 27. Disturbances in the Sunrise River watershed and St. Croix River near St. Croix Falls, Wisconsin.

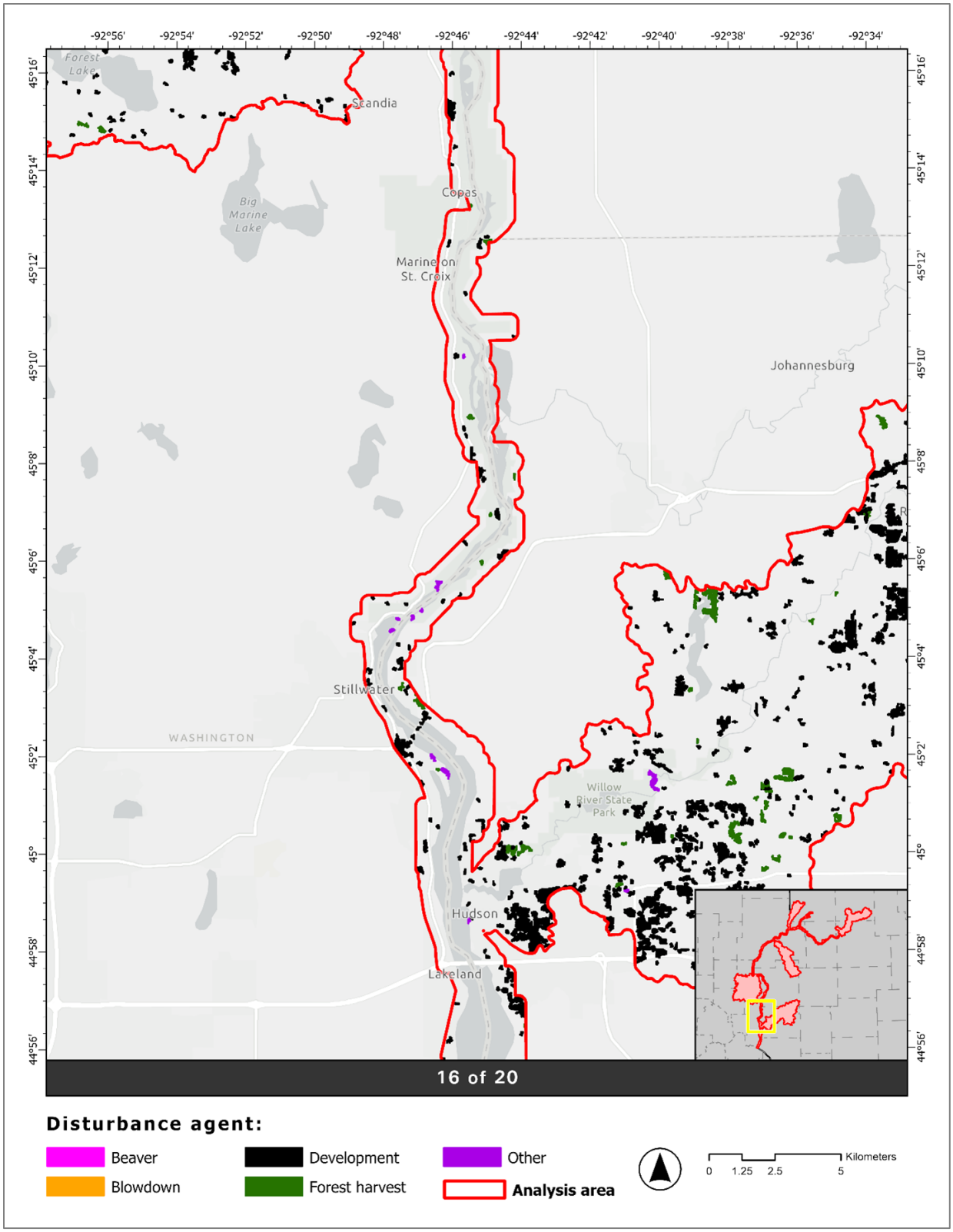


Figure 28. Disturbances along the St. Croix River near Stillwater, Minnesota.

