National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

# Natural Resource Condition Assessment

## *Voyageurs National Park*

Natural Resource Report NPS/VOYA/NRR—2015/1007

**ON THE COVER**
Beaver Point overlook, Voyageurs National Park
Photograph by: Dave Mechenich

# Natural Resource Condition Assessment

## *Voyageurs National Park*

Natural Resource Report NPS/VOYA/NRR—2015/1007

Christine Mechenich[1], Justin A. VanDeHey[2], James E. Cook[2], David J. Mechenich[1], Jennifer L. McNelly[1], and George J. Kraft[1]

[1]Center for Watershed Science and Education
College of Natural Resources
University of Wisconsin – Stevens Point
Stevens Point, Wisconsin 54481

[2]College of Natural Resources
University of Wisconsin – Stevens Point
Stevens Point, Wisconsin 54481

August 2015

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from the Natural Resource Publications Management website [(http://www.nature.nps.gov/publications/nrpm/](http://www.nature.nps.gov/publications/nrpm/)). To receive this report in a format optimized for screen readers, please email [irma@nps.gov](mailto:irma@nps.gov).

Please cite this publication as:

Mechenich, C., J. A. VanDeHey, J. E. Cook, D. J. Mechenich, J. L. McNelly, and G. J. Kraft. 2015. Natural resource condition assessment: Voyageurs National Park. Natural Resource Report NPS/VOYA/NRR—2015/1007. National Park Service, Fort Collins, Colorado.

NPS 172/129525, August 2015

# Contents

Page

## Contents (continued)

Page

# Contents (continued)

Page

# Figures

## Figures (continued)

## Figures (continued)

## Figures (continued)

Page

# Tables

# Tables (continued)

Page

# Executive Summary

Voyageurs National Park (VOYA) was formally established as a unit of the National Park Service (NPS) in 1975 after the passage of Public Law 91-661 in 1971. Its purpose is:

> *"to preserve, for the inspiration and enjoyment of present and future generations, the outstanding scenery, geological conditions and waterway system which constituted a part of the historic route of the Voyageurs who contributed significantly to the opening of the Northwestern United States."*

VOYA is located in a sparsely populated area of northern Minnesota along the US border with Ontario. Its 829 $km^2$ area is part of a larger ecosystem that includes the 4,856 $km^2$ Boundary Waters Canoe Area Wilderness and the 4,452 $km^2$ Quetico Provincial Park in Canada. VOYA lies within the lower end of the Rainy River watershed, which is one of the upper headwaters of Hudson Bay. Land ownership in the watershed upstream of VOYA is a mosaic of national forest, state, private, and private industrial (pulpwood production) lands in Minnesota and crown land (publicly owned mixed use land) in Ontario.

VOYA is located in the Laurentian Mixed Forest ecological province and is at the southern end of the southern boreal forest type. The most abundant forest associations are Aspen-Birch/Boreal Conifer and its close associate Aspen-Birch/Red Maple, Spruce-Fir-Aspen, and Pine-Aspen-Birch. These are indicative of the influence of past logging and fires on the park.

Approximately 40% of VOYA is covered by water, and four major lakes (Kabetogama, Namakan, Rainy, and Sand Point) make up 96% of the park's total lake area. Lake levels in the park's four largest lakes are controlled by a dam crossing the Rainy Lake outlet at the international border between Fort Frances, ON and International Falls, MN, as well as by small dams at Kettle Falls and Squirrel Falls on Namakan Lake and two natural spillways. VOYA also has 26 interior lakes and numerous streams and wetlands.

This Natural Resource Condition Assessment was undertaken to evaluate current conditions for a subset of natural resources and resource indicators in VOYA. Using a framework developed by the Science Advisory Board of the United States Environmental Protection Agency, natural resources were evaluated in six categories: natural disturbance regimes, landscape condition, biotic condition, chemical and physical characteristics, ecological processes, and hydrology and geomorphology. A total of 39 resources and indicators were evaluated (Table i) by reviewing existing data from peer-reviewed literature and state and federal agencies, including NPS. Data were analyzed where possible to provide summaries or new statistical or spatial representations. Of these 39 natural resource condition indicators, 17 were in "good" condition, eight were in condition of "moderate concern," 11 were in condition of "significant concern," and the condition of the remaining three was "unknown." Three had an improving trend, 21 were stable, one showed a deteriorating trend, and the trend for 14 was uncertain. Confidence in the assessment was high for 24 indicators, moderate for 12, and unknown for three.

**Table i.** Condition and trend of natural resources and resource indicators evaluated for Voyageurs National Park.

| **Condition and Trend** | | **Confidence** | **Natural Resource or Resource Indicator** |
|---|---|---|---|
| 🟢↑ | Condition good, improving trend | High | Water quality – dissolved oxygen – large lakes |
| 🟢↔ | Condition good, stable trend | High | Land cover change<br>Road density<br>Fish communities<br>Water quality – pH , dissolved oxygen, total nitrogen, total phosphorus, water clarity, chlorophyll *a* – interior index lakes<br>Water quality – water clarity – large lakes |
| 🟢↔ | Condition good, stable trend | Moderate | Impervious surfaces<br>Zoobenthic community |
| 🟢 | Condition good, uncertain trend | High | Water quality – pH – large lakes<br>Water quality – chloride – interior index lakes |
| 🟢 | Condition good, uncertain trend | Moderate | Lightscape<br>Terrestrial exotic plants |
| 🟡↑ | Condition of moderate concern, improving trend | High | Water quality – chlorophyll *a* – large lakes |
| 🟡↔ | Condition of moderate concern, stable trend | High | Air quality – ozone<br>Air quality – visibility<br>Water quality – total phosphorus – large lakes |
| 🟡↔ | Condition of moderate concern, stable trend | Moderate | Vegetation structure and composition |
| 🟡 | Condition of moderate concern, uncertain trend | High | Water quality – alkalinity – large lakes |
| 🟡 | Condition of moderate concern, uncertain trend | Moderate | Forest density<br>Earthworms |
| 🔴↑ | Condition of significant concern, improving trend | High | Mercury in precipitation |
| 🔴↔ | Condition of significant concern, stable trend | High | Air quality – overall<br>Air quality – wet deposition of nitrogen<br>Air quality – wet deposition of sulfur |

**Table i (continued).** Condition and trend of natural resources and resource indicators evaluated for Voyageurs National Park.

| Condition and Trend | | Confidence | Natural Resource or Resource Indicator |
|---|---|---|---|
| ↔ | Condition of significant concern, stable trend | Moderate | Moose (short term)<br>Aquatic invasive species |
| ● | Condition of significant concern, uncertain trend | High | Mercury in fish tissue (effects on fish)<br>Water quality – alkalinity – interior index lakes |
| ● | Condition of significant concern, uncertain trend | Moderate | Mercury in fish tissue (human consumption)<br>Mercury in surface waters |
| ⇩ | Condition of significant concern, deteriorating trend | Moderate | Zooplankton community |
| ◌ | Condition unknown, unknown trend | n/a | Forest morphology<br>Soundscape<br>Water quality – specific conductance |

Resources and resource indicators that are in good condition, with an improving or stable trend at VOYA, are land cover stability; low road density and density of impervious surfaces; the fish and zoobenthic communities; most water quality indicators (pH, dissolved oxygen, total nitrogen, total phosphorus, water clarity, and chlorophyll a) in the interior lakes; and water quality indicators (dissolved oxygen and water clarity) in the large lakes. Other indicators that appear to be in good condition but have insufficient information to determine a trend are the lightscape, low incidence of terrestrial exotic plants, and the water quality indicators of pH in the large lakes and chloride in the interior lakes.

The condition of the forest at VOYA is of moderate concern, with a stable trend. The vegetation structure and composition, and the forest density, are likely outside the historic range of variability because of the importance of fire to the boreal forest.

Conditions of significant concern, but with an improving or stable trend, are mercury in precipitation, overall air quality, wet deposition of nitrogen and sulfur from the atmosphere, aquatic invasive species, and the moose population. Other conditions of significant concern with an uncertain trend are mercury in fish tissue, both as a human health issue and a fish health issue; the low alkalinity levels in interior lakes (although this is a natural condition, it highlights their susceptibility to acid precipitation), and the condition of the zooplankton community, which is being harmed by the invasion of the exotic spiny water flea in the large lakes.

A condition that was not specifically evaluated was the water level manipulation that occurs within Rainy Lake and the Namakan Reservoir. Early indications are that the 2000 rule curves, which allowed for water levels more similar to natural conditions, have had beneficial effects on wetlands, water quality, macroinvertebrate communities, and ecosystem health in the Namakan Reservoir. A final decision on the rule curves and water level management, based on the results of 18 current research projects, will be made following an International Joint Commission review which will begin in 2015.

Natural resources and resource indicators at VOYA are affected by activities and processes at scales ranging from local to global. Within VOYA, recreational users may be responsible for improper human waste and trash disposal and the spread of invasive species such as the spiny water flea. Endocrine-disrupting chemicals found in the sediments of Kabetogama Lake may indicate inputs from onsite wastewater disposal systems in the watershed. Management of the water levels in VOYA's large lakes is based on decisions made by an international agency, the International Joint Commission. Mercury in the interior lakes in VOYA may have been deposited from industrial use in the region or globally. Climate change, which is not a focus of this report, could have significant effects on VOYA's ecosystems and is a global phenomenon. VOYA resource managers will need help from local, state, federal, and international agencies and groups to address the threats to its airshed and its terrestrial and aquatic ecosystems.

# Acknowledgments

We gratefully acknowledge the contributions of all those who assisted in the preparation of this report. Mary Graves, Chief of Resource Management; Steve Windels, Wildlife Biologist; Ryan Maki, Aquatic Ecologist; and John Snyder, GIS Specialist; all of VOYA, were particularly helpful in scoping the report and providing data for our analyses; they also gave us a tour of the park and helped us to see VOYA through their eyes. Bill Route of the GLKN served as the liaison between UWSP and GLKN. Dan Mechenich prepared Appendix B. The report was reviewed by Mary Graves, Ryan Maki, and John Snyder of VOYA and Brenda Moraska Lafrancois, Aquatic Ecologist, NPS Midwest Region.

# List of Terms

| | |
|---|---|
| AOA | Area of analysis |
| BWCAW | Boundary Waters Canoe Area Wilderness |
| CASTNet | Clean Air Status and Trends Network |
| CPUE | Catch per unit effort |
| DO | Dissolved oxygen |
| DR | Disturbance regime |
| ECS | Ecological classification systems |
| FRI | Fire return interval |
| GCM | General circulation model |
| GLKN | NPS Great Lakes Inventory and Monitoring Network |
| IJC | International Joint Commission |
| IRMA | NPS Integrated Resource Management Applications web portal |
| ISRO | Isle Royale National Park |
| MDH | Minnesota Department of Health |
| MDN | Mercury Deposition Network |
| MDNR | Minnesota Department of Natural Resources |
| MeHg | Methylmercury |
| MISS | Mississippi National River and Recreation Area |
| MPCA | Minnesota Pollution Control Agency |
| NADP | National Atmospheric Deposition Program |
| NALC | North American Landscape Characterization data |
| NLCD | National Land Cover Database |
| NOAA | National Oceanic and Atmospheric Administration |
| NPS | National Park Service |
| NPScape | National Park Service landscape dynamics monitoring project |
| NRCA | Natural Resource Condition Assessment |
| NVCS | National Vegetation Classification Standard |
| SACN | Saint Croix National Scenic Riverway |
| SOP | Standard operating procedure |
| TMDL | Total maximum daily load |
| TN | Total nitrogen |
| TP | Total phosphorus |
| USDA | United States Department of Agriculture |
| USEPA | United States Environmental Protection Agency |
| USGS | United States Geological Survey |
| UWSP | University of Wisconsin – Stevens Point |
| VOYA | Voyageurs National Park |
| WDNR | Wisconsin Department of Natural Resources |
| WTD | white-tailed deer |

# 1. NRCA Background Information

Natural Resource Condition Assessments (NRCAs) evaluate current conditions for a subset of natural resources and resource indicators in national park units, hereafter "parks." NRCAs also report on trends in resource condition (when possible), identify critical data gaps, and characterize a general level of confidence for study findings. The resources and indicators emphasized in a given project depend on the park's resource setting, status of resource stewardship planning and science in identifying high-priority indicators, and availability of data and expertise to assess current conditions for a variety of potential study resources and indicators.

***NRCAs Strive to Provide…***

*Credible condition reporting for a subset of important park natural resources and indicators*

*Useful condition summaries by broader resource categories or topics, and by park areas*

NRCAs represent a relatively new approach to assessing and reporting on park resource conditions. They are meant to complement—not replace—traditional issue- and threat-based resource assessments. As distinguishing characteristics, all NRCAs:

- are multi-disciplinary in scope;[1]
- employ hierarchical indicator frameworks;[2]
- identify or develop reference conditions/values for comparison against current conditions;[3]
- emphasize spatial evaluation of conditions and GIS (map) products;[4]
- summarize key findings by park areas; and[5]
- follow national NRCA guidelines and standards for study design and reporting products.

Although the primary objective of NRCAs is to report on current conditions relative to logical forms of reference conditions and values, NRCAs also report on trends, when appropriate (i.e., when the underlying data and methods support such reporting), as well as influences on resource conditions.

---

[1] The breadth of natural resources and number/type of indicators evaluated will vary by park.

[2] Frameworks help guide a multi-disciplinary selection of indicators and subsequent "roll up" and reporting of data for measures ⇨ conditions for indicators ⇨ condition summaries by broader topics and park areas

[3] NRCAs must consider ecologically-based reference conditions, must also consider applicable legal and regulatory standards, and can consider other management-specified condition objectives or targets; each study indicator can be evaluated against one or more types of logical reference conditions. Reference values can be expressed in qualitative to quantitative terms, as a single value or range of values; they represent desirable resource conditions or, alternatively, condition states that we wish to avoid or that require a follow-on response (e.g., ecological thresholds or management "triggers").

[4] As possible and appropriate, NRCAs describe condition gradients or differences across a park for important natural resources and study indicators through a set of GIS coverages and map products.

[5] In addition to reporting on indicator-level conditions, investigators are asked to take a bigger picture (more holistic) view and summarize overall findings and provide suggestions to managers on an area-by-area basis: 1) by park ecosystem/habitat types or watersheds, and 2) for other park areas as requested.

These influences may include past activities or conditions that provide a helpful context for understanding current conditions, and/or present-day threats and stressors that are best interpreted at park, watershed, or landscape scales (though NRCAs do not report on condition status for land areas and natural resources beyond park boundaries). Intensive cause-and-effect analyses of threats and stressors, and development of detailed treatment options, are outside the scope of NRCAs.

Due to their modest funding, relatively quick timeframe for completion, and reliance on existing data and information, NRCAs are not intended to be exhaustive. Their methodology typically involves an informal synthesis of scientific data and information from multiple and diverse sources. Level of rigor and statistical repeatability will vary by resource or indicator, reflecting differences in existing data and knowledge bases across the varied study components.

The credibility of NRCA results is derived from the data, methods, and reference values used in the project work, which are designed to be appropriate for the stated purpose of the project, as well as adequately documented. For each study indicator for which current condition or trend is reported, critical data gaps are identified and the level of confidence is described in at least qualitative terms. Involvement of park staff and National Park Service (NPS) subject-matter experts at critical points during the project timeline is also important. These staff assist with the selection of study indicators; recommend data sets, methods, and reference conditions and values; and help provide a multi-disciplinary review of draft study findings and products.

***Important NRCA Success Factors***

*Obtaining good input from park staff and other NPS subject-matter experts at critical points in the project timeline*

*Using study frameworks that accommodate meaningful condition reporting at multiple levels (measures ⇨ indicators ⇨ broader resource topics and park areas)*

*Building credibility by clearly documenting the data and methods used, critical data gaps, and level of confidence*

NRCAs can yield new insights about current park resource conditions but, in many cases, their greatest value may be the development of useful documentation regarding known or suspected resource conditions within parks. Reporting products can help park managers as they think about near-term workload priorities, frame data and study needs for important park resources, and communicate messages about current park resource conditions to various audiences. A successful NRCA delivers science-based information that is both credible and has practical uses for a variety of park decision-making, planning, and partnership activities.

However, it is important to note that NRCAs do not establish management targets for study indicators. That process must occur through park planning and management activities. What an NRCA can do is deliver science-based information that will assist park managers in their ongoing, long-term efforts to describe and quantify a park’s desired resource conditions and management targets. In the near term, NRCA findings assist strategic park resource planning[6] and help parks to report on government accountability measures.[7] In addition, although in-depth analysis of the effects of climate change on park natural resources is outside the scope of NRCAs, the condition analyses and data sets developed for NRCAs will be useful for park-level climate-change studies and planning efforts.

NRCAs also provide a useful complement to rigorous NPS science support programs, such as the NPS Natural Resources Inventory & Monitoring (I&M) Program.[8] For example, NRCAs can provide current condition estimates and help establish reference conditions, or baseline values, for some of a park's vital signs monitoring indicators. They can also draw upon non-NPS data to help evaluate current conditions for those same vital signs. In some cases, I&M data sets are incorporated into NRCA analyses and reporting products.

Over the next several years, the NPS plans to fund a NRCA project for each of the approximately 270 parks served by the NPS I&M Program. For more information on the NRCA program, visit http://nature.nps.gov/water/nrca/index.cfm.

***NRCA Reporting Products…***

***Provide a credible, snapshot-in-time evaluation for a subset of important park natural resources and indicators, to help park managers:***

*Direct limited staff and funding resources to park areas and natural resources that represent high need and/or high opportunity situations*
***(near-term operational planning and management)***

*Improve understanding and quantification for desired conditions for the park's "fundamental" and "other important" natural resources and values*
***(longer-term strategic planning)***

*Communicate succinct messages regarding current resource conditions to government program managers, to Congress, and to the general public*
***("resource condition status" reporting)***

---

[6] An NRCA can be useful during the development of a park's Resource Stewardship Strategy (RSS) and can also be tailored to act as a post-RSS project.

[7] While accountability reporting measures are subject to change, the spatial and reference-based condition data provided by NRCAs will be useful for most forms of "resource condition status" reporting as may be required by the NPS, the Department of the Interior, or the Office of Management and Budget.

[8] The I&M program consists of 32 networks nationwide that are implementing "vital signs" monitoring in order to assess the condition of park ecosystems and develop a stronger scientific basis for stewardship and management of natural resources across the National Park System. "Vital signs" are a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values.

# 2. Introduction and Resource Setting

## 2.1. Introduction

### *2.1.1. Enabling Legislation*

Public Law 91-661, authorizing the secretary of the Department of the Interior to establish a Voyageurs National Park in northern Minnesota, was signed into law by President Richard Nixon on January 8, 1971, and the park was formally established in 1975 (Witzig 2000, Holmberg et al. 2005). The purpose of the law was:

> *"to preserve, for the inspiration and enjoyment of present and future generations, the outstanding scenery, geological conditions and waterway system which constituted a part of the historic route of the Voyageurs who contributed significantly to the opening of the Northwestern United States."*

### *2.1.2. Geographic Setting*

Voyageurs National Park (VOYA) is located in northern Minnesota (MN) (Figure 1) along the US border with Ontario (ON). Its 829 km$^2$ area is part of a larger ecosystem that includes the 4,856 km$^2$ Boundary Waters Canoe Area Wilderness (BWCAW) and the 4,452 km$^2$ Quetico Provincial Park in Canada (Figure 2). In MN, land ownership within the Rainy Lake watershed upstream of VOYA is mainly a mosaic of USDA Forest Service (national forest), state, private, and private industrial (pulpwood production) lands (MDNR 2002, 2008). In ON, the majority of land north and east of VOYA is crown land (publicly owned land) with a variety of commercial and recreational uses (LIO 2014). West of Fort Frances, the majority of land is in private ownership (LIO 2008a, 2008b, 2008c).

VOYA lies within the lower end of the 38,600 km$^2$ Rainy watershed, which is one of the upper headwaters of Hudson Bay (Figure 3). Thirty-eight percent of VOYA is covered by water, and four major lakes (Kabetogama, Namakan, Rainy and Sand Point) make up 96% of the park's total lake area (Kallemeyn et al. 1993). Lake levels in the park's four largest lakes are controlled by a dam crossing the Rainy Lake outlet at the international border between Fort Frances, ON and International Falls, MN and influenced by small dams at Kettle Falls and Squirrel Falls on Namakan Lake. The management of these dams and their consequences for the VOYA ecosystem will be discussed in Chapter 5.

### *2.1.3. Demographics and Visitation*

VOYA is located in a generally sparsely populated area; within a 30-km radius of the park, the population density is approximately 2.71 people km$^{-2}$. This is a 3.1% decrease from ten years ago, when it was 2.81 people km$^{-2}$ (Statistics Canada 2013, U.S. Census Bureau 2014a, 2014b).

In the VOYA vicinity, the largest population centers are in International Falls, MN and Fort Frances, ON. Approximately 14,250 people lived there in 2010, but the populations of both communities have been in decline since the 1980s and the population of International Falls is expected to decline further (Minnesota State Demographic Center 2001, 2007, Statistics Canada 2006, 2011, U.S. Census Bureau 2014c) (Figure 4). Other population concentrations around VOYA are along Minnesota 11 west of VOYA and on the south and west sides of Kabetogama Lake (Figure 5).

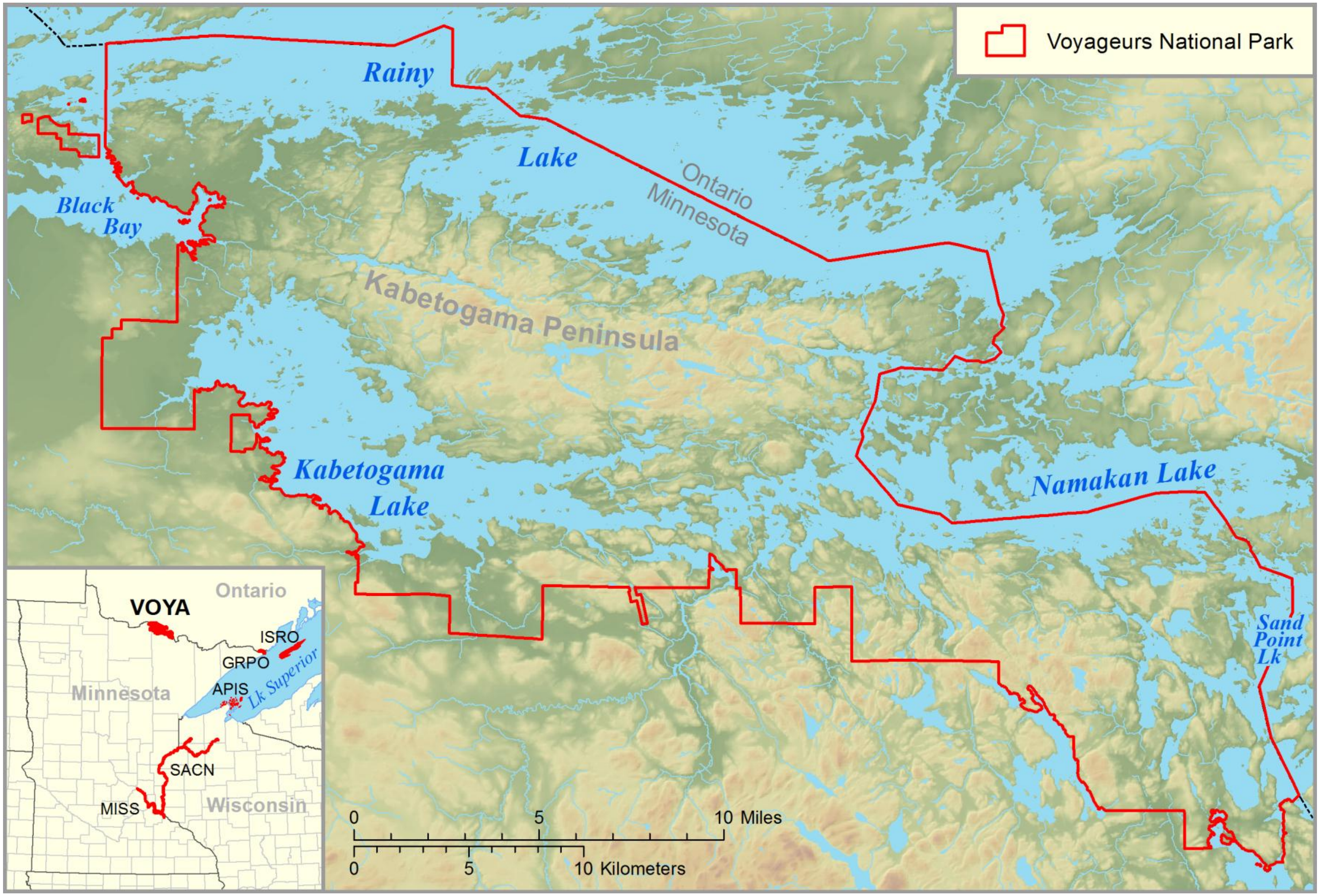

**Figure 1.** Location of Voyageurs National Park. (see Appendix A for sources).

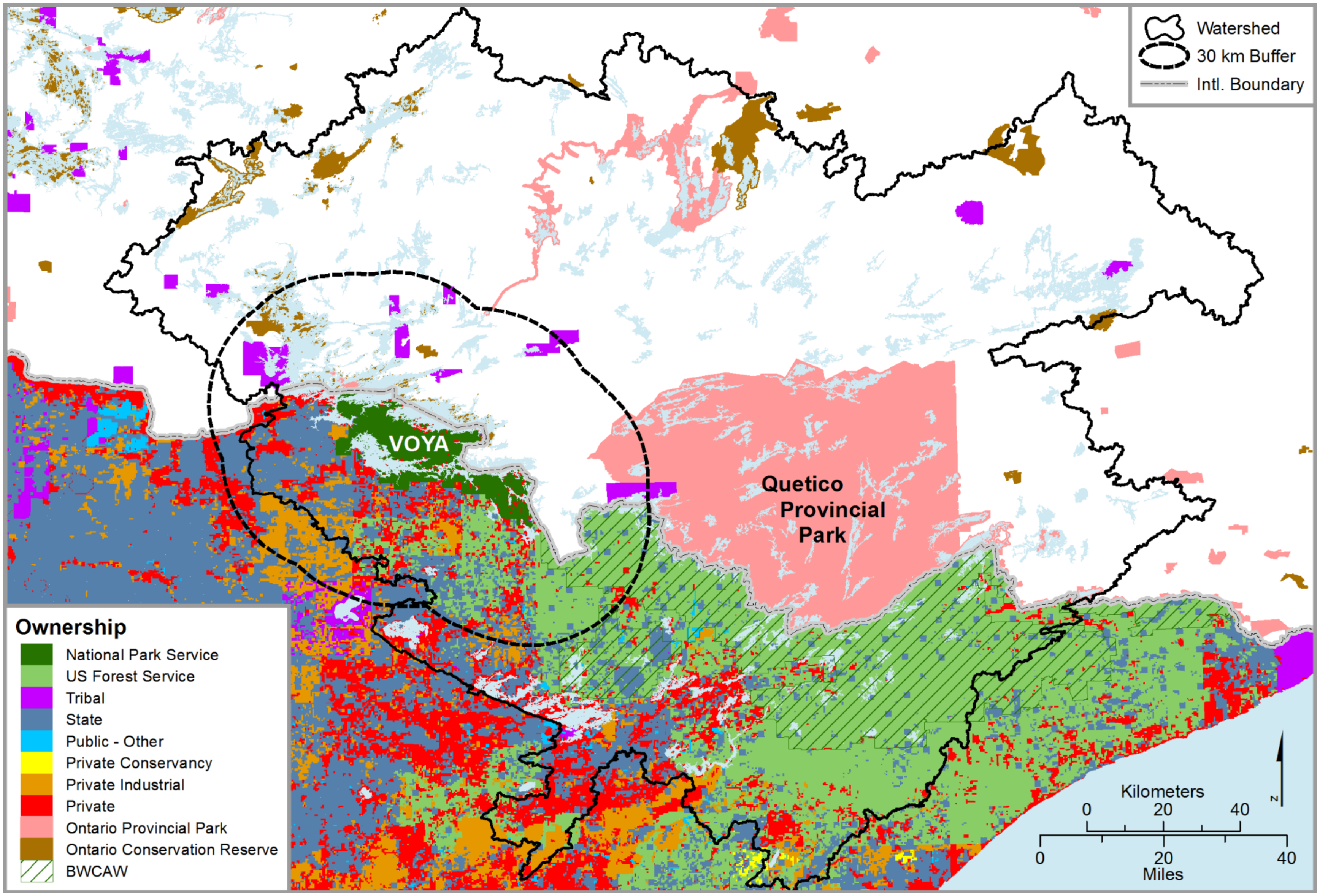

**Figure 2.** Ownership of lands within the watershed of Voyageurs National Park (LIO 2008a, 2008b, 2008c, MDNR 2002, 2008).

**Figure 3.** Location of Voyageurs National Park in the Rainy watersheds and subwatersheds (USGS 2012).

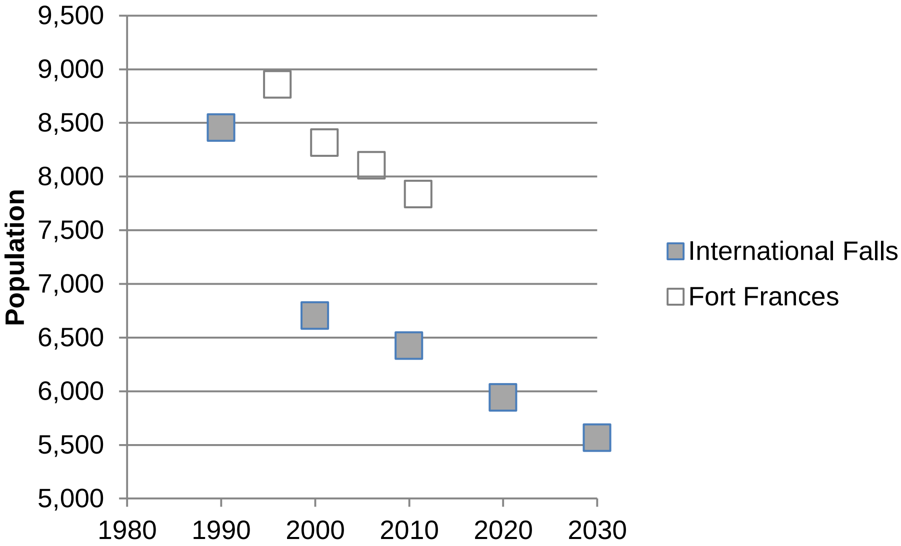

**Figure 4.** Historic and projected populations for two communities near Voyageurs National Park (Minnesota State Demographic Center 2001, 2007, Statistics Canada 2006, 2011, U.S. Census Bureau 2014c).

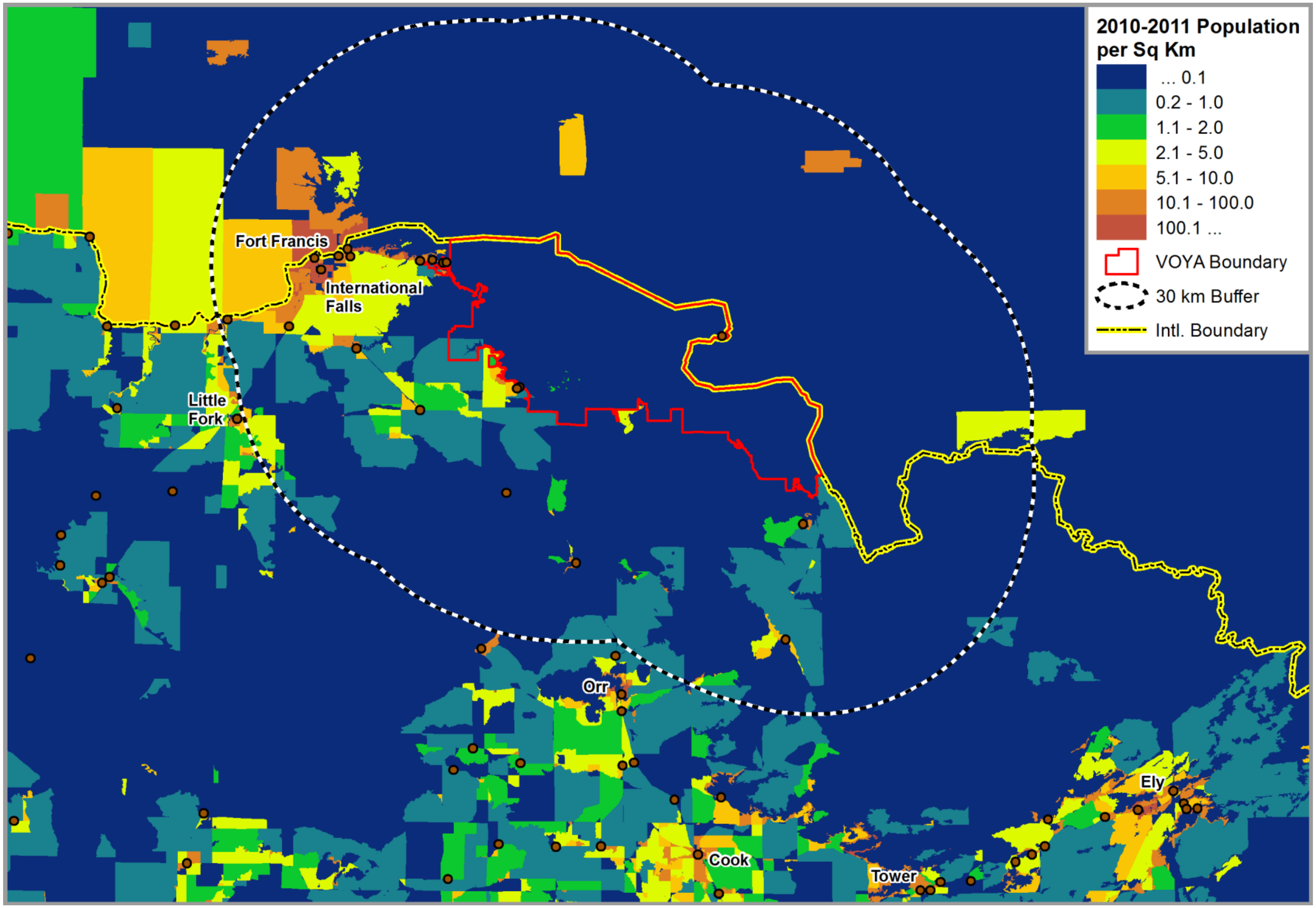

**Figure 5.** Population in the vicinity of Voyageurs National Park, 2010–2011 (Statistics Canada 2013, U.S. Census Bureau 2014a, 2014b).

VOYA has averaged 214,275 visitors per year since 1976, with a low of 121,200 in 1976 to a high of 266,935 in 1980 (NPS 2014a) (Figure 6). From 2010–2013, the most popular visitor activities were fishing (125,451–140,883 users), houseboating (25,535–31,649 users), and visiting the backcountry (16,131–21,808 users) (Table 1) (NPS 2014b).

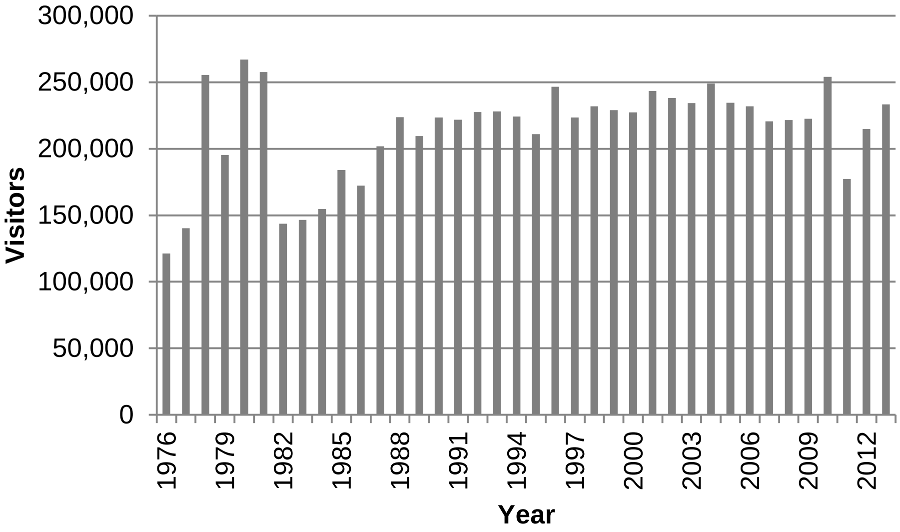

**Figure 6.** Visitation at Voyageurs National Park from 1976–2013 (NPS 2014a).

**Table 1.** Visitor activities in Voyageurs National Park, 2010–2013 (NPS 2014b).

| Activities | 2013 | 2012 | 2011 | 2010 |
|---|---:|---:|---:|---:|
| Number of Anglers | 140,883 | 131,257 | 126,764 | 125,451 |
| Number of Houseboaters | 31,649 | 27,835 | 26,055 | 25,535 |
| Backcountry Users | 21,808 | 18,267 | 16,614 | 16,131 |
| Visitors to Rainy Lake Visitor Center | 9,298 | 12,430 | 12,561 | 13,859 |
| Visitors to Ash River Visitor Center | 6,193 | 4,070 | 5,787 | 6,759 |
| Visitors to Kabetogama Visitor Center | 4,120 | 11,075 | 14,657 | 13,939 |
| Snowmobilers | 8,821 | 12,633 | 8,109 | 10,567 |
| Cross-Country Skiers | 689 | 522 | 470 | 574 |
| Ice Fishers | 6,310 | 3,682 | 20 | 2,883 |
| Visitor Days | 116,334 | 271,847 | 226,978 | 327,874 |
| Total Recreation Visitors | 233,388 | 214,841 | 177,184 | 253,892 |
| Backcountry Overnight Stays | 21,808 | 18,267 | 16,614 | 16,131 |
| Kettle Falls Hotel Overnight Stays | 3,617 | 4,065 | 4,434 | 3,674 |
| Houseboat Overnight Stays | 31,649 | 27,835 | 26,055 | 25,535 |

## 2.2. Natural Resources

### *2.2.1. Climate*

The climate of VOYA is continental, characterized by moderately warm summers and long, cold winters (Kallemeyn et al. 2003). NPS (2007) analyzed National Oceanic and Atmospheric Administration (NOAA) cooperative weather station data for Big Falls, Kettle Falls, and International Falls (stations 210746, 1948–present; 214026, 1948–present; and 214306, 1948–1982, respectively) to characterize climate for the park. The mean annual temperature at VOYA was 6.5°C with a range of annual means of 0.7°C–6.6°C. Mean annual precipitation was 64.5 cm with a range of annual means of 43.4–89.4 cm (NPS 2007). The mean monthly maximum precipitation for 1981–2010 (10.0 cm) occurs in June, and the minimum (1.44 cm) occurs in February (NCDC 2014). Mean annual snowfall for the period was 180 cm (NCDC 2014).

Although a thorough analysis of climate change is outside the scope of NRCAs, it is discussed briefly in Section 4.3.7. and will be considered as a stressor in the discussion of natural resources in Chapter 4.

### *2.2.2. Geology*

The enabling legislation for VOYA recognized the significance of its geologic resources; these contribute to the park's cultural resources and help create a "hydrologically complex and sensitive environment" for the park's waters (Graham 2007). VOYA is at the southern end of the Canadian Shield, which contains some of the oldest rocks in North America. Most rocks in VOYA are of Archean age (2.5– >3.8 billion years old) and are of global significance for their relative rarity. Thirty-two distinct rock units have been mapped in the vicinity of VOYA. Biotite schist forms the bedrock of most of the Kabetogama Peninsula and is the most widespread rock type in VOYA (Graham 2007 and citations therein). A broad band of mixed gneiss trends through the middle of Namakan and Kabetogama Lakes, while granitic rocks occur south of Kabetogama Lake and Sullivan Bay (Graham 2007).