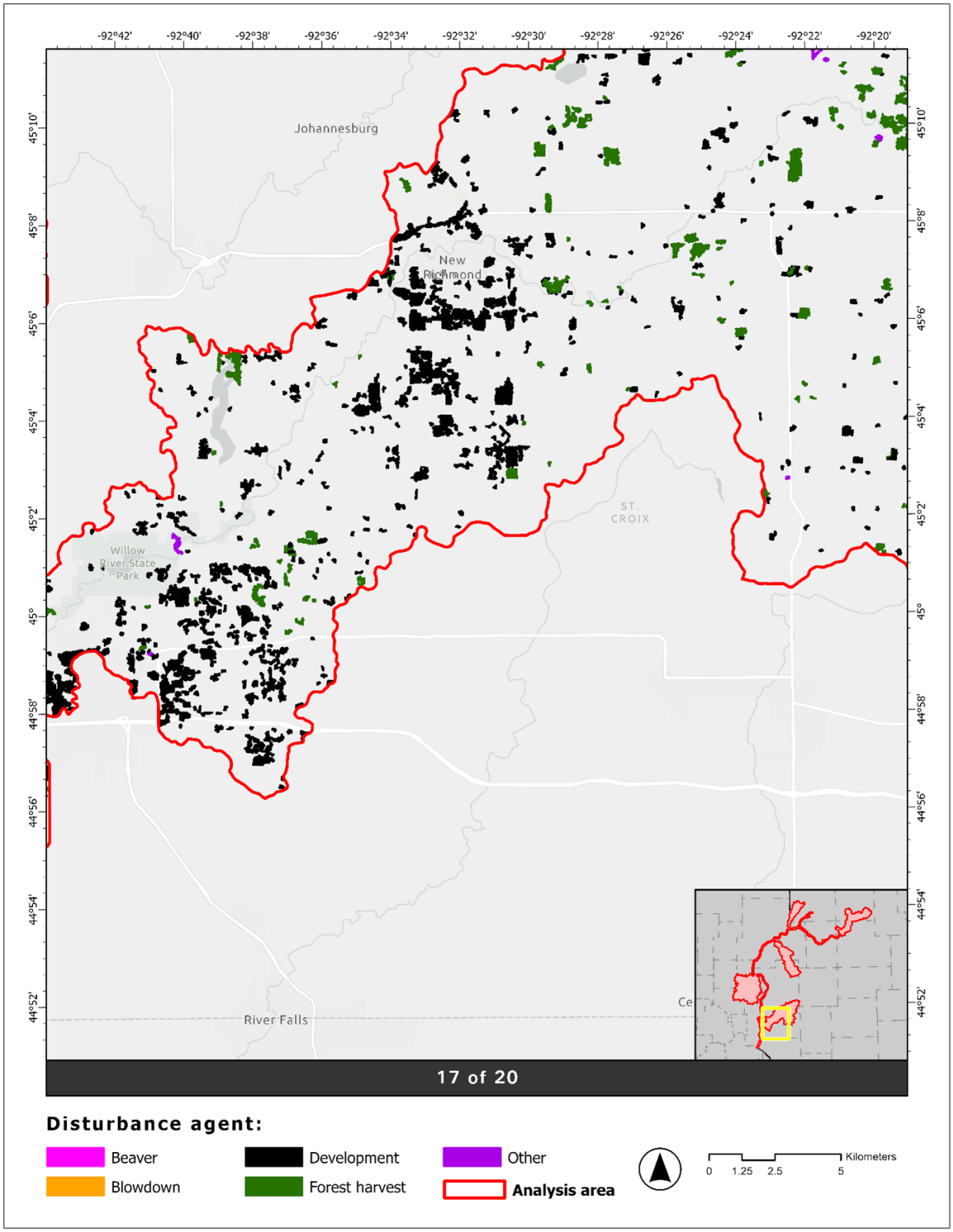


Figure 29. Disturbances in the lower Willow River watershed near Boardman, Wisconsin.

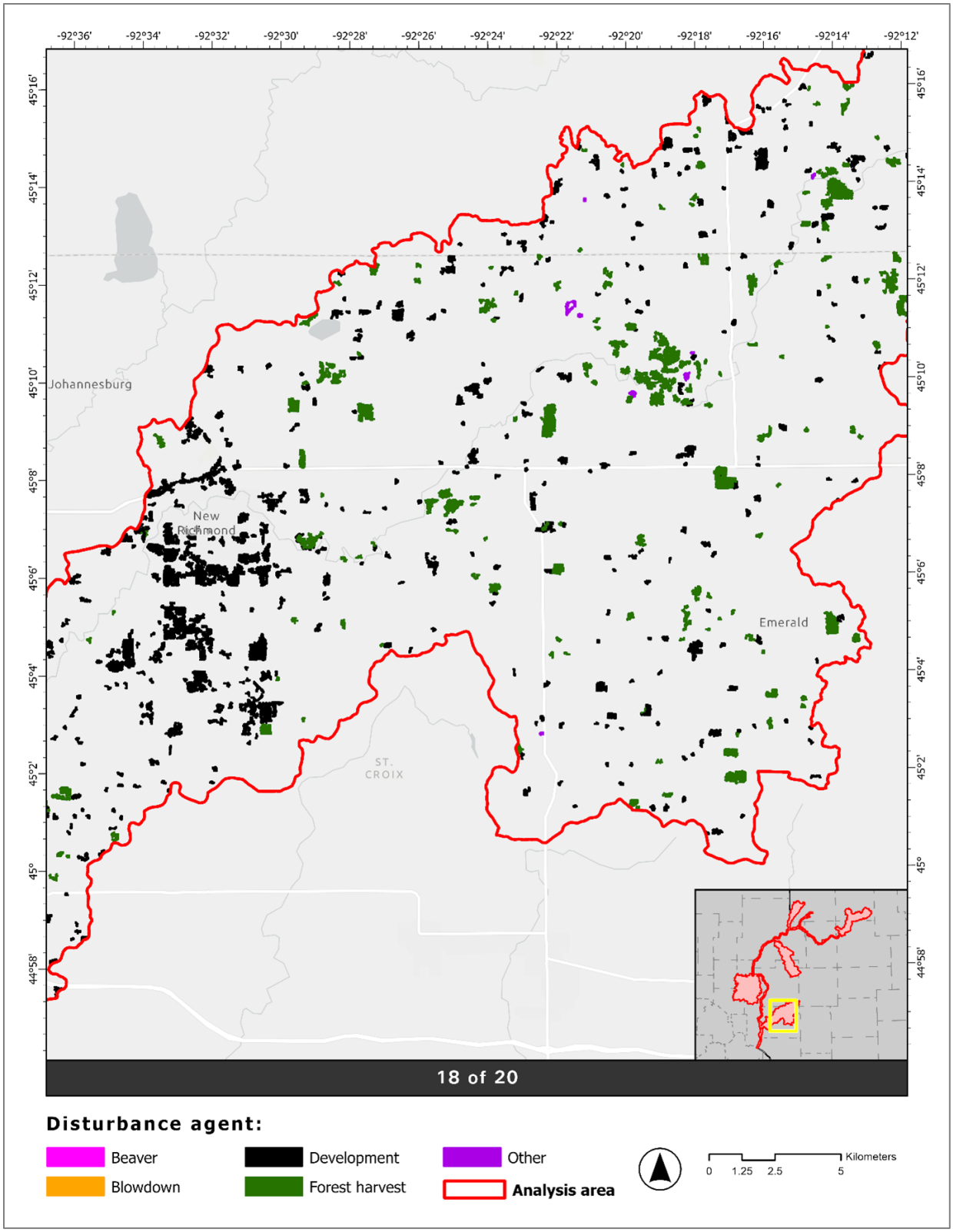


Figure 30. Disturbances in the Willow River watershed near New Richmond, Wisconsin.