The landscape of VOYA was also sculpted by glacial processes, leaving grooves and striations on bedrock, glacial erratics, and unconsolidated sediment during the Pleistocene ice age as recently as 10,000 years ago. American Indians have lived in the VOYA vicinity for over 8,000 years, leaving pictographs on rock cliffs and artifacts such as slate knives and arrowheads (Graham 2007). In the 1890s, miners created gold mines and a mica mine in VOYA; there are 12 mines with 16 known openings, and other mine openings may be present but as yet undiscovered (Graham 2007, review comments, Mary Graves, chief of resource management, VOYA, 12/12/14).

### *2.2.3. Ecological Units and Watersheds*

Ecological classification systems (ECS) are intended to create a format to convey basic information on both the biological and physical characteristics of a landscape. MN has developed ECS mapping schema based on the National Hierarchical Framework of Ecological Units (MDNR 1999, IIC 2011). Provinces, the first level within the ECS, are further divided into sections, subsections, land type associations, land types, and land type phases.

VOYA is entirely within the Laurentian Mixed Forest (LMF) Province, which traverses northern MN, Wisconsin, and Michigan, southern Ontario, and the less mountainous portions of New England. In MN, the Province is characterized by broad areas of conifer forest, mixed hardwood and conifer forests, and conifer bogs and swamps. The landscape ranges from rugged lake-dotted terrain with thin glacial deposits over bedrock, to hummocky or undulating plains with deep glacial drift, to large, flat, poorly drained peatlands (MDNR 2014). Most of VOYA is in the Border Lakes subsection of the Northern Superior Uplands section of this province (Figure 7), with a small portion on the west side of Kabetogama Lake in the Littlefork-Vermilion Uplands subsection of the Northern Minnesota and Ontario Peatlands section. The soil types, terrain, presettlement vegetation, and present vegetation of the ECS subsections and land type associations present at VOYA are described in Table 2.

### *2.2.4. Resource Descriptions*

VOYA, as a National Park, is designated as a Class I airshed, giving it particular protections against air emissions that are further described in Section 4.4.1. All of the waters within VOYA have been designated as "Outstanding Resource Value Waters" by the state of Minnesota (MPCA Ch. 7050.0180, MPCA 2013). Proposed wilderness makes up 58.4% of VOYA; this is 98.9% of the area that met initial wilderness qualifications. Areas proposed as wilderness are administered so as not to impair their suitability for eventual designation while awaiting congressional action (Holmberg et al. 2005, NPS 2007, review comments, Mary Graves, chief of resource management, VOYA, 12/12/14).

The Great Lakes Network Inventory and Monitoring Program of the NPS (GLKN) lists the following "critical resources" for VOYA (NPS 2007):

- Loons (*Gavia* spp.), other aquatic-nesting birds, and bald eagles (Haliaeetus leucocephalus), due to regulated lake levels and aquatic contamination.
- Walleye (*Sander vitreum*), due to its importance in sport fishing.
- Gray wolves (*Canis lupus*).
- Common terns (*Sterna hirundo*) and other colonial nesting birds, which have experienced declines throughout the region.
- A number of rare plant communities associated with the southern end of the boreal forest.

### *2.2.5. Resource Issues Overview*

The GLKN lists the following issues related to natural resources at VOYA: unnatural fluctuations in water levels, airborne pollutants, waters contaminated with toxic chemicals, invasive exotic plants and animals, diseases spread from domestic animals, and disturbance from certain human uses (NPS 2007).

Issues discussed as of significance during the initial scoping meeting with VOYA resource professionals included mercury contamination of water and aquatic biota; cyanotoxin production by

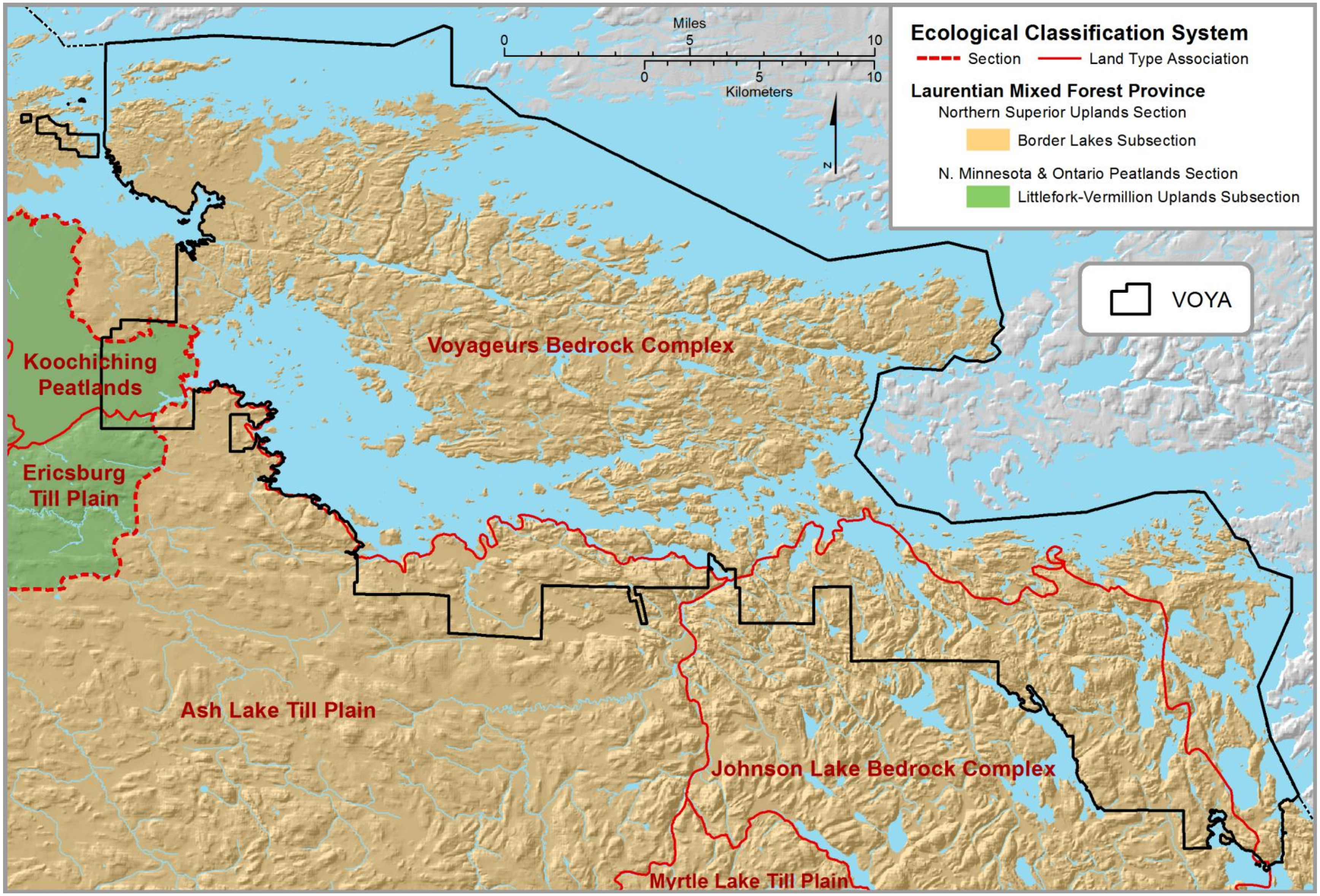

**Figure 7.** Ecological classification system provinces, sections, and subsections for Voyageurs National Park (MDNR 1999).

**Table 2.** Soil and vegetative characteristics of ecological classification system subsections and land type associations in Voyageurs National Park (MDNR 2000, 2007, Pro West et al. 2010).

| Subsection | Presettlement Vegetation | Present Vegetation | Land Type Association | Terrain | Soil Descriptions |
|---|---|---|---|---|---|
| Border Lakes 212 La | Jack pine, white pine-red pine, and hardwood-conifer forests, all characterized by fire dependence. | Mostly forested (69%), with most forest types persisting with stand composition and structure similar to that present originally, 17% water, 12% bog/marsh/fen | Ash Lake Till Plain 212La17 | Rolling to steep bedrock-controlled, intertwined with nearly level to rolling plains. | Upland soils are generally thick with scattered areas of thin soil on ridge tops. Clayey soils over most of the LTA, with sandy loam and sandy soils in the higher portions of the landscape. |
| | | | Johnson Lake Bedrock Complex 212La07 | Very hilly, with steep irregular slopes. Bedrock outcrops over much of area. | Glacially deposited thin blanket of reddish brown sandy or sandy loam soil with many rocks. Lower hill sides and valleys occasionally contain grey clay. |
| | | | Voyageurs Bedrock Complex 212La09 | Very hilly, with steep irregular slopes. Bedrock outcrops over much of area. | Same as Johnson Lake Bedrock Complex. |
| Littlefork-Vermilion Uplands 212Ma | Aspen-birch forest that would eventually become conifer dominated (white pine, white spruce, and balsam fir). Eastern portion dominated by white pine, red pine, and jack pine forest. Lowlands occupied by sedge fen, black spruce-sphagnum bog, and white cedar-black ash swamp. Low moraines and beach ridges dominated by jack pine forest or trembling aspen-paper birch forest. | Crop and grass is 35% of present cover, upland conifer forest 26%, and aquatic environments 13%. Quaking aspen is most common tree. | Koochiching Peatlands 212Ma01 | Low relief. | Large peatlands with minor inclusions of upland mineral soils. |
| | | | Ericsburg Till Plain 212Ma02 | Rolling till plain smoothed by wave action. | Mostly clay, with the remaining mineral soils ranging from sand to sandy loam over bedrock. |

algae in Kabetogama Lake; water level fluctuations; aquatic and terrestrial invasive species; declining lake trout populations in interior lakes; forest pests; mining; and climate change.

Although as noted in chapter 1, climate change is not a primary focus of Natural Resource Condition Assessments such as this, the large predicted impacts make it necessary to address this topic at least briefly. A 2010 report projects that annual temperatures in the Great Lakes region, of which VOYA is a part, will increase 1.4°C ± 0.6°C from 2010–2039, 2.0°C ± 0.7°C to 3.0°C ± 1.0°C (depending on emissions levels) by 2069, and 3.0°C ± 1.0°C to 5.0°C ± 1.2°C by 2099 (Hayhoe et al. 2010).

Global air temperatures increased 0.74°C ± 0.18°C from 1906–2005, mostly attributable to human activities (IPCC 2007). In addition to creating this general warming, climate change also likely contributes to rises in sea level; changes in wind patterns and extra-tropical storm tracks; increased temperatures on extreme hot nights, cold nights, and cold days; increased risk of heat waves; increased area affected by drought; and greater frequency of heavy precipitation events (IPCC 2007). Signs that climate change is already occurring in the Great Lakes region include increases in average annual temperatures, more frequent severe rainstorms, shorter winters, and decreases in the duration of lake ice cover (Kling et al. 2003a). By the end of the 21st century, winter and summer temperatures in Minnesota may increase 3°C–6°C and 4°C–9°C, respectively (Kling et al. 2003b). Annual average precipitation may not change much, but may increase in winter and decrease in summer to the point where soil moisture declines and more droughts occur. The frequency of heavy rainstorms could increase 50%–100% (Kling et al. 2003b).

The GLKN (2013) compared recent (2008–2012) precipitation and temperature data for International Falls and Littlefork, MN, (1.3 km W and 3.1 km WSW of VOYA, respectively), to the 30-year climate normal at International Falls for 1971–2000. Precipitation in the recent four-year period was nearly average relative to the 30-year baseline, but wetter than the 65-year baseline. Average summer precipitation was generally below the 65-year baseline. The pattern in the long-term temperature data was unclear.

Monahan and Fisichelli (2014), in an analysis of climate in US national parks, used 10, 20, and 30-year moving windows to calculate running means and standard deviations for 25 biologically relevant climate variables for 289 NPS parks. They used this information to identify parks that are presently experiencing "extreme" climates (<5th percentile or >95th percentile) relative to their 1901–2012 range of variability. In their analysis (Table 3), VOYA is experiencing extremes in annual mean temperature, loss of temperature seasonality, mean temperature of the coldest quarter, loss of cloud seasonality, vapor pressure of the warmest quarter, and a low annual number of frost days. VOYA is also experiencing reduced variability in mean diurnal temperature range, mean temperature of the driest quarter, and mean annual percentage of cloud cover.

More detailed discussions of climate change are included in the context of stressors to resources assessed in Chapter 4.

**Table 3.** Statistical analysis of climate data for Voyageurs National Park (from Monahan and Fisichelli 2014).

| Variable | | Mean percentile across windows (means) | Maximum difference in percentile across windows (means) | Mean percentile (standard deviations) | Maximum difference in percentile (standard deviations) |
|---|---|---|---|---|---|
| Bio1 | Annual mean temperature | **99.4**[9] | **1.9**[10] | 83.6 | 13.4 |
| Bio2 | Mean diurnal range (mean of monthly (max temp – min temp)) | 36 | 24.2 | **4.3**[11] | 9.9 |
| Bio3 | Isothermality (Bio2/Bio7) | 77.6 | 11.1 | 19.5 | 23.7 |
| Bio4 | Temperature seasonality (standard deviation) | **3.7**[12] | 6.6 | 31.8 | 46.4 |
| Bio5 | Maximum temperature of the warmest month | 52.3 | 29.7 | 73.5 | 56.6 |
| Bio6 | Minimum temperature of the coldest month | 93 | 15.5 | 54.5 | 28.8 |
| Bio7 | Temperature annual range (Bio5– Bio6) | 11.5 | 19.2 | 13.7 | 32.8 |
| Bio8 | Mean temperature of the wettest quarter | 80.4 | 34 | 19.5 | 27.8 |
| Bio9 | Mean temperature of the driest quarter | 90.3 | 9.1 | **3.8**[13] | **4.6**[14] |
| Bio10 | Mean temperature of the warmest quarter | 86 | 29.4 | 59.2 | 83.6 |
| Bio11 | Mean temperature of the coldest quarter | **95.4**[15] | 11.7 | 59.2 | 13.7 |
| Bio12 | Annual precipitation | 94.4 | 13.5 | 74.4 | 33 |
| Bio13 | Precipitation of the wettest month | 57.6 | 47.7 | 71.9 | 24.6 |
| Bio14 | Precipitation of the driest month | 52.3 | 42.9 | 94.5 | 15.7 |
| Bio15 | Precipitation seasonality (coefficient of variation) | 34.7 | 47.6 | 60.6 | 33.6 |
| Bio16 | Precipitation of the wettest quarter | 82.5 | 41.7 | 71.7 | 34 |
| Bio17 | Precipitation of the driest quarter | 46.4 | 47.6 | 92.7 | 11 |
| Bio18 | Precipitation of the warmest quarter | 68.4 | 57.8 | 54.5 | 31.5 |
| Bio19 | Precipitation of the coldest quarter | 55.2 | 40.1 | 83.2 | 24.5 |
| Cld1 | Mean annual percentage cloud cover | 83.9 | 16.2 | **3.8**[16] | 5.7 |
| Cld4 | Cloud seasonality (standard deviation) | **1.4**[17] | **0.9**[18] | 19.8 | 54.3 |
| Vap18 | Vapor pressure of the warmest quarter | **96.8**[19] | 9.7 | 69.6 | 39.4 |
| Wet12 | Annual number of wet days | 70.9 | 19.2 | 89.8 | 15.6 |
| Wet18 | Number of wet days of the warmest quarter | 70.5 | 8.2 | 71.2 | 42.4 |
| Frs12 | Annual number frost days | **4.1**[20] | **3.1**[21] | 49.4 | 57.4 |

---

[9] Annual mean temperature is higher than in 99.4% of past windows.

[10] The assessment that annual mean temperatures are higher applies to the 10, 20, and 30-year windows.

[11] Mean diurnal range has been less variable in only 4.3% of past windows.

[12] Temperature seasonality has been lower in only 3.7% of past windows.

[13] Mean temperature of the driest quarter has been less variable in only 3.8% of past windows.

[14] The assessment that mean temperature of the driest quarter is less variable applies to the 10, 20, and 30-year windows.

[15] Mean temperature of the coldest quarter is higher than in 95.4% of past windows.

[16] Mean annual percentage cloud cover has been less variable in only 3.8% of past windows.

[17] Cloud seasonality (standard deviation) has been lower in only 1.4% of past windows.

[18] The assessment that cloud seasonality is lower applies to the 10, 20, and 30-year windows.

[19] The vapor pressure of the warmest quarter is higher than in 96.8% of past windows.

[20] The annual number of frost days has been lower in only 4.1% of past windows.

[21] The assessment that frost days are lower applies to the 10, 20, and 30-year windows.

## 2.3. Resource Stewardship

### *2.3.1. Management Directives and Planning Guidance*

VOYA has a General Management Plan, which was issued in 2002 and provides guidance for managing the park for 15–20 years (NPS 2002). The plan lists the following purpose and significance statements relevant to ecological monitoring (NPS 2002, 2007):

- Preserve the scenery, geologic conditions, and interconnected waterways in northern Minnesota for the inspiration and enjoyment of people now and in the future.
- Preserve, in an unimpaired condition, the ecological processes, biological and cultural diversity, and history of the northwoods lake country border shared with Canada.
- Provide opportunities for people to experience, understand, and treasure the lake country landscape — its clean air and water, forests, islands, wetlands, and wildlife — in a manner that is compatible with the preservation of park values and resources.
- VOYA is integral to the protection of the boundary waters ecosystem. Along with Quetico Provincial Park and the Boundary Waters Canoe Area Wilderness, VOYA was and remains at the heart of a major conservation effort to protect the boreal forest landscape, its interconnected waterways, and associated wildlife.

### *2.3.2. Status of Supporting Science*

VOYA is one of nine National Park units in the GLKN, one of 32 similar networks across the United States and part of the NPS strategy to improve park management through greater reliance on scientific information. The purpose of the GLKN Inventory and Monitoring program is to design and implement long-term ecological monitoring and provide results to park managers, science partners, and the public. The intent is to provide periodic assessments of critical resources, to evaluate the integrity of park ecosystems, and to better understand ecosystem processes.

In 2007, GLKN completed its long-term ecological monitoring plan (NPS 2007) which included a list of Vital Signs (select indicators that represent the health of natural resources in the nine parks) (Table 4). Specific GLKN goals for Vital Signs monitoring are:

- Determine status and trends of selected indicators of the condition of park ecosystems to help managers make better-informed decisions and work more effectively with other agencies and individuals for the benefit of park resources.
- Provide early warning of abnormal conditions and impairment of selected resources to promote effective mitigation and reduce management costs.
- Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other, altered environments.
- Provide data to meet certain legal and congressional mandates related to natural resource protection and visitor enjoyment.

**Table 4.** Vital Signs for parks in the Great Lakes Network Inventory and Monitoring Program (NPS 2007).

| National Level[1] | | Great Lakes Network[2] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Level 1** | **Level 2** | **Vital Sign name** | **APIS** | **GRPO** | **INDU** | **ISRO** | **MISS** | **PIRO** | **SACN** | **SLBE** | **VOYA** |
| Air and Climate | Air Quality | Air Quality | • | • | • | • | • | • | • | • | • |
| | | Air Quality (AQRV) | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | Weather | Weather | • | • | • | • | • | • | • | • | • |
| | | Phenology | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| Geology and Soils | Geomorphology | Aeolian, Lacustrine Geomorphology | Δ | - | Δ | - | Δ | Δ | Δ | Δ | - |
| | | Geological Processes | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Stream Dynamics | Δ | Δ | Δ | Δ | + | Δ | + | Δ | Δ |
| | Soil Quality | Soils | + | + | + | + | + | + | + | + | + |
| | | Sediment Analysis | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| Water | Hydrology | Water Level Fluctuations | + | + | + | + | + | + | + | + | + |
| | Water Quality | Core Water Quality Suite | + | + | + | + | + | + | + | + | + |
| | | Advanced Water Quality Suite | + | + | + | + | + | + | + | + | + |
| | | Toxics in Water | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Toxics in Sediments | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Pathogens in Water | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | IBI | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Benthic Inverts | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Freshwater Sponges | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Phytoplankton | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Diatoms | + | - | + | + | + | + | + | + | + |
| Biological Integrity | Invasive Species | Plant and Animal Exotics | • | • | • | • | • | • | • | • | • |
| | Infestations and Disease | Terrestrial Pests and Pathogens | + | + | + | + | + | + | + | + | + |
| | Focal Species or Communities | Aquatic Plant Communities | + | + | + | + | + | + | + | + | + |
| | | Mussels and Snails | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Mammal Communities | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Problem Species (White-tailed deer) | + | + | + | + | + | + | + | + | + |
| | | Special Habitats | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Lichens and Fungi | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Terrestrial Plants | + | + | + | + | + | + | + | + | + |
| | | Fish Communities | + | + | + | + | + | + | + | + | + |
| | | Zooplankton | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Terrestrial Invertebrate Communities | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Amphibians and Reptiles | + | + | + | + | + | + | + | + | + |
| | | Bird Communities | • | • | • | • | • | • | • | • | • |
| | | Biotic Diversity | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | At-risk Biota | Species Health, Growth and Reproductive Success | + | + | + | + | + | + | + | + | + |
| | | Threatened and Endangered Species | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| Human Use | Non-point Source Human Effects | Trophic Bioaccumulation | + | + | + | + | + | + | + | + | + |
| | Consumptive Use | Harvested Species | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | Visitor Use | Land use Fine Scale | + | + | + | + | + | + | + | + | + |
| Ecosystem Pattern and Processes | Land Use and Cover | Land use Coarse Scale | + | + | + | + | + | + | + | + | + |
| | Soundscape | Soundscapes and Light Pollution | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | Nutrient Dynamics | Nutrient Dynamics | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Trophic Relations | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | Productivity | Primary Productivity | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |
| | | Succession | + | + | + | + | + | + | + | + | + |

**+** = The Network plans to develop a monitoring protocol or SOP.
• = Park or partner monitoring will continue with Network collaboration.
Δ = Time and funds are currently not available.
**–** = Not applicable in this park
1 = Level names are from the National Park Service's Vital Signs Ecological Framework.
2 = APIS=Apostle Islands National Lakeshore; GRPO=Grand Portage National Monument; INDU=Indiana Dunes National Lakeshore; ISRO=Isle Royale National Park; MISS= Mississippi National River and Recreation Area; PIRO=Pictured Rocks National Lakeshore; SACN=Saint Croix National Scenic Riverway; SLBE=Sleeping Bear Dunes National Lakeshore; VOYA=Voyageurs National Park.

- Provide a means of measuring progress towards achieving performance goals that are mandated by Government Performance Results Act (GPRA).

From these Vital Signs, GLKN selected nine focal indicators: Climate, Inland Lakes Water Quality, Large Rivers Water Quality, Diatoms, Terrestrial Plants, Amphibians, Land Birds, Persistent Contaminants, and Land Cover and Land Use. Monitoring protocols have been developed for all these except Amphibians, Climate, and Persistent Contaminants in Fish and Dragonflies; those protocols are in development. Current GLKN activities for VOYA are in the areas that have monitoring protocols.

Literature Cited

GLKN (Great Lakes Network Inventory and Monitoring Program). 2013. Climate trends at Voyageurs National Park. Resource Brief-2196584. GLKN, Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/2196584 (accessed 5 August 2014).

Graham, J. 2007. Voyageurs National Park geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2007/007. National Park Service, Denver, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/649172 (accessed 4 August 2014).

Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegald, and D. Wuebbles. 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research* 36 (Supplement 2):7–21.

Holmberg, K. L., B. Y. Odde, and J. Perry. 2005. Water resources management plan: Voyageurs National Park. NPS, Fort Collins, Colorado. Available at http://www.nature.nps.gov/water/planning/management_plans/voya_wrmp_final.pdf (accessed 4 August 2014).

IIC (Interagency Information Cooperative). 2011. ECS overview (webpage). Available at http://iic.gis.umn.edu/finfo/ecs/ecs2.htm (accessed 4 December 2012).

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007–the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK. Available at www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm (accessed 7 January 2013).

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001. USGS Columbia Environmental Research Center, Columbia, Missouri. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Kling, G. W., K. Hayhoe, L. B. Johnson, J. J. Magnuson, S. Polasky, S. K. Robinson, B. J. Shuter, M. M. Wander, D. J. Wuebbles, D. R. Zak, and others. 2003a. Confronting climate change in the Great Lakes region: impacts on our communities and ecosystems. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C. Available at http://www.ucsusa.org/greatlakes/glchallengereport.html (accessed 7 January 2013).

Kling, G. W., L. B. Johnson, and S. Polasky. 2003b. State summary: Minnesota. Findings from Confronting climate change in the Great Lakes region: impacts on our communities and ecosystems. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C. Available at http://www.ucsusa.org/greatlakes/glchallengereport.html (accessed 7 January 2013).

LIO (Land Information Ontario). 2008a. Conservation reserve regulated (map). Land Information Ontario, Ontario Ministry of Natural Resources and Forestry, Peterborough, Ontario. Available at http://www.ontario.ca/environment-and-energy/land-information-ontario (accessed 29 May 2014).

LIO (Land Information Ontario). 2008b. Indian reserve (map). Land Information Ontario, Ontario Ministry of Natural Resources and Forestry, Peterborough, Ontario. Available at http://www.ontario.ca/environment-and-energy/land-information-ontario (accessed 2 June 2014).

LIO (Land Information Ontario). 2008c. Provincial park regulated (map). Land Information Ontario, Ontario Ministry of Natural Resources and Forestry, Peterborough, Ontario. Available at http://www.ontario.ca/environment-and-energy/land-information-ontario (accessed 15 May 2014).

LIO (Land Information Ontario). 2014. CLUPA primary land use areas. Ontario Ministry of Natural Resources Crown Land Use Policy Atlas viewer. Available at http://www.giscoeapp.lrc.gov.on.ca/web/MNR/NHLUPS/CLUPA/Viewer/Viewer.html (accessed 2 June 2014).

MDNR (Minnesota Department of Natural Resources) Division of Forestry. 1999. Ecological Land Type Associations of Minnesota. MDNR, St. Paul, Minnesota. Available at http://deli.dnr.state.mn.us (accessed 30 August 2012).

MDNR (Minnesota Department of Natural Resources). 2000. Border Lakes subsection forest resource management plan: preliminary issues & assessment. MDNR, St. Paul, Minnesota. Available at http://www.dnr.state.mn.us/forestry/subsection/borderlakes/assessment.html (accessed 13 May 2014).

MDNR (Minnesota Department of Natural Resources). 2002. BWCA boundary based on the 1978 legislation (bdry_bwcapy3). MDNR, St. Paul, Minnesota. Available at http://deli.dnr.state.mn.us (accessed 15 November 2011).

MDNR (Minnesota Department of Natural Resources). 2007. St. Louis Moraines, Tamarack Lowlands, Nashwauk Uplands, and Littlefork-Vermilion Uplands subsection forest resource management plan assessment. MDNR, St. Paul, Minnesota. Available at http://www.dnr.state.mn.us/forestry/subsection/north4/preliminary.html (accessed 13 May 2014).

MDNR (Minnesota Department of Natural Resources). 2008. GAP stewardship 2008 – all ownership types (own_mnstwdpy2). MDNR, St. Paul, Minnesota. Available at http://deli.dnr.state.mn.us (accessed 7 April 2014).

MDNR (Minnesota Department of Natural Resources). 2014. Ecological classification system: Laurentian mixed forest province (webpage). MDNR, St. Paul, Minnesota. Available at http://www.dnr.state.mn.us/ecs/212/index.html (accessed 1 August 2014).

Minnesota State Demographic Center. 2001. Population by minor civil division: Census 2000. Available at http://www.demography.state.mn.us/Cen2000redistricting/Cen00mcd.html (accessed 2 June 2014).

Minnesota State Demographic Center. 2007. Minnesota minor civil division extrapolated population. Available at http://www.demography.state.mn.us/a2z.html#Census (accessed 2 June 2014).

Monahan, W. B., and N. A. Fisichelli. 2014. Climate exposure of US National Parks in a new era of change. *PLoS ONE* 9: e101302. doi:10.1371/journal.pone.0101302.

MPCA (Minnesota Pollution Control Agency). 2013. Waters of the state: water quality standards for protection of waters of the state. Minnesota Administrative Rules Chapter 7050. MPCA, St. Paul, Minnesota. Available at https://www.revisor.mn.gov/rules/?id=7050&version=2014-01-18T07:06:14-06:00&format=pdf (accessed 4 August 2014).

NCDC (National Climatic Data Center). 2014. Data tools: 1980–2010 normals – International Falls, Minnesota. Available at http://www.ncdc.noaa.gov/cdo-web/datatools/normals (accessed 1 August 2014).

NPS (National Park Service). 2002. General management plan: Voyageurs National Park, Minnesota. NPS, US Department of the Interior, Washington, D.C.

NPS (National Park Service). 2007. Long-term Ecological Monitoring Plan: Great Lakes Inventory and Monitoring Network. Natural Resource Report NPS/GLKN/NRR—2007/001. National Park Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/645523 (accessed 28 October 2013).

NPS (National Park Service). 2014a. Annual park recreation visitation graph (1904–last calendar year) – Voyageurs National Park. Available at https://irma.nps.gov/Stats/SSRSReports/Park_Specific_Reports/Annual_Park_Recreation_Visitation_Graph_(1904_-_Last_Calendar_Year)?Park=VOYA (accessed 2 June 2014).

NPS (National Park Service). 2014b. Summary of visitor use by month and year (1979–last calendar year) – Voyageurs National Park. Available at https://irma.nps.gov/Stats/SSRSReports/Park%20Specific%20Reports/Park%20YTD%20Version%201?RptMonth=12/1/2013&Park=VOYA (accessed 2 June 2014).

Pro-West and Associates, Inc., Applied Insights North, and Koochiching County Department of Land and Forestry. 2010. A long-range plan for the management of tax-forfeited land and forest resources of Koochiching County. Koochiching County, International Falls, Minnesota. Available at http://www.co.koochiching.mn.us/dept/land_&_forestry/Kooch%20Forest%20Plan%20%20Approved%209-14-10.pdf (accessed 13 May 2014).

Statistics Canada. 2006. Selected trend data for Fort Frances (T), 1996, 2001 and 2006 censuses. Available at https://www12.statcan.gc.ca/census-recensement/2006/dp-pd/92-596/P1-2.cfm?Lang=eng&T=CSD&PRCODE=35&GeoCode=59012&GEOLVL=CSD&TID=0 (accessed 2 June 2014).

Statistics Canada. 2011. Census profile: Fort Frances, Ontario. Available at http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/details/page.cfm?Lang=E&Geo1=POPC&Code1=0290&Geo2=PR&Code2=35&Data=Count&SearchText=Fort%20Frances&SearchType=Begins&SearchPR=01&B1=All&Custom=&TABID=1 (accessed 2 June 2014).

Statistics Canada. 2013. 2011 Census-Boundary files. Available at http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2011-eng.cfm (accessed 5 May 2014).

U.S. Census Bureau. 2014a. TIGER/Line Shapefiles: tract, block group, and block level shapefiles for 2000 and 2010. Available at https://www.census.gov/geo/maps-data/data/tiger-line.html (accessed 5 May 2014).

U.S. Census Bureau. 2014b. Population by block group for 2000 and 2010. Available at http://factfinder2.census.gov/faces/nav/jsf/pages/download_center.xhtml (accessed 5 May 2014).

U.S. Census Bureau. 2014c. 2010 Census interactive population search: MN - International Falls city. Available at http://www.census.gov/2010census/popmap/ipmtext.php?fl=27 (accessed 2 June 2014).

USGS (United States Geological Survey). 2012. NHD…Flowline/NHD…Area/NHD…Waterbody/WBD_HUC… USGS, Reston, Virginia. Available at http://nhd.usgs.gov/data.html (accessed 4 June 2012).

Witzig, F. T. 2000. Eighty years in the making: A legislative history of Voyageurs National Park. National Park Service, Voyageurs National Park, International Falls, Minnesota. Available at http://www.nps.gov/history/history/online_books/voya/legislative_history/contents.htm (accessed 27 May 2014).

# 3. Study Scoping and Design

## 3.1. Preliminary Scoping

A scoping meeting of VOYA resource staff and University of Wisconsin – Stevens Point (UWSP) researchers was held at VOYA on June 18, 2013. Topics discussed included the VOYA aquatic ecology program, the wildlife and terrestrial ecology program, and the status of terrestrial vegetation. Small groups discussed specific park information needs and data sources, and a general outline for the NRCA was developed. On June 19, park staff gave the UWSP researchers a tour of some significant park resources, including the Rainy Lake marina, Anderson Bay, Cruiser Lake trail, Peary Lake overlook, Kettle Falls, and Cranberry Bay.

## 3.2. Study Design

### *3.2.1. Indicator Framework, Focal Study Resources and Indicators*

The VOYA NRCA uses the six-category assessment and reporting framework developed by the U.S. Environmental Protection Agency Science Advisory Board (USEPA–SAB) (USEPA 2002). The top reporting categories in this framework are landscape condition; biotic condition; chemical and physical characteristics of water, air, soil, and sediment; ecological processes; hydrology and geomorphology; and natural disturbance regimes. It was chosen because it was developed to build on the strengths of several of the alternative frameworks (such as the Heinz Center or National Research Council frameworks) and the key natural resources for VOYA fit well into its categories.

### *3.2.2. Reference Conditions and Trends*

Reference conditions (sometimes called benchmarks, standards, trends, thresholds, desired future conditions, or norms) give a point of reference to which to compare a measurement or statement about an indicator (USDA Forest Service 2004). A large body of literature has been developed around the development and interpretation of reference conditions. All NRCAs are required to define and apply reference conditions, but NPS has adopted a "pragmatic approach" that requires only that NRCAs apply "logical and clearly documented forms of reference conditions and values" (http://www.nature.nps.gov/water/nrca/conditionsandvalues.cfm).

Stoddard et al. (2006) has suggested that reference conditions fall into four categories, which they name "historic condition," "minimally disturbed condition," "least disturbed condition," and "best attainable condition." We have attempted, where possible, to apply this reference condition scheme as follows:

"Historic condition," in our judgment, is the condition of VOYA before European settlement. It assumes the absence of contaminants known to be primarily anthropogenic in origin or the presence of naturally sustainable populations of organisms.

"Minimally disturbed condition" is defined by Stoddard et al. (2006) as "the condition of systems in the absence of significant human disturbance" and we apply this definition.

"Least disturbed condition" is defined by Stoddard et al. (2006) as "the best of today's existing conditions." We apply this reference condition in conjunction with regulatory standards or peer-reviewed guidelines; resources with levels of contaminants that do not exceed standards are deemed to be in “least disturbed condition.”

“Best attainable condition” is defined by Stoddard et al. (2006) as “the condition that today’s sites might achieve if they were better managed.”

We use professional judgment to assess the trend of resource conditions, using statistical methods where appropriate data are available. We also use professional judgment to give a confidence ranking of high, moderate, or low to our assessments; these are based on the amount of data, the age of the data, and the proximity of the sampling locations to VOYA.

Symbols were developed to provide a graphic representation of the status and trend of resources (Table 5).

**Table 5.** Key to the Status and Trend symbols used throughout this report The background color represents the current condition status, the direction of the arrow summarizes the trend in condition, and the thickness of the outside line represents the degree of confidence in the assessment.

| **Condition Status** | | **Trend in Condition** | | **Confidence in Assessment** | |
|---|---|---|---|---|---|
| 🔴 | Warrants<br>Significant Concern | ⇧ | Condition is Improving | ◯ | High |
| 🟡 | Warrants<br>Moderate Concern | ⇔ | Condition is Unchanging | ○ | Moderate |
| 🟢 | Resource is in Good Condition | ⇩ | Condition is Deteriorating | ◌ | Low |
| ◌ | An open (uncolored) circle indicates that current condition is unknown or indeterminate; this condition status is typically associated with unknown trend and low confidence | | | | |

### *3.2.3. Reporting Areas*

The focus of this report was the natural resource condition of the lands and waters within VOYA. Evaluation of condition sometimes required evaluation of conditions at other scales, such as in the Rainy Lake watershed or a 30-km buffer of the park.

### *3.2.4. General Approach and Methods*

As noted in Chapter 1, the primary objective of the VOYA NRCA is to report on current natural resource conditions relative to logical forms of reference conditions and values. Emphasis was placed on gathering existing natural resource data about VOYA. NPS inventory and monitoring reports and plans, management plans, and study reports by independent researchers were provided by VOYA and GLKN staff and taken from the VOYA, GLKN, and other NPS websites, including the IRMA web portal.

Data at larger scales were also collected. Many of these data are managed by state and other agencies and fall into the category of grey literature. Agency staff in relevant programs was contacted when clarification or documentation was needed. Past and current peer-reviewed journals were also extensively reviewed to obtain general background information and appropriate data for reference conditions.

Extensive gathering and analysis of spatial data was conducted to create maps and summary statistics used to evaluate the natural resource conditions of VOYA.

The report was reviewed by Mary Graves, Ryan Maki, and John Snyder of VOYA and Brenda Moraska Lafrancois, NPS Midwest Region Aquatic Ecologist before being submitted to NPS for final approval and publication.

Literature Cited

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

USDA (United States Department of Agriculture) Forest Service. 2004. Reference values (fact sheet). USDA Forest Service, Washington, D.C. Available at http://www.fs.fed.us/emc/rig/readingroom/library/Reference_Values_Fact_Sheet_2004.pdf (accessed 8 July 2012).

USEPA (United States Environmental Protection Agency) Science Advisory Board. 2002. A framework for assessing and reporting on ecological condition: an SAB report. EPA-SAB-EPEC-02-009. USEPA, Washington, D.C. Available at http://www.epa.gov/sab/pdf/epec02009.pdf (accessed 23 September 2013).

# 4. Natural Resource Conditions

## 4.1. Disturbance Regimes

The USEPA-SAB framework (USEPA 2002) lists natural disturbance regimes as one of its six major categories and states that all ecological systems are dynamic, due in part to discrete and recurrent disturbances that may be physical, chemical, or biological in nature. The primary natural disturbances of VOYA (fire, wind, and herbivory) are described below. In addition, we evaluate the effects of past logging.

The dominant forces structuring the ecologic character of a landscape are climate, large-scale and severe disturbances that have occurred in the recent past, topography, and parent material (Barnes et al. 1998, Wimberly and Spies 2001). These dominant structuring forces operate primarily at large spatial scales in a hierarchical fashion. Thus, these are primarily top-down influences in that they set the range of ecologic units that may occur. Within this framework, differences manifest at smaller scales due to features such as topography, aspect, and small scale disturbances, and due to the autecology of individual species (Schwartz et al. 2003).

Among the dominant structuring forces, disturbances are the most variable in space, time, areal extent, and impact (Sousa 1984, Hong and Mladenoff 1999, Frelich 2002). Disturbances interact with climate (e.g., drought), parent materials (e.g., soil texture and depth), and physiographic features (e.g., aspect, elevation, and depth to water table) to affect, directly and indirectly, plant composition and community structure. When a landscape is impacted by large, severe disturbances at short or intermediate intervals, many characteristics of the landscape are tied to the occurrence of these disturbances. This is true because a severe disturbance drastically changes the abiotic conditions and sets in motion a series of changes that play out over hundreds of years (Halpern and Franklin 1990).

The disturbance regime (DR) of a community or landscape is not static. Because weather and climate play such an important role for the occurrence of fires, floods, and wind events, any major change in the former will manifest in the latter. Hence, it is important to recognize the historic variation in disturbance occurrence and severity (i.e., the historic range of variability).

All terrestrial ecosystems in the temperate and boreal regions have, throughout their evolutionary history, been subjected to a suite of disturbances (White 1979, Frelich 2002). Thus, there is no factor more integral to the short- and long-term dynamics of plant communities than the disturbances they experience. Though we cannot fully describe the historic DR for the communities at VOYA (Frelich 2012), we need to do so to the extent possible to help understand the current vegetation patterns and composition, and how the vegetation is likely to change in the future. A complete DR is described by these components:

- frequency
- intensity – a measure of the force of the phenomenon
- timing [season]
- extent
- duration [for some]

- variation in frequency and
- variation in intensity

of each type of disturbance (White 1979, Sousa 1984).

Severe disturbances (severity describes the impact of a disturbance; e.g., Nguyen-Xuan et al. 2000) have significant and immediate direct impacts on vegetation, some of the animals in the area, and abiotic conditions. The indirect effects of a disturbance often stress a large number of organisms. The combined direct and indirect effects explain why succession is usually set back to a pioneer stage. The reduction in vegetation and alteration of site conditions often provide opportunity for invasion and establishment of novel species. In some cases, a specific DR is necessary for the maintenance of specific communities or landscape pattern (Sousa 1984, Baker 1989, Turner et al. 1997, Frelich 2002).

To understand the adaptations to disturbance that plants and animals may have, the variability of frequency, intensity, and seasonality are critical (Sousa 1984, Gauthier et al. 1996). For recolonization purposes, the size of each event can be important. For example, Frelich (2002) estimated that the average fire size in the southern boreal forest was 4,000 ha in pre-settlement times. This size of impact area can slow down vegetative recovery due to seed limitation. This is a function of distance to seed sources and due to limited use of the middle portion of the area by birds and mammals. However, the seed bank can provide thousands of new plants per hectare (Nguyen-Xuan et al. 2000).

#### *4.1.1. Fire*

Fire is one of the most important types of disturbance for all pine forests in the Great Lakes region (Heinselman 1973, Whitney 1986, Frelich 2002), and is the dominant disturbance type for the southern boreal region (Frelich 2002). Although the disturbance history of VOYA is not well known due to the few studies conducted within the current park boundaries (Frelich 2012), the fire regime has been described, though most of it is extrapolated from the BWCAW (Frelich 2012). The fire regimes of boreal forests in general have been well described in northern MN (Heinselman 1973, Frelich and Reich 1995, Frelich 2002), and parts of Canada (Bergeron 1991, Arseneault and Sirois 2004). Only a small portion of VOYA is true boreal forest (Frelich 2012), though there are many boreal species, including Jack pine (*Pinus banksiana*), black spruce (*Picea mariana*), white spruce (*P. glauca*), trembling aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*) among the more common tree species in the park. The fire return interval (FRI) is variable across the southern broad region, ranging from 50–200 years.

Very few fires have been documented as to approximate size, year, and severity. Two years in the first half of the 20th century – 1923 and 1936 – had large fires on the Kabetogama Peninsula. The 1923 fire burned 4,453 ha, whereas two separate fires in 1936 burned a total of 9,380 ha. The smaller of these (2,093 ha) burned in the vicinity of Mica Bay; the other ("Cruiser Lake fire") occurred in the center of the Peninsula and was rather severe (Coffman et al. 1980, Rakestraw 1980). Rakestraw (1980) described the Cruiser Lake fire as having "… burned all vegetation down to bedrock." Nonetheless, the area was re-populated rapidly by jack pine and aspen. A notable amount (quantity unknown) of wildfire activity may also have occurred in 1918. There were a number of very large fires near Cloquet, MN, that year, and Coffman (1980) stated there was "… evidence in Voyageurs National Park also." From a variety of sources, Edlund et al. (2014) compiled fire histories for Quetico Provincial Park, BWCAW, and VOYA from 1860–1971.

In 1979, Coffman et al. (1980) put in 89 nested sample plots, all of which were located within 3.2 km (2 mi) of known logging camps from the early 20th century. Evidence of fire was noted at 67% of the locations, and 20% had burned at least twice. This suggests that fire occurred rather frequently in the recent past across much of the Peninsula, but there may be some location bias in the data because of the proximity of logging camps.

Studies by Bergeron (1991) and Drobyshev et al. (2010) in Quebec may help us extrapolate or interpret information from the Kabetogama Peninsula. Bergeron (1991) compared fire regimes on islands and an adjacent mainland and found that islands experienced more fires than the lakeshore, but fire years were uncorrelated. He also documented a greater range of fire size on the islands. Drobyshev et al. (2010) compared lakeshore and island habitats in northwestern Quebec and found more but smaller fires on the islands.

DRs change naturally on the scale of hundreds to thousands of years (Heinselman 1973, Niklasson and Granstrom 2000, Bergeron et al. 2004), and some components (especially fire) can be altered by human action (Heinselman 1973). In both the island and lakeshore landscapes examined by Bergeron (1991), fire frequency declined over the past approx. 120 years (i.e., from 1870–1990). The fire cycle on the islands was 74 years prior to 1870 and 112 years thereafter. A substantial change in the DR can affect the relative abundance of species and community types, the average patch size and shape, connectivity across the landscape, and successional trends (Turner et al. 1997).

One important dimension of this topic, and a future issue for the park, is how much the DR is likely to be altered by changes in climate. Extensive work in Canada has documented notable shifts in the fire cycle within the past 500 years or less (reviewed in Johnson et al. 2001) and over longer time scales in a black spruce-jack pine forest (Arseneault and Sirois 2004). Other reviews (e.g., Dale et al. 2001) have concluded that many types of disturbances will be affected. Frelich (2012) claimed the fire regime (or at least return intervals) in VOYA have been relatively stable for approximately 1,000 years. This is very likely to change in the next 50 years.

To facilitate comparisons and integration with other work, the DR of several community types is described below based on the forest types identified by Frelich (2012). The FRIs presented by Frelich (2012) are 'stand replacing' type of fires, unless noted otherwise.

- Jack pine-black spruce. Heinselman (1973, 1981) reported FRI of 50 years for Jack pine, and Frelich (2012) reports a range of 50–100 years.
- Mesic birch-aspen-spruce-fir. The FRI is 100–200 years (Frelich 2012).
- Dry-mesic red and white pine**.** Whitney (1986) found a range of FRI of 120–260 years for the mixed pine type in Michigan, and Heinselman (1973) estimates a 180-year FRI for mixed pine for the BWCAW. Frelich (2012) presents a FRI of 150–300 years for severe fires and 40 years for lower severity surface fires.

- Jack pine-oak-aspen. Frelich (2012) presents a FRI of 250–500 years for severe fires and 40 years for lower severity surface fires.
- Lowland conifer. Frelich (2012) presents a FRI of 150–300 years for severe fires.
- Rich swamps. Frelich (2012) presents a FRI of 500–1,000 years.

Though the data are limited, it is clear that a wide range of fire regimes existed in the past. The timing of these fires is a bit of a conundrum. The spring (April–May) is considered the primary fire season in this region; i.e., this is when most fires occur. However, the severe fires, which dominate the regimes here, typically occurred from mid-summer through early fall (Heinselman 1973, Coffman et al. 1980). This may be explained by the limited and 'fading record' (Swetnam et al. 1999) type of evidence left by many surface fires.

#### *4.1.2. Wind*

Wind disturbance is a ubiquitous force in forests and forested landscapes. It produces small scale openings on a regular and frequent basis and large scale, severe impacts at a very long return interval (Runkle 1982, Everham 1996, Dahir and Lorimer 1996).

Though the effects of this 'agent' can range from a few broken branches to complete leveling of an entire landscape (Everham 1996), the effects, and hence role, of wind is generally broken down into two categories: gap-forming phenomena in which the majority of the trees are unaffected, and 'catastrophic' type winds. This latter group includes meteorologic events such as hurricanes, tornadoes, downdrafts, and derechoes (Everham 1996, Frelich 2012). These phenomena can impact hundreds to hundreds of thousands of acres and restructure the forests impacted. The typical outcome is to move the forest to a later successional stage, because large diameter trees (Everham 1996) and early successional species (Frelich 2012) are more susceptible. The reader is referred to these two sources for further details on catastrophic wind events.

Extensive data from many parts of the eastern US prove the regularity and abundance of small spatial scale disturbances. These are commonly produced by wind events, insects, and/or disease, working singly or in combination (Runkle 1982, Clinton et al. 1993). In mature forests in the Great Lakes region, the rate at which the canopy is opened up is 0.5%–1.5% per year (Frelich and Lorimer 1991, Dahir and Lorimer 1996). Younger forests have less area affected than older forests, which may lose up to 4% of the canopy per year (Runkle 1982, Dahir and Lorimer 1996, Busing 2005). In most systems, larger trees are more likely to die (Busing 2005, Runkle 2013) and hence produce a larger gap (Clebsch and Busing 1989). The potential importance of this DR component is indicated by the amount (2.5% to 40%) of the forest in an 'open canopy' condition at any one time (Runkle 1982, Dahir and Lorimer 1996, Kneeshaw and Bergeron 1998).

Windthrow is the primary form of disturbance in the mesic northern hardwoods and swamp forests due to their long FRIs (Whitney 1986, Frelich 2002). Physiography (aspect, elevation), soil characteristics, water movement, and tree characteristics influence the magnitude and frequency of wind disturbance. Soils that are commonly saturated and have high levels of organic matter make trees with shallow roots susceptible to windthrow. When a tree is windthrown, micro-topographic heterogeneity in the form of pit-n-mound topography is created. The mound part of this provides a micro-site that is considerably drier than the area in general. The bole of the tree also provides surface heterogeneity that is important for the regeneration of some plant species (e.g. white cedar [*Thuja occidentalis*] [Rooney et al. 2002] and conifers in general [St. Hilaire and Leopold 1995]). These micro-sites result in greater plant diversity as they provide places for species to survive that are not so tolerant of saturated soils.

Studies within the boreal zone have found patterns very similar to those of the temperate zone, though the specific magnitude can differ. For example, a 50-year-old aspen forest had 7% of its area in gaps, and gap size influenced which species were most abundant in the understory (Kneeshaw and Bergeron 1998). Experimental gaps in spruce-fir forests in Quebec revealed that spruce benefited more [established more regeneration] than balsam fir (Ruel and Pineau 2002). In a mixed-species forest in central Quebec, balsam fir dominated the tree regeneration, but other species were able to maintain their dominance in the community due to greater longevity and lower susceptibility to pathogens (Kneeshaw and Prevost 2007). In the southern boreal forest of BWCAW, Peterson (2004) determined that tree size and identity were accurate predictors of wind-induced damage; balsam fir was the most vulnerable species.

The return interval for ‘stand leveling’ wind events for all forest types in northern MN was estimated by Frelich (2012) as 1,000–2,000 years. These estimates are generally consistent with estimates from Michigan (Whitney 1986). Though we do not have direct estimates of the return interval for this type of event in VOYA, there are several lines of evidence that suggest that there would be substantial and relatively consistent differences among forest types. At the landscape level in Michigan, Whitney (1986) found that blowdowns had a greater frequency in swamp conifer forests than any of the pine-dominated forests. This is probably due to the consistently positive association between soil water [amount] and wind damage (Everham 1996). Secondly, in general, species vary significantly in their susceptibility to damage by strong winds (Everham 1996). An assessment of the 1999 catastrophic windstorm in BWCAW determined that the level of trees thrown varied from 30% to 87% among species, and that balsam fir (*Abies balsamea*) was the most vulnerable (Peterson 2004). These two characteristics should result in more frequent windthrow, and greater severity, in swamp conifer forests and in those with a high level of balsam fir. Though fir is capable of performing like a late-successional species, it can invade many forests shortly after canopy closure, but it is a relatively short-lived species. Thus, its abundance varies substantially over time within a forest and across the landscape. The assessment by Frelich (2012) suggests that its abundance is increasing and will continue to do so in the near future.

### *4.1.3. Herbivory*

Herbivory, the consumption of live vegetative material by animals, is a common interaction in all plant communities (Perry 1994). In some communities (e.g., grasslands with ungulates), it is a dominant structuring and selective force. In forest communities, an endemic level of herbivory is carried out by hundreds of herbivores, primarily insects. The vast majority of the herbivores have no noticeable impact on the forest community, and, in fact, the total effect of this endemic herbivory may be trivial in terms of community structure, composition, and plant succession (Mattson and

Addy 1975). Nonetheless, the interactions between herbivores and plants are a vital part of the ecological dynamics of a forest. Many examples of co-evolution between plants and herbivores are documented (Perry 1994), and many traits in plant populations are due in part to the selective pressure of herbivores. Three key factors in this interaction are the intensity of herbivory (i.e., how much of the plant and population is affected), how regularly this interaction occurs, and the genetic variation within (and among) plant population(s). The variation among plants (i.e., genotypes) within a population can result in differences in resistance and induced defenses (Dimock et al. 1976, Hunter and Schultz 1995), and thus preferential selection and differential impact. The amount and "content" of the genetic variation are also vital in determining if and how a plant population might evolve in response to this selective pressure. Populations and species vary widely in their tolerance of low-to-moderate levels of herbivory, but in many, a 10%–30% loss of vegetative matter does not have a negative impact if the plant is healthy (Mattson and Addy 1975).

Some forest insects reach a level of impact well beyond this background level. In the Great Lakes region, this group includes native and exotic species; notable examples are the gypsy moth (*Lymantria dispar dispar*), forest tent caterpillar (*Malacosoma disstria*), emerald ash borer (*Agrilus planipennis*), jack pine budworm (*Choristoneura pinus*), eastern spruce budworm (*C. fumiferana*, ESB) and bark beetles (Volney and McCullough 1994, USDA Forest Service 2003, Faber-Langendoen et al. 2007, MDNR 2012). Of most direct relevance to VOYA are the ESB and the forest tent caterpillar. The most heavily utilized trees are balsam fir (Morin et al. 2007) and aspen (Katovich et al. 1998, Edmonds et al. 2011), respectively. These herbivores have a pronounced and long-term impact on community structure, composition, succession, and ecosystem processes such as nutrient cycling.

### *Forest Tent Caterpillar*

The defoliation caused by tent caterpillars in MN has been significant for more than 65 years, and the first outbreak was documented in the 1870s (Duncan and Hodson 1958); however, these older reports and more recent Forest Health Summaries (MDNR 2012) indicate the insect's presence is concentrated in the central, north-central, and northeastern part of the state. Aspen is the preferred host (Duncan and Hodson 1958), and given that aspen contributed almost 20% of the witness trees noted by the original land survey (Coffman et al. 1980), this herbivore is likely to have been present historically. Because aspen increased during the 20th century, we expect this insect to have more influence in the near future. Outbreaks of tent caterpillar occur every 6–16 years and may last 2–6 years (Duncan and Hodson 1958, USDA Forest Service 1996). Though healthy trees can typically withstand one, and possibly two, years of defoliation, two or more consecutive years causes substantial morality. During extensive outbreaks, up to 80% mortality may occur (Duncan and Hodson 1958). The forest tent caterpillar will consume foliage of other broadleaved species (e.g., maple and oak), but does not utilize conifers (USDA Forest Service 1996).

### *Eastern Spruce Budworm (ESB)*

In eastern North America, the ESB has frequently impacted large areas during outbreaks since at least the 1920s (Peltonen et al. 2002). The scale of impact of a single outbreak can be as large as 20,000,000 ha in eastern Canada (Attiwell 1994).

The ESB reaches epidemic levels from time to time and defoliated more than 50,000 ha in MN in 2010 and 2011. During an epidemic, the repeated defoliation commonly results in extensive mortality. The population dynamics of this species has been tracked for more than 60 years, and massive outbreaks occurred in the mid-1950s, early 1960s and 1970s, and in the mid-1980s and 1990s. Coffman et al. (1980) reported that this species is relatively new to VOYA but had caused some stand level mortality (# of stands and extent not specified). An ESB outbreak occurred in the 1930s which killed a large number of trees, mostly balsam fir. Though balsam fir is the preferred host, white spruce is readily eaten and black spruce is eaten to a limited extent (Taylor and MacLean 2009, Edmonds et al. 2011). The primary feeding period is from late May to mid-July, and the larvae utilize staminate flowers, older needles, vegetative buds, and then newly formed needles.

Based on tree composition in the mid-1800s, ESB was probably present, but it is not likely there were ‘epidemic-level’ effects due to the relatively small amount of balsam fir. Su et al. (1996) reported for 25 stands in New Brunswick that defoliation of balsam fir decreased significantly and steadily as the proportion of broad-leaved species in the canopy increased. The same effect, though probably of smaller magnitude, applies to increasing amounts of spruce relative to the amount of fir (Edmonds et al. 2011). The increase in abundance of fir since the mid-20th century has set the stage for more impact by this insect herbivore. Areas with dense, mature fir are most likely to experience extensive mortality, but it is unknown if the food resource is large enough and continuous enough to support a landscape-level outbreak.

### *Mammalian Herbivory*

Large mammalian herbivores are an important group for VOYA; historically this group included caribou, elk, moose, and white-tailed deer (WTD) (*Odocoileus virginianus*). Caribou and elk were eliminated from the area due to uncontrolled hunting by the mid-1920s (Cole 1987).

The population density of WTD has fluctuated significantly over the past approx. 115 years. Cole (1987) provided an estimate of approx. 0.4 deer km$^{-2}$ at the turn of the 20th century. This density probably represents reasonably well the density prior to European settlement. The population increased very rapidly in the early 20th century, reaching a peak density of approx. 8.0 deer km$^{-2}$ in the 1930s. This change was largely fueled by an increase in forage and habitat carrying capacity due to human disturbance. This same effect—landscape-level changes associated with settlement that have provided almost ideal habitat for WTD (Rogers et al. 1981, Van Deelen et al. 1996, Rudolph 2005)—has been noted across the region (Waller et al. 2009). The population density gradually contracted to approx. 5.0 deer km$^{-2}$ by 1975 and then declined at a more rapid rate to approx. 1.5 deer km$^{-2}$ by 1985 (Cole 1987). Cole (1982) suggested this increased rate of decline was due to a combination of 1) ongoing habitat changes due to succession, 2) severe winters, and 3) wolf predation. However, Gogan et al. (1997) described the Cole (1987) estimate as “suspiciously low” and gave an estimate of 2.94 deer km$^{-2}$ for the Kabetogama Peninsula in 1992. Lenarz (2011) provided estimates of winter deer density from 2001–2011 in the two deer management units immediately south of VOYA, ranging from 3.5 deer km$^{-2}$ in 2009 and 2011 in unit 108 to 5.8 deer km$^{-2}$ in 2003 in unit 119 (Figure 8).

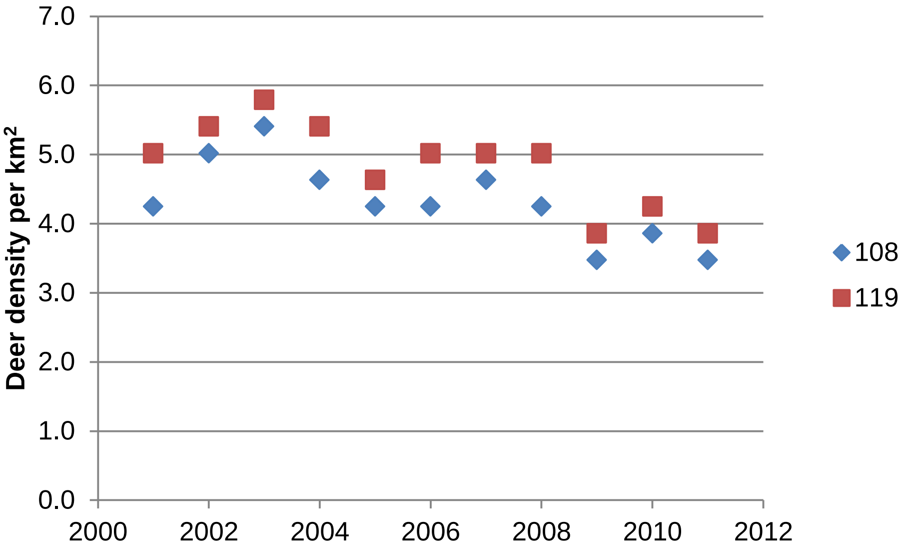

**Figure 8.** White-tailed deer density (deer km$^{-2}$) estimates for the two deer management units immediately south of Voyageurs National Park (Lenarz 2011).

Due to the large increase in deer density during the past century, there is concern that this species may be having a greater impact on vegetation than pre-1900. This question related to WTD has two parts. The first relates to the interaction that occurred from approx. 1920 to 1975. Clearly, density was at an unnaturally high level compared to 19th century levels. Thus, the issue becomes "did the intensity of herbivory by WTD rise to a level, and occur over a long enough period of time, to cause permanent to semi-permanent change in one or more community attributes?" (Russell et al. 2001, Waller et al. 2009). In VOYA, the forest communities most at risk are the lowland conifer forests that contain white cedar (Van Deelen et al. 1996), the communities that contain oak (Waller et al. 2009), and any of the communities that have a substantial forb component, especially species with limited natural defenses and low tolerance of repeated browsing (Waller et al. 2009). Based on long-term impacts of browsing by ungulates in forest systems (e.g., Rooney et al. 2004, Allombert et al. 2005), deer density was elevated over a long enough period of time for the potential of widespread impacts. Less clear is whether the intensity exceeded what the landscape and plant species could tolerate. As noted above, the carrying capacity of the landscape was increased substantially, though by exactly how much is unknown, during the early to mid-20th century. Thus, the pressure exerted by higher density may not be in proportion to the increase in density. Nonetheless, the indirect evidence available (Stromayer and Warren 1997, Rooney et al. 2004) suggests some unprecedented impacts were likely. Due to the lack of a systematic, scientific survey of the understory community prior to approx. 1905–1910, this question cannot be answered definitively.

The second issue is whether the role(s) and impact(s) of WTD are likely to change in the next few decades. The vegetative structure of the landscape will change due to succession and due to climate-induced effects. With a warming climate, the area could become more suitable for deer, and the vegetation is likely to become more temperate and thus contain more habitat for WTD. It should be noted that deer are a natural, though not dominant, part of this landscape, and thus a small-to-modest increase in their density is not inherently a cause for concern. This is true because the presence of deer, at certain levels, can have positive effects. Two studies have documented a positive effect on understory richness and/or diversity at an "intermediate" level of browsing (Royo et al. 2010 – oak dominated forest; Hegland et al. 2013 – Scots pine forest in Norway). The second positive effect is that deer can serve as a long distance dispersal agent (Vellend et al. 2003); this could be important for long term maintenance of understory species that otherwise have to rely on gravity or ants for dispersal.

### *Impacts*

Concerns have been raised for more than 60 years (e.g., Swift 1948) in the Lake States region about "damage" caused by WTD herbivory. Until the 1980s, these concerns were largely focused on commercially important tree species, with American yew (*Taxus canadensis*, Beals et al. 1960) being an exception. Since the 1980s, interest has expanded to understory cover and structure, understory diversity, plant population structure, sex ratio, growth rate, reproductive output, plant succession, threatened and endangered species, and non-preferred species. The many review articles on this subject include Alverson et al. (1988), Russell et al. (2001), Cote et al. (2004), Waller et al. (2009), and Heckel et al. (2010).

There is disagreement over the WTD density at which damage is likely to occur. Russell et al. (2001) surveyed a large amount of literature and concluded that all studies that documented reduced recruitment had a density of at least 8.5 deer km$^{-2}$. Alverson et al. (1988) suggest densities as low as 4 deer km$^{-2}$ may be enough to have impacts on yew, hemlock (*Tsuga canadensis*), and white cedar. Augustine and Frelich (1998) did not find any noticeable impacts on trillium (*Trillium* spp.) until density reached 25 deer km$^{-2}$. Frelich and Lorimer (1985) determined that hemlock is impacted at a density between 2–10 deer km$^{-2}$ in Michigan's Porcupine Mountains. There are few controlled deer density studies, Horsley et al. (2003) found that most understory attributes were negatively affected at between 4–8 deer km$^{-2}$. Heckel et al. (2010) found increasing impacts on the soil and litter depth as density increased from 4–18 deer km$^{-2}$.

This myriad of results (thresholds) has been noted because density is not the whole equation. As stated above, the landscape structure influences how much deer are concentrated and where they feed at different times of the year. Of special relevance is the winter, and whether or not deer will "yard up" for any appreciable length of time. Other factors that will determine how much impact and which species are affected include snow depth, plant height, plant growth rate, abundance by species, and total browse abundance (Curtis 1959, Rogers et al. 1981, Russell et al. 2001). Rogers et al. (1981) stated that deer will not dig through more than 10–30 cm of snow to reach food. By summer, woody material usually comprises <5% of deer diet (McCaffery et al. 1974, Rogers et al. 1981).

The density of balsam fir saplings (Borgmann et al. 1999) influenced browse intensity on hemlock. That is, a preferred species was partially protected by an abundance of a non-preferred species. It seems reasonable to expect that this type of influence could manifest in a variety of forest types. Despite the variation in conclusions regarding a WTD threshold, it seems prudent to become concerned if the density is 2 km$^{-2}$ and monitor very closely if the density approaches 4 deer km$^{-2}$ for any length of time or over a large area.

The understory of forests that have ‘spring ephemeral’ assemblages are a special concern. In spring, deer are moving around the landscape looking for food sources that are more nutritious than the woody browse they rely on during winter (Rogers et al. 1981). Almost any non-woody tissue is preferred at this time of year because it is lush and nutritious. Several studies have suggested that a number of species in the lily family are part of the vulnerable, spring ephemeral assemblage (Alverson et al. 1988, Hurley and Flaspoler 2005, Waller et al. 2009).

*Is Recovery Possible?*

A comparison of the understory on two islands in Lake Michigan, one (North Manitou) with a history of deer density similar to VOYA, and the other (South Manitou) without deer, sheds some light on the possibility of recovery and documents the precise nature of long-term, fairly intense browsing (Hurley and Flaspoler 2005). WTD density peaked in the mid-1980s at approx. 30 deer km$^{-2}$ on North Manitou and then declined to approx. 3 deer km$^{-2}$. North Manitou, in comparison to South Manitou, had: i) more tree seedlings and a shift to much greater relative abundance of beech; ii) strong domination of small saplings (<5 cm diameter at breast height) by beech and greater overall density; iii) approximately 1/6 as much herb cover in mid-summer; iv) much less fern, shrub, and yew cover; but v) more grass cover mid-summer. The spring ephemeral cover on North Manitou is about half that on South Manitou. These authors note that there are minor signs of recovery in the 20 years since browsing pressure started to decline, and that it was proceeding very slowly.

The effects from high WTD densities are not restricted to plant composition, abundance, growth, and form. Cote et al. (2004) concluded that the effects can cascade through the system and affect insects, birds, and other organisms. There has been very little study of ecosystem-level effects from WTD herbivory (Russell et al. 2001), but Cote et al. (2004) concluded that both carbon and nitrogen cycling can be altered. Heckel et al. (2010) determined that soil penetration resistance (i.e., difficulty of infiltration) was increased, and litter depth reduced, by higher deer densities in an Appalachian hardwood forest. However, the analyses of Mladenoff and Stearns (1993), Rooney et al. (2000), and Russell et al. (2001), and the findings of Stromayer and Warren (1997), should be carefully considered to avoid assigning unwarranted influence to WTD browsing.

Conclusions

The frequency of occurrence and the range of severity are not known for any of the insects that can reach epidemic proportions, but it is hypothesized that the severity was lower than what has been occurring in other parts of the state over the past 70+ years. It is probable that a small-moderate increase in impacts will occur in the next several decades. Browsing by WTD from approx. 1920–1975 probably reduced the abundance of some herbaceous species and could have extirpated others; the extent of this is unknown, however. Given the prevalence of windthrow in these forest types (see previous section), small-scale refugia are likely, which reduces the chance of total extirpation.

#### *4.1.4. Logging (1800s–1971)*

The peak logging period at VOYA was approx. 1910–1930. The heavy utilization of trees began on the eastern end of the Kabetogama Peninsula, with red and white pine being the primary species of interest (Coffman et al. 1980). White spruce was also taken in large quantities. Towards the end of this period, harvesting of spruce and fir on the western end of the Kabetogama Peninsula rapidly increased (Rakestraw 1980). Though large volumes of timber left the area, the precise severity of the logging is unclear, as is the total area affected. Faber-Langendoen et al. (2007) stated that logging had minimal impact on the central, roadless core of the Kabetogama Peninsula, though approximately 25% of the Peninsula was logged in the 1950s and 1960s.

The direct and indirect impacts of logging on the understory are an important and valid concern (Gilliam and Roberts 2003). This is true because the vast majority of plant species are found in this layer, and there is potential to substantially change the composition by harvesting (Craig and Macdonald 2009). The abundance and composition of the ground layer also can play an important role in nutrient retention, as documented in Appalachian spruce-fir (Moore et al. 2007) and boreal forests in Sweden (Nilsson and Wardle 2005). The more intensive the tree utilization, the greater is the potential for a reduction in diversity (Craig and Macdonald 2009) and/or the initiation of a novel successional pathway (Roberts 2004). However, many understory species survive a harvest, even a clearcut (Crowell and Freedman 1994), and thus the understory can be more diverse after a harvest than before (Crowell and Freedman 1994, Gilliam and Roberts 2003). This net increase involves the loss of a few late-successional species and the invasion of many pioneer species. Whether or not logging has decreased the vascular plant richness on VOYA is unknown due to the lack of pre-logging data. Climate, growth rates, and dispersal capacity of many species affect recovery time from severe disturbance. In southern mixedwood boreal forests of Saskatchewan, understory richness was still declining 200 years after stand-replacing fires (Chipman and Johnson 2002).

Sources of Expertise

James Cook, UWSP.

Literature Cited

Allombert, S., A. J. Gaston, and J.-L. Martin. 2005. A natural experiment on the impact of overabundant deer on songbird populations. *Biological Conservation* 126:1–13.

Alverson, W. S., D. M. Waller, and S. Solheim. 1988. Forest too deer: edge effects in northern Wisconsin. *Conservation Biology* 2:348–358.

Arseneault, D., and L. Sirois. 2004. The millenial dynamics of a boreal forest stand from buried trees. *Journal of Ecology* 92:490–504.

Attiwell, P. M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecology and Management* 63:247–300.

Augustine, D. J., and L. E. Frelich. 1998. Effects of white-tailed deer populations on an understory forb in fragmented deciduous forests. *Conservation Biology* 12:995–1004.

Baker, W. L. 1989. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. *Ecology* 70:23–35.

Barnes, B. V., D. R. Zak, S. R. Denton, and S. H. Spurr. 1998. Forest Ecology, Fourth Edition. John Wiley and Sons, New York, New York. 792 pp.

Beals, E. W., G. Cottam, and R. J. Vogl. 1960. Influence of deer on vegetation of the Apostle Islands, Wisconsin. *Journal of Wildlife Management* 24:68–80.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. *Ecology* 72:1980–1992.

Bergeron, Y., S. Gauthier, M. Flannigan, and V. Kafka. 2004. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. *Ecology* 85:1916–1932.

Borgmann, K. L., D. M. Waller, and T. P. Rooney. 1999. Does balsam fir (*Abies balsamea*) facilitate the recruitment of eastern hemlock (*Tsuga canadensis*)? *American Midland Naturalist* 141:391–397.

Busing, R. T. 2005. Tree mortality, canopy turnover, and woody detritus in old cove forests of the southern Appalachians. *Ecology* 86:73–84.

Chipman, S. J., and E. A. Johnson. 2002. Understory vascular plant species diversity in the mixedwood boreal forest of western Canada. *Ecological Applications* 12:588–601.

Clebsch, E. E., and R. T. Busing. 1989. Secondary succession, gap dynamics, and community structure in a Southern Appalachian cove forest. *Ecology* 70:728–735.

Clinton, B. D., L. R. Boring, and W. T. Swank. 1993. Canopy gap characteristics and drought influence in oak forests of the Coweeta Basin. *Ecology* 74:1551–1558.

Coffman, M. S., L. Rakestraw, and J. E. Ferris. 1980. The fire and logging history of Voyageurs National Park. Michigan Technological University, Houghton, Michigan. 108 pp.

Cole, G. F. 1982. Restoring natural conditions in a boreal forest park. Paper presented at the 47th North American Wildlife and Natural Resources Conference, March 26–31, 1982, Portland, Oregon.

Cole, G. F. 1987. Changes in interacting species with disturbance. *Environmental Management* 11:257–264.

Cote, S. D., T. P. Rooney, J. Tremblay, C. Dussault, and D. M. Waller. 2004. Ecological impacts of deer overabundance. *Annual Review of Ecology Evolution and Systematics* 35:113–147.

Craig, A., and S. E. Macdonald. 2009. Threshold effects of variable retention harvesting on understory plant communities in the boreal mixedwood forest. *Forest Ecology and Management* 258:2619–2627.

Crowell, M., and B. Freedman. 1994. Vegetation development in a hardwood-forest chronosequence in Nova Scotia. *Canadian Journal of Forest Research* 24:260–271.

Curtis, J. T. 1959. The vegetation of Wisconsin. University of Wisconsin Press, Madison, Wisconsin.

Dahir, S. E., and C. G. Lorimer. 1996. Variation in canopy gap formation among development stages of northern hardwood stands. *Canadian Journal of Forest Research* 26:1875–1892.

Dimock, E. J. II, R. R. Silen, and V. E. Allen. 1976. Genetic resistance in Douglas-fir to damage by snowshoe hare and black-tailed deer. *Forest Science* 22:106–121.

Drobyshev, I., M. D. Flannigan, Y. Bergeron, M.-P. Girardin, and B. Suran. 2010. Variation in local weather explains differences in fire regimes within a Québec south-eastern boreal forest landscape. 2010. *International Journal of Wildland Fire* 19:1073–1082.

Duncan, D. P., and A. C. Hodson. 1958. Influence of the forest tent caterpillar upon the aspen forests of Minnesota. *Forest Science* 4:71–93.

Edlund, M. B., C. A. Serieyssol Bleser, L. W. Kallemeyn, and D. R. Engstrom. 2014. Determining the historical impact of water-level management on lakes in Voyageurs National Park. Natural Resource Technical Report NPS/VOYA/NRTR—2014/920. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2217009 (accessed 8 July 2015).

Edmonds, R. L., J. K. Agee, and R. I. Gara. 2011. Forest health and protection. 2nd edition. Waveland Press, Long Grove, Illinois.

Everham, E. M. III. 1996. Forest damage and recovery from catastrophic wind. *Botanical Review* 62:1113–1185.

Faber-Langendoen, D., N. Aaseng, K. Hop, M. Lew-Smith, and J. Drake. 2007. Vegetation classification, mapping, and monitoring at Voyageurs National Park, Minnesota: An application of the U.S. National Vegetation Classification. *Applied Vegetation Science* 10:361–374.

Frelich, L. E. 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen-Deciduous Forests. Cambridge University Press, New York, New York.

Frelich, L. 2012. Vegetation and landscape change. *In* L. Frelich and S. Windels, editors. Terrestrial Synthesis for Voyageurs National Park. Draft document to Voyageurs National Park, International Falls, Minnesota.

Frelich, L. E., and C. G. Lorimer. 1985. Current and predicted long-term effects of deer browsing in hemlock forests in Michigan, USA. *Biological Conservation* 34:99–120.

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. 1995. Spatial patterns and succession in a Minnesota southern-boreal forest. *Ecological Monographs* 65:325–346.

Gauthier, S., Y. Bergeron, and J. Simon. 1996. Effects of fire regime on the serotiny level of jack pine. *Journal of Ecology* 84:539–548.

Gilliam, F. S. and M. R. Roberts (editors). 2003. The herbaceous layer of forests of eastern North America. Oxford University Press, New York, New York.

Gogan, P. J. P., K. D. Kozie, E. M. Olexa, and N. S. Duncan. 1997. Ecological status of moose and white-tailed deer at Voyageurs National Park, Minnesota. *Alces* 33:187–201.

Halpern, C. B., and J. F. Franklin. 1990. Physiognomic development of *Pseudotsuga* forests in relation to initial structure and disturbance intensity. *Journal of Vegetation Science* 1:475–482.

Heckel, C. D., N. A. Bourg, W. J. McShea, and S. Kalisz. 2010. Nonconsumptive effects of a generalist ungulate herbivore drive decline of unpalatable forest herbs. *Ecology* 91:319–326.

Hegland, S. J., M. S. Lilleeng, and S. R. Moe. 2013. Old-growth forest floor richness increases with red deer herbivory intensity. *Forest Ecology and Management* 310:267–274.

Heinselman, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area. *Minnesota Quaternary Research* 3:329–382.

Heinselman, M. L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. Pages 7–57 *in* Mooney, H. A., T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners, editors. Proceedings of the Conference Fire Regimes and Ecosystem Properties. Honolulu. General Technical Report WO-26. USDA–Forest Service, Washington, D.C.

Hong, H. S., and D. J. Mladenoff. 1999. Spatially explicit and stochastic simulation of forest-landscape fire disturbance and succession. *Ecology* 80:81–99.

Horsley, S. B., S. L. Stout, and D. S. Decalesta. 2003. White-tailed deer impact on the vegetation dynamics of a northern hardwood forest. *Ecological Applications* 13:98–118.

Hunter, M. D., and J. C. Schultz. 1995. Fertilization mitigates chemical induction and herbivore responses within damaged oak trees. *Ecology* 76:1226–1232.

Hurley, P. M., and D. Flaspohler. 2005. An assessment of long-term biodiversity recovery from intense and sustained deer browse on North Manitou Island, Sleeping Bear Dunes National Lakeshore. Proceedings of the Conference Forests & Whitetails—Striving for Balance, Michigan Society of American Foresters, June 9–10, 2005, St. Ignace, Michigan. Available at http://michigansaf.org/Tours/05Deer/06-Flaspohler.pdf (accessed 12 August 2014).

Johnson, E. A., K. Miyanishi, and S. R. J. Bridge. 2001. Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. *Conservation Biology* 15:1554–1557.

Katovich, S., D. McDougall, and Q. Chavez. 1998. Impact of forest stressors on the tree species of the Nicolet National Forest – past, present and future. Publication NA-TP-02-98. USDA-Forest Service Northeast Area State and Private Forestry, Newtown Square, Pennsylvania.

Kneeshaw, D. D., and M. Prévost. 2007. Natural canopy gap disturbances and their role in maintaining mixed-species forests of central Quebec, Canada. *Canadian Journal of Forest Research* 37:1534–1544.

Kneeshaw, D. D., and Y. Bergeron. 1998. Canopy gap characteristics and tree replacement in the southeastern boreal forest. *Ecology* 79:783–794.

Lenarz, M. S. 2011. Population trends of white-tailed deer in the forest zone – 2011. *In* Status of Wildlife Populations, 2011. Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/publications/wildlife/populationstatus2011/4_forest_wildlife.pdf (accessed 12 August 2014).

Mattson, W. J., and N. D. Addy. 1975. Phytophagous insects as regulators of forest primary production. *Science* 190:512–522.

McCaffery, K. R., J. Tranetzki, and J. Pierhura. 1974. Summer foods of deer in northern Wisconsin. *Journal of Wildlife Management* 38:215–219.

MDNR (Minnesota Department of Natural Resources). 2003. Field guide to the native plant communities of Minnesota: the Laurentian Mixed Forest province. Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program. MDNR, St. Paul, Minnesota.

MDNR (Minnesota Department of Natural Resources). 2012. Division of Forestry, Forest Health Unit. Minnesota forest health 2012 annual report. MDNR, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/assistance/backyard/treecare/forest_health/annualreports/2012annualReport.pdf (accessed 12 August 2014).

Mladenoff, D. J., and F. Stearns. 1993. Eastern hemlock regeneration and deer browsing in the northern Great Lakes region: A reexamination and model simulation. *Conservation Biology* 7:889–900.

Moore, P. T., H. Van Miegroet, and N. S. Nicholas. 2007. Relative role of understory and overstory in carbon and nitrogen cycling in a southern Appalachian spruce–fir forest. *Canadian Journal of Forest Research* 37:2689–2700.

Morin, H., Y. Jardon, and R. Gagnon. 2007. Relationship between spruce budworm outbreaks and forest dynamics in eastern North America. Pages 555–578 *in* E.A. Johnson and K. Miyanishi, editors. Plant Disturbance Ecology – The Process and the Response. Elsevier Academic Press, New York, New York.

Nguyen-Xuan, T., Y. Bergeron, D. Simard, J. W. Fyles, and D. Pare. 2000. The importance of forest floor disturbance in the early regeneration patterns of the boreal forest of western and central

Quebec: a wildfire versus logging comparison. *Canadian Journal of Forest Research* 30:1353–1364.

Niklasson, M., and A. Granstrom. 2000. Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology* 81:1484–1499.

Nilsson, M.-C., and D. A. Wardle. 2005. Understory vegetation as a forest ecosystem driver: evidence from the northern Swedish boreal forest. *Frontiers in Ecology and the Environment* 3:421–428.

Peltonen, M., A. M. Liebhold, O. N. Bjornstad, and D. W. Williams. 2002. Spatial synchrony in forest insect outbreaks: roles of regional stochasticity and dispersal. *Ecology* 83:3120–3129.

Perry, D. A. 1994. Forest ecosystems. John Hopkins University Press, Baltimore, Maryland. 649 pp.

Peterson, C. J. 2004. Within-stand variation in windthrow in southern boreal forests of Minnesota: Is it predictable? *Canadian Journal of Forest Research* 34:365–375.

Rakestraw, L. 1980. Fire, logging and the face of the forest. Appendix E *in* Coffman, M. S., L. Rakestraw, and J. E. Ferris. 1980. The fire and logging history of Voyageurs National Park. Michigan Technological University, Houghton, Michigan.

Roberts, M. R. 2004. Response of the herbaceous layer to natural disturbance in North American forests. *Canadian Journal of Botany* 82:1273–1283.

Rogers, L. L., J. J. Mooty, and D. Dawson. 1981. Foods of white-tailed deer in the Upper Great Lakes regions – a review. General Technical Report NC-65. USDA-Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Rooney, T. P., R. J. McCormick, S. L. Solheim, and D. M. Waller. 2000. Regional variation in recruitment of hemlock seedlings and saplings in the Upper Great Lakes, USA. *Ecological Applications* 10:1119–1132.

Rooney, T. P., S. L. Solheim, and D. M. Waller. 2002. Factors affecting the regeneration of northern white cedar in lowland forests of the Upper Great Lakes region, USA. *Forest Ecology and Management* 163:119–130.

Rooney, T. P., S. M. Wiegmann, D. A. Rogers, and D. M. Waller. 2004. Biotic impoverishment and homogenization in unfragmented forest understory communities. *Conservation Biology* 18:787–798.

Royo, A. A., R. Collins, M. B. Adams, C. Kirschbaum, and W. P. Carson. 2010. Pervasive interactions between ungulate browsers and disturbance regimes promote temperate forest herbaceous diversity. *Ecology* 91:93–105.

Rudolph, B. A. 2005. Population biology, abundance and management history of Michigan white-tailed deer. Proceedings of the Conference Forests & Whitetails—Striving for Balance, Michigan

Society of American Foresters, June 9–10, 2005, St. Ignace, Michigan. Available at http://michigansaf.org/Tours/05Deer/02-Rudolph.pdf (accessed 12 August 2014).

Ruel, J.-C., and M. Pineau. 2002. Windthrow as an important process for white spruce regeneration. *The Forestry Chronicle* 78:732–738.

Runkle, J. R. 1982. Patterns of disturbance in some old-growth forests of the eastern United States. *Ecology* 63:1533–1546.

Runkle, J. R. 2013. Thirty-two years of change in an old-growth Ohio beech-maple forest. *Ecology* 94:1165–1175.

Russell, F. L., D. B. Zippin, and N. L. Fowler. 2001. Effects of white-tailed deer (*Odocoileus virginianus*) on plants, plant populations and communities: a review. *American Midland Naturalist* 146:1–26.

Schwartz, P. A., T. J. Fahey, and C. E. McCulloch. 2003. Factors controlling spatial variation of tree species abundance in a forested landscape. *Ecology* 84:1862–1878.

Sousa, W. P. 1984. The role of disturbance in natural communities. *Annual Review of Ecology and Systematics* 15:353–391.

St. Hilaire, L. R., and D. J. Leopold. 1995. Conifer seedling distribution in relation to micro-site conditions in a central New York forested minerotrophic peatland. *Canadian Journal of Forest Resources* 25:261–269.

Stromayer, K. A., and R. J. Warren. 1997. Are overabundant deer herds in the eastern U.S. creating alternate stable states in forest plant communities? *Wildlife Society Bulletin* 25:227–234.

Su, Q., D. A. MacLean, and T. D. Needham. 1996. The influence of hardwood content on balsam fir defoliation by spruce budworm. *Canadian Journal of Forest Research* 26:1620–1628.

Swetnam, T., C. D. Allen, and J. L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9:1189–1206.

Swift, E. 1948. Wisconsin’s deer damage to forest reproduction survey – final report. Publication number 347. Wisconsin Conservation. Department, Madison, Wisconsin.

Taylor, S. L., and D. A. MacLean. 2009. Legacy of insect defoliators: increased wind-related mortality two decades after a spruce budworm outbreak. *Forest Science* 55:256–267.

Turner, M. G., V. H. Dale, and E. E. Everham III. 1997. Fires, hurricanes, and volcanoes: comparing large-scale disturbances. *Bioscience* 47:758–768.

USDA Forest Service (United States Department of Agriculture Forest Service). 1996. Pest alert – forest tent caterpillar. NA-PR-02-96. USDA Forest Service Northeastern Area, State and Private Forestry, Newtown Square, Pennsylvania.

USDA Forest Service (United States Department of Agriculture Forest Service). 2003. Forest insect and disease conditions in the United States 2002. USDA Forest Service Forest Health Protection, Washington, D.C. Available at http://www.fs.fed.us/foresthealth/publications/ConditionsReport_2002.pdf (accessed 12 August 2014).

USEPA (United States Environmental Protection Agency) Science Advisory Board. 2002. A framework for assessing and reporting on ecological condition: an SAB report. EPA-SAB-EPEC-02-009. USEPA, Washington, D.C. Available at www.epa.gov/sab/pdf/epec02009.pdf (accessed 19 September 2013).

Van Deelen, T. R., K. S. Pregitzer, and J. B. Haufler. 1996. A comparison of presettlement and present-day forests in two northern Michigan deer yards. *American Midland Naturalist* 135:181–194.

Vellend, M., J. A. Myers, S. Gardescu, and P. L. Marks. 2003. Dispersal of *Trillium* seeds by deer: implications for long-distance migration of forest herbs. *Ecology* 84:1067–1072.

Volney, W. J. A., and D. G. McCullough. 1994. Jack pine budworm population behaviour in northwestern Wisconsin. *Canadian Journal of Forest Research* 24:502–510.

Waller, D. M., S. Johnson, R. Collins, and E. Williams. 2009. Threats posed by ungulate herbivory to forest structure and plant diversity in the upper Great Lakes region with a review of methods to assess those threats. Natural Resource Report NPS/GLKN/NRR–2009/102. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/661464 (accessed 10 September 2013).

White, P. S. 1979. Pattern, process and natural disturbance in vegetation. *The Botanical Review* 45:229–299.

Whitney, G. G. 1986. Relation of Michigan's presettlement pine forests to substrate and disturbance history. *Ecology* 67:1548–1559.

Wimberley, M. C., and T. A. Spies. 2001. Influences of environment and disturbance on forest patterns in coastal Oregon watersheds. *Ecology* 82:1443–1459.

## 4.2. Landscape Condition

The USEPA-SAB framework defines a landscape as “a mosaic of interacting ecosystems or habitat patches” and emphasizes the potential effects of changes in patch size, number, or connectivity on both biotic and abiotic processes. The framework recommends consideration of landscape extent, composition, and pattern and structure with metrics such as perimeter to area ratio, number of habitat types, and longitudinal and lateral connectivity. It identifies managing landscapes, not just individual habitat types, as an important element in insuring the maintenance of native plant and animal diversity (USEPA 2002). Topics considered in this NRCA under Landscape Condition are land cover, impervious surfaces, landscape pattern and structure, road density, lightscapes, and soundscapes.

Our primary source of data and methodology is the NPS NPScape landscape dynamics monitoring program (Monahan et al. 2012), which recommends a 30 km buffer around a park as an appropriate-sized area of analysis (AOA) for understanding park condition in a landscape context. This area is approximately ten times the size of VOYA (8,345 km$^2$ vs 829 km$^2$).We also examine the VOYA watershed upgradient of the outlet of Rainy Lake, an area approximately 46 times the size of VOYA (38,219 km$^2$). A watershed is an appropriate way to analyze the myriad forces and pressures operating on the landscape because it captures most cumulative effects (Potyondy and Geier 2011).

### *4.2.1. Land Cover*

Description

VOYA is located in a region of forests and lakes; North American Landscape Characterization (NALC) data (USGS et al. 2013) show that within VOYA, the largest land cover type is water (337.5 km$^2$, 40.7%), followed by temperate or sub-polar broadleaf deciduous forest (264.3 km$^2$, 31.8%) and temperate or sub-polar needleleaf forest (147.7 km$^2$, 17.8%) (Table 6, Figure 9). The 30-km AOA and the watershed above VOYA are less covered by water (18.7% and 17.3%, respectively) and have more mixed forest (14.6% and 29.3%, respectively) than does VOYA. VOYA has more wetlands (80.3 km$^2$, 9.7%) than its AOA or upgradient watershed; more extensive wetlands occur to the west of the AOA (Figure 9). Cropland, barren land, and urban and built-up land are minor components in this landscape, each representing <1% of the land in the park, AOA, or watershed.

Data and Methods

Land cover data were obtained from the NALC 2005, version 2 (USGS et al. 2013). Change data were obtained from Kirschbaum and Gafvert (2010), in which disturbances in and around VOYA were delineated for six years (2002–2007) using a combination of Landsat satellite imagery and high resolution aerial photos. Computer algorithms collectively known as LandTrendr were used with Landsat imagery to identify apparent disturbances, which were verified by examination of air photos, to track vegetation changes in and around the park. Kirschbaum and Gafvert (2010) divided their results into VOYA, the surrounding area in MN up to 3 km from the VOYA boundary (MN AOA in Table 7), and the surrounding area in Canada up to 6 km from the boundary (Canada AOA in Table 7). For each validated disturbance, the authors identified the agent of change (patch creation by beaver, blowdown, building, fire, flooding caused by beaver, and forest harvest), the year of occurrence, and the starting and ending vegetation classes. In 2014, the 2011 National Land Cover

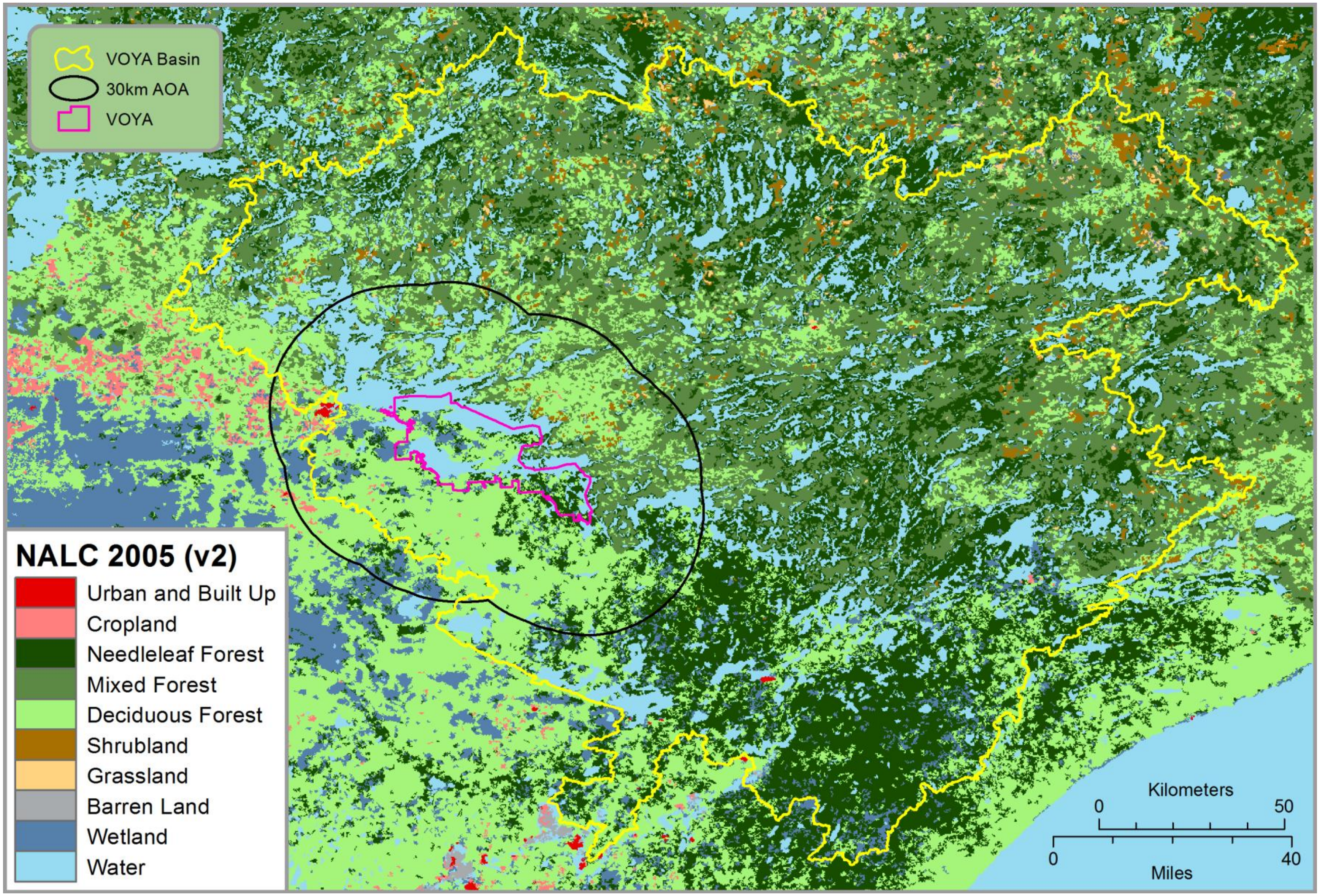

**Figure 9.** Land cover in the vicinity of Voyageurs National Park (USGS et al. 2013).

**Table 6.** Area and percentage of area in NALC land cover categories, 2005 (USGS et al. 2013).

| | VOYA | | 30 km AOA | | VOYA Watershed | |
| --- | --- | --- | --- | --- | --- | --- |
| **Level 1 NALC Land Cover Class** | *km$^2$* | *%* | *km$^2$* | *%* | *km$^2$* | *%* |
| Temperate or sub-polar needleleaf forest | 147.7 | 17.8 | 1,048.4 | 12.6 | 10,832.9 | 28.3 |
| Temperate or sub-polar broadleaf deciduous forest | 264.3 | 31.8 | 3,796.1 | 45.5 | 7,600.1 | 19.9 |
| Mixed forest | 0.1 | <0.1 | 1,222.3 | 14.6 | 11,210.3 | 29.3 |
| Temperate or sub-polar shrubland | <0.1 | <0.1 | 57.9 | 0.7 | 600.6 | 1.6 |
| Temperate or sub-polar grassland | <0.1 | <0.1 | 10.0 | 0.1 | 165.9 | 0.4 |
| Wetland | 80.3 | 9.7 | 574.3 | 6.9 | 1,169.1 | 3.1 |
| Cropland | <0.1 | <0.1 | 64.6 | 0.8 | 32.1 | 0.1 |
| Barren land | <0.1 | <0.1 | <0.1 | <0.1 | 4.6 | <0.1 |
| Urban and built-up | <0.1 | <0.1 | 12.1 | 0.1 | 7.0 | <0.1 |
| Water | 337.5 | 40.7 | 1,560.2 | 18.7 | 6,594.3 | 17.3 |
| Total | 829.8 | | 8,345.8 | | 38,216.8 | |

**Table 7.** Percent of land disturbed in Voyageurs National Park and its surroundings by disturbance agent and year (Kirschbaum and Gafvert 2010).

| | | Disturbance Agent | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Analysis Area** | **Year** | ***Beaver*** | ***Blowdown*** | ***Building*** | ***Fire*** | ***Flooding*** | ***Forest Harvest*** | **Total** |
| VOYA | 2002 | 0.08 | 0.09 | 0.00 | 0.00 | <0.01 | 0.00 | 0.17 |
| | 2003 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 |
| | 2004 | 0.03 | 0.00 | 0.00 | 0.23 | 0.00 | 0.00 | 0.25 |
| | 2005 | 0.03 | 0.01 | 0.00 | 0.11 | 0.00 | 0.00 | 0.15 |
| | 2006 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 |
| | 2007 | 0.01 | 0.00 | 0.00 | <0.01 | <0.01 | 0.00 | 0.01 |
| | Total | 0.18 | 0.15 | 0.00 | 0.33 | 0.01 | 0.00 | 0.67 |
| | Average total change yr$^{-1}$ 0.11% | | | | | | | |
| Canada AOA | 2002 | 0.07 | 0.05 | 0.00 | 0.00 | 0.00 | 1.06 | 1.18 |
| | 2003 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 2.34 | 2.36 |
| | 2004 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 1.74 | 1.75 |
| | 2005 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.97 | 0.97 |
| | 2006 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.25 |
| | 2007 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.36 | 0.36 |
| | Total | 0.10 | 0.05 | 0.00 | 0.00 | 0.00 | 6.72 | 6.87 |
| | Average total change yr$^{-1}$ 1.15% | | | | | | | |
| Minnesota AOA | 2002 | 0.01 | 0.06 | <0.01 | 0.00 | 0.00 | 0.50 | 0.57 |
| | 2003 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 1.20 | 1.22 |
| | 2004 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.73 | 0.77 |
| | 2005 | <0.01 | 0.00 | <0.01 | 0.00 | 0.00 | 0.80 | 0.80 |
| | 2006 | 0.00 | 0.00 | <0.01 | 0.00 | 0.00 | 0.48 | 0.48 |
| | 2007 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.41 | 0.44 |
| | Total | 0.06 | 0.06 | 0.05 | 0.00 | 0.00 | 4.13 | 4.29 |
| | Average total change yr$^{-1}$ 0.72% | | | | | | | |

Database (NLCD) was released (Jin et al. 2013); this contained land cover change statistics for 2001–2006 and 2006–2011.

Stueve et al. (2011) investigated the amount of disturbance in the Lake Superior and Lake Michigan basins from 1985–2008 using another computer algorithm called Vegetation Change Tracker (VCT). Kirschbaum and Gafvert (2013) calculated the changes measured by Stueve et al. (2011) for the lower Lake Superior basin as 0.26% yr$^{-1}$ for 1985–1999 and 0.32% yr$^{-1}$ from 2000–2008.

### Reference Condition

The GLKN has identified land use and land cover at the coarse scale as a key Vital Sign across a wide range of ecosystems (ranked 6th of 46 with a score of 3.8 out of 5) (NPS 2007).

Loveland et al. (1999) describe three drivers of land use and land cover changes: natural processes such as wildfire or pest infestation; direct effects of human activity, such as deforestation and road building; and indirect effects of human activity, such as water diversion that lowers a water table. Turner and Meyer (1991, in Loveland et al. 1999) emphasize the importance of distinguishing beneficial from detrimental changes. Frelich (2012) similarly emphasizes that natural landscape processes occur over time, and that maintaining a natural system in a pre-defined condition may not be achievable or even desirable.

Thus, a suitable reference condition might be the stability of the landscape, defined as its capacity to endure chronic stressors and low severity disturbances without undergoing a significant change. However, lacking the detailed, historic data needed to evaluate such a reference condition, we have chosen a reference condition that places VOYA within the context of its region and of other national parks in the region.

The annual land cover change in the VOYA watershed or 30 km AOA should not exceed that measured by Stueve et al. (2011) in the nearby lower Lake Superior basin (0.26% yr$^{-1}$ for 1985–1999 and 0.32% yr$^{-1}$ from 2000–2008), or in other national parks in the western Great Lakes region (0–0.36% yr$^{-1}$). These represent “least disturbed conditions” or the “best of today’s existing conditions” (Stoddard et al. 2006).

### Condition and Trend

↔ Annual land cover change in VOYA since 2001 is within the range of values for the region and for other national parks; thus, we rate the status of VOYA for land cover change as high, with a short-term stable trend. Our confidence in this assessment is high. It should be noted that land cover change over a longer period could produce much larger values.

Kirschbaum and Gafvert (2010) found that from 2002–2007, a total of 0.67% (361 ha) of the land inside the VOYA administrative boundary was disturbed (Table 7); the range among years was 0.01–0.25% yr$^{-1}$, meeting the chosen reference condition of 0.32% yr$^{-1}$. Most of the change was attributable to a fire caused by lightning in 2004 (34% of the total disturbance observed), aftereffects of the fire which continued into 2005 (16%), a blowdown in 2002 (13%), and beaver activity in 2002 (12%). In the Canadian AOA, 3,831 ha (6.87%) were disturbed; forest harvest accounted for 6.72% (98% of the total disturbance observed). Similarly, in the MN AOA, forest harvest accounted for

96% of the 1,622 ha (4.29%) disturbed. The 2011 NLCD showed that from 2001–2006, the level 2 land cover classification changed for 276 ha (0.33%) of the land within VOYA; from 2006–2011, change occurred on 364 ha (0.44%) (USGS 2011, Jin et al. 2013). All these changes were from one natural category to another.

VOYA had a higher rate of disturbance than APIS, ISRO, or MISS over a six-year period, although the periods studied varied in time (Table 8). A six-year window may not capture the infrequent, moderate to severe natural disturbances that can occur in these parks, so this comparison should be made over a longer time frame as the LandTrendr assessments are repeated in the GLKN cycle.

**Table 8.** Disturbance in and around Voyageurs National Park compared to other NPS units in the GLKN (Kirschbaum and Gafvert 2010, 2013 and citations therein).

| **NPS Unit (national park, lakeshore, river, or scenic riverway)** | **In-park % area disturbed** | | **% disturbed area in surrounding analysis area** | | |
|---|---|---|---|---|---|
| | ***Total*** | ***Yearly Range*** | ***Total*** | ***Yearly Range*** | **Time period** |
| VOYA | 0.67 | 0.01–0.25 | 11.2 | 0.73–3.58 | 2002–2007 |
| APIS | <0.1* | 0–0.02 | 3.94 | 0.33–0.98 | 2004–2009 |
| ISRO | <0.1 | 0–0.02 | 2.66 | 0.15–0.61 | 2003–2008 |
| SACN | 1.12 | 0.04–0.36 | 0.85 | 0.11–0.18 | 2005–2010 |
| MISS | 0.28 | 0–0.11 | 0.57 | 0.01–0.22 | 2005–2010 |

*a forest pathogen event which caused defoliation but not mortality was excluded

Sources of Expertise

Kirschbaum and Gafvert (2010); James Cook, Christine Mechenich, UWSP.

Literature Cited

Frelich, L. 2012. Vegetation and landscape change. *In* L. Frelich and S. Windels, editors, Terrestrial Synthesis for Voyageurs National Park. Draft document to Voyageurs National Park, International Falls, Minnesota.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment* 132:159–175. Available at http://www.mrlc.gov/nlcd2011.php (accessed 13 May 2014).

Kirschbaum, A. A., and U. B. Gafvert. 2010. Landsat-based monitoring of landscape dynamics at Voyageurs National Park, 2002–2007. Natural Resource Technical Report. NPS/GLKN/NRTR—2010/356. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2124866 (accessed 5 May 2014).

Kirschbaum, A. A., and U. B. Gafvert. 2013. Landsat-based monitoring of landscape dynamics at Mississippi National River and Recreation Area, 2005–2010. Natural Resource Technical Report NPS/GLKN/NRTR—2013/745. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2195280 (accessed 27 May 2014).

Loveland, T. R., T. Sohl, K. Sayler, A. Gallant, J. Dwyer, J. Vogelmann, G. Zylstra, T. G. Wade, C. M. Edmonds, D. Chaloud, and B. Jones. 1999. Land cover trends: Rates, causes, and consequences of late-twentieth century US land cover change. USEPA, Las Vegas, Nevada. Available at http://www.epa.gov/esd/land-sci/trends/pdf/trends_research_plan.pdf (accessed 6 May 2014).

Monahan, W. B., J. E. Gross, L. K. Svancara, and T. Philippi. 2012. A guide to interpreting NPScape data and analyses. Natural Resource Technical Report NPS/NRSS/NRTR—2012/578. National Park Service, Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/interpguide.cfm (accessed 13 May 2014).

NPS (National Park Service). 2007. Long-term Ecological Monitoring Plan: Great Lakes Inventory and Monitoring Network. Natural Resource Report NPS/GLKN/NRR—2007/001. National Park Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/645523 (accessed 27 May 2014).

Potyondy, J. P., and T. W. Geier. 2011. Watershed condition classification technical guide. Publication FS-978. USDA Forest Service, Washington, D.C. Available at. http://www.fs.fed.us/publications/watershed/watershed_classification_guide.pdf (accessed 27 May 2014).

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

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. 2011. Snow-covered Landsat time series stacks improve automated disturbance mapping accuracy in forested landscapes. *Remote Sensing of Environment* 115:3203–3219.

Turner, B. L. II, and W. B. Meyer, 1991. Land use and land cover in global environmental change: considerations for study. *International Social Science Journal* 130:669–677.

USEPA (United States Environmental Protection Agency) Science Advisory Board. 2002. A framework for assessing and reporting on ecological condition: an SAB report. EPA-SAB-EPEC-02-009. USEPA, Washington, D.C. Available at http://www.epa.gov/sab/pdf/epec02009.pdf (accessed 27 May 2014).

USGS (United States Geological Survey). 2011. National Land Cover Database 2006. USGS, Sioux Falls, South Dakota. Available at http://www.mrlc.gov/nlcd2006.php (accessed 28 November 2011).

USGS (United States Geological Survey), Natural Resources Canada/Canadian Center for Remote Sensing (NRCan/CCRS), Insituto Nacional de Estadística y Geografía (INEGI), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), and Comisión Nacional

Forestal (CONAFOR). 2013. 2005 North American Land Cover at 250 m spatial resolution, version 2. Available at http://landcover.usgs.gov/nalcms.php (accessed 2 April 2014).

### *4.2.2. Impervious Surfaces*

Description

Monahan et al. (2012) reviewed literature on the effects of impervious surfaces on ecosystems and reported thresholds of 2%–10% for effects on stream geomorphology, 10%–15% for effects on fish diversity, and 1%–33% for invertebrate diversity. They further reported impacts to “more sensitive species” at 3%–5% impervious cover and stated that thresholds vary geographically and with a variety of physical and biotic factors. Klein (1979), in a study of 27 small watersheds in Maryland, suggested that watershed impervious surface should not exceed 10% for sensitive stream ecosystems, such as those containing self-sustaining trout populations. Stranko et al. (2008) reported on six eastern Piedmont (Maryland) streams whose watersheds had impervious land cover >4%, as assessed from the 2001 NLCD. Only one of these streams had brook trout.

Data and Methods

We analyzed percent impervious surface using the NLCD 2006 Percent Developed Imperviousness dataset (USGS 2011) for VOYA and the portion of the 30-km AOA on the MN side (such data are not available for the Canadian side of the park).

Reference Condition

Impervious land cover should not exceed 10% within VOYA or its 30-km AOA for the protection of sensitive stream ecosystems. This represents a “least disturbed condition” or “the best of today’s existing conditions” (Stoddard et al. 2006).

Condition and Trend

↔ Within VOYA, 99.9% of the land area is 0% impervious, and the mean impervious value for the park is 0.02%. In the MN AOA, 99.1% is 0%–2% impervious, and the mean impervious value is 0.34%. Our confidence in this assessment is moderate; we have no trend data, but given population and land cover trends previously discussed, we do not expect this condition to change. Also, population and land cover data for the Canadian side leads us to believe that the condition in the Canadian AOA is similar.

Sources of Expertise

Dave Mechenich, Christine Mechenich, UWSP.

Literature Cited

Klein, R. 1979. Urbanization and stream quality impairment. *Water Resources Bulletin* 15:948–963.

Monahan, W. B., J. E. Gross, L. K. Svancara, and T. Philippi. 2012. A guide to interpreting NPScape data and analyses. Natural Resource Technical Report NPS/NRSS/NRTR—2012/578. National Park Service, Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/interpguide.cfm (accessed 13 May 2014).

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

Stranko, S. A., R. H. Hilderbrand, R. P. Morgan II, M. W. Staley, A. J. Becker, A. Roseberry-Lincoln, E. S. Perry, and P. T. Jacobson. 2008. Brook trout declines with land cover and temperature changes in Maryland, North America. *Journal of Fisheries Management* 28:1223–1232.

USGS (United States Geological Survey). 2011. NLCD (National Land Cover Database) 2006 percent developed imperviousness. USGS, Sioux Falls, South Dakota. Available at http://www.mrlc.gov/nlcd06_data.php (accessed 10 September 2012).

### *4.2.3. Landscape Pattern and Structure*

Description

The NPScape project allows for the calculation of metrics for forest density and forest morphology. Forest density is a measure of area-density which describes a very broad habitat category, and forest morphology is a metric that indicates the amount of core habitat vs. edge in a landscape.

NPScape uses the NLCD definition of "forest" to distinguish forest from nonforest cells (Monahan et al. 2012). A grid cell is considered "forest" if the proportion of vegetative cover contributed by woody vegetation generally greater than 5 m tall is at least 20% (http://www.mrlc.gov/nlcd06_leg.php). For the forest density metric, a cell is considered "forest dominant" if at least 60% but <90% of the grid cells surrounding it in a 7 x 7 cell window (4.4 ha) meet the definition for forest. This means that a given window could have anywhere from approx. 12%–90% tree cover, and the cell at its center would meet the definition of "forest dominant." The metric does not distinguish between forest types with natural differences in tree cover, nor between very young forests and mature ones.

The categories with the highest area-density are "dominant" (60%–90%), "interior" (90%–100%), and "intact" (100%). Percolation theory suggests that 60% area-density is a threshold below which a landscape may "flip" from mostly interconnected areas to mostly small, isolated patches (Monahan et al. 2012 and citations therein). Wickham et al. (2007, in Monahan et al. 2012) found area-density to be sensitive to loss in the area of dominant forest, even when patch size distribution was unchanged.

Forest morphology is a metric related to core habitat, which is significant to both biotic and abiotic processes in the landscape (Turner 1989). Edge effects on vertebrates, especially birds, are well known and may include increased nest predation and parasitism and creation of a biological sink (Ries and Sisk 2004). All sharp edges also alter the micro-environment (temperature, relative humidity, and wind) for an appreciable distance into the taller community type (Matlack 1993, Chen et al. 1995). The spatial extent of these influences, and the corresponding changes in vegetation, vary substantially among studies, which have noted differences by aspect, region or forest type, and edge structure (Matlack 1993, Cadenasso and Pickett 2001, Nelson and Halpern 2005). A study in the boreal mixed-wood forest type of Alberta found a distinct aspect effect, with the edge width for shrubs narrowest on the east; shrub and herb abundance varied up to 20 m into the forest (Gignac and Dale 2007). Of particular note is that narrow communities generally contained more alien species, which reached their peak abundance 5–15 m from the forest edge and occurred up to 40 m from the edge (Gignac and Dale 2007). Changes in the size or number of natural habitat patches, or a change in the connectivity between those patches, can lead to loss of diversity of native species, among other effects (Fahrig and Merriam 1985).

### Data and Methods

The degree to which the current habitat of VOYA is intact was assessed using NPScape. Forest density and morphology statistics were calculated for VOYA, its upgradient watershed, and its 30 km AOA. The current version of NPScape data that includes both the US and Canada is from the 2005 NALC, which has a 250 m grid size. This is less detailed than the NLCD data, which has a 30 m grid size. However, the NLCD data is not available for Canada. We used both the NLCD and NALC data for VOYA itself for comparison (NPS 2012).

### Reference Condition

The chosen reference condition for forest density is the historic range of variability. This is a "historic condition" (Stoddard et al. 2006). A reference condition for forest morphology was not established.

### Condition and Trend

As calculated using NPScape and the NLCD data (NPS 2014a), 57.6% of VOYA is covered with dominant to intact forest (Table 9). However, 35.8% of VOYA is covered by open water, and 4.5% is covered by herbaceous wetlands. Of the NLCD grid cells that are characterized as forest (deciduous, evergreen, and mixed forests and woody wetlands), 55.7% are intact (100% forest), and 93.9% are dominant to intact (60%–100% forest).

The main factor limiting the amount of intact forest in VOYA is the presence of open water and wetlands. This can be seen by visually comparing the map of forest density (Figure 10) to the land cover map for VOYA (Figure 9). Forest areas within VOYA not characterized as intact forest are generally bordering open water, herbaceous wetlands, or shrub/scrub/grassy areas. Figure 11 is a detailed view of forest density in the vicinity of Locator and War Club Lakes. Areas characterized as background, rare, or patchy forest are near the centers of the lakes or herbaceous wetlands. Areas of shrub/scrub/grass also create patches of less dense forest in the overall landscape mosaic. Some of these forest openings may be related to natural or human-caused disturbance, but Kirschbaum and Gafvert (2010) found a very low level of disturbance within VOYA.

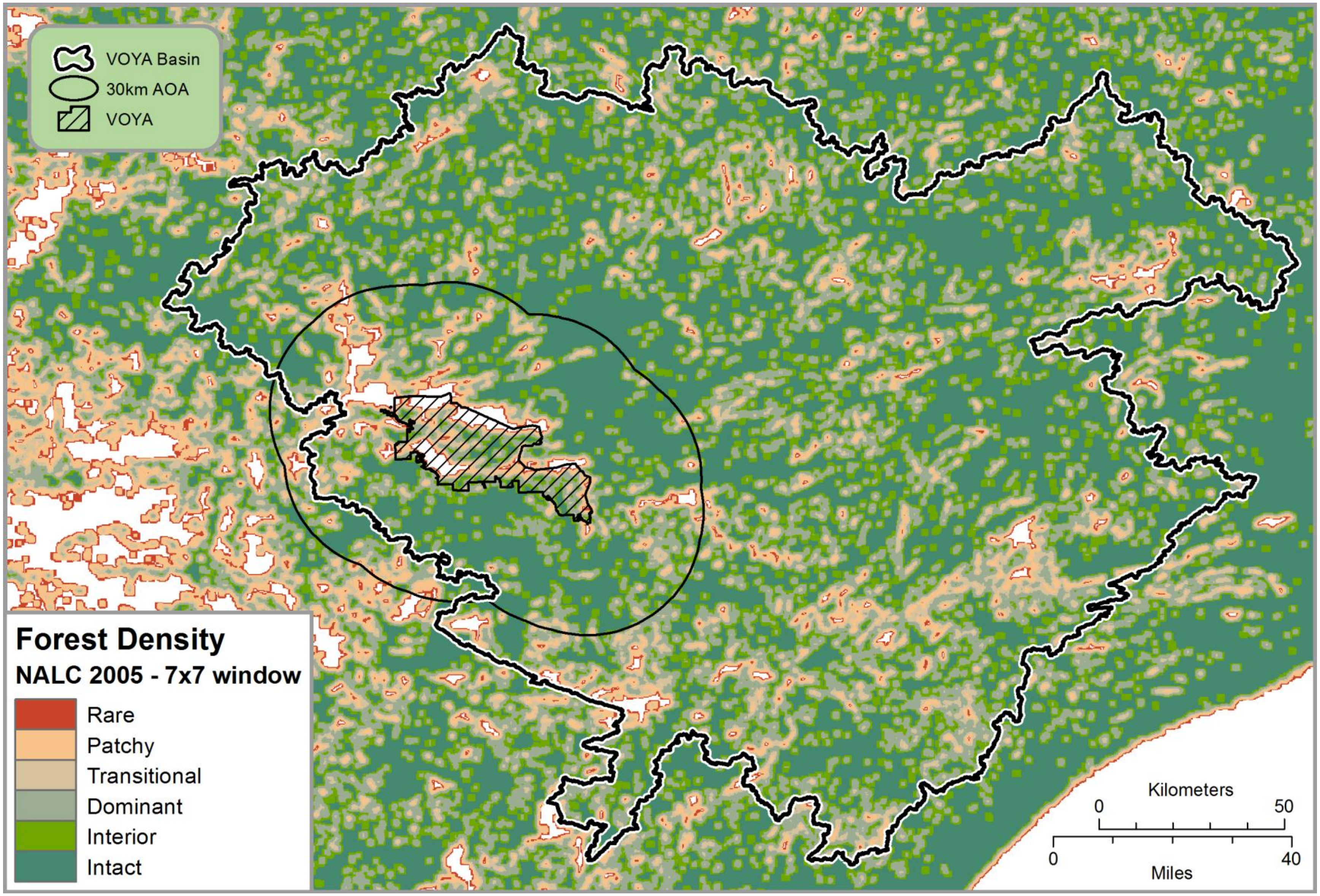

**Figure 10.** Forest density in the vicinity of Voyageurs National Park (NPS 2012).

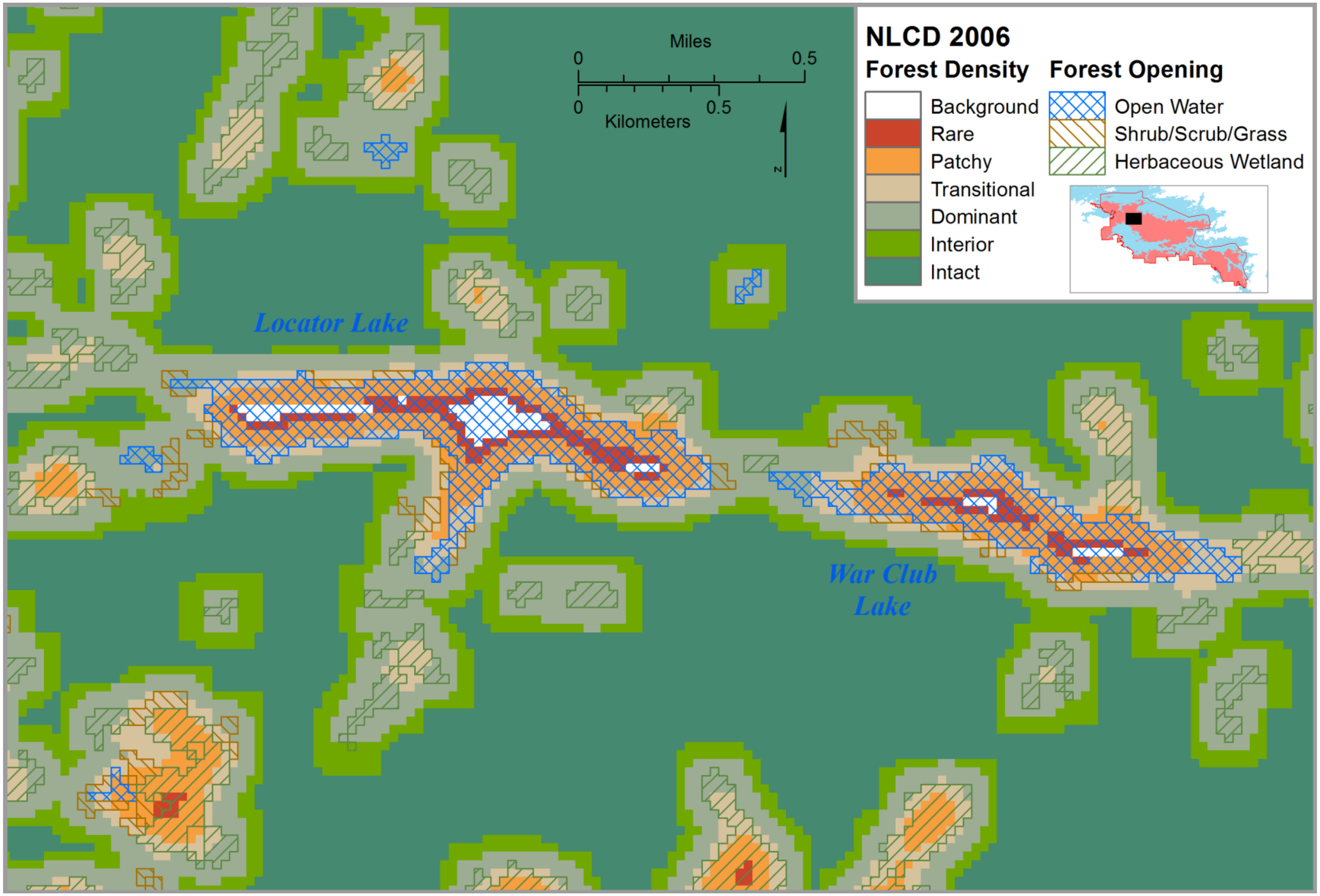

**Figure 11.** Detailed view of the distribution of intact forest around Locator Lake in Voyageurs National Park (USGS 2011, NPS 2012).

**Table 9.** Forest density metric for Voyageurs National Park, its upgradient watershed, and its 30 km AOA (NPS 2012).

| | | **NCLD 30 m grid** | | | | **NALC 250 m grid** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Density Class Name** | **Area-Density for Forest Cover (p)** | ***VOYA (forest only)*** | | ***VOYA*** | | ***VOYA*** | | ***VOYA 30 km AOA*** | | ***VOYA Watershed*** | |
| | | *km²* | *%* | *km²* | *%* | *km²* | *%* | *km²* | *%* | *km²* | *%* |
| Background | p = 0% | <1.0 | <1.0 | 202.6 | 24.4 | 143.7 | 17.3 | 385.1 | 4.6 | 573.0 | 1.5 |
| Rare | 0% < p < 10% | <1.0 | <1.0 | 26.4 | 3.2 | 53.6 | 6.5 | 222.3 | 2.7 | 439.4 | 1.1 |
| Patchy | 10% ≤ p < 40% | 6.6 | 1.4 | 69.8 | 8.4 | 146.4 | 17.7 | 785.2 | 9.4 | 2,177.8 | 5.7 |
| Transitional | 40% ≤ p < 60% | 23.7 | 4.9 | 52.6 | 6.3 | 110.5 | 13.3 | 727.5 | 8.7 | 2,892.0 | 7.6 |
| Dominant | 60% ≤ p < 90% | 105.8 | 21.7 | 124.9 | 15.1 | 220.9 | 26.7 | 1,910.0 | 22.9 | 9,910.2 | 25.9 |
| Interior | 90% ≤ p < 100% | 80.5 | 16.5 | 80.9 | 9.8 | 97.8 | 11.8 | 1,311.4 | 15.7 | 7,791.3 | 20.4 |
| Intact | p = 100% | 271.9 | 55.7 | 271.9 | 32.8 | 56.1 | 6.8 | 3,003.6 | 36.0 | 14,435.4 | 37.8 |
| Subtotal – Dominant to Intact | | 458.2 | 93.9 | 477.8 | 57.6 | 374.8 | 45.2 | 6,225.0 | 74.6 | 32,136.9 | 84.1 |
| Total | | 488.4 | | 829.2 | | 829.0 | | 8,345.1 | | 38,219.1 | |

At the 250 m grid scale of the NALC data, the proportion of dominant to intact forest in VOYA decreases to 45.2%. This is a natural consequence of using a larger grid size. In this larger landscape context, the proportion of dominant to intact forest in the 30-km AOA and upgradient watershed is 74.6% and 84.1%, respectively. Thus, VOYA exists in a landscape of largely dominant forest habitat.

● However, three of the dominant forest types at VOYA had severe fires as part of their historic disturbance regime (Section 4.1.1. Frelich 2012). The intervals for these fires ranged from 100 or more years for aspen-birch-conifer to 250–500 years for Jack pine-oak-aspen. In almost all cases, a severe fire would have reduced the canopy cover to a very low value, almost certainly below the NPScape definition of forest. We do not know the size distribution of these fires, but a severe fire rarely stays small. Frelich (2002) estimated that the average size of fire in the ‘southern boreal’ region was 4,000 ha. Thus, after these severe fires, large section of the landscape would change from ‘forest’ to non-forest. For these reasons, it is likely that the current level of forest cover (approx. 94%) is at the upper end of, or outside, the historic range of variability for land cover and is of moderate concern. No trend was determined. Our level of confidence in this assessment is moderate.

We next examined landscape-level data regarding forest morphology with an NPScape SOP (NPS 2014b) that uses Morphological Spatial Pattern Analysis (MSPA). This process uses image segmentation to classify individual grid cells in binary (forest/nonforest) maps into a set of pattern types (Figure 12).

In NPScape, the eight basic landscape pattern types are core, islet, perforation, edge, loop, bridge or corridor, branch, and background (Monahan et al. 2012).

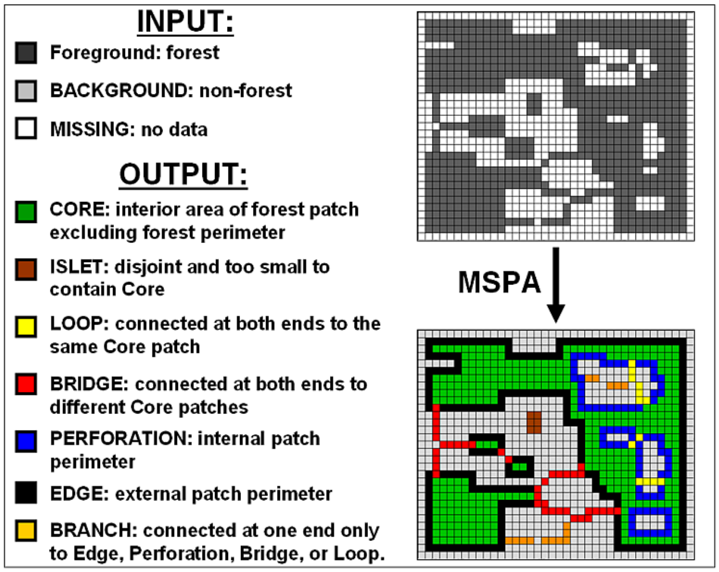

**Figure 12.** Explanation of Morphological Spatial Pattern Analysis (figure obtained from http://ies.jrc.ec.europa.eu/news/108/354/Highlight-November-2009/d,ies_highlights_details.html).

The results, which are a snapshot of NLCD forest morphology in 2006 for VOYA, the upgradient watershed, and the AOA, indicate that using a 30 m edge width, 48.7% of VOYA was core forest, and 4.1% was edge (Table 10). Background (not forest) was 41.1%, and the remaining 6.1% was in one of five categories (branch, islet, bridge, perforated, or loop) that identified it as an area that was either a type of connector between core forest areas or too small to be core forest.

**Table 10.** Forest morphology metrics for Voyageurs National Park, its upgradient watershed, and its 30 km AOA (NPS 2012).

| | VOYA | | VOYA | | VOYA 30 km AOA | | VOYA Watershed | |
|---|---|---|---|---|---|---|---|---|
| | NLCD 2006 | | | | NALC 2005 | | | |
| | 30 m edge width | | | | 250 m edge width | | | |
| **Morphology Class Name** | ***km$^2$*** | ***%*** | ***km$^2$*** | ***%*** | ***km$^2$*** | ***%*** | ***km$^2$*** | ***%*** |
| Background | 340.8 | 41.1 | 420.6 | 50.7 | 2,065.1 | 24.7 | 6,726.9 | 17.6 |
| Branch | 7.3 | 0.9 | 19.8 | 2.4 | 153.8 | 1.8 | 571.6 | 1.5 |
| Edge | 34.3 | 4.1 | 115.3 | 13.9 | 526.1 | 6.3 | 921.6 | 2.4 |
| Islet | 1.5 | 0.2 | 1.9 | 0.2 | 17.5 | 0.2 | 30.8 | 0.1 |
| Core | 403.6 | 48.7 | 235.3 | 28.4 | 4,884.6 | 58.5 | 24,706.6 | 64.6 |
| Bridge | 1.1 | 0.1 | 10.1 | 1.2 | 58.9 | 0.7 | 300.3 | 0.8 |
| Perforated | 37.4 | 4.5 | 14.6 | 1.8 | 560.1 | 6.7 | 4,629.3 | 12.1 |
| Loop | 3.4 | 0.4 | 11.6 | 1.4 | 79.1 | 0.9 | 330.9 | 0.9 |
| Total | 829.3 | | 829.3 | | 8,345.1 | | 38,217.9 | |

With an edge width of 250 m, there is less core forest and more edge. Using the NALC data, which provides a snapshot of conditions in 2005, the VOYA upgradient watershed and AOA have more core forest (64.6% and 58.5%, respectively) than does VOYA at that scale (28.4%). Thus, VOYA exists in a region in which more than half the landscape is in core forest. As with forest density, the pattern of forest morphology strongly mirrors the pattern of open water and wetlands on the landscape (Figure 13).

The historic occurrence of severe fires, supplemented by the occasional wind events, would have also played a major role in the forest morphology of the VOYA landscape. Studies after the infamous 1988 fires in Yellowstone National Park documented a surprising range of impacts on the overstory and the production of a habitat mosaic in many areas (Turner et al. 2003). Thus, the average patch size was smaller than expected after a severe (stand replacing) fire, and the connectivity of the landscape was strongly altered. It is not possible to quantify the historic forest morphology at VOYA with the information available. For this reason, and because of the variability of species response (positive, negative, or neutral) to edge (Ries and Sisk 2004), a reference condition for forest morphology was not established.

Sources of Expertise

Monahan et al. (2012); James Cook, Dave Mechenich, Christine Mechenich, UWSP.

Literature Cited

Cadenasso, M. L., and S. T. A. Pickett. 2001. Effect of edge structure on the flux of species into forest interiors. *Conservation Biology* 15:91–97.

Chen, J., J. F. Franklin, and T. A. Spies. 1995. Growing-season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. *Ecological Applications* 5:74–86.

Fahrig, L., and G. Merriam. 1985. Habitat patch connectivity and population survival. *Ecology* 66:1762–1768.

Frelich, L. E. 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen-Deciduous Forests. Cambridge University Press, New York, New York.

Frelich, L. 2012. Vegetation and landscape change. *In* L. Frelich and S. Windels, editors, Terrestrial Synthesis for Voyageurs National Park. Draft document to Voyageurs National Park, International Falls, Minnesota.

Gignac, L. D., and M. R. T. Dale. 2007. Effects of size, shape, and edge on vegetation in remnants of the upland boreal mixed-wood forest in agro-environments of Alberta, Canada. *Canadian Journal of Botany* 85:273–284.

Kirschbaum A. A., and U. B. Gafvert. 2010. Landsat-based monitoring of landscape dynamics at Voyageurs National Park, 2002–2007. Natural Resource Technical Report. NPS/GLKN/NRTR—2010/356. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2124866 (accessed 5 May 2014).

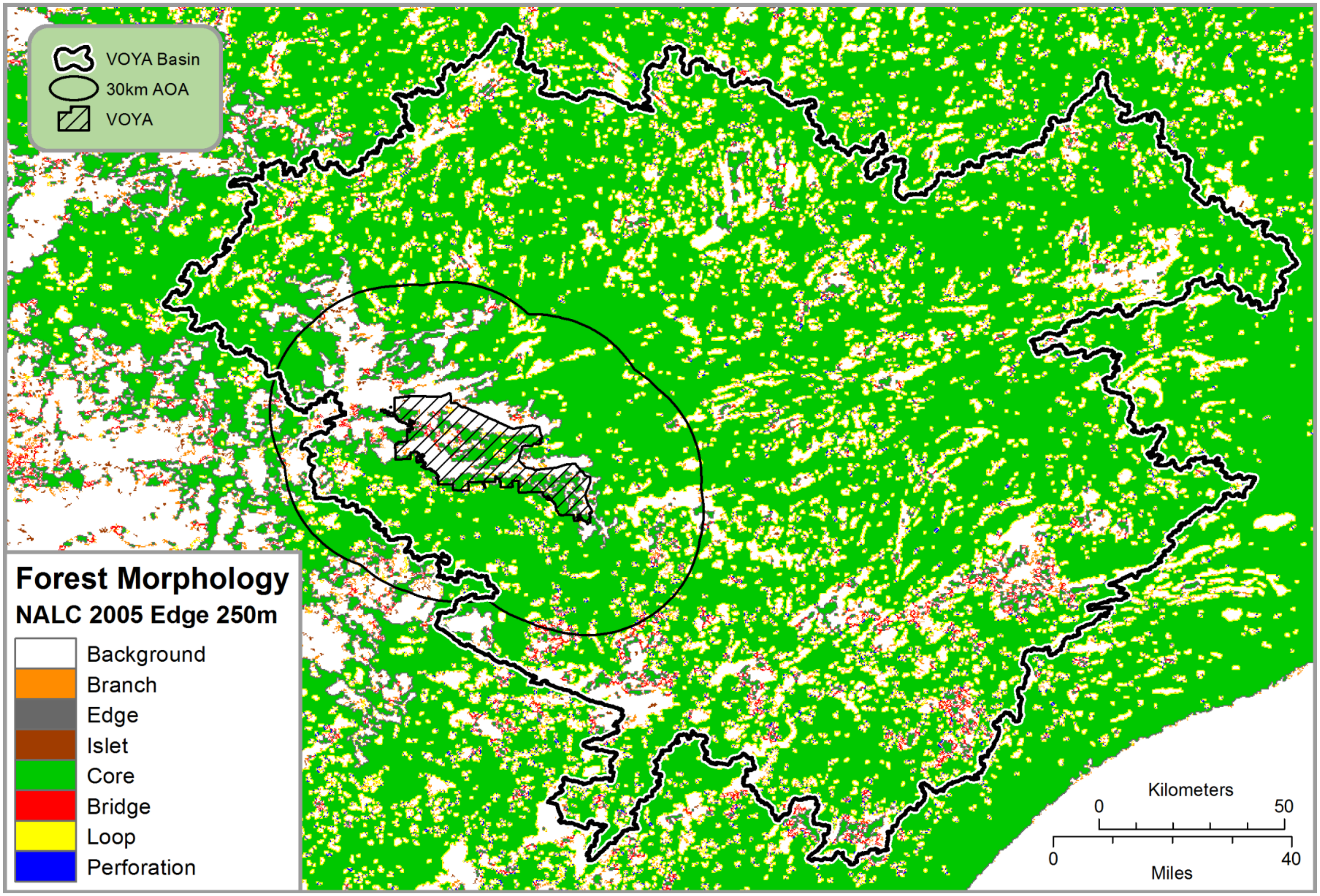

**Figure 13.** Forest morphology in the vicinity of Voyageurs National Park (NPS 2012).

Matlack, G. R. 1993. Microenvironment variation within and among forest edge sites in the eastern United States. *Biological Conservation* 66:185–194.

Monahan, W. B., J. E. Gross, L. K. Svancara, and T. Philippi. 2012. A guide to interpreting NPScape data and analyses. Natural Resource Technical Report NPS/NRSS/NRTR—2012/578. National Park Service, Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/interpguide.cfm (accessed 13 May 2014).

Nelson, C. R., and C. B. Halpern. 2005. Short-term effects of timber harvest and forest edges on ground-layer mosses and liverworts. *Canadian Journal of Botany* 83:610–620. Available at http://www.cfc.umt.edu/nelsonrestorationlab/files/Pubs/CRNelson%20and%20Halpern_bot63.pdf (accessed 5 August 2013).

NPS (National Park Service). 2012. NPS Natural Resource Stewardship and Science Inventory and Monitoring Division. NPScape Metric GIS Data—Landscape pattern. Geospatial Dataset-2184565. Available at https://irma.nps.gov/App/Reference/Profile/2184565 (accessed 11 December 2013 for NLCD and 31 March 2014 for NALC).

NPS (National Park Service). 2014a. NPScape standard operating procedure: Pattern measure—Area density. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/methods_sops.cfm (accessed 8 August 2014).

NPS (National Park Service). 2014b. NPScape standard operating procedure: Pattern measure—Morphology. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/methods_sops.cfm (accessed 8 August 2014).

Ries, L., and T. D. Sisk. 2004. A predictive model of edge effects. *Ecology* 85:2917–2926.

Turner, M. G. 1989. Landscape ecology: the effect of pattern on process. *Annual Review of Ecology and Systematics* 20:171–197.

Turner, M. G., W. H. Romme, and D. B. Tinker. 2003. Surprises and lessons from the 1988 Yellowstone fires. *Frontiers in Ecology and the Environment* 1:351–358.

USGS (United States Geological Survey). 2011. NLCD (National Land Cover Database) 2006 percent developed imperviousness. USGS, Sioux Falls, South Dakota. Available at http://www.mrlc.gov/nlcd06_data.php (accessed 10 September 2012).

Wickham, J. D., K. H. Riitters, T. G. Wade, and J. W. Coulston. 2007. Temporal change in forest fragmentation at multiple scales. *Landscape Ecology* 22:481–489.

### *4.2.4. Road Density*

Description

An extensive body of literature has documented the effects of roads on both terrestrial and aquatic environments. Gross et al. (2009) stated that "Even in areas where human population densities are relatively low and landscapes are perceived as natural, the impacts of roads are pervasive and may extend hundreds to thousands of meters from the roadside."

Roads have a wide variety of ecological effects, including altered hydrology, increased erosion, habitat segregation, migration barriers, and direct mortality (Forman and Alexander 1998). For mammals, noise may be more important than collisions due to its effect on behavior. A full evaluation of the effect of roads must include the 'road-effect zone', not just the road and associated altered habitat (Forman and Alexander 1998). For large mammals in woodland areas, this typically extends 100–200 m out from the road. Physical and biological effects of roads are summarized in Table 11.

VOYA is home to a number of large mammals that may be influenced by road density, including the moose (*Alces alces*), gray wolf (*Canis lupus*), American black bear (*Ursus americanus*), and the federal-threatened Canada lynx (*Lynx canadensis*). Forman and Alexander (1998) stated that large and mid-sized mammals are especially susceptible to two-lane, high-speed roads. Though animals generally stay 500 m or more away from roads, some herbivores may be drawn to the road corridor due to a different vegetative complex, ease of access, phenology of the vegetation, and nutrition; predators may use them due to enhanced prey abundance. These results, as well as the species-specific results that follow, should be applied with caution at VOYA because most came from other regions. The landscape context of each study is pertinent. Over time, a population/species may change its tolerance of humans and human-generated habitat features.

**Table 11.** Pervasive effects of roads on natural resources, park visitors, and park operations (adapted from Gross et al. 2009).

| Physical Effects | Biological Effects |
|---|---|
| Alter temperature, humidity, and other weather attributes | Increase mortality |
| Increase rate and amount of water runoff | Physical barrier to movement |
| Alter surface and ground water flows | Habitat loss |
| Alter rates of sediment and nutrient dispersal | Habitat fragmentation |
| Runoff of chemicals applied to road surface | Behavioral avoidance of disturbances |
| Alter geological and soil substrates | Corridor for invasive species |
| Increase production and propagation of noise | Indirect effects like poaching, fire ignition |
| Alter light | Noise interference with species communication |
| Increase trash in area | Habitat alteration |

Data and Methods

Road metrics were based on the Ontario Road Network (LIO 2001/2010) and MN Department of Transportation basemap roads (MDNR 2002) and calculated according to methods delineated in the NPScape Roads Measure SOP (NPS 2014). We calculated metrics for "major roads" (which are our best estimate of the U.S Census A10-A38 Feature Class Codes for primary, state, and county roads and for "all roads." We focused on the metrics for "all roads" because even that broad category met the chosen reference conditions. Trails were not used for the metric calculation. Road density calculations are based on a one $km^2$ cell size.

Laurian et al. (2008) monitored moose movement by capturing adult moose and attaching radio collars on 47 individuals over a 3-year period. The locations used by the collared animals were overlain on 1:20,000 digital maps to determine proximity to roads suitable for motor vehicle travel. The study was conducted in a wildlife reserve in Quebec. The moose density had increased in recent years and was estimated at 0.22 moose $km^{-2}$. The road densities in the region were determined to be 0.06 km $km^{-2}$ for highways and 0.16 km $km^{-2}$ for forest roads. The forests in the region were described as “typical of the boreal region” with balsam fir and black spruce dominating the uplands.

Movement of collared moose in Quebec indicated strong avoidance of all types of roads, but their behavior was affected more by highways (Laurian et al. 2008). This is consistent with the review of Forman and Alexander (1998), which stated that large and mid-sized mammals are especially susceptible to two-lane, high-speed roads. Though animals generally stayed 500 m or more away from roads, 20% of the moose made visits within 50 m of highways. These occurred primarily in spring and summer. Laurian et al. (2008) interpret their results to indicate that moose interact with roads at two scales: at a coarse scale they avoid roads, but at a local scale they may preferentially use road right-of-ways to address a dietary need. As documented in other studies (e.g., Leblond et al. 2007), Laurian et al. (2008) found significantly higher levels of sodium in the vegetation near roads compared to that farther away.

Moose make fairly extensive use of recently disturbed areas for foraging (Peek et al. 1976, Rempel et al. 1997, Lenarz et al. 2011). Rempel et al. (1997) used Landsat cover data and 16 years of aerial surveys to document moose use in five regions of Ontario. The regions differed in type of disturbance (fire versus harvesting), road density, and hunter access. In general, population growth is enhanced equally by recent fire or harvesting, but when road density goes up substantially, the population can be repressed by increased hunter use (Rempel et al. 1997).

Peek et al. (1976) combined aerial surveys and ground censuses to determine habitat selection by moose over a 3-year period in the Boundary Waters Canoe Area. Joyce and Mahoney (2001) examined historic records of moose-vehicle collisions in Newfoundland to determine if time of day, season, road condition, visibility, or moose gender influenced the likelihood of a collision. Seventy percent or more of recorded moose-vehicle collisions occurred between dusk and dawn and between June and October (Joyce and Mahoney 2001). Part of the reason for the seasonal pattern is that moose use a much smaller home range in winter than summer (Cederlund and Okarma 1988), and the habitats they most use also shift, with greater use of upland conifer forests (Peek et al. 1976).

These results should be applied with caution in northeastern Minnesota, because most came from other regions. The landscape context of each study is pertinent; the annual home range of 29 moose in northeastern Minnesota was 32.8 $km^2$ (Lenarz et al. 2011), but adult females in Sweden averaged 12.6 $km^2$ (Cederlund and Okarma 1988). Populations of moose in rural and more wild areas do not always respond the same to roads as moose in more urban settings, and benefits other than sodium can be provided by roads (Laurian et al. 2008). Over time, a population/species may change its tolerance of humans and human-generated habitat features. We currently lack context-specific data to establish minimum road-density thresholds for moose in northeastern Minnesota; however, the levels noted in Quebec (Laurian et al. 2008) are a reasonable first approximation.

Mladenoff et al. (1995) used data collected by radio collaring gray wolves to establish predictors of preferred habitat in northern Wisconsin and the upper peninsula of Michigan; road density had the greatest explanatory effect. Further work on the model (Mladenoff et al. 1999) indicated that it applied well in the larger Great Lakes region, including Minnesota. Mladenoff et al. (1995) cited areas of low human contact as important to recovering or colonizing gray wolf populations. They stated that in the northern Great Lakes region, few portions of any pack territory were located in areas of road density >0.45 km $km^{-2}$, and none were in areas of road density >1.0 km $km^{-2}$. Potvin et al. (2005) predicted a road density threshold of 0.7 km $km^{-2}$ along with a deer density threshold of 2.3–5.8 deer $km^{-2}$ for successful wolf occupation of areas in upper Michigan.

Mladenoff et al. (1995) noted that the existence of roads is not in itself problematic for wolves, but that road density serves as an index to human contact, which has meant “high levels of legal, illegal, and accidental killing of wolves.” They noted that wolves had moved into territory formerly thought to be marginal in northern MN; for example, where road densities exceeded 0.7 km $km^{-2}$. Where wolves were “present and tolerated by humans,” adequate prey density appeared to be the major limiting factor for wolves. Similarly, Merrill (2000) reported on an area in central MN where wolves were breeding successfully in an area with a road density of 1.42 km $km^{-2}$. The rapid expansion of the wolf population in WI eastward and southward supports the suggestion that wolves are tolerant of road densities higher than 0.45 km $km^{-2}$ (Wydeven et al. 2012).

In a study of variables predicting lynx occurrence in the eastern United States, Hoving et al. (2005) observed that the effect of road density on lynx occurrence switched between positive and negative associations in 19 logistic regression models and was inconclusive. However, among the top six models, three showed a positive association with roads, and none showed a negative association.

Moen et al. (2010) analyzed data collected from a radio collar study tracking 12 Canada lynx between 2003 and 2009. The authors found that when lynx made long-distance movements through roaded areas of the Superior National Forest in northeastern MN, over 2/3 of their locations were within 200 m of a road, trail, or other linear feature. When traveling near paved roads, lynx tended to stay within 15 m of the road. Lynx also tended to stay within 200 m of roads within their home ranges. The authors attributed this finding to the “energetic efficiency” of moving along a road rather than through a forest. They suggested that the road and trail network increased the connectivity of parts of the forest and enabled lynx to travel longer distances. They also noted the risk of lynx mortality due to increased human contact along roads, although none occurred during their study.

Obbard et al. (2010) examined black bear habitat selection on the Bruce Peninsula between Lake Huron and Georgian Bay in southern Ontario. The authors showed that all age classes of bears showed less use of areas in close proximity to settlement and developed areas. Subadult bears avoided roads during spring to summer but selected for them during late summer to fall. The authors noted that traffic on the roads was highest in spring and that berries eaten by bears were available along the roads in late summer. Martin et al. (2010) found that in Sweden, female brown bears (*Ursus arctos*) used areas of steep slopes to avoid contact with humans during daylight hours, but visited roadsides at night to consume vegetation and ants.

Beringer et al. (1990) found that an interstate road in the Pisgah National Forest in North Carolina appeared to act as a barrier to black bear movement, but Class II (75 vehicles day$^{-1}$) and Class III (15 vehicles day$^{-1}$) roads were crossed equally by bears. Brody (1994) conducted a regression analysis relating the number of times individual black bears crossed roads to the density of roads in their home ranges. He indicated that bear movements may begin to be restricted by logging road densities of 1.25 km km$^{-2}$ and open improved road densities of 0.5 km km$^{-2}$.

Reference Condition

For moose, the reference condition is the existence of areas at least 10 km$^2$ in size that are at least 500 m from roads. For gray wolves and black bears, the reference condition is the existence of areas with a road density of <0.7 and <0.5 km km$^{-2}$, respectively. These reference conditions are based on observations of the presence or absence of these species under varying road density conditions and reported in the peer-reviewed literature. This represents a “least disturbed condition” (Stoddard et al. 2006).

We did not establish a reference condition for road density for Canada lynx because Hoving et al. (2005) observed that the direction of the effect of road density with lynx occurrence switched between positive and negative associations in 19 logistic regression models and was inconclusive. Moen and Windels (2009) reported that the net effect of roads and trails on lynx habitat in VOYA could not be determined without further study.

Condition and Trend

⇔ For all roads, road densities of <0.5 km km$^{-2}$ were found in 99.0% of VOYA, 82.9% of the 30 km AOA, and 78.9% of the VOYA watershed (NPS 2014); these areas meet the reference condition for black bear habitat. Road densities of <0.7 km km$^{-2}$ were found in 99.2% of VOYA, 84.6% of the AOA, and 81.1% of the VOYA watershed; these areas meet the reference condition for gray wolf habitat. The most abundant road density categories for all roads is “no roads” (98.7% for VOYA, 78.1% for the AOA, and 73.1% for the watershed). Areas at least 10 km$^2$ in size that are at least 500 m from roads make up 99.5% of VOYA, 93.9% of the AOA, and 96.1% of the watershed (Figure 14); these areas meet the reference condition for moose habitat. Given the relatively stable population trends in the basin (see section 2.1.3. ), these conditions are expected to be stable. Our confidence in this assessment is high.

Sources of Expertise

NPScape website; Dave Mechenich, James Cook, Christine Mechenich, UWSP.

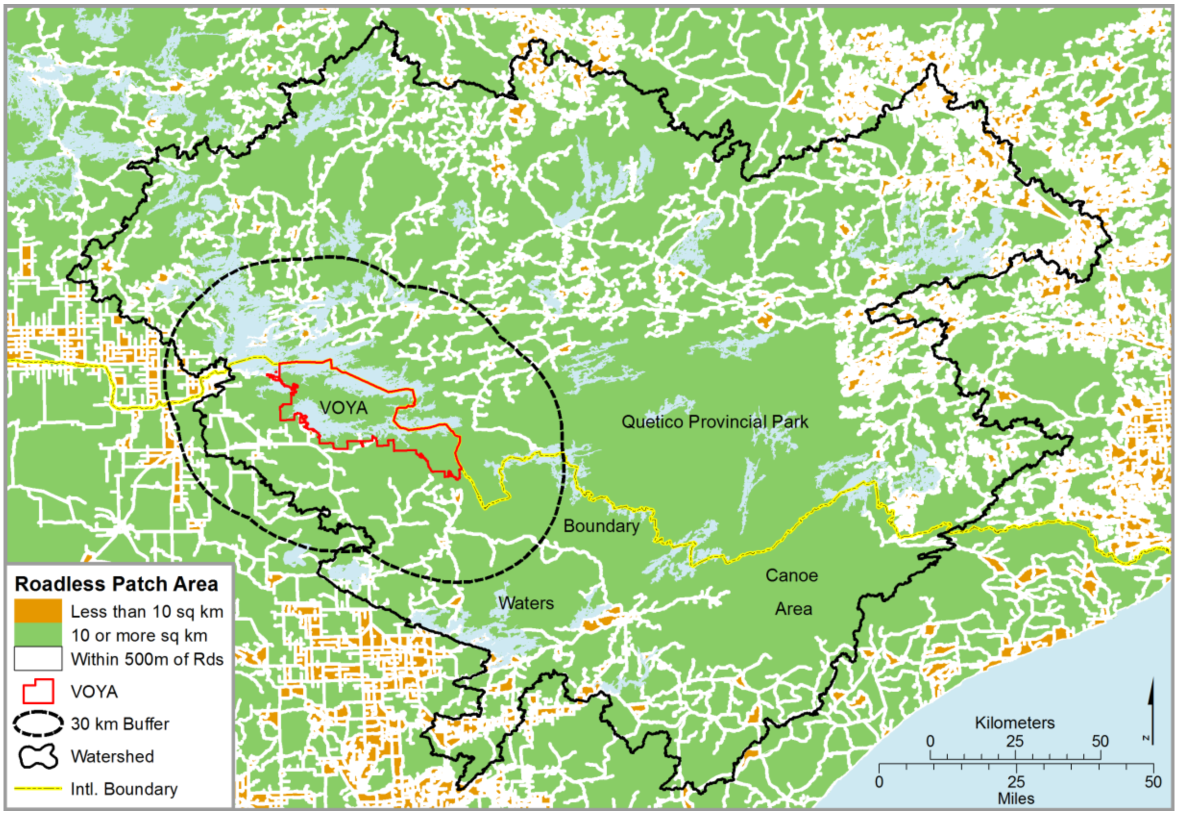

**Figure 14.** Roadless patches by area in the vicinity of Voyageurs National Park (NPS 2014).

## Literature Cited

Beringer, J. J., S. G. Seibert, and M. R. Pelton. 1990. Incidence of road crossing by black bears on Pisgah National Forest, North Carolina. Pages 85–92 *in* L. M. Darling and W. R. Archibald, editors. Bears—their biology and management: proceedings of the Eighth International Conference on Bear Research and Management, Victoria, British Columbia, 20–25 February 1989. Available at http://www.bearbiology.com/index.php?id=ursvol8 (accessed 13 May 2014).

Brody, A. J. 1984. Habitat use by black bears in relation to forest management in Pisgah National Forest, North Carolina. Master's Thesis, University of Tennessee. Available at http://trace.tennessee.edu/utk_gradthes/1235 (accessed 12 May 2014).

Cederlund, G. N., and H. Okarma. 1988. Home range and habitat use of adult female moose. *Journal of Wildlife Management* 52:336–343.

Forman, R. T. T., and L. E. Alexander. 1998. Roads and their major ecological effects. *Annual Review of Ecology and Systematics* 29:207–231.

Gross, J. E., L. K. Svancara, and T. Philippi. 2009. A guide to interpreting NPScape data and analyses. NPS/IMD/NRTR—2009/IMD/XXX. National Park Service, Fort Collins, Colorado. Available at http://www.cfc.umt.edu/CESU/Reports/NPS/UID/2008/08_09Scott_IM_landscape%20metrics_finalrpt.pdf (accessed 13 May 2014).

Hoving, C. L., D. J. Harrison, W. B. Krohn, R. A. Joseph, and M. O'Brien. 2005. Broad-scale predictors of Canada lynx occurrence in eastern North America. *Journal of Wildlife Management* 69:739–751.

Joyce, T. L., and S. P. Mahoney. 2001. Spatial and temporal distributions of moose-vehicle collisions in Newfoundland. *Wildlife Society Bulletin* 29:281–291.

Laurian, C., C. Dussault, J. Ouellet, R. Courtois, M. Poulin, and L. Breton. 2008. Behavior of moose relative to a road network. *Journal of Wildlife Management* 72:1550–1557.

Leblond, M., C. Dussault, J. Ouellet, R. Courtois, M. Poulin, and J. Fortin. 2007. Electric fencing as a measure to reduce moose-vehicle collisions. *Journal of Wildlife Management* 71:1695–1703.

Lenarz, M. S., R. G. Wright, M. W. Schrage, and A. J. Edwards. 2011. Compositional analysis of moose habitat in northeastern Minnesota. *Alces* 47:135–149.

LIO (Land Information Ontario). 2001 (2010 revision). Ontario road network segment with address. Land Information Ontario, Peterborough, Ontario. Available at http://www.mnr.gov.on.ca/en/Business/LIO/index.html (accessed 15 May 2014).

Martin, J., M. Basille, B. Van Moorter, J. Kindberg, D. Allainé, and J. E. Swenson. 2010. Coping with human disturbance: spatial and temporal tactics of the brown bear (*Ursus arctos*). *Canadian Journal of Zoology* 88:875–883.

MDNR (Minnesota Department of Natural Resources) MIS Bureau. 2002. DOT Basemap roads – all types. MDNR, St. Paul, Minnesota. Available at http://deli.dnr.state.mn.us (accessed 16 May 2014).

Merrill, S. B. 2000. Road densities and wolf, *Canis lupus*, habitat suitability: an exception. *Canadian Field-Naturalist* 114:312.

Mladenoff, D. J., T. A. Sickley, R. G. Haight, and A. P. Wydeven. 1995. A regional landscape analysis and prediction of favorable gray wolf habitat in the northern Great Lakes region. *Conservation Biology* 9:279–294.

Mladenoff, D. J., T. A. Sickley, and A. P. Wydeven. 1999. Predicting gray wolf landscape recolonization: logistic regression models vs. new field data. *Ecological Applications* 9:37–44. Available at http://landscape.forest.wisc.edu/PDF/Mladenoff_etal1999_EA.pdf (accessed 13 May 2014).

Moen, R., and S. K. Windels. 2009. Lynx habitat suitability in and near Voyageurs National Park. NRRI Technical Report No. NRRI/TR-2009/19, Release 1.0. Natural Resources Research Institute, University of Minnesota, Duluth, Minnesota. Available at http://www.nps.gov/voya/naturescience/voya-lynx.htm (accessed 27 May 2014).

Moen, R., L. Terwilliger, A. R. Dohmen, and S. C. Catton. 2010. Habitat and road use by Canada lynx making long-distance movements. NRRI Technical Report No. NRRI/TR-2010-02 Release 1.0. Natural Resources Research Institute, University of Minnesota, Duluth, Minnesota. Available at http://www.nrri.umn.edu/lynx/publications/Moen_etal_NRRI_TR_2010_02.pdf (accessed 13 May 2014).

NPS (National Park Service). 2014. NPScape standard operating procedure: Roads measure –road density, distance from roads, and areas without roads. Version 2014-01-06. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/methods_sops.cfm (accessed 6 May 2014).

Obbard, M. E., M. B. Coady, B. A. Pond, J. A. Schaefer, and F. G. Burrows. 2010. A distance-based analysis of habitat selection by American black bears (*Ursus americanus*) on the Bruce Peninsula, Ontario, Canada. *Canadian Journal of Zoology* 88:1063–1076.

Peek, J. M., D. L. Urich, and R. J. Mackie. 1976. Moose habitat selection and relationships to forest management in northeastern Minnesota. *Wildlife Monographs* 48.

Potvin, M. J., T. D. Drummer, J. A. Vucetich, D. E. Beyer, Jr., R. O. Peterson, and J. H. Hammill. 2005. Monitoring and habitat analysis for wolves in upper Michigan. *Journal of Wildlife Management* 69:1660–1669.

Rempel, R. S., P. C. Elkie, A. R. Rodgers, and M. J. Gluck. 1997. Timber-management and natural disturbance effects on moose habitat: landscape evaluation. *Journal of Wildlife Management* 61:517–524.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

Wydeven, A. P., J. E. Wiedenhoeft, and J. Bruner. 2012. Gray wolf population, 2011–2012. Wisconsin Department of Natural Resources, Madison, Wisconsin. Available at http://dnr.wi.gov/topic/wildlifehabitat/documents/reports/graywolfpop.pdf (accessed 13 May 2014).

### *4.2.5. Lightscapes*

Description

The NPS uses the term “natural lightscape” for those resources and values that exist in the absence of human-caused light at night (NPS 2013). Through its management policies (NPS 2006), the NPS directs VOYA and all other NPS units to preserve, to the greatest extent possible, the natural lightscapes and thus avoid light pollution. The GLKN recognizes the importance of natural lightscapes as a Vital Sign; it received a rank of 2.3 on a 5-point scale (45th of 46 Vital Signs) (NPS 2007).

Longcore and Rich (2004) distinguish between "astronomical light pollution," which affects the ability of people to see the stars and is a degradation of human views of the night sky, and "ecological light pollution," which alters the natural light regimes of terrestrial and aquatic ecosystems. For NPS units, astronomical light pollution may also affect historic and cultural values (NPS 2013). In the broadest terms, ecological light pollution may cause changes for organisms in orientation, disorientation, or misorientation, and attraction or repulsion from the altered light environment. These, in turn, may affect the foraging, reproductive, migrating, and communication behaviors of wildlife (Longcore and Rich 2004).

### Data and Methods

Albers and Duriscoe (2001) modeled light conditions for National Parks based on 1990 data. They assigned a mean Schaaf class of 7.00 (the lowest level of light pollution) to VOYA. An environmental impact statement by the US Department of Homeland Security (USDHS 2012) described the natural lightscape of VOYA as "undisturbed, making for excellent astronomical viewing."

### Reference Condition

The reference condition for natural lightscape at VOYA is the natural night sky condition, as recommended by the NPS Natural Sounds and Night Skies Division (Chad Moore, NPS Night Skies Team Leader, email, 2/19/2013). This is a historic condition (Stoddard et al. 2006).

### Condition and Trend

● We rate the condition of VOYA for natural lightscape as high, with an unknown trend and a moderate degree of confidence because population trends are relatively stable around VOYA.

### Sources of Expertise

Chad Moore, NPS Night Skies Team Leader; Albers and Duriscoe (2001); Christine Mechenich, UWSP.

### Literature Cited

Albers, S., and D. Duriscoe. 2001. Modeling light pollution from population data and implications for National Park Service lands. *The George Wright Forum* 18:56–68. Available at http://www.georgewright.org/184albers.pdf (accessed 27 May 2014).

Longcore, T., and C. Rich. 2004. Ecological light pollution. *Frontiers in Ecology and the Environment* 2:191–198.

NPS (National Park Service). 2006. NPS management policies 2006. National Park Service, Washington, D.C. Published Report-2173472. Available at http://www.nps.gov/policy/MP2006.pdf (accessed 27 May 2014).

NPS (National Park Service). 2007. Long-term ecological monitoring plan: Great Lakes Inventory and Monitoring Network. Natural Resource Report NPS/GLKN/NRR—2007/001. National Park

Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/645523 (accessed 27 May 2014).

NPS (National Park Service). 2013. Night sky website. NPS, Fort Collins, Colorado. Available at http://www.nature.nps.gov/night/index.cfm (accessed 27 May 2014).

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

USDHS (United States Department of Homeland Security), US Customs and Border Protection. 2012. Programmatic environmental impact statement for northern border activities, final volume 1. USDHS, Washington, D.C. Available at http://www.cbp.gov/sites/default/files/documents/Northern%20Border%20PEIS%20Vol.%201.pdf (accessed 27 May 2014).

### *4.2.6. Soundscapes*

Description

Soundscape resources encompass all the natural sounds that occur in national parks, including the physical capacity to transmit sounds and interrelationships between natural sounds (NPS 2006). Among visitors to national parks who were surveyed, 91% considered enjoyment of natural quiet and the sounds of nature as compelling reasons for visiting (McDonald et al. 1995 in Lynch 2012). In addition, sound plays a critical role for wildlife and affects intra-species communication, courtship, predation and predator avoidance, and effective use of habitat (Stein 2012 and citations therein).

NPS management policies recognize the importance of monitoring the frequencies, magnitudes, and durations of unnatural sounds as well as preserving those natural sounds that are part of the biological and physical resource components of the park. The policies recognize that in some parks, cultural and historic sounds are also important and appropriate to the purposes and values of the park.

A recent NPS-wide study reported that mean ambient sound levels in park transportation corridors are more than four orders of magnitude higher than the natural condition (Barber et al. 2010). A recent Congressional Research Service report (Comay et al. 2013) lists off-highway vehicles such as all-terrain vehicles, snowmobiles, personal watercraft, and others, and recreational activities such as mountain biking, snow biking, heli-skiing, and aircraft tours, as potential sources of unnatural sounds in national parks, and notes that these vehicles and activities are increasing in popularity.

Soundscapes are a Vital Sign for VOYA (ranked 45th of 46 with a score of 2.3 on a five-point scale) (NPS 2007).

Data and Methods

No data on soundscapes or sound pollution were found for VOYA.

Reference Condition

NPS Management Policy 8.2.3, Use of Motorized Equipment, provides that the natural ambient sound level is the baseline condition against which current conditions in a soundscape should be measured unless specific significant cultural or historic sounds have been recognized by NPS (NPS 2006). This represents a historic condition (Stoddard et al. 2006).

Condition and Trend

◌ We rate the condition of VOYA for natural soundscape as unknown, but likely of moderate concern, with an unknown trend, because of the growing popularity of motorized vehicle use in the US.

Sources of Expertise

Christine Mechenich, UWSP.

Literature Cited

Barber, J. R., C. L. Brown, A. R. Hardy, K. M. Fristrup, and L. M. Angeloni. 2010. State of Science: Conserving the wild life therein: Protecting park fauna from anthropogenic noise. Park Science 26:26–31. Available at http://www.nature.nps.gov/ParkScience/archive/PDF/Article_PDFs/ParkScience26(3)Winter2009-2010_26-31_Barber_et_al_2682.pdf (accessed 27 May 2014).

Comay, L. B., C. H. Vincent, and K. Alexander. 2013. Motorized recreation on National Park Service Lands. Congressional Research Service, Washington, D.C. Available at http://www.fas.org/sgp/crs/misc/R42955.pdf (accessed 27 May 2014).

Lynch, E. 2012. Saint Croix National Scenic Riverway: Acoustical monitoring 2011. Natural Resource Technical Report NPS/NRSS/NRTR—2012/544. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile?Code=2183395 (accessed 27 May 2014).

McDonald, C. D., Baumgarten, R. M., and Iachan, R. 1995. Aircraft management studies: National Park Service Visitors Survey. HMMH Report No. 290940.12; NPOA Report No. 94-2, National Park Service, U.S. Department of the Interior.

NPS (National Park Service). 2006. NPS management policies 2006. National Park Service, Washington, D.C. Published Report-2173472. Available at http://www.nps.gov/policy/MP2006.pdf (accessed 27 May 2014).

NPS (National Park Service). 2007. Long-term ecological monitoring plan: Great Lakes Inventory and Monitoring Network. Natural Resource Report NPS/GLKN/NRR—2007/001. National Park Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/645523 (accessed 27 May 2014).

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

## 4.3. Biotic Condition

In the USEPA-SAB framework, biotic condition includes structural and compositional aspects of the biota below the landscape level at the organizational levels of ecosystems or communities, species and populations, individual organisms, and genes (USEPA 2002). We will discuss the biotic condition of the terrestrial and aquatic ecosystems, focusing on the plant, bird, fish, aquatic macroinvertebrate, and mussel communities; tree regeneration; invasive terrestrial and aquatic species; and the presence of mercury and persistent organic contaminants in biota.

### *4.3.1. Vegetation*

Description

The current vegetation of VOYA is a result of climate, physiography and soils (and hence geologic past), and natural and anthropogenic disturbances over the last approx. 300 years. The various efforts to classify the plant communities of VOYA are thoroughly discussed by Frelich (2012) in the draft Terrestrial Synthesis for VOYA. Two important conclusions from this Synthesis are the difference between ecosystem (e.g., Faber-Langendoen et al. 2007) and vegetation classification (Kurmis et al. 1986), and the pivotal role of disturbance since approx. 1900. Historic efforts at classification relied on floristics or the dominant species (e.g., cover types). These are useful for short-term management decisions, but do not provided a long-term foundation due to both natural disturbances and the ephemeral nature of some cover types. The MDNR has produced a classification (see details below) that is intermediate between ecosystem and vegetation classifications. Frelich (2012) presents a table (his Table 4) that compares the three classifications.

The vegetation of VOYA, as mapped in 2001, is listed by Level 2 Anderson Land Use/Cover classification, ecological group and subgroup, and association name in Table 12. Faber-Langendoen et al. (2007) later made some modifications to the associations. The 49 associations identified by these authors include 29 associations that have a tree component; this includes some barrens, woodlands, bogs, and fens with limited tree cover. There are seven types of communities that have a significant shrub component but are essentially treeless. This group includes bog, fen, swamp, and one dry ("rocky") shrubland association. The remaining 13 associations have no woody component and includes three types of fen, two wet meadows, five marshes, two aquatic wetlands, and one grass-dominated barrens.

Faber-Langendoen et al. (2007) identified three associations of some global conservation concern in VOYA. These are: i. Red Pine/Blueberry Dry Forest; ii. Northern Sedge Poor Fen; and iii. White Pine/Mountain Maple Mesic forest. The global level of risk assigned to these three associations by NatureServe is G3 (vulnerable) or G3/G4 (vulnerable/apparently secure).

An analysis of the cover types that existed prior to European settlement (from the Original Land Survey, MDNR 1994) (Figure 15) can be of some help in understanding the vegetation of the VOYA landscape. We do not have the data to map the vegetation from this time period in the same way we can today (Frelich 2012), and thus, direct comparisons of abundance are not warranted. The data from the Original Land Survey tend to underestimate community types with limited or no woody vegetation, and they also tend to overestimate certain tree species due to size or commercial importance. For example, Coffman et al. (1980) estimated that red and white pine contributed only

**Table 12.** Land use and land cover categories, ecological groups and subgroups, and vegetation associations in Voyageurs National Park (USGS 2001).

| **Land Use and Land Cover Category Level 2** (Anderson et al. 1976) | **Ecological Group** (Faber-Langendoen 2001) | **Ecological SubGroup** (Faber-Langendoen 2001) | **National Vegetation Classification Standard (NVCS) Association Common Name** (FGDC 2008) | **Area** | |
|---|---|---|---|---|---|
| | | | | **km$^2$** | **%** |
| 11 - Residential | Land Use/Land Cover | Developed Lands | Land Use (non-NVCS) | 0.2 | <0.1 |
| 12 - Commercial and Services | | | | 0.3 | <0.1 |
| 14 - Transportation, Communications, and Utilities | | | | 0.4 | <0.1 |
| 31 - Herbaceous Rangeland | Rock Barrens | Shrub and Herb Rock Barrens | Poverty Grass Granite Barrens | 0.3 | <0.1 |
| | Small Islands and Natural Ponds | Small Islands | Small Island with Vegetation | <0.1 | <0.1 |
| 32 - Shrub and Brush Rangeland | Rock Barrens | Shrub and Herb Rock Barrens | Boreal Hazelnut-Serviceberry Rocky Shrubland | 2.9 | 0.4 |
| | Small Islands and Natural Ponds | Small Islands | Small Island with Vegetation | 0.1 | <0.1 |
| 41 - Deciduous Forest Land | Boreal Hardwood Forests | | Paper Birch/Fir Forest | 0.2 | <0.1 |
| | | | Aspen-Birch/Boreal Conifer Forest AND/OR Aspen-Birch-Red Maple Forest | 105.4 | 12.7 |
| | Northern Hardwood Forests | | Northern Bur Oak Mesic Forest | 1.5 | 0.2 |
| | Rock Barrens | Treed Rock Barrens | Mixed Aspen Rocky Woodland | 10.8 | 1.3 |
| | | | Northern Pin Oak-Bur Oak-(Jack Pine) Rocky Woodland | 33.5 | 4.0 |
| 42 - Evergreen Forest Land | Northern Pine-(Hardwood) Forests | | Jack Pine/Balsam Fir Forest | 17.6 | 2.1 |
| | | | Red Pine/Blueberry Dry Forest | 3.1 | 0.4 |
| | | | White Pine/Mountain Maple Mesic Forest | 9.0 | 1.1 |
| | Northern Spruce-Fir-(Hardwood) Forests | | Black Spruce/Feathermoss Forest | 4.7 | 0.6 |
| | | | Spruce-Fir/Mountain Maple Forest | 13.7 | 1.7 |
| | Northern White Cedar-(Hardwood) Forests | | White Cedar-Boreal Conifer Mesic Forest | 0.8 | 0.1 |
| | Rock Barrens | Treed Rock Barrens | Boreal Pine Rocky Woodland | 33.1 | 4.0 |
| 43 - Mixed Forest Land | Northern Pine-(Hardwood) Forests | | White Pine-Aspen-Birch Forest AND/OR Red Pine Aspen-Birch Forest | 52.1 | 6.3 |

**Table 12.** Land use and land cover categories, ecological groups and subgroups, and vegetation associations in Voyageurs National Park (continued).

| **Land Use and Land Cover Category Level 2** (Anderson et al. 1976) | **Ecological Group** (Faber-Langendoen 2001) | **Ecological SubGroup** (Faber-Langendoen 2001) | **National Vegetation Classification Standard (NVCS) Association Common Name** (FGDC 2008) | **Area** | |
|---|---|---|---|---|---|
| | | | | **km$^2$** | **%** |
| 43 - Mixed Forest Land (continued) | Northern Spruce-Fir-(Hardwood) Forests | | Spruce-Fir -Aspen Forest AND/OR Black Spruce-Aspen Forest | 77.1 | 9.3 |
| | Northern White Cedar-(Hardwood) Forests | | White Cedar-Yellow Birch Forest | 1.7 | 0.2 |
| | Small Islands and Natural Ponds | Small Islands | Small Island with Vegetation | 0.8 | 0.1 |
| Mosaic (41 - Deciduous Forest Land, 42 - Evergreen Forest Land), 43 - Mixed Forest Land when true mixed forest | Northern Pine-(Hardwood) Forests | | Mosaic (Jack Pine/Balsam Fir Forest Association AND Quaking Aspen-Paper Birch Forest Alliance) | 32.8 | 4.0 |
| 51 - Streams and Canals | Land Use/Land Cover | Lakes and Streams | Lakes, Ponds, and Streams (non-NVCS) | <0.1 | <0.1 |
| 52 - Lakes | | | | 288.7 | 34.8 |
| 61 - Forested Wetland | Bogs | Shrub Bogs | Mosaic (Northern Sedge Wet Meadow, Midwest Pondweed Submerged Aquatic Wetland, Leatherleaf Bog, Black Spruce / Leatherleaf Semi-treed Bog, Leatherleaf - Sweet Gale Shore Fen, AND/OR Northern Water Lily Aquatic Wetland) | 0.6 | 0.1 |
| | | | Black Spruce/Leatherleaf Semi-treed Bog | 5.7 | 0.7 |
| | | | Leatherleaf Bog | 5.3 | 0.6 |
| | | Treed Bogs | Black Spruce Bog | 0.4 | <0.1 |
| | Boreal Hardwood Forests | | Trembling Aspen-Balsam Poplar Lowland Forest | 5.3 | 0.6 |
| | Northern Conifer and Hardwood Swamps | Poor Conifer Swamps | Black Spruce/Labrador Tea Poor Swamp | 17.1 | 2.1 |
| | | Rich Conifer Swamps | Black Spruce/Alder Rich Swamp | 4.1 | 0.5 |
| | | | Northern Tamarack Rich Swamp | 3.6 | 0.4 |
| | | | White Cedar-(Mixed Conifer)/Alder Swamp | 2.4 | 0.3 |
| | | Rich Hardwood Swamps | Black Ash-Mixed Hardwood Swamp | 9.8 | 1.2 |
| | | | White Cedar-Black Ash Swamp | 1.9 | 0.2 |

**Table 12.** Land use and land cover categories, ecological groups and subgroups, and vegetation associations in Voyageurs National Park (continued).

| **Land Use and Land Cover Category Level 2** (Anderson et al. 1976) | **Ecological Group** (Faber-Langendoen 2001) | **Ecological SubGroup** (Faber-Langendoen 2001) | **National Vegetation Classification Standard (NVCS) Association Common Name** (FGDC 2008) | **Area** | |
|---|---|---|---|---|---|
| | | | | **$km^2$** | **%** |
| 61-Forested Wetland (continued) | Northern Shrub and Graminoid Fens | Shrub Fens | Bog Birch-Willow Shore Fen | 1.9 | 0.2 |
| | | | Leatherleaf-Sweet Gale Shore Fen | 2.6 | 0.3 |
| | | | Tamarack Scrub Poor Fen | 0.1 | <0.1 |
| | Northern Shrub Swamps | | Dogwood-Pussy Willow Swamp | 2.9 | 0.3 |
| | | | Speckled Alder Swamp | 12.4 | 1.5 |
| 62 - Nonforested Wetland | Marshes | Emergent Marshes | Mosaic/Complex (Midwest Pondweed Submerged Aquatic Wetland, Freshwater Bulrush Marsh, Midwest Cattail Deep Marsh, Wild Rice Marsh, Northern Water Lily Aquatic Wetland, Eastern Reed Marsh, AND/OR Water Horsetail - Spikerush Marsh) | 12.5 | 1.5 |
| | | | Eastern Reed Marsh | <0.1 | <0.1 |
| | | | Freshwater Bulrush Marsh | <0.1 | <0.1 |
| | | | Midwest Cattail Deep Marsh | 1.7 | 0.2 |
| | | | Wild Rice Marsh | 0.6 | 0.1 |
| | | Rooted and Floating Aquatic Marshes | Midwest Pondweed Submerged Aquatic Wetland | 7.4 | 0.9 |
| | | | Northern Water Lily Aquatic Wetland | 5.6 | 0.7 |
| | Small Islands and Natural Ponds | Small Natural Ponds | Lakes, Ponds, and Streams (non-NVCS) | 1.3 | 0.1 |
| | Wet Meadows | | Canada Bluejoint Eastern Meadow | 5.2 | 0.6 |
| | | | Mosaic/Complex (Northern Sedge Wet Meadow, Midwest Cattail Deep Marsh, Eastern Reed Marsh, Canada Bluejoint Eastern Meadow, AND/OR Wiregrass Sedge Shore Fen) | 26.7 | 3.2 |

**Table 12.** Land use and land cover categories, ecological groups and subgroups, and vegetation associations in Voyageurs National Park (continued).

| **Land Use and Land Cover Category Level 2** (Anderson et al. 1976) | **Ecological Group** (Faber-Langendoen 2001) | **Ecological SubGroup** (Faber-Langendoen 2001) | **National Vegetation Classification Standard (NVCS) Association Common Name** (FGDC 2008) | **Area** **km$^2$** | **%** |
|---|---|---|---|---|---|
| 74 – Bare Exposed Rock | Rock Barrens | Treed Rock Barrens | Jack Pine / Lichen Rocky Barrens | 0.6 | 0.1 |
| | Small Islands and Natural Ponds | Small Islands | Small Island with Vegetation | 0.0 | 0.0 |
| 75 - Strip Mines, Quarries, and Gravel Pits | Land Use/Land Cover | Developed Lands | Land Use (non-NVCS) | <0.1 | <0.1 |
| | | | Total | 828.6 | |

Associations recognized by Faber-Langendoen et al. (2007) but not represented in the original mapping data are Leatherleaf Poor Fen, Northern Sedge Poor Fen, Boreal Sedge Rich Fen, and Jack Pine-Aspen/Bush Honeysuckle Forest.

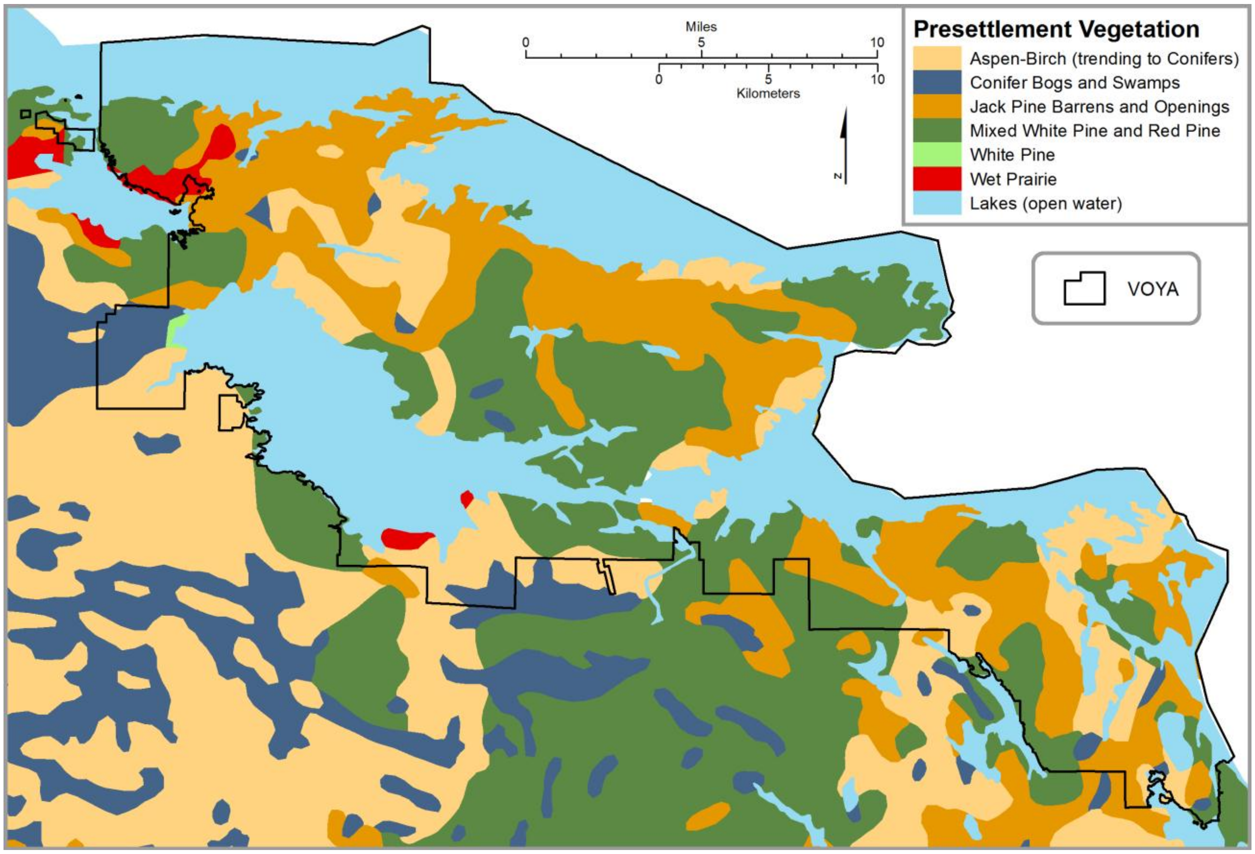

**Figure 15.** Presettlement vegetation of Voyageurs National Park (MDNR 1994).

8% and 3% of witness trees, respectively, yet Figure 15 suggests a far greater abundance of these two pines. The map confirms why the early logging of the area was concentrated on the eastern end of the park, especially on the Kabetogama Peninsula, and suggests a substantial portion of the area was not ‘forest-like’ due to limited tree cover.

Data and Methods

Kurmis et al. (1986) installed plots (50 x 25 m) in 120 non-randomly selected communities using aerial photographs and ground checking. Their stated purpose was to sample all cover types. Within this larger data set, 46 communities were chosen for investigation in greater detail and to establish permanent plot locations.

Using the U.S. National Vegetation Classification Standard (NVCS) and the NPS Vegetation Mapping Program, Faber-Langendoen et al. (2007) mapped the vegetation of VOYA based on aerial photographs produced in fall 1995 and 1996. A preliminary classification was generated from the 1995/1996 photographs and then field verified with point observational data in 1996. The field data to generate the classification were collected in three plots, on average, in each association type. The plots were 20 x 20 m in forests and woodlands and 10 x 10 m in other community types. This team installed 191 plots and added 68 other plots from those used by Kurmis et al. (1986) and MDNR (described below). An accuracy assessment based on 1,251 plots was done after the first full draft of the classification was completed. The overall accuracy of their mapping effort was 82.4%. The three associations that did not meet the pre-study accuracy target of 80% were aspen-birch, spruce-fir-aspen, and northern water lily wetland.

The GLKN vegetation monitoring effort at VOYA began in 2008 with the installation of 38 plots in four habitat types. These general habitats ranged from dry to wet mesic/wet. These plots are scheduled to be resampled in 2014 (Sanders and Grochowski 2009).

Minnesota has developed a hierarchical vegetation classification scheme of its own called “Minnesota’s Native Plant Community Classification” (Aaseng et al. 2011). This scheme was based on a very large number of plots and was structured to parallel the NVCS by stratifying the native plant communities of MN into four ecological provinces. VOYA falls within the Laurentian Mixed Forest province (MDNR 2014). The ‘working units’ in this classification are the Native Plant Community (NPC) classes, which are roughly equivalent to habitat types (e.g., Kotar et al. 1988) and which correspond approximately to associations within the NVCS (Aaseng et al. 2011).

### Reference Condition

The vegetation in a naturally-functioning landscape is quite dynamic at multiple temporal and spatial scales due to weather fluctuation, stochastic process, and disturbance. Consequently, the concept of historic range of variability is applicable to this landscape (Landres et al. 1999), as the composition of a single site or region, and the abundance and distribution of different community types, would have naturally varied over time (Frelich 2002, Faber-Langendoen et al. 2007). The intensive anthropogenic disturbance of part of the park during the 20th century has probably obscured some of the natural variability (Frelich 2012). These considerations dictate that no single reference condition is identifiable or warranted, and that any reference condition has to factor out human impacts over the past approx. 115 years.

An appropriate long-term target is a “best attainable condition” (Stoddard et al. 2006). An appropriate target for VOYA would be a modest increase in the under-represented associations. This would require active management, especially the increase of prescribed fire and incorporation of natural ignitions into the fire management program.

### Condition and Trend

We believe the composition and structure of the landscape, and the structure and abundance of forest and woodland communities (and perhaps others) are probably outside their historic range of variability. Our level of confidence in this assessment is moderate. All assessments indicate a larger amount of aspen-birch dominated area and less pine-dominated area than what existed historically. It is not yet possible to document the trend in these characteristics due to lack of repeat inventories.

When the current vegetation cover is compiled at the Ecological Group level for the Kabetogama Peninsula (Figure 16, Table 13), the scale more closely matches the scale of the pre-settlement data. These numbers indicate that the Northern Spruce-Fir (Hardwood) Forest type is most abundant (22.1%), but is followed very closely by the Boreal Hardwood Forest type (20.8%). The dominance of these two ecological groups reflects the large increase in aspen and birch after harvesting and fire

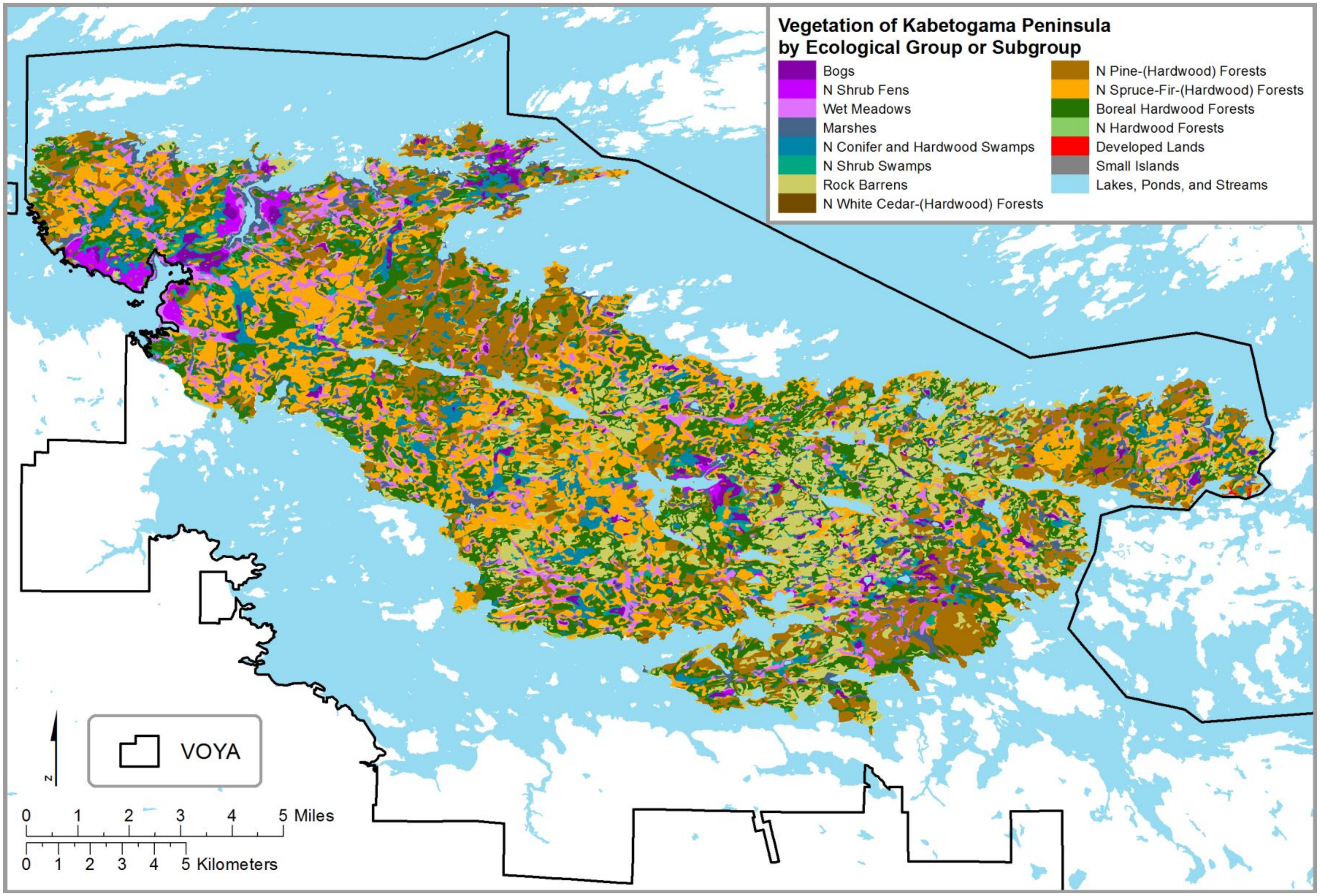

**Figure 16.** Current vegetation of the Kabetogama Peninsula in Voyageurs National Park by ecological groups and subgroups (USGS 2001).

**Table 13.** Vegetation on the Kabetogama Peninsula in Voyageurs National Park by ecological groups and subgroups (USGS 2001).

| Ecological Group | Hectares | % | Ecological Subgroup | Hectares | % |
|---|---|---|---|---|---|
| Northern Spruce-Fir-(Hardwood) Forests | 66,152.0 | 22.1 | Northern Spruce-Fir-(Hardwood) Forests | 66,152.0 | 22.1 |
| Boreal Hardwood Forests | 62,037.8 | 20.8 | Boreal Hardwood Forests | 62,037.8 | 20.8 |
| Northern Pine-(Hardwood) Forests | 51,579.1 | 17.3 | Northern Pine-(Hardwood) Forests | 51,579.1 | 17.3 |
| Rock Barrens | 40,710.2 | 13.6 | Shrub and Herb Rock Barrens | 1,272.1 | 0.4 |
| | | | Treed Rock Barrens | 39,438.1 | 13.2 |
| Wet Meadows | 19,930.4 | 6.7 | Wet Meadows | 19,930.4 | 6.7 |
| Northern Conifer and Hardwood Swamps | 17,328.4 | 5.8 | Poor Conifer Swamps | 8,886.2 | 3.0 |
| | | | Rich Conifer Swamps | 4,861.5 | 1.6 |
| | | | Rich Hardwood Swamps | 3,580.7 | 1.2 |
| Marshes | 14,885.0 | 5.0 | Emergent Marshes | 9,101.8 | 3.0 |
| | | | Rooted and Floating Aquatic Marshes | 5,783.3 | 1.9 |
| Northern Shrub Swamps | 8,132.5 | 2.7 | Northern Shrub Swamps | 8,132.5 | 2.7 |
| Bogs | 6,235.0 | 2.1 | Shrub Bogs | 6,012.3 | 2.0 |
| | | | Treed Bogs | 222.8 | 0.1 |
| Land Use/Land Cover | 6,111.3 | 2.0 | Developed Lands | 73.8 | 0.0 |
| | | | Lakes and Streams | 6,037.5 | 2.0 |
| Northern Shrub and Graminoid Fens | 3,756.5 | 1.3 | Shrub Fens | 3,756.5 | 1.3 |
| Small Islands and Natural Ponds | 1,440.0 | 0.5 | Small Islands | 383.1 | 0.1 |
| | | | Small Natural Ponds | 1,056.9 | 0.4 |
| Northern Hardwood Forests | 268.5 | 0.1 | Northern Hardwood Forests | 268.5 | 0.1 |
| Northern White Cedar-(Hardwood) Forests | 155.2 | 0.1 | Northern White Cedar-(Hardwood) Forests | 155.2 | 0.1 |
| | | | Total: | 298,722.0 | 100.0 |

in the early to mid 20th century. The Northern Pine (Hardwood) Forest type, which also includes some areas dominated by aspen-birch, is third in this ranking at 17.3%. These sum to just over 60%; of the remaining, 2.4% is open water, 5.8% is Northern Conifer and Hardwood Swamp, and the remainder is non-tree-dominated community types.

Faber-Langendoen et al. (2007) concluded that the least fire tolerant forest types (aspen-birch and spruce-fir-aspen) dominate the Kabetogama Peninsula, and fire dependent associations such as theJack Pine-Aspen Forest Mosaic have declined. Despite this claim, they estimated that ‘historic records and maps’ [time frame and specific sources not identified] indicate that approx. 60% of the Peninsula was impacted by fire.

The NVCS analysis of VOYA (USGS 2001, Table 12) indicates that the most abundant forest association is the Aspen-Birch/Boreal Conifer and its close associate Aspen-Birch/Red Maple (12.7%). The next most common forest type is Spruce-Fir-Aspen Forest (9.3%). The only other association with >5% is the Pine-Aspen-Birch association (6.3%), which can include red and/or white pine. Three community types scaled out at 4%: Northern Pin Oak-Bur Oak-(Jack Pine) Rocky Woodland; Boreal Pine Rocky Woodland; and one termed a ‘Mosaic’ which includes an interspersed mixture of Jack Pine/Balsam Fir and Aspen-Birch.

Monitoring efforts by GLKN (Sanders and Grochowski 2009) indicate that spruce and fir are regenerating adequately, but Jack pine, red pine, and white cedar are not. Consequently, spruce and fir have their greatest densities among the smaller size classes, whereas Jack pine and white cedar are abundant in large size classes only. The lack of regeneration was attributed to fire suppression (pines) and deer browsing (cedar).

Sources of Expertise

Faber-Langendoen et al. (2007); Aaseng et al. (2011); James Cook, UWSP.

Literature Cited

Aaseng, N. E., J. C. Almendinger, R. P. Dana, D. S. Hanson, M. D. Lee, E. R. Rowe, K. A. Rusterholz, and D. S. Wovcha. 2011. Minnesota’s native plant community classification: A statewide classification of terrestrial and wetland vegetation based on numerical analysis of plot data. Biological Report 108, Minnesota Biological Survey Program, Ecological Land Classification Program, Natural Heritage and Nongame Research Program, Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/natural_resources/npc/npc_methods_paper.pdf (accessed 21 July 2014).

Anderson, J. A., E. E. Hardy, J. T. Roach, and R. E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. United States Geological Survey Professional Paper 964. USGS, Washington, D.C. Available at http://landcover.usgs.gov/pdf/anderson.pdf (accessed 29 April 2014).

Coffman, M. S., L. Rakestraw, and J. E. Ferris. 1980. The fire and logging history of Voyageurs National Park. Michigan Technological University, Houghton, Michigan.

Faber-Langendoen, D., editor. 2001. Plant communities of the Midwest: classification in an ecological context. Association for Biodiversity Information, Arlington, Virginia. Available at http://www.natureserve.org/library/plantcommNoplates.pdf (accessed 5 May 2014).

Faber-Langendoen, D., N. Aaseng, K. Hop, M. Lew-Smith, and J. Drake. 2007. Vegetation classification, mapping, and monitoring at Voyageurs National Park, Minnesota: An application of the U.S. National Vegetation Classification. *Applied Vegetation Science* 10:361–374.

FGDC (Federal Geographic Data Committee). 2008. National vegetation classification standard, version 2. FGDC, U.S. Geological Survey, Reston, Virginia. Available at http://usnvc.org/wp-content/uploads/2011/02/NVCS_V2_FINAL_2008-02.pdf (accessed 5 May 2014).

Frelich, L. E. 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen-Deciduous Forests. Cambridge University Press, New York, New York.

Frelich, L. 2012. Vegetation and landscape change. *In* L. Frelich and S. Windels, editors. Terrestrial Synthesis for Voyageurs National Park. Draft document to Voyageurs National Park, International Falls, Minnesota.

Kotar, J., J. A. Kovach, and C. T. Locey. 1988. Field guide to forest habitat types of northern Wisconsin. Department of Forestry, University of Wisconsin-Madison and Wisconsin Department of Natural Resources, Madison, Wisconsin.

Kurmis, V, S. L. Webb, and L. C. Merriam, Jr. 1986. Plant communities of Voyageurs National Park, Minnesota, U.S.A. *Canadian Journal of Botany* 64:531–540.

Landres, P. B., P. Morgan, and F. J. Swanson. 1999. Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications* 9:1179–1188.

MDNR (Minnesota Department of Natural Resources). 1994. Presettlement vegetation. MDNR Division of Forestry, St. Paul, Minnesota. Available at http://deli.dnr.state.mn.us/ (accessed 9 January 2013).

MDNR (Minnesota Department of Natural Resources). 2014. Ecological classification system: Laurentian mixed forest province (webpage). MDNR, St. Paul, Minnesota. Available at http://www.dnr.state.mn.us/ecs/212/index.html (accessed 21 July 2014).

Sanders, S., and J. Grochowski. 2009. Implementation of a long-term vegetation monitoring program at Voyageurs National Park. National Park Service Great Lakes Network Report GLKN/2009/09. GLKN, Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/661439 (accessed 22 July 2014).

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

USGS (United States Geological Survey). Center for Biological Informatics. 2001. Spatial vegetation data for Voyageurs National Park vegetation mapping project. USGS Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/2167387 (accessed 3 June 2013).

#### *4.3.2. Wetlands – Wild Rice Marshes*

VOYA contains significant wetlands with well-recognized ecological values (Kallemeyn et al. 2003 and citations therein). The NALC data (USGS et al. 2013) indicates that at a relatively coarse scale (250 m grid size), 9.7% of VOYA consists of wetlands. Based on National Wetlands Inventory maps, 11,997 ha (13.6%) of VOYA is palustrine wetlands (including those commonly called marsh, swamp, bog, fen, and shallow pond), some of which lie within the park's lacustrine system (Kallemeyn et al. 2003 and citations therein). The NVCS mapping of VOYA (Hop et al. 2001) indicates that wetlands cover 14.8% of VOYA. Of 50 identified plant communities, 26 are identified as bog, swamp, marsh, fen, or pond (Hop et al. 2001).

Among the wetland plant communities identified at VOYA is 'wild rice (*Zizania aquatica, palustris*) marsh' (Figure 17) (Unit A28, Faber-Langendoen et al. 2007). This community is found across the upper Midwest and as far east as Vermont and New York, as well as in adjacent parts of Canada. The status of this community type is G3/G4 (vulnerable/apparently secure; NatureServe 2014), though the distribution in the Midwest has been greatly reduced in southern Michigan, WI, and MN since European settlement (MDNR 2008, Pillsbury and McGuire 2009). A report six years ago (MDNR 2008) to the Minnesota Legislature stated that there was approximately 26,044 ha (64,328 acres) of 'natural wild rice coverage' at 777 locations throughout the state. In the 1980s, the Shallow Lake Program of the MDNR compiled a data set from numerous sources and found 700 lakes, totaling 1.5 million basin acres (607,287 ha) had 61,000 acres (24,696.4 ha) of wild rice (MDNR 2008). This suggests that the total area in wild rice has been reasonably stable, at a state level, for approximately 25 years. The situation at VOYA may differ from this trend, as observations by VOYA staff have suggested a decline in recent years (Steve Windels, wildlife biologist, VOYA, personal communication).

Wild rice is an annual that grows along lake margins, along streams, and at stream mouths. It is part of an emergent vegetative community and needs constant or slowly declining water levels during the growing season to thrive. It can grow at very high densities (350 plants $m^{-2}$) and has mechanisms that minimize intraspecific competition (Lee 2002). However, because it must re-establish from seed each year and is sensitive to water depth (Stevenson and Lee 1987, Pillsbury and McGuire 2009), the occurrence and extent of rice stands changes substantially from year-to-year. At VOYA, wild rice presence is linked to both natural and human-caused water level fluctuations (Faber-Langendoen et al. 2007).

It has long been known that rice is sensitive to turbidity and water depth. An assessment of 60 wild rice wetlands and their associated watersheds was conducted by Pillsbury and McGuire (2009) in WI and MN. They found that the wetlands with the greatest loss of *Zizania* had higher water levels, higher concentrations of ammonia, greater pH, and more residential development in the watershed. Stevenson and Lee (1987) experimentally determined that water depths greater than 60 cm led to less

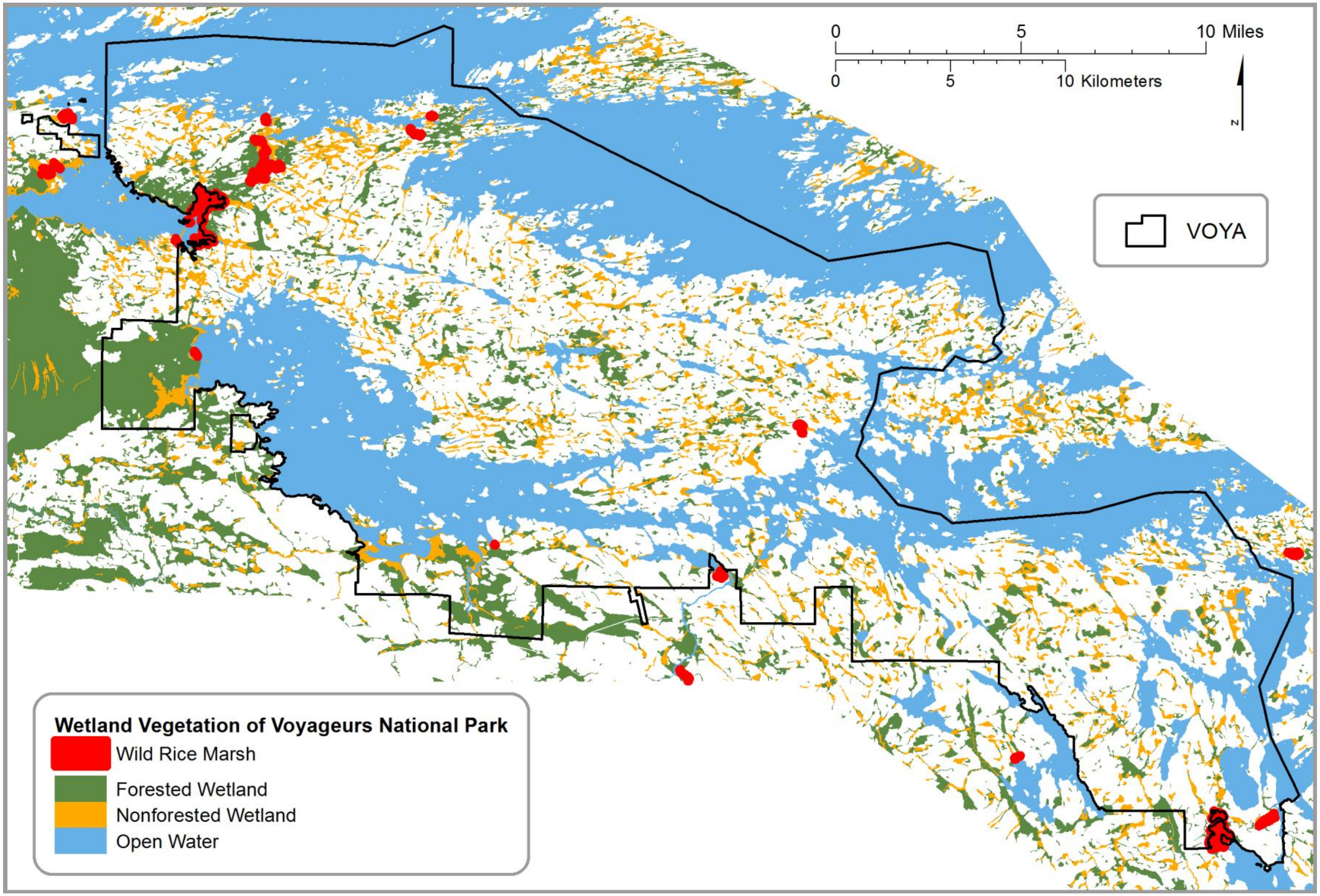

**Figure 17.** Wetland vegetation of Voyageurs National Park (USGS 2001; wild rice boundaries exaggerated for emphasis).

total biomass and fewer tillers than depths of 45 or 60 cm. Wild rice roots in the sediment (largely decayed organic matter) on the lake or stream bottom, and this sets a finite water depth it can tolerate. If much nutrient input from the watershed is occurring, this will give a competitive advantage to other species that can acquire nutrients directly from the water column (Pillsbury and McGuire 2009).

The state of MN has had a sulfate standard (10 mg $L^{-1}$) for wild rice-producing waters since 1973. In 2011, MPCA initiated a program to re-examine this standard. The state funded field- and controlled-environment studies to assess the standard and to determine the mechanism(s) by which sulfate can harm wild rice. The results of this effort were summarized in 2014 and published on the MPCA website at http://www.pca.state.mn.us/index.php/water/water-permits-and-rules/water-rulemaking/minnesotas-sulfate-standard-to-protect-wild-rice.html.

The field work documented that wild rice cover was independent of sulfate level in the surface water up to concentrations of at least 30 mg $L^{-1}$. The connection is via a biochemical transformation that occurs in the sediments. The controlled experiments pinpointed that it is the sulfide concentration in the water in the pore spaces of the sediments that is potentially toxic. This derivative of sulfate is produced by sulfate-reducing bacteria. See Swain (2013-Mid-Project Review) on the MPCA website for a useful diagram of all the chemical reactions relevant to sulfide levels in sediments. Thus, the amount of sulfate in the water column sets the upper bounds on how much sulfide could occur in the sediment layer.

Sulfide has been repeatedly shown to be toxic to a number of wetland plants, and it probably creates some of the negative effects previously ascribed to eutrophication (e.g., Lamers et al. 1998, Geurts et al. 2009). However, MPCA-funded studies also revealed that the sulfide concentration is significantly affected by two conditions in the sediment layer. As the concentration of iron increases, sulfide concentration decreases because iron bonds with the sulfide and forms an insoluble compound. Hence, sulfide and iron show a significant, inverse correlation. Organic carbon has an opposite effect; as its concentration increases, the sulfide concentration does also. The role of organic carbon appears to be two-fold. It contributes electrons to the sulfate-reducing bacteria. It also contributes to the bonding of iron ($Fe^{3+}$) with phosphorus to form a solid, reducing the amount of iron sulfide that is precipitated and increasing the concentration of detrimental hydrogen sulfide in the pore water. Due to the pronounced effects of iron and organic carbon, the MPCA is developing a site-specific sulfate level standard that incorporates the concentrations of these two constituents.

Sources of Expertise

James Cook, UWSP.

Literature Cited

Faber-Langendoen, D., N. Aaseng, K. Hop, and M. Lew-Smith. 2007, Field guide to the plant community types of Voyageurs National Park: U.S. Geological Survey Techniques and Methods 2–A4, 156 p. USGS, Reston, Virginia. Available at http://pubs.usgs.gov/tm/2007/tm2a4/ (accessed 3 September 2014).

Geurts, J. M., J. M. Sarneel, B. J. Willers, J. G. Roelofs, J. T. Verhoeven, and L. P. Lamers. 2009. Interacting effects of sulphate pollution, sulphide toxicity and eutrophication on vegetation development in fens: a mesocosm experiment. *Environmental Pollution* 157:2072–2081.

Hop, K. D. Faber-Langendoen, M. Lew-Smith, N. Aaseng, and S. Lubinski. 2001. USGS-NPS vegetation mapping program, Voyageurs National Park, Minnesota. USGS Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin. Available at http://www.usgs.gov/core_science_systems/csas/vip/parks/voya.html (accessed 3 September 2014).

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001. USGS Columbia Environmental Research Center, Columbia, Missouri. 95 pp. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Lamers, L. P., H. B. Tomassen, and J. G. Roelofs. 1998. Sulfate-induced eutrophication and phytotoxicity in freshwater wetlands. *Environmental Science and Technology* 32:199–205.

Lee, P. F. 2002. Ecological relationships of wild rice, *Zizania* spp. 10. Effects of sediment and among-population variations on plant density in *Zizania palustris*. *Canadian Journal of Botany* 80*:*1283–1294.

MDNR (Minnesota Department of Natural Resources). 2008. Natural wild rice in Minnesota: A wild rice study document submitted to the Minnesota Legislature by the Minnesota Department of Natural Resources, February 15, 2008. MDNR, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/fish_wildlife/wildlife/shallowlakes/natural-wild-rice-in-minnesota.pdf (accessed 3 September 2014).

NatureServe. 2014. NatureServe Explorer: An online encyclopedia of life [web application] - *Zizania* (*aquatica, palustris*) herbaceous vegetation. Version 7.1. NatureServe, Arlington, Virginia. Available at http://explorer.natureserve.org (accessed 3 September 2014).

Pillsbury, R., and M. McGuire. 2009. Factors affecting the distribution of wild rice (*Zizania palustris*) and the associated macrophyte community. *Wetlands* 29:724–734.

Stevenson, S. C., and P. F. Lee. 1987. Ecological relationships of wild rice, *Zizania aquatica*. 6. The effects of increases in water depth on vegetative and reproductive production. *Canadian Journal of Botany* 65:2128–2132.

USGS (United States Geological Survey). Center for Biological Informatics. 2001. Spatial vegetation data for Voyageurs National Park vegetation mapping project. USGS Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/2167387 (accessed 3 June 2013).

USGS (United States Geological Survey), Natural Resources Canada/Canadian Center for Remote Sensing (NRCan/CCRS), Insituto Nacional de Estadística y Geografía (INEGI), Comisión

Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), and Comisión Nacional Forestal (CONAFOR). 2013. 2005 North American Land Cover at 250 m spatial resolution, version 2. Available at http://landcover.usgs.gov/nalcms.php (accessed 2 April 2014).

### *4.3.3. Terrestrial Exotic Plants*

Description

The introduction of exotic plant species probably began with the arrival of European settlers (DiTomaso 2000). It was not unusual for immigrants to bring useful plants or seeds with them from their native lands. Collectively, exotic plants represent an important ecological threat (Ehrenfeld 2003, Heneghan et al. 2006). In the recent past, eastern North America has experienced a rapidly increasing number of exotic plant populations. Concurrently, there have been widespread effects of these exotic plant species, including, as a minimum: 1) alteration of community structure (Heneghan et al. 2006), 2) reduction of native richness (Rooney et al. 2004), 3) alteration of ecosystem process such as decomposition, mineralization, and primary productivity (Ehrenfeld 2003, Heneghan et al. 2006), and 4) altered fire regimes (Brooks et al. 2004). It should be noted that most exotics do not have any appreciable ecological effects, and among those that are do, some have minor impacts.

Many, though not all, of the problem exotic species are especially adept at invading recently disturbed areas. Examples found at VOYA include lambs-quarters (*Chenopodium album*), bindweed (*Convolvulus arvensis*), thistle (*Cirsium* spp.), ox-eye daisy (*Leucanthemum vulgare*), brome (*Bromus* spp.), foxtail (*Alepecurus* spp.), and quackgrass (*Elymus repens*) (NPS n.d.). Spotted knapweed (*Centaurea stoebe*, formerly *C. biebersteinii*) is another such species that is rapidly expanding its range in the Lake States. The establishment of a park does not guard land against further exotic invasion. A recent study of a small (19 km$^2$), newly-established national park in Quebec found that the proportion of exotics increased from 16% to 25% in just 21 years (1984 to 2005) (Lavoie and Saint-Louis 2008). At VOYA, the areas in which exotics are most likely to enter the park are entrance roads, camping areas, around the boat, canoe, and kayak launching areas, and along the hiking and biking trails. In the BWCAW, non-native richness and cover were negatively related to distance from trails (Dickens et al. 2005).

Even in largely unfragmented landscapes and mature forests, more subtle human manipulation of the landscape and accidental introduction can lead to steady increases in the number and dominance of exotics in the flora (Martin et al. 2009). This was recently documented for a 50 year period in upland forests of northern WI (Rooney et al. 2004), where an increase in exotics led to an 18.5% decrease in native species density at a 20 m$^2$ scale.

For forests in general, the exotic taxa in VOYA which have become serious concerns in eastern North America are the alien buckthorns (*Rhamnus* spp.–reported by Eisterhold 2003 in Frelich 2012) and the honeysuckles (*Lonicera* spp.) (Woods 1993, Czarapata 2005, Martin et al. 2009). These species can invade intact communities and reduce the number and/or diversity of native species. The buckthorns can thrive in richer soils, and thus could invade birch, aspen, mixed pine-hardwood, and northern hardwood forests.

### Reference Condition

Less than 10% of VOYA should be infested with populations of terrestrial invasive species that could necessitate treatment (Potyondy and Geier 2011). This is a “least disturbed condition” or “the best of today’s existing conditions” (Stoddard et al. 2006).

### Condition and Trend

The Checklist of Plants and Animals at Voyageurs National Park (NPS n.d.) lists 24 exotic species in the category of grasses, sedges, and rushes (9.8% of all species); one exotic species in the category of ferns and mosses (2.4%); 10 exotic species in the category of trees, shrubs, and vines (6.0%), and 110 in the category of “wildflowers” (19.7%). Five exotic plants are highlighted on the VOYA website at http://www.nps.gov/voya/naturescience/exotic-plants.htm: wild parsnip (*Pastinaca sativa*), reed canary grass (*Phalaris arundinacea*), birdsfoot trefoil (*Lotus corniculatus*), Canada thistle (*Cirsium arvense*), and bull thistle (*C. vulgare*).

Twenty-four plants identified to species were present in sufficient numbers to be treated by the Great Lakes Exotic Plant Management Team (GLEPMT) in 2012 and 2013 (GLEPMT 2012, 2013). The largest areas treated contained thistles, bird’s foot trefoil, and oxeye daisy (Table 14). Eight species had a maximum cover class rating greater than 25%. No exotic species in VOYA are on the federal noxious weed list (http://plants.usda.gov/java/noxious), and only two (*Cirsium* and *Convulvus*) are on the MN list (http://files.dnr.state.mn.us/eco/invasives/weedlist.pdf). *Toxicodendron*, a native species, is on the MN list because of its human health effects.

In VOYA, the gross area treated or inventoried for invasive plants was 838,186 $m^2$ (83.8 ha) in 2012 and 1,344,348 $m^2$ (134.4 ha) in 2013 (Table 14). When the actual percent cover of these species is considered, the inventoried and treated area drops to 139,105 $m^2$ (13.9 ha) in 2012 and 143,832 $m^2$ (14.4 ha) in 2013. These figures are <1% of the total area of VOYA (0.1%–0.2% gross area and 0.02% when adjusted for cover class).

● We rate the condition of VOYA for terrestrial exotic species as very good, but with an unknown trend. Our confidence in this assessment is moderate.

### Sources of Expertise

Great Lakes Exotic Plant Management Team; James Cook, UWSP.

### Literature Cited

Brooks, M. L., C. M. D’Antonio, D. M. Richardson, J. B. Grace, J. E. Keeley, J. M. DiTomaso, R. J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. *Bioscience* 54:677–685.

Czarapata, E. J. 2005. Invasive plants of the Upper Midwest – an illustrated guide to their identification and control. University of Wisconsin Press, Madison, Wisconsin.

Dickens, S. M., F. Gerhardt, and S. K. Collinge. 2005. Recreational portage trails as corridors facilitating non-native plant invasions of the Boundary Waters Canoe Area Wilderness (U.S.A.). *Conservation Biology* 19:1653–1657.

**Table 14.** Exotic plans inventoried and treated by the Great Lakes Exotic Plant Management Team in Voyageurs National Park in 2012 and 2013 (GLEPMT 2012, 2013).

| | | 2012 | | 2013 | | 2012–2013 | |
|---|---|---|---|---|---|---|---|
| **Scientific Name** | **Common Name** | ***# of Locations*** | ***Gross Area ($m^2$)*** | ***# of Locations*** | ***Gross Area ($m^2$)*** | ***Mean % cover*** | ***Greatest observed % cover class*** |
| ***Inventoried*** | | | | | | | |
| *Centaurea stoebe* | Spotted knapweed | - | - | 1 | 0.0 | 0.5 | <1 |
| *Cirsium arvense* | Canada thistle | 158 | 34,685 | - | - | <0.1 | 6–25 |
| *Hieracium aurantiacum* | Orange hawkweed | - | - | 1 | 20 | 15.0 | 6–25 |
| *Solanum dulcamara* | Bittersweet | - | - | 1 | 44 | 0.5 | <1 |
| ***Treated*** | | | | | | | |
| *Achillea millefolium* | Common yarrow | 1 | 2,165 | - | - | 15.0 | 6–25 |
| *Barbarea vulgaris* | Garden yellowrocket | 1 | 2,165 | - | - | 3.0 | 1–5 |
| *Capsella bursa-pastoris* | Shepherd's purse | 1 | 2,165 | - | - | 3.0 | 1–5 |
| *Caragana arborescens* | Siberian pea-shrub | - | | 1 | 6,902 | 15.0 | 6–25 |
| *Cirsium* | Thistle | - | | 10 | 121,392 | 15.0 | 6–25 |
| *Cirsium arvense* | Canada thistle | 64 | 118,179 | 19 | 109,289 | 7.1 | 6–25 |
| *Cirsium vulgare* | Bull thistle | 27 | 106,043 | - | - | 0.7 | 6–25 |
| *Convolvulus arvensis* | Field bindweed | 1 | 2,165 | - | - | 15.0 | 6–25 |
| *Galeopsis tetrahit* | Brittle-stem hemp-nettle | 7 | 5,156 | - | - | 8.0 | 96–100 |
| *Hieracium vulgatum* | Orange hawkweed | - | - | 1 | 6,317 | 3.0 | 1–5 |
| *Leucanthemum vulgare* | Oxeye daisy | 39 | 39,624 | 15 | 131,122 | 21.2 | 26–50 |
| *Linaria vulgaris* | Yellow toadflax | 1 | 83 | 1 | 13 | 0.5 | <1 |
| *Lotus corniculatus* | Bird's-foot trefoil | - | - | 36 | 171,678 | 29.2 | 51–75 |
| *Medicago lupulina* | Black medick | - | - | 5 | 233 | 8.9 | 26–50 |
| *Melilotus* | Sweetclover | - | - | 8 | 77,068 | 15.0 | 6–25 |
| *Melilotus albus* | White sweetclover | 1 | 5,500 | - | - | 0.5 | <1 |
| *Pastinaca sativa* | Wild parsnip | 2 | 5,578 | 11 | 118,715 | 2.2 | 1–5 |
| *Phleum pratense* | Timothy grass | 1 | 2,165 | - | - | 0.5 | <1 |
| *Plantago major* | Common plantain | - | - | 5 | 233 | 8.9 | 26–50 |
| *Rhamnus cathartica* | Common buckthorn | - | | 1 | 3 | 15.0 | 6–25 |
| *Silene latifolia* | Bladder campion | 1 | 2,165 | - | - | 3.0 | 1–5 |
| *Syringa* | Lilac | - | - | 1 | 6,902 | 15.0 | 6–25 |
| *Tanacetum vulgare* | Tansy | 3 | 32,129 | 8 | 42,798 | 0.5 | 51–75 |
| *Thlaspi arvense* | Field pennycress | 1 | 2,165 | - | - | 3.0 | 1–5 |
| *Toxicodendron radicans** | Poison ivy | 64 | 55,193 | - | - | 0.6 | 26–50 |
| *Trifolium repens* | Dutch clover | 1 | 2,165 | - | - | 3.0 | 1–5 |
| *Verbascum thapsus* | Common mullein | 24 | 86,672 | 3 | 45,459 | 2.7 | 26–50 |

*native species

DiTomaso, J. M. 2000. Invasive weeds in rangelands: species, impacts and management. *Weed Science* 48:255–265.

Ehrenfeld, J. G. 2003. Effects of exotic plant invasions on soil nutrient cycling processes. *Ecosystems* 6:503–523.

Eisterhold, J. G. 2003. Exotic plant management team report, Voyageurs National Park, Minnesota, September 2003. Voyageurs National Park, International Falls, Minnesota.

Frelich, L. 2012. Vegetation and landscape change. *In* L. Frelich and S. Windels, editors. Terrestrial Synthesis for Voyageurs National Park. Draft document to Voyageurs National Park, International Falls, Minnesota.

GLEPMT (Great Lakes Exotic Plant Management Team). 2012. Great Lakes exotic plant management locations, 2012. Geodatabase-2203537. Available at https://irma.nps.gov/App/Reference/Profile/2203537 (accessed 13 August 2014).

GLEPMT (Great Lakes Exotic Plant Management Team). 2013. Great Lakes exotic plant management locations, 2013. Geodatabase-2203538. Available at https://irma.nps.gov/App/Reference/Profile/2203538 (accessed 13 August 2014).

Heneghan, L., F. Fatemi, L. Umek, K. Grady, K. Fagen, and M. Workman. 2006. The invasive shrub European buckthorn (*Rhamnus cathartica* L.) alters soil properties in Midwestern U.S. woodlands. *Applied Soil Ecology* 32:142–148.

Lavoie, C., and A. Saint-Louis. 2008. Can a small park preserve its flora? A historical study of Bic National Park, Quebec. *Botany* 86:26–35.

Martin, P. H., C. D. Canham, and P. L. Marks. 2009. Why forests appear resistant to exotic plant invasions: intentional introductions, stand dynamics, and the role of shade tolerance. *Frontiers in Ecology and the Environment* 7:142–149.

NPS (National Park Service). n.d. A checklist of plants and animals in Voyageurs National Park. Voyageurs National Park, International Falls, Minnesota. Available at http://www.nps.gov/voya/planyourvisit/loader.cfm?csModule=security/getfile&PageID=359900 (accessed 14 August 2014).

Potyondy, J. P., and T. W. Geier. 2011. Watershed condition classification technical guide. Publication FS-978. USDA Forest Service, Washington, D.C. Available at http://www.fs.fed.us/publications/watershed/watershed_classification_guide.pdf (accessed 18 August 2014).

Rooney, T. P., S. M. Wiegmann, D. A. Rogers, and D. M. Waller. 2004. Biotic impoverishment and homogenization in unfragmented forest understory communities. *Conservation Biology* 18:787–798.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

Woods, K. D. 1993. Effects of invasion by *Lonicera tatarica* L. on herbs and tree seedlings in four New England forests. *American Midland Naturalist* 130:62–74.

#### ***4.3.4. Exotic Organisms—Earthworms***

Description

The scientific consensus is that there are no native earthworms in the forests of the western Great Lakes Region because they have not migrated back since the retreat of the Wisconsin glacier (Hendrix and Bohlen 2002). However, due to human migration and commerce (e.g., use of worms as fish bait and for composting), at least 45 exotic species have been introduced to North America. The most common exotics are from Europe, and they have spread substantially over the past few decades (Bohlen et al. 2004). A 2009 survey in Grand Portage National Monument showed a high frequency of earthworm presence at sites along the portage trail corridor (unpublished data of Dr. Cindy Hale provided in an email by Brandon Seitz, NPS, 10/31/2012). Gundale et al. (2005) found that the Ottawa National Forest had greater abundance and species of earthworms than the nearby Sylvania Wilderness Area, and that the presence of roads and a history of timber harvest were associated with invaded sites. These studies illustrate the risk of invasion that characterizes many NPS and USDA Forest Service units, and where it is most likely to occur.

Earthworms are placed into three broad major ecological groups (epigeic, endogeic, and anecic) based on their burrowing habits. Those that live and feed only at the surface, and sometimes only in the litter layer, are called epigeic. Earthworms that live and feed in the mineral soil are called endogeic. Those that burrow very deeply (down to 2 m) but feed on fresh surface litter are called anecic. Earthworms that live and feed in the litter layer and the top few inches of mineral soil are sometimes referred to as epi-endogeic (Great Lakes Worm Watch 2011).

When earthworms invade a site, there is typically a succession of species, similar to the changes of plant species during succession (Hale et al. 2005, Suárez et al. 2006). Typically, the members of the first group to invade a site are smaller, stay in the litter layer, and have almost no impact on soil properties or nutrient cycling (Frelich et al. 2006). The second and third waves, or stages, include larger species that move between the litter/duff layer and mineral soil or burrow deeper into the soil (Frelich et al. 2006, Hale et al. 2006). However, the dominant species near an earthworm-free area is likely to invade first (Frelich et al. 2006). Most authors believe that the larger the number of species, the greater the magnitude of impacts (e.g., Wironen and Moore 2006).

The most numerous are members of the family Lumbricidae (Hendrix and Bohlen 2002). As early as the 1960s, it was noted that these species have significant impact on soil properties in areas devoid of native species (Hendrix and Bohlen 2002). More recently, some far-reaching implications for the composition and function of northern hardwood forests, aspen forests, and pine-dominated forests in the northern parts of the Great Lakes region and Canada have been identified (Hale et al. 2005, Frelich et al. 2006, Corio et al. 2009, Nuzzo et al. 2009).

Of particular note and influence seem to be the species *Lumbricus rubellus* (Hale et al. 2005) and *L. terrestris* (Suárez et al. 2006, Shartell et al. 2012). These later-successional species reduce the depth of the litter layer and move substantial amounts of carbon into the soil to depths of 25–30 cm (Bohlen et al. 2004, Frelich et al. 2006). The presence of earthworms increased the rate of litter breakdown by 1.5–3.0 times under field conditions in a northern hardwood forest (Suárez et al. 2006). Subsequently, this alters the dynamics of carbon, nitrogen in the soil, and soil structure (e.g., bulk density). It is possible that these changes are due, in part, to changes in the microbial community (Frelich et al. 2006). Exotic earthworms have consistently increased the total nitrogen in the system (Groffman et al. 2004, Wironen and Moore 2006), but the effect on availability and movement have been variable – ranging from no change (Groffman et al. 2004) to increased availability and increased leaching (Bohlen et al. 2004). Consequently, there is typically a major shift in understory composition after anecic species have invaded (Hale et al. 2005, Frelich et al. 2006).

After invasion, the understory community in the northern hardwood forest will typically have reduced species richness, reduced recruitment of sugar maple saplings, and increasing amounts of Pennsylvania sedge (*Carex pensylvanica*) (Hale et al. 2006). It has also been noted that at least one species of moonwort (*Botrychium mormo*) is negatively correlated with the abundance of *L. rubellus* (Gundale 2002), adding to the threat these exotics may represent. In the Northeast, it was found that the sharp reduction of the litter layer was contributing to the decline of woodland salamanders (Maerz et al. 2009).

Most of the work in North America has been in northern hardwood forests. However, studies from Europe indicate significant differences in invasion potential among the various forests at VOYA. A strong majority of earthworm species are sensitive to litter quality, dry conditions, and soil pH. Frelich and Reich (2009) reported that *L. rubellus* was capable of consuming the forest floor duff layer in all forest types in the Quetico-Superior ecoregion of North America (in which VOYA is included) except for spruce, Jack pine, and red pine. Thus, forest ecosystems such as the spruce-fir, pine, or pine-fir types are not likely to be invaded due to acidic conditions and low-quality (high lignin and low nitrogen) litter (Frelich et al. 2006). These forest types have not been invaded in northern Scandinavia despite the presence of earthworms for thousands of years. However, a mixed deciduous-conifer forest (e.g., aspen-spruce) has a substantially higher risk of invasion due to the moderating effects of the deciduous species.

Hale and Host (2005) found four exotic earthworm genera in the aspen-fir forest type of VOYA; *Lumbricus* and *Dendrobaena* (a common epigeic) were the two most abundant genera in their samples. Numbers of *L. terrestris* adults were three times higher in the northern hardwood forests of Pictured Rocks National Lakeshore than in the VOYA aspen-fir forest, but *L. rubellus* numbers were similar. The presence of *L. terrestris* was correlated with the distance to human development.

In the aspen-fir forest type at VOYA, the thickness of the O horizon layers of litter ($O_{litter}$) and moderately decomposed plant material ($O_e$) decreased with increasing total earthworm biomass, but the highly decomposed plant material layer ($O_a$) and the total O horizon thickness did not (Hale and Host 2005). The thickness of the A horizon increased with increasing total earthworm biomass. Combined herbaceous plant and tree seedling richness and herbaceous plant total percent cover increased weakly with total earthworm biomass and earthworm diversity.

Shartell et al. (2012) found that in the Great Lakes region, four stand level variables were associated with increased earthworm biomass: high soil pH, high basal area of earthworm-preferred species, high percent anthropogenic cover, and low conifer dominance. Proximity to agricultural areas plus the four stand-level variables influenced earthworm community composition. However, only epi-endogeic species were significantly associated with anthropogenic land cover, and earthworm community diversity was greatest in areas with a variety of natural land cover components.

### Reference Condition

Because of the far-reaching effects of earthworm invasion in mixed deciduous-conifer forests, the most desirable condition would be to have no earthworms present, or to have only epigeic species present. The former would be a "historic condition" (Stoddard et al. 2006).

### Condition and Trend

● The condition of VOYA for the presence of exotic earthworms is of moderate concern, with an unknown trend. Our confidence in this assessment is moderate. Hale and Host (2005) have documented the presence of earthworms in the aspen-fir forest at VOYA and some of their effects on soil properties. Avoiding further invasion would likely depend on educating boaters and anglers about the potential adverse effects of releasing these organisms in the park.

### Sources of Expertise

publications of Dr. Cindy Hale; James Cook, UWSP.

### Literature Cited

Bohlen, P. J., S. Scheu, C. M. Hale, M. A. McLean, S. Migge, P. M. Groffman, and D. Parkinson. 2004. Non-native invasive earthworms as agents of change in northern temperate forests. *Frontiers in Ecology and Environment* 2:427–435.

Corio, K., A. Wolf, M. Draney, and G. Fewless. 2009. Exotic earthworms and Great Lakes forests: a search for indicator plant species in maple forests. *Forest Ecology and Management* 258:1059–1066.

Frelich, L. E., C. M. Hale, S. Scheu, A. R. Holdsworth, L. Heneghan, P. J. Bohlen, and P. B. Reich. 2006. Earthworm invasion into previously earthworm-free temperate and boreal forests. *Biological Invasions* 8:1235–1245. DOI 10.1007/s10530-006-9019-3.

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. Available at http://forestecology.cfans.umn.edu/research.html (accessed 1 May 2012).

Great Lakes Worm Watch. 2011. Earthworm ecological groups (online). Natural Resources Research Institute, University of Minnesota-Duluth, Duluth, Minnesota. Available at http://www.nrri.umn.edu/worms/identification/ecology_groups.html (accessed 18 August 2014).

Groffman, P. M., P. J. Bohlen, M. C. Fisk, and T. J. Fahey. 2004. Exotic earthworm invasion and microbial biomass in temperate forest soils. *Ecosystems* 7:45–54. DOI: 10.1007/s10021-003-0129-9.

Gundale, M .J. 2002. Influence of exotic earthworms on the soil organic horizon and the rare fern *Botrychium mormo*. *Conservation Biology* 16:1555–1561.

Gundale, M .J., W.M. Jolly, and T. H. Deluca. 2005. Susceptibility of a northern hardwood forest to exotic earthworm invasion. *Conservation Biology* 19:1075–1083.

Hale, C. M., and G. E. Host. 2005. Assessing the impacts of European earthworm invasions in beech-maple hardwood and aspen-fir forests of the western Great Lakes Region. National Park Service Great Lakes Inventory & Monitoring Network Report GLKN/2005/11. GLKN, Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/592019 (accessed 18 August 2014).

Hale, C. M, L. E. Frelich, and P. B. Reich. 2005. Exotic European earthworm invasion dynamics in northern hardwood forests of Minnesota, USA. *Ecological Applications* 15:848–860.

Hale, C. M., L. E. Frelich, and P. B. Reich. 2006. Changes in hardwood forest understory plant communities in response to European earthworm invasions. *Ecology* 87:1637–1649.

Hendrix, P. F and P. J. Bohlen. 2002. Exotic earthworm invasions in North America: ecological and policy implications. *Bioscience* 52:801–811.

Maerz, J. C., V. A. Nuzzo, and B. Blossey. 2009. Declines in woodland salamander abundance associated with non-native earthworm and plant invasions. *Conservation Biology* 23:975–981.

Nuzzo, V. A., C. Maerz, and B. Blossey. 2009. Earthworm invasion as the driving force behind plant invasion and community change in northeastern North American forests. *Conservation Biology* 23:966–974.

Shartell, L. M., A. J. Storer, and R. G. Corace III. 2012. Influences of exotic earthworm invasion on forest ecosystems across Great Lakes biology network national wildlife refuges. Presented at the NPS Western Great Lakes Resource Management Conference, Ashland, Wisconsin, April 17–18, 2012.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

Suárez, E. R., T. J. Fahey, J. B. Yavitt, P. M. Groffman, and P. J. Bohlen. 2006. Patterns of litter disappearance in a northern hardwood forest invaded by exotic earthworms. *Ecological Applications* 16:154–165.

Wironen, M., and T. R. Moore. 2006. Exotic earthworm invasion increases soil carbon and nitrogen in an old-growth forest in southern Quebec. *Canadian Journal of Forest Research* 36:845–854

### ***4.3.5. Moose***

#### Description

This species has a long standing history as part of northern MN ecosystems, but the density of the species probably declined as European settlement and utilization of the landscape intensified in the early 20th century (Cole 1987). It is presumed that a small increase in moose numbers occurred mid-century; by the mid-1980s, the density was approximately 10% of that in 1900. This period coincides with the beginning of a precipitous decline of the species in the northwestern part of MN (Murray et al. 2006). Despite intensive management efforts by the state to increase forage availability, the population was nearly extirpated in this region by approx. 2000 (MDNR 2011). The population in the northeastern region began to decline shortly after this, decreasing from 8,160 to 2,760 animals (66%) from 2005 to 2013 (Lenarz 2012, DelGiudice et al. 2013a, 2013b). A study of 150 collared adult moose in the northeast found an annual, non-harvest mortality rate of 20.5% (Lenarz et al. 2011). This is 8%–12% higher than populations outside Minnesota (Lenarz et al. 2011), but matches very closely the rate in the northwestern population (Murray et al. 2006).

The consistent and large decline in the two primary populations in the state has spurred a surge in research, which has provided significant insight into the dynamics of the northeast population; however, important questions still remain. In addition, a moose advisory board was established, and from that group the Moose Research and Management Plan (MDNR 2011) emerged.

The Moose Research and Management Plan lists moose habitat in northern MN comprising young forest, old forest with canopy gaps, wetlands, riparian areas, brushlands with abundant deciduous browse, and adequate summer and winter thermal cover. The Plan noted that there are important differences in the habitats and landscape structure between the northwest and the northeast; the northwest is described as ‘aspen parkland’ and the northeast as ‘dominated by near boreal forest’ (MDNR 2011). Deciduous browse is the primary type of forage for the species, and the animals often utilize aquatic plants seasonally.

#### *Mortality Factors*

Because populations on the southern end of the range of a species are especially vulnerable to climate change, temperature changes are suspected to be one of the causes of moose decline in Minnesota (Lenarz et al. 2010). Moose become stressed at summer temperatures exceeding 14°C and winter temperatures above -5°C (Lenarz et al. 2010). The direct effects of temperature change are altered survival and reproductive rates. Warmer than average temperatures in January exerted a strong influence on moose survival in northeast MN in the following spring and fall, and warm-season temperatures were important in explaining survival during the following winter (Lenarz et al. 2008). In contrast, a study in Norway found that body mass during autumn (an index of nutritional status) was more strongly associated with late spring weather conditions than those in winter (Herfindal et al. 2006). Of equal importance, they noted that populations living in ‘good environmental conditions’ are partially buffered against environmental fluctuations; populations along range borders generally do not have good environmental conditions.

The analysis by Lenarz et al. (2010) found that hunting and predation were small contributors to the total mortality rate in the northeastern population. Only 2% of the adult bulls have been harvested in the recent past (MDNR 2011). Wolf predation has not played a strong role in the population dynamics of moose in northern MN or at ISRO (Post et al. 2002, Vucetich et al. 2002). An analysis of the role of weather uncovered an important signal (Peckarsky et al. 2008) that may underlie the predation level by wolf. In particular, the North American Oscillation, which exerts a large influence on snowfall totals, impacts wolf predation rates due to the concentration of its prey during high snowfall years or their dispersion during low snow years.

The possible role of malnutrition during winter was examined by DelGiudice et al. (2013a). Using a urinary urea nitrogen to creatinine ratio as an index, they found that approximately 41% of all samples indicated moderate or severe dietary restriction; the bulk of this nutritional stress occurred from late February to late March. A dietary restriction can be based on summer forage also. A comparison of two populations in Alaska found that the more productive herd had 23% more digestible protein in the leaves consumed. A higher level of tannin in the forage of the less productive herd accounted for a large portion of protein reduction (McArt et al. 2009).

There is general consensus that the decline in moose populations has multiple causes (e.g., malnutrition, pathogens, predation, weather), and that pathogens and malnutrition appear to have been the more important causes. Two parasites (liver fluke and brainworm) caused 37%–62% of the annual mortality in the northwestern population; an additional 255 may have succumbed to pathogens, but a definitive diagnosis was not possible (Murray et al. 2006). Malnourishment was evident in slightly over half (51.4%). However, what triggered the decline, and why the rate exceeds that of other populations of moose, are still in question.

It is quite possible that two or three factors are working synergistically to cause the moose density declines in northern MN. Temperature can have both indirect and direct effect on vertebrate survival and distribution (Lawler et al. 2009, Matthews et al. 2011). Furthermore, the response of a species may show a non-linear trend with climate (Ibanez et al. 2007). The population in northwestern MN in the 1980s could have reached a point (see Figure 6 in Lenarz et al. 2010) at which a strong effect was initiated, thus leading to a steady decline by increasing stress and lowering overall physiological health, and thereby increasing susceptibility to pathogens, parasites, and predation. Reduced health often leads to lower reproductive rates, which means that even a slight increase in adult mortality becomes problematic for the long-term persistence of the population.

### Data and Methods

Cole (1987) obtained his estimates of the species at the turn of the 20th century from species distribution records, unpublished diaries from 1899–1901, and interviews with early residents. A winter aerial count of 18 plots of 0.2 km$^2$ was conducted in 1975, and strip counts were conducted in 1983–1985.

Gogan et al. (1997) reported on aerial strip counts that began in 1982 and were repeated in 1983–1988, 1991–1992, and 1997–1998. Starting in 2009, a more intensive study of the moose population in and around VOYA was initiated. This included tracking with GPS collars and use of an ‘overlapping circle’ inventory method (Windels 2014).

Reference Condition

Cole (1987) estimated approximately 0.8 moose km$^{-2}$ around 1900. Estimates since the early 1990s have been much lower (<0.3 km$^{-2}$) (Gogan et al. 1997, Windels 2014). Though the inventory method used in the 1980s is less reliable and consistent, the population trend reported by Gogan et al. (1997) suggests the density was higher in the mid-1980s. Though not firmly pinned down, it seems the minimum moose density that might approximate a “historic condition” (Stoddard et al. 2006) is 0.25 moose km$^{-2}$.

Condition and Trend

↔ The moose population probably declined after 1900 (Cole 1987) and stayed low for quite some time. When the density began to go up is unknown; it may have been as recently as the late 1970s or early 1980s. Estimates for 1991 and 1992 were 0.28 and 0.23 moose km$^{-2}$, respectively (Gogan et al. 1997). In 2014, Windels reported a density for the Kabetogama Peninsula of 0.13 moose km$^{-2}$ and a population that had been moderately stable since 2009 (in contrast to the population farther east). Thus the current condition is poor, with a stable trend, and our confidence in this assessment is moderate.

From 2010–2014, the population had a low pregnancy rate and an annual mortality rate of approx. 10% (Windels 2014). As noted for the region, wolf predation does not appear to be a major limiting factor; this may be due to the relatively high populations of WTD and beaver, which are easier prey for the wolf (Windels 2014).

*Role of Moose in the Ecology of the Boreal System*

It is next to impossible to pin down the precise role of moose in northern MN prior to 1900 because the population density is unknown. Though an adult moose needs to consume approximately 15 kg of food per day (Pastor et al. 1988), its home range is typically quite large (e.g., Cederlun and Okarma 1988) and thus the moose densities are low. Nonetheless, studies elsewhere have shown that the impacts can be far-reaching.

The conclusions regarding the impacts of this large herbivore are based on exclosures or on patterns noted across gradients of moose density that occur naturally in such areas as ISRO. The diet of moose is mostly deciduous browse and aquatic herbaceous species (MDNR 2011); however, when these foods are scarce or unavailable, conifer seedlings and saplings are utilized (Pastor et al. 1988).

*Effect on Plant Composition and Abundance*

The effects of moose at ISRO are probably indicative of the maximum impact that the species can have in this region. Canada yew was practically eliminated from the main island (Slavik and Janke 1987), and red-osier dogwood (*Cornus stolonifera*) and mountain ash (*Sorbus americana*) have declined precipitously in some areas, as has balsam fir. However, there are a suite of other influences (or lack of in some cases) that should be noted to fully understand the impacts of moose. Total tree seedling density typically shows no increase with moose exclusion and is not lower in high moose density areas (Janke 1979, Risenhoover and Maass 1987). Where balsam fir sapling densities are low, moose suppress the trees and limit their height growth (Brandner et al. 1990). A similar effect was noted for sugar maple in ‘transitional’ and boreal forests (Sell and Jordan, ca. 2006). However, where sapling densities are high, moose serve to release the residual balsam fir saplings, resulting in increased height growth and recruitment to larger size classes. For patches of low balsam fir density, the longer-term effect is to reduce its abundance in the canopy and thereby favor white spruce (Brandner et al. 1990). At a density of 3.7 moose km$^{-2}$, Pastor et al. (1998) noted elimination of aspen and birch stems less than 10–15 cm; neither balsam fir nor white spruce showed this effect. A wide range of impacts on the shrub layer has been noted. Janke (1979) noted reduced heights, an increase in biomass was reported by McInnes et al. (1992), and Snyder and Janke (1976) found no effect on tall shrubs. As moose density increases, herb layer diversity and biomass typically increase (McInnes et al. 1992). Low levels of browsing permit greater numbers of stems (and perhaps species) to recruit to the canopy, which in turn may suppress the shrub and herb layers. However, the composition of the herb layer may not be affected.

*Effect of Moose on Aquatic Communities*

Moose utilize aquatic vegetation and may alter the aquatic community through direct consumption of aquatic vegetation and by disturbing sediment while foraging, thereby increasing turbidity. These impacts may in turn negatively affect fish and invertebrate communities. Meeker et al. (2007) compared photographs of their sample sites from the early 1900s, before moose arrived on ISRO, to conditions present during 2003–2006 to illustrate that aquatic vegetation in several ISRO lakes has been reduced or eradicated. However, the impacts within VOYA have not been documented.

*Effect of Moose on Ecosystem Processes*

The documented effects of moose browsing on ecosystem processes are rather limited and based on few locations, and the vast majority are restricted to areas of high (above average) moose density (e.g., Pastor et al. 1993 at ISRO). Thus, the results from these studies should be viewed as an indication of the potential effects at densities above a sustainable level. The most consistent effects have been seen in productivity, nitrogen availability and cycling, and cation concentrations (McInnes et al. 1992, Pastor et al. 1993, 1998). For example, in an areas protected from moose browsing, tree and litter production were greater, but growth of the herbaceous layer was less (McInnes et al. 1992).

There has been long-term (40 years) study of below-ground processes at ISRO. Whereas up to 10 parameters differed between exclosures and controls, there was much site-to-site variation, and the impacts declined where moose density was lower. Important conditions and processes such as soil nitrogen (N), cation exchange capacity, N mineralization, and microbial respiration were higher in the exclosure (Pastor et al. 1988). At a site with intermediate moose density, only N mineralization differed.

These studies indicate that low levels of herbivory may result in forest structural changes, but no suppressive effects on the woody species. At moderate-to-high densities, the shrub and tree layers are affected, which has cascading effects on the understory and below-ground processes. Processes are affected by enhanced warming of the litter layer and waste deposition; both of these impacts enhance nutrient cycling (Pastor et al. 1993).

This body of work suggests that the role of moose in the VOYA landscape has varied significantly since 1900. Unfortunately, the magnitude of this variation is largely unknown. During much of the 20th century, the densities were lower than the historic level, and thus any impacts would have faded. Though moose density was much higher for a brief period in the recent past, the impacts on composition, structure, and processes would have been minimal and transient. This is true because either the level of browsing was below the threshold level, or the browsing lasted too short a period to have the effects noted at ISRO.

Sources of Expertise

James Cook, UWSP.

Literature Cited

Brandner, T. A., R. O. Peterson, and K. L. Risenhoover. 1990. Balsam fir on Isle Royale: effects of moose herbivory and population density. *Ecology* 71:155–164.

Cederlund, G. N., and H. Okarma. 1988. Home range and habitat use of adult female moose. *Journal of Wildlife Management* 52:336–343.

Cole, G. F. 1987. Changes in interacting species with disturbance. *Environmental Management* 11:257–264.

DelGiudice, G.D., E. Butler, M. Carstensen and W.J. Severud. 2013a. Assessing nutritional restriction of moose in northeastern Minnesota, winter 2013: a pilot. *In* L. Cornicelli, M. Carstensen, M. D. Grund, M. A. Larson, and J. S. Lawrence, editors. Summary of research findings 2012. Minnesota Department of Natural Resources, Division of Fish and Wildlife, Wildlife Populations and Research Unit. St Paul, Minnesota. Available at http://files.dnr.state.mn.us/publications/wildlife/research2012/binder.pdf (accessed 19 August 2014).

DelGiudice, G. D., W. J. Severud, and R. G. Wright. 2013b. Helicopter capture of newborn moose calves in northeastern Minnesota: an evaluation. *In* L. Cornicelli, M. Carstensen, M. D. Grund, M. A. Larson, and J. S. Lawrence, editors. Summary of research findings 2012. Minnesota Department of Natural Resources, Division of Fish and Wildlife, Wildlife Populations and Research Unit. St Paul, Minnesota. Available at http://files.dnr.state.mn.us/publications/wildlife/research2012/binder.pdf (accessed 19 August 2014).

Gogan, P. J. P., K. D. Kozie, E. M. Olexa, and N. S. Duncan. 1997. Ecological status of moose and white-tailed deer at Voyageurs National Park, Minnesota. *Alces* 33:187–192.

Herfindal, I., B. Saether, E. J. Solberg, R. Andersen, and K. A. Hogda. 2006. Population characteristics predict responses in moose body mass to temporal variation in the environment. *Journal of Animal Ecology* 75:1110–1118.

Ibanez, I., J. S. Clark, S. LaDeau, and J. H. Lambers. 2007. Exploiting temporal variability to understand tree recruitment response to climate changes. *Ecological Monographs* 77:163–177.

Janke, R. A. 1979. Moose-forest-fire ecology in Isle Royale National Park. Proceedings of the First Conference on Scientific Research in the National Parks, USDI, *National Park Service Transactions and Proceedings* 5:1243–1251.

Lawler, J. L., S. L. Shafer, D. White, P. Kareiva, E. P. Maurer, A. R. Blaustein. and P. J. Bartlein. 2009. Projected climate-induced faunal change in the Western Hemisphere. *Ecology* 90:588–597.

Lenarz, M. S., M. E. Nelson, M. W. Schrage, and A. J. Edwards. 2008. Temperature mediated moose survival in northeastern Minnesota. *Journal of Wildlife Management* 73:503–510.

Lenarz, M. S., J. Fieberg, M. W. Schrage, and A. J. Edwards. 2010. Living on the edge: viability of moose in northeastern Minnesota. *Journal of Wildlife Management* 74:1013–1023.

Lenarz, M. S., R. G. Wright, M. W. Schrage, and A. J. Edwards. 2011. Compositional analysis of moose habitat in northeastern Minnesota. *Alces* 47:135–149.

Lenarz, M. S. 2012. 2012 aerial moose survey. *In* Dexter, M. H., editor. Status of wildlife populations, fall 2012. Unpublished report, Division of Fish and Wildlife, Minnesota Department of Natural Resources, St. Paul, Minnesota. 311 pp. Available at http://www.dnr.state.mn.us/publications/wildlife/populationstatus2012.html (accessed 19 August 2014).

Matthews, S. N., L. R. Iverson, A. M. Prasad, and M. P. Peters. 2011. Changes in potential habitat of 147 North American breeding bird species in response to redistribution of trees and climate following predicted climate change. *Ecography* 34:933–945.

McArt, S. H., D. E. Spalinger, W. B. Collins, E. R. Schoen, T. Stevenson, and M. Bucho. 2009. Summer dietary nitrogen availability as a potential bottom-up constraint on moose in south-central Alaska. *Ecology* 90:1400– 1411.

McInnes, P. F., R. J. Naiman, J. Pastor, and Y. Cohen. 1992. Effects of moose browsing on vegetation and litter of the boreal forest, Isle Royale, Michigan, USA. *Ecology* 73:2059–2075.

MDNR (Minnesota Department of Natural Resources), Division of Fish and Wildlife. 2011. Minnesota moose research and management plan. MDNR, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/fish_wildlife/wildlife/moose/management/mooseplan-final.pdf (accessed 19 August 2014).

Meeker, J., A. Harris, V. Hofman, E. Judziewicz, and J. Marr. 2007. Assessment of wetland communities at Isle Royale National Park. National Park Service, Great Lakes Inventory and Monitoring Network Report GLKN/2007/04. National Park Service, Ashland, Wisconsin.

Murray, D. J., E. W. Cox, W. B. Ballard, H. A. Whitlaw, M. S. Lenarz, T. W. Custer, T. Barnett, and T. K. Fuller. 2006. Pathogens, nutritional deficiency, and climate influences on a declining moose population. *Wildlife Monographs* 166:1–30.

Pastor, J., R. J. Naiman, B. Dewey, and P. McInnes. 1988. Moose, microbes, and the boreal forest. *Bioscience* 38:770–777.

Pastor, J., B. Dewey, R. J. Naiman, P. McInnes, and Y. Cohen. 1993. Moose browsing and soil fertility in the boreal forests of Isle Royale National Park. *Ecology* 74:467–480.

Pastor, J., B. Dewey, R. Moen, D. J. Mladenoff, M. White, and Y. Cohen. 1998. Spatial patterns in the moose-forest-soil ecosystem on Isle Royale, Michigan, USA. *Ecological Applications* 8:411–424.

Peckarsky, B. L., P. A. Abrams, D. I. Bolnick, L. M. Dill, J. H. Grabowski, B. Luttbeg, J. L. Orrock, S. D. Peacor, E. L. Preisser, O. J. Schmitz, and G. C. Trussell. 2008. Revisiting the classics: Considering nonconsumptive effects in textbook examples of predator–prey interactions. *Ecology* 89:2416–2425.

Post, E. S., N. C. Stenseth, R. O. Peterson, J. A. Vucetich, and A. M. Ellis. 2002. Phase dependence and population cycles in a large mammal predator-prey system. *Ecology* 83:2997–3002.

Risenhoover, K. L., and S. A Maass. 1987. The influence of moose on the composition and structure of Isle Royale forests. *Canadian Journal of Forest Research* 17:357–364.

Sell, S. M., and P. A. Jordan. ca. 2006. Factors influencing the intensity of moose herbivory on sugar maple within the boreal/northern hardwood ecotone, Isle Royale National Park, Michigan. University of Minnesota, Saint Paul, Minnesota.

Slavik, A. D., and R. A. Janke. 1987. The vascular flora of Isle Royale National Park. *Michigan Botanist* 26:91–134.

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.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. Ecological Applications 16:1267–1276.

Vucetich, J. A, R. O. Peterson, and C. L. Schaefer. 2002. The effect of prey and predator densities on wolf predation. *Ecology* 83:3003–3013.

Windels, S. K. 2014. 2014 Voyageurs National Park moose population survey report. Natural Resource Data Series NPS/VOYA/NRDS—2014/645. National Park Service, Fort Collins, Colorado.

### *4.3.6. Beaver Population Dynamics and Landscape Influence*

Description

The beaver has been characterized as an ecosystem engineer and keystone species (Naiman et al. 1986, Collen and Gibson 2000) due to its impacts on hydrology, area with surface water, carbon and sediment distribution, physical characteristics of water in streams and impoundments, total number of invertebrates, and, in some cases, fish composition and channel geomorphology. The dams erected by a colony, which typically include primary and secondary dams, and their food cache, have a multitude of influences. They temporarily create or extend shallow, flooded wetland habitat in and adjacent to the stream, bog, or lake. The dam(s) erected along channels catch sediment, moderate some floods, alter hydrology, change channel shape and depth, and alter biogeochemical pathways such as denitrification (Naiman et al. 1986). The scope of influence of this species is starkly illustratred by the increase from 1% to 13% of impounded area on the Kabetogama Peninsula (Johnson and Naiman 1990a) due to increasing population density. Because beaver can fell relatively large trees, they have profound effects on riparian community structure and composition (Johnston and Naiman 1990a, Donkor 2007). These effects fall into two distinct classes when viewed from the standpoint of temporal persistence. All effects directly or indirectly associated with dams are typically short lived (<10 years) because most colony sites are not used consistently for extended periods of time (Fryxell 2001, Peterson and Romanski 2008). In contrast, effects related to the utilization of trees; i.e., succession, can last for many decades and even exceed 100 years (Donkor 2007).

Utilization of woody plants by beaver is concentrated in a small area; for streams, the beaver do not commonly forage more than 50–70 m from the water's edge. Within this zone, tree basal area can be reduced up to 43% over a six year period. Beaver show strong preference for deciduous species, especially aspen, willow, and birch, and avoid conifers and sometimes alder (Johnston and Naiman 1990a, Donkor 2007). In one study, about two-thirds of all stems cut were <5 cm, but the average size of aspen used was 12 cm, and the largest was 43.5 cm (Johnston and Naiman 1990a). This selective foraging shifts the woody plant composition toward conifers, non-palatable hardwoods, and shrubs. Thus, over decades, the long-term effect of beaver activity is to make the habitat decidedly sub-optimal for itself.

Food resource level and predation affect the dynamics of the species. The wolf is the primary predator. Shelton (2004) reported that wolves heavily preyed upon the beaver population at Isle Royale, whereas Mech (1966) found that between 7% and 19% of wolf scat contained evidence of beaver. Fluctuating food resources are to be expected due to beavers' preference and ability to deplete the local resource. Fryxell (2001) reported an association between colony size and local food availability in Algonquin Provincial Park. Fryxell (2001) concluded that local interactions were more important than broad scale influences, such as weather, in determining the fate of local populations.

*Population Dynamics at VOYA*

By 1900, there were very few beaver remaining in Minnesota (Erickson 1939) and the species was almost extinct in North America (Naiman et al. 1986). In contrast to these characterizations, Cole (1987) rated their density as "abundant" around 1900, and it stayed at this approximate population size through the mid-1980s. Johnston and Naiman (1990a) estimated the area of impoundment, and thus indirectly beaver population size, on the Kabetogama Peninsula from aerial photos for the period 1940–1986. The area of impoundment increased more than 10-fold over this period; they estimated the number of colonies in 1940 as less than 20. Given all the assessments, it is highly likely that Cole (1987) greatly overstated beaver density for the first half or more of the 20th century. It is most probable that beavers were very scarce in the area around the turn of the 20th century, and stayed at low densities during the most active logging period. Johnston and Naiman (1990) estimated that the beaver population exhibited its most rapid increase from the mid-1940s through 1960, and peaked in the 1980s. Host and Meysembourg (2010) stated that colony density was 'consistently very high' from the late 1970s to the late 1990s and documented a decline in beaver cache density (and thus presumably beaver population size) from the early 1990s–2005. Windels (2014) estimates a current population of 5 beavers km$^{-2}$ in the VOYA vicinity, which is at least 33% lower than the 1980s density (Johnson and Naiman 1990b, Host and Meysembourg 2010). Thus, the population has been in a long period of decline, but current levels are higher than in the first part of the 20th century. However, it is unknown how recent densities compared to the 'historic condition.'

Sources of Expertise

James Cook, UWSP.

Literature Cited

Cole, G. F. 1987. Changes in interacting species with disturbance. *Environmental Management* 11:257–264.

Collen, P., and R. J. 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.

Donkor, N. T. 2007. Impact of beaver (*Castor canadensis* Kuhl) foraging on species composition of boreal forests. Chap. 18 *in* E.A. Johnson and K. Miyanishi, editors. Plant Disturbance Ecology – The Process and the Response Elsevier Publishers, Boston.

Erickson, A. B. 1939. Beaver populations in Pine County Minnesota. *Journal of Mammology* 20:195–201.

Fryxell, J. M. 2001. Habitat suitability and source-sink dynamics of beavers. *Journal of Animal Ecology* 70:310–316.

Host, G., and P. Meysembourg. 2010. Historic and recent landscape changes in relation to beaver activity in Voyageurs National Park, Minnesota, USA. Final report to National Park Service, Great Lakes Inventory & Monitoring Network/Voyageurs National Park, April 2010. Natural Resources Research Institute, University of Minnesota-Duluth, Duluth, Minnesota. Available at https://irma.nps.gov/App/Reference/Profile/2169980 (accessed 19 August 2014).

Johnston, C. A., and R. J. Naiman. 1990a. Browse selection by beaver: effects on riparian forest composition. *Canadian Journal of Forest Research* 20:1036–1043.

Johnston, C. A., and R. J. Naiman. 1990b. Aquatic patch creation in relation to beaver population trends. *Ecology* 71:1617–1621.

Mech, L. D. 1966. Fauna of the National Parks of the United States: the wolves of Isle Royale. National Park Service Fauna Series #7. U.S. Government Printing Office, Washington, D.C. Available at http://www.nps.gov/history/history/online_books/fauna7/fauna.htm (accessed 19 August 2014).

Naiman, R. J., J. M. Melillo, and J. E. Hobbie. 1986. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). *Ecology* 67:1254–1269.

Peterson R. O., and M. Roma(n)ski. 2008. Beaver survey 2008, Isle Royale National Park. Isle Royale National Park, Houghton, Michigan.

Shelton, P. C. 2004. Beaver studies, Isle Royale National Park, 2002 and 2004. Isle Royale National Park, Houghton, Michigan.

Windels, S. K. 2014. 2014 Voyageurs National Park moose population survey report. Natural Resource Data Series NPS/VOYA/NRDS—2014/645. National Park Service, Fort Collins, Colorado.

### *4.3.7. Climate Change and Terrestrial Systems*

Description

Significant uncertainty accompanies most predictions related to global climate change, not only in the magnitude of changes in physical parameters, but also in their ecological implications. The uncertainty, though, is not in the general trend, but rather in how large the changes will be, the rate at which they occur, and the net effect of all of the indirect and interactive effects. A wide variety of ecological processes (Aber et al. 2001) and species-specific responses (Walther et al. 2002, McKenney et al. 2007) have been, or will be, affected. An additional source of uncertainty is that average climate changes may not be key. As noted above, many dimensions of climate other than annual averages will change, and some of these could have more impact than averages (Morris et al. 2008). Furthermore, it is not always clear whether a pair of changes will act synergistically or antagonistically (e.g., Isard et al. 2007 – winter soil temperatures).

All predictions of future climate are based on one of several General Circulation Models (GCM), which vary in their predictions for the 21st century. Predictions of the ecological impacts of climate change are achieved by taking the predictions of a GCM and plugging them into one or more other models (see Hansen et al. [2001] and Aber et al. [2001] for the common models used in this way). These, as well as the GCM models, are simplifications of reality and are based on a set of assumptions, creating further uncertainty in the predictions. Furthermore, there is not a single model that can even begin to predict the full range of phenomena that are likely to be affected, their interactions, and the net outcome. Thus, all models focus on a few of the changes and ignore the others. For example, we have limited capacities to predict what biotic disturbances are likely to influence a community if the average temperature increases by 3°C or 4°C, or where ice storms are going to be most frequent (Dale et al. 2001). The predictions of models apply to a finite scale, and the majority of ecological models project for a smaller spatial scale than the GCMs. To make these mesh, either the GCM predictions have to be interpolated or the ecological model extrapolated, creating yet another source of uncertainty.

The analyses conducted by Davis et al. (2000) for Western Great Lakes parks (including VOYA) found that they are important reservoirs of biologic diversity in a landscape that has been altered by logging, mineral extraction, agriculture, and urbanization. The accumulated pollen record over the Holocene suggests that proximity to Lake Superior may buffer the regional level effects of temperature changes, at least temporarily. This could be supplemented at VOYA by the large area of water in the park, and thus heighten the value for the Kabetogama Peninsula as a short term refuge for plants and animals.

Winter soil temperatures decreased as air temperatures warmed from 1951–2000 in the Great Lakes region (Isard et al. 2007). This is probably a function of warmer winter air temperatures leading to less and more variable snow pack, and is an example of the interactions that will manifest in the future. A decrease in soil temperature would work to delay the onset of plant growth in the spring and thus minimize some of the phenologic changes noted below. In turn, this could mean a shorter growing season, which could offset the increased productivity related to higher $CO_2$.

Two recent analyses provide additional information and insight on how many aspects of climate have changed in the recent past in comparison to the historic trend (Monahan and Fisichelli 2014), and how the occurrence of trees and 'pest' species are likely to change (Fisichelli et al. 2014). These assessments used two climate change scenarios ['least change' and 'major change'] to determine the sensitivity of the predictions; i.e., was an outcome basically the same regardless of the magnitude of change? The climatic change predictions and possible biotic responses were estimated with coarse scale data and models, and thus are not predictions of what will happen at a given point on the ground for a specific time period. Nonetheless, they provide new and additional insight into the likely changes at a broad scale. The Upper Midwest is one of two regions forecast to have the greatest potential change, and this magnitude is linked to the predicted temperature increase.

### *Projected Impacts on Plants*

Plants and plant communities may be affected by climate change in myriad ways that involve a large number of interacting conditions and biotic interactions, as constrained by the local site conditions and genetic variation of each species (Davis et al. 2000, Pfeifer-Meister et al. 2013). These effects will include very basic, cellular level processes; whole plant processes; interactions between plants (e.g., competition), between plants and their mutualists, and between plants, insects, and pathogens; the frequency and severity of disturbances; and community-wide processes and characteristics. In the earlier stages of $CO_2$-induced warming, the photosynthetic rate and water use efficiency is expected to increase, and thus plant growth may increase (Aber et al. 2001). This will probably not be a universal response; species near the southern end of their range and those closely adapted to mesic site conditions will most likely be stressed by the increased temperatures (Davis et al. 2000). In all likelihood the increase in productivity will be short-lived as temperatures continue to rise, and drought becomes more common or severe (Dale et al. 2001).

Another well-established response to climate change is phenology. An increase in temperature over the past 100 years (primarily 1910–1945 and 1976 to date) has altered the timing of important life history stages of many species (reviewed in Walther et al. 2002). For example, a broad-scale assessment of initiation of spring growth in North America found that it has occurred 1.2–2.0 days earlier per decade for the past 35–63 years (Walther et al. 2002). Following warm, wet winters, nine of 13 European species bloomed earlier by 13–26 days, and one-third bloomed 13–19 days longer (Post and Stenseth 1999); however, woody plants were less sensitive than herbaceous species to climatic variability. A greater impact on spring stages of life history has been noted as opposed to late summer or fall (Walther et al. 2002). A detailed study of a spring ephemeral documented that the time of flowering and emergence of pollinators can be pushed out of synchrony by an early spring, and thus lead to lower levels of seed production (Kudo and Ida 2013). Shifts of this type and magnitude will probably continue through the 21st century. The result could apply to any taxa that key in on a particular stage of the life cycle of plants. Obvious examples include nectar-gathering insects and folivores that feed on new leaves and shoots. These are examples of cascading, or indirect, effects of climate change. Physiologic and phenologic adjustments will continue until climate change exceeds the tolerance of the species and its capacity to adapt (Davis et al. 2005). Alternatively, the species may migrate to an area with a more favorable climate (Davis et al. 2005).

Hansen et al. (2001) predicted the impacts of climate change on forest types and major tree species in the conterminous US. The future distribution of trees and forest types was based on changes in hydrology, light, nutrients, and plant response to increased $CO_2$. Predictions that might apply to VOYA include that suitable habitat for both spruce-fir and aspen-birch will decrease significantly, and species whose ranges might contract of similar scope include quaking aspen, northern white cedar, balsam fir, and paper birch. As noted earlier, these are broad-scale predictions, and they may not apply directly or across the park because of local influences and the moderating effects of Lake Superior (Davis et al. 2000). Currie (2001) predicted the long-term change in richness (number of species within a community) of trees under a scenario of doubling of $CO_2$ and found that short-term changes are likely to be negative, but tree richness will increase in cooler climates and mountainous areas.

The predictions of Fisichelli et al. (2014) are generally in line with those predictions; they estimated that more than 2/3 of the tree species at VOYA will experience a ‘large change’ in habitat suitability; ‘large’ was defined as either a 50%+ decrease or >100% increase by 2100. However, these predictions had a high (72%–84%) degree of uncertainty. That is, the predictions are closely predicated on the actual temperature shift. The authors also generated predictions for a few tree species over the course of the 21st century. For VOYA, the predictions included a steady decrease for black spruce, a decline starting mid-century for paper birch, and an increase in suitability for red maple (Fisichelli et al. 2014).

At the community scale, it is highly probable that at least a few community types as we currently know them will ‘disassemble’ and reform in different combinations. Others will disappear from the landscape, and species that currently do not commonly associate will do so in the future (Hansen et al. 2001, Williams et al. 2007). This will result in communities that are novel (*sensu* Williams et al.

2007), without a current or prior analog. It is highly unlikely that communities will migrate as a unit because of differences among species (in reality, populations) in genotypic variation, generation time, dispersal mode and capacity, phenotypic plasticity and subtle differences in physiologic tolerances. Imposed on top of this may be impacts of novel insect and fungal pests (e.g., Bentz et al. 2010) and differences among species in the need for mutualists. This multitude of drivers makes prediction difficult, and thus there will be groups of species occurring together that are unanticipated. Management efforts will then be dealing with novel entities or assemblages with unknown levels of temporal stability.

The populations of a species at or near the southern end of the range are generally thought to be most susceptible to predicted warming; the same principle would apply for precipitation and the seasonality of moisture. The same comparison would apply at biome borders as well (Frelich and Reich 2010). Hence, the ‘southern boreal forest’ in northern MN is more likely to be affected than the central hardwood forest in southern Indiana. However, it would be presumptive to extrapolate from one or a few species in an assemblage to all of the species; the dendro-chronologic and pollen records clearly show that co-occurring species can respond in very different ways to decade- and century-long climatic change (Villalba et al. 1994, Villalba and Veblen 1998, Black and Abrams 2005). Two key components to the response by a species (or population) are how quickly it can adapt, if at all, and how rapidly it can disperse (Davis et al. 2005, McKenney et al. 2007). The capacity to adapt increases with greater population-level genetic variation and effective population size, a mating system that is partially or entirely out-crossing but does not rely on a specialized pollinator, and a larger range size. It is anticipated that adaptation will vary tremendously among life forms and significantly among species within a life form (Dale et al. 2001, Davis et al. 2005). Herbaceous species should adapt more quickly than trees, and insects more quickly than most plants; this is primarily a function of life cycle length. However, annual plants and short-lived species are more sensitive than longer-lived species to temperature fluctuation (Morris et al. 2008). The second component is migration. Based on the pollen record, we know that species, even within a life form, migrate at very different rates (e.g., Graumlich and Davis 1993) at the scale of millennia. The primary question is whether a species will be able to disperse rapidly enough to match the rates of change in temperature and precipitation regimes (Williams et al. 2007).

*Projected Impacts on Animal Communities*

The richness of birds and mammals is tied closely to temperature, but only weakly to precipitation (Hansen et al. 2001), and thus in North America the greatest levels of vertebrate richness is in moderately warm areas. Therefore, if animals can disperse to northeastern MN, the richness of these two groups may increase by a magnitude similar to the prediction (11%–100%) for the upper montane areas of the US (Currie 2001). It should be noted that these predictions are based solely on temperature and precipitation by season, and thus do not account for all of the indirect influences (see below for moose) that could come into play. Nonetheless, they establish a benchmark from which to work.

As noted for plants, phenologic shifts have been noted for other life forms. Earlier arrival of migrant birds and butterflies and early nesting has been noted in many species (Walther et al. 2002). This is an additional mechanism leading to asynchrony between flowering and pollinator activity, or the arrival of migratory birds and the availability of their prey (Kling et al. 2003).

Post and Stenseth (1999) examined long-term trends in fecundity, body mass, and population size of 16 populations of six ungulate species and related these characteristics to the North Atlantic Oscillation (NAO). The NAO is a large-scale alternation in atmospheric pressure between Iceland and the Azores, and has direct and strong impacts on climatic variation and temperature over the span of years and decades. Hence, it functions similarly to the El Nino Southern Oscillation in the Pacific. Some important demographic responses (body mass, fecundity) varied between mainland and maritime populations. Moose density on Isle Royale declined two years after warm, wet winters, and moose populations in Scandinavia exhibited significant changes in calf, yearling, and adult female mass with changes in winter characteristics. The population in Norway, which inhabits an area with a more maritime climate, had heavier yearling moose following a warmer-than-average winter. Though these two outcomes work in opposite directions, the prevailing indication is that warmer winters lead to reduced moose density.

LaSorte and Thompson (2007) estimated the poleward movement of 254 winter avifauna of North America from 1975 to 2004. The center of occurrence shifted 0.45 km $yr^{-1}$, and the northern boundary changed 1.48 km $yr^{-1}$. Thus, many bird species would likely disappear from VOYA but many more southern species would migrate into the area.

## Conclusions

Given current climate change scenarios, biologically significant changes will likely occur in plant species ranges, bird and mammal composition and abundance, community composition, and many ecosystem properties. Novel assemblages may form, creating many challenges because we will not know the outcome of interactions like competition and predation, nor will we know the successional pathways some communities will take. The dispersal capacity of each species will play a key role. Under current climate change projections, it is almost certain that some species that are at or near the southern limit of their range will disappear. Concurrently, an unknown number of novel plant species, but more insects, will expand northward and colonize northern MN. Species that are scattered and uncommon, have highly specialized environmental requirements, have limited genetic variation, or rely on specialized pollinators, will be more vulnerable to local extinction. It is likely that mammalian richness will decrease, but avian richness will not. It is unknown how important groups like amphibians and fungi will respond, but clearly there will be important ecologic alterations as the climatic regime changes (Treu et al. 2014).

## Sources of Expertise

James Cook, UWSP.

## Literature Cited

Aber, J, R. P. Neilson, S. McNulty, J. M. Lenihan, D. Bachelet, and R. J. Drapek. 2001. Forest processes and global environmental change: predicting the effects of individual and multiple stressors. *BioScience* 51:735–750.

Bentz, B. J., J. Regniere, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negron, and S. J. Seybold. 2010. Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *BioScience* 60:602–613.

Black, B. A., and M. D. Abrams. 2005. Disturbance history and climate response in an old-growth hemlock-white pine forest, central Pennsylvania. *Journal of the Torrey Botanical Society* 132:103–114.

Currie, D. J. 2001. Projected effects of climate changes on patterns of vertebrate and tree species richness in the conterminous United States. *Ecosystems* 4:216–225.

Dale, V. H., L. A. Joyce, S. McNulty, R. P. Neilson, M. P. Ayres, M. D. Flannigan, P. J. Hanson, L. C. Irland, A. E. Lugo, C. J. Peterson, D. Simberloff, F. J. Swanson, B. J. Stocks, and B. M. Wotton. 2001. Climate change and forest disturbances. *Bioscience* 51:723–734. Available at http://www.srs.fs.usda.gov/pubs/ja/uncaptured/ja_dale003.pdf (accessed 28 October 2013).

Davis, M. B., R. G. Shaw, and J. R. Etterson. 2005. Evolutionary responses to changing climate. *Ecology* 86:1704–1714.

Davis, M., C. Douglas, R. Calcote, K. L. Cole, M. G. Winkler, and R. Flakne. 2000. Holocene climate in the western Great Lakes national parks and lakeshores: implications for future climate change. *Conservation Biology* 14:968–983.

Fisichelli, N. A., S. R. Abella, M. Peters, and F. J. Krist, Jr. 2014. Climate, trees, pests and weeds: change, uncertainty, and biotic stressors in eastern U.S. national park forests. *Forest Ecology and Management* 327:31–39.

Frelich, L.E., and P. B. Reich. 2010. Will environmental changes reinforce the impact of global warming on the prairie-forest border of central North America? Frontiers Ecology Environment 8(7):371–378.

Graumlich, L. J., and M. B. Davis. 1993. Holocene variation in spatial scales of vegetation patterns in the Upper Great Lakes. *Ecology* 74:826–839.

Hansen, A. J., R. P. Neilson, V. H. Dale, C. H. Flather, L. R. Iverson, D. J. Currie, S. Shafer, R. Cook, and P. J. Bartlein. 2001. Global change in forests: responses of species, communities and biomes. *BioScience* 51:765–779.

Isard, S. A., R. J. Schaetzl, and J. A. Andresen. 2007. Soils cool as climate warms in the Great Lakes region: 1951–2000. *Annals of the Association of American Geographers* 97:467–476.

Kling, G. W., L. B. Johnson, and S. Polasky. 2003. State summary: Minnesota. Findings from Confronting climate change in the Great Lakes region: impacts on our communities and ecosystems. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C. Available at http://www.ucsusa.org/greatlakes/glchallengereport.html (accessed 7 January 2013).

Kudo, G., and T. Y. Ida. 2013. Early onset of spring increases the phenological mismatch between plants and pollinators. *Ecology* 94:2311–2320.

LaSorte, F. A., and F. R. Thompson. 2007. Poleward shifts in winter ranges of North American birds. *Ecology* 88:1803–1812.

McKenney, D. W., J. H. Pedlar, K. Lawrence, K. Campbell, and M. F. Hutchinson. 2007. Potential impacts of climate change on the distribution of North American trees. *BioScience* 57:939–948.

Monahan, W. B., and N. A. Fisichelli. 2014. Climate exposure of US National Parks in a new era of change. *PLoS ONE* 9: e101302. doi:10.1371/journal.pone.0101302.

Morris, W. F., C. A. Pfister, S. Tuljapurkar, C. V. Haridas, C. L. Boggs, M. S. Boyce, E. M. Bruna, D. R. Church, T. Coulson, D. F. Doak, S. Forsyth, J. Gaillard, C. C. Horvitz, S. Kalisz, B. E. Kendall, T. M. Knight, C. T. Lee, and E. S. Menges. 2008. Longevity can buffer plant and animal populations against changing climatic variability. *Ecology* 89:19–25.

Pfeifer-Meister, L., S. D. Bridgham, C. J. Little, L. L. Reynolds, M. E. Goklany, and B. R. Johnson. 2013. Pushing the limit: experimental evidence of climate effects on plant range distributions. *Ecology* 94:2131–2137.

Post, E., and N. C. Stenseth. 1999. Climatic variability, plant phenology and northern ungulates. *Ecology* 80:1332–1339.

Treu, R., J. Karst, M. Randal, G. J. Pec, P. W. Cigan, S. W. Simard, J. E. Cooke, N. Erbilgin, and J. F. Cahill, Jr. 2014. Decline of ectomycorrhizal fungi following a mountain pine beetle epidemic. *Ecology* 95:1096–1103.

Villalba, R., and T. T. Veblen. 1998. Influences of large-scale climatic variability on episodic tree mortality in northern Patagonia. *Ecology* 79:2624–2640.

Villalba, R., T. T. Veblen, and J. Ogden. 1994. Climatic influences on the growth of subalpine trees in the Colorado Front Range. *Ecology* 75:1450–1462.

Walther, G, E. Post, P. Convey, A. Menzel, C. Parmeson, T. J. Beebee, J. Fromentin, O. Voegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature* 416:389–395.

Williams, J., S. T. Jackson, and J. E. Kutzbach. 2007. Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* 104:5738–5742.

### ***4.3.8. Fish Communities***

Description

The nearly 40% of VOYA that is covered with water is home to a vast array of aquatic organisms. The water bodies within VOYA and adjacent to the park boundaries (26 interior lakes and the five large lakes) contain at least 54 species of fish from 16 different families (Kallemeyn et al. 2003; Table 15). Additionally, based on species distributions and capture in connecting water bodies, it is likely that several other species, including the creek chub (*Semotilus atromaculatus*) and river shiner (*Notropis blennius*), are present in VOYA (Underhill 1957, Wepruk et al. 1992). The large lakes have more diverse fish communities than the interior lakes.

Northern pike (*Esox lucius*) and yellow perch (*Perca flavescens*), both important recreational species, are the most common species, with each being present in 23 or more lakes within the park (Table 15). The most popular sport fish, walleye (*Sander vitreus*), occurs in all the large lakes but in only three interior lakes. Other recreationally important species present include largemouth bass (*Micropterus salmoides*) and smallmouth bass (*M. dolomieu*) (both believed to be non-native), black crappie (*Pomoxis nigromaculatus*), sauger (*Sander canadensis*), muskellunge (*Esox masquinongy*), and lake trout (*Salvelinus namaycush*). Lake trout are present in three interior lakes (Cruiser, Little Trout, and Mukooda) and have been captured in Rainy Lake.

The waters within VOYA are heavily fished, with the average annual number of angler hours exceeding 750,000 during 1977–1999. Further, during this same time period, average angler harvest during summer months has typically exceeded 90,000 kg, with summer harvest exceeding 135,000 kg in some years (Burri 2000, Kallemeyn et al. 2003). The most sought after fishes were walleye and northern pike. The commercial fishery for walleye in Rainy Lake closed during 1987 in the MN waters and in 1991 in the ON waters. However, despite the closure of the commercial fishery and relatively low angler harvest rates, walleye total harvest has exceeded targeted yield values during some years due to high angler effort. Walleye harvest on the MN portions of Namakan and Sand Point Lakes has also exceeded target levels during some years, and the MDNR has implemented more restrictive harvest regulations in an attempt to prevent overharvest. Similarly, Kabetogama Lake historically experienced high levels of angler harvest of walleye; however, angler effort has decreased on this lake in recent years (post 1994) with more effort being focused on Rainy Lake. Extensive information on angler effort and harvest and the relative abundance of several sport fishes found within VOYA can be found in Kallemeyn et al. (2003). Gamefish analyses are being compiled, and production of young of the year fishes in Rainy Lake and Namakan Reservoir are being assessed, in preparation for the International Joint Commission (IJC; Canadian and United States representatives) review of rules governing dam operations (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14). (See section 4.6. for a more detailed description of the IJC process.)

**Table 15.** Fish species collected from water bodies within Voyageurs National Park, Minnesota, USA and Ontario, Canada (Table recreated from Kallemeyn et al. 2003).

| Scientific name | Common name | Scientific family | Abbreviation | # of lakes present |
|---|---|---|---|---|
| *Ichthyomyzon unicuspis* | Silver Lamprey | Petromyzontidae | SIL | 4 |
| *Acipenser fulvescens* | Lake Sturgeon | Acipenseridae | LKS | 4 |
| *Hiodon tergisus* | Mooneye | Hiodontidae | MOE | 2 |
| *Couesius plumbeus* | Lake Chub | Cyprinidae | LKC | 1 |
| *Hybognathus hankinsoni* | Brassy Minnow | Cyprinidae | BRM | 1 |
| *Luxilux cornutus* | Common Shiner | Cyprinidae | CSH | 5 |
| *Margariscus margarita* | Pearl Dace | Cyprinidae | PRD | 4 |
| *Notemigonus crysoleucas* | Golden Shiner | Cyprinidae | GOS | 15 |
| *Notropis atherinoides* | Emerald Shiner | Cyprinidae | EMS | 7 |
| *Notropis heterodon* | Blackchin Shiner | Cyprinidae | BCS | 1 |
| *Notropis heterolepis* | Blacknose Shiner | Cyprinidae | BNS | 19 |
| *Notropis hudsonius* | Spottail Shiner | Cyprinidae | SPO | 6 |
| *Notropis volucellus* | Mimic Shiner | Cyprinidae | MMS | 5 |
| *Phoxinus eos* | Northern Redbelly Dace | Cyprinidae | NRD | 9 |
| *Phoxinus neogaeus* | Finescale Dace | Cyprinidae | FND | 9 |
| *Pimephales notatus* | Bluntnose Minnow | Cyprinidae | BNM | 8 |
| *Pimephales promelas* | Fathead Minnow | Cyprinidae | FHM | 8 |
| *Rhinichthys atratulus* | Blacknose Dace | Cyprinidae | BND | 3 |
| *Rhinichthys cataractae* | Longnose Dace | Cyprinidae | LND | 2 |
| *Catostomus catostomus* | Longnose Sucker | Catostomidae | LND | 1 |
| *Catostomus commersoni* | White Sucker | Catostomidae | WTS | 19 |
| *Moxostoma anisurum* | Silver Redhorse | Catostomidae | SLR | 2 |
| *Moxostoma macrolepidotum* | Shorthead Redhorse | Catostomidae | SHR | 4 |
| *Ameiurus melas* | Black Bullhead | Ictaluridae | BLB | 8 |
| *Ameiurus nebulosus* | Brown Bullhead | Ictaluridae | BRB | 1 |
| *Noturus gyrinus* | Tadpole Madtom | Ictaluridae | TPM | 4 |
| *Esox lucius* | Northern Pike | Esocidae | NOP | 23 |
| *Esox masquinongy* | Muskellunge | Esocidae | MUE | 3 |
| *Umbra limi* | Central Mudminnow | Umbridae | CNM | 2 |
| *Osmerus mordax* | Rainbow Smelt | Osmeridae | RBS | 3 |
| *Coregonus artedi* | Cisco | Salmonidae | TLC | 8 |
| *Coregonus clupeaformis* | Lake Whitefish | Salmonidae | LKW | 4 |
| *Salvelinus namaycush* | Lake Trout | Salmonidae | LAT | 3 |
| *Percopsis omiscomayacus* | Trout Perch | Percopsidae | TRP | 4 |
| *Lota lota* | Burbot | Gadidae | BUB | 4 |
| *Culaea inconstans* | Brook Stickleback | Gasterosteidae | BST | 5 |
| *Pungitius pungitius* | Ninespine Stickleback | Gasterosteidae | NST | 4 |
| *Cottus bairdi* | Mottled Sculpin | Cottidae | MTS | 3 |
| *Cottus cognatus* | Slimy Sculpin | Cottidae | SMS | 6 |
| *Ambloplites rupestris* | Rock Bass | Centrarchidae | RKB | 11 |
| *Lepomis cyanellus* | Green Sunfish | Centrarchidae | GSF | 1 |
| *Lepomis gibbosus* | Pumpkinseed | Centrarchidae | PMK | 13 |
| *Lepomis macrochirus* | Bluegill | Centrarchidae | BLG | 4 |
| **Lepomis megalotis* | Longear Sunfish | Centrarchidae | LES | 2 |
| *Micropterus dolomieu* | Smallmouth Bass | Centrarchidae | SMB