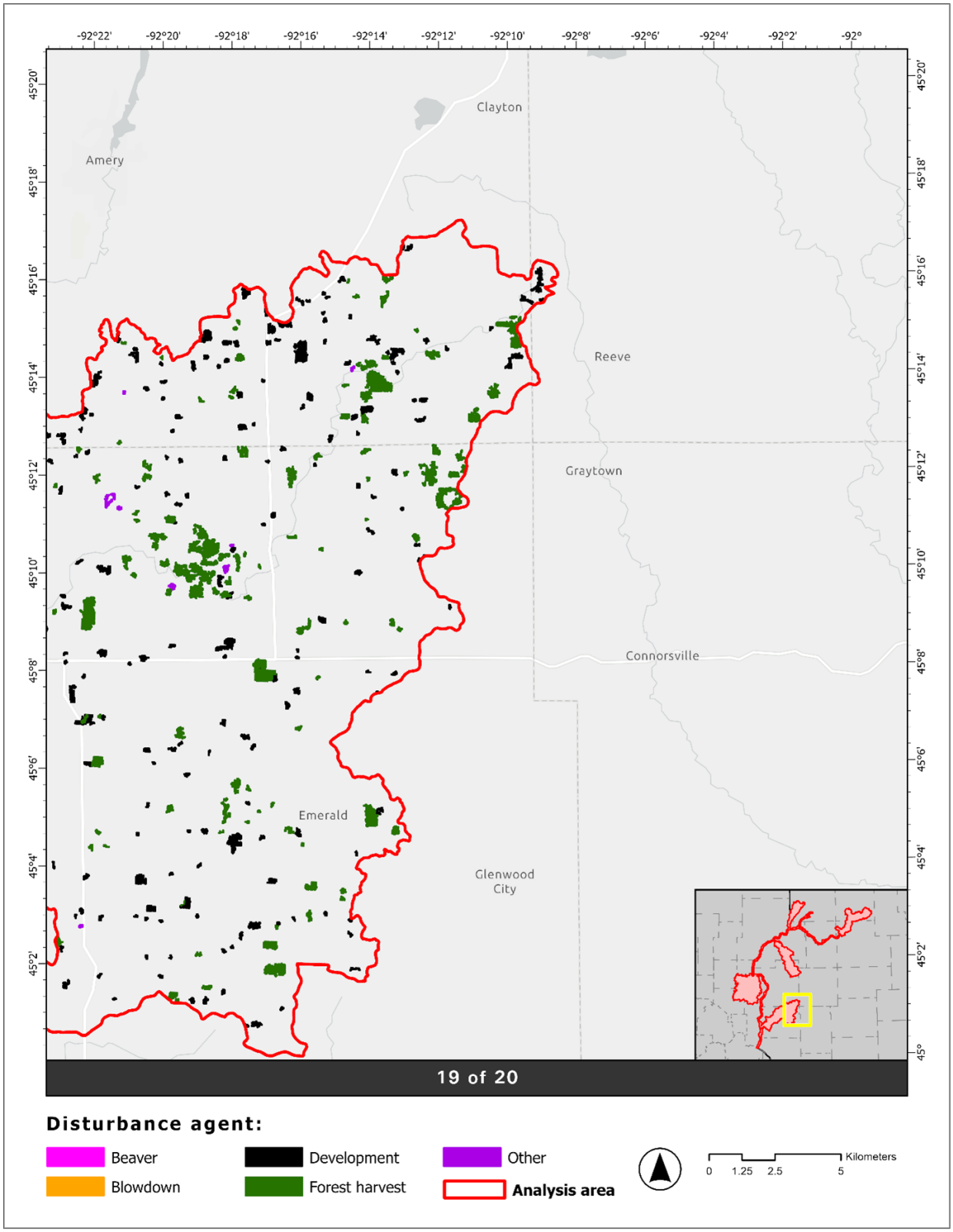


Figure 31. Disturbances in the upper Willow River watershed near Connorsville, Wisconsin.

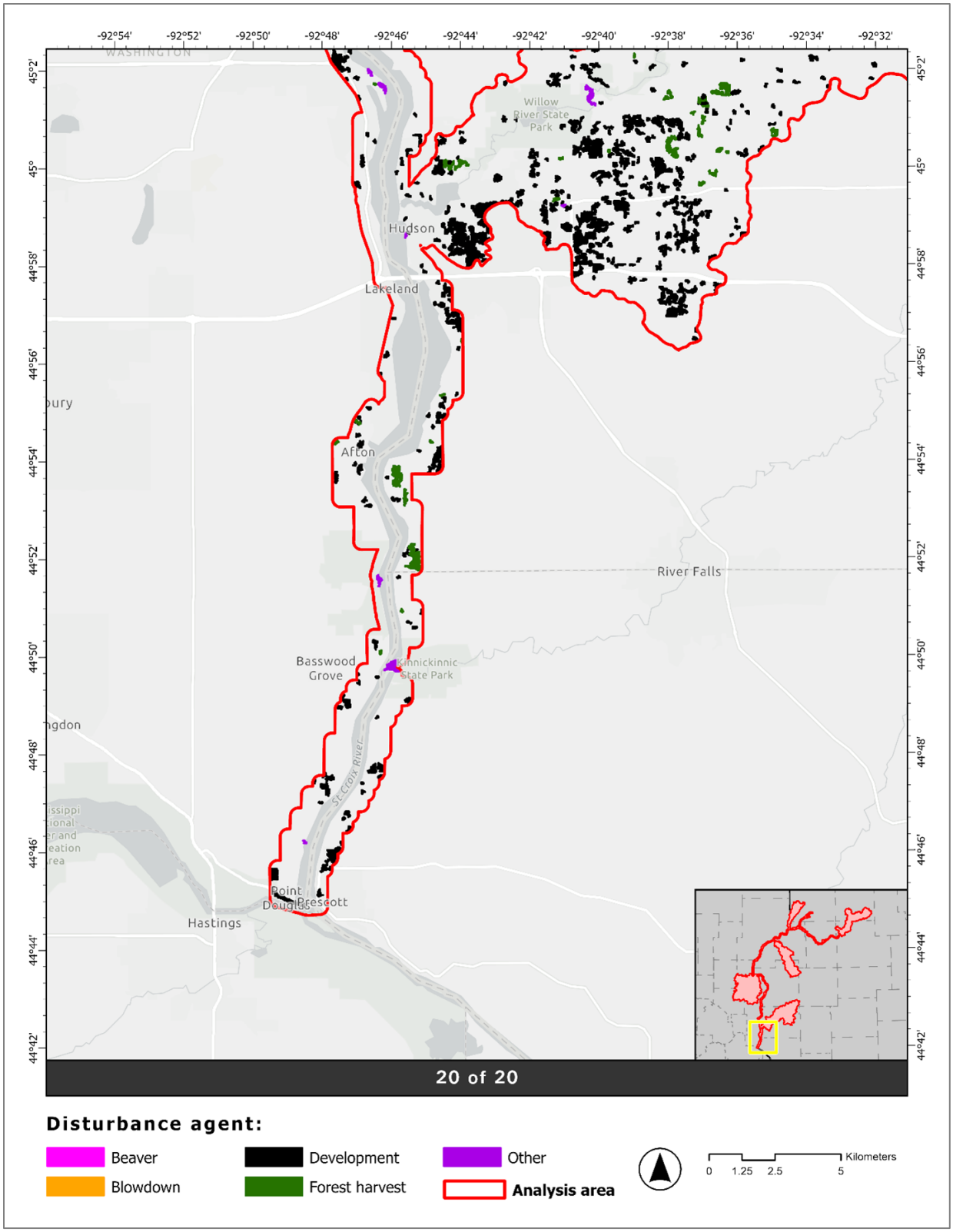


Figure 32. Disturbances around the lower St. Croix River near the confluence to the Mississippi River.

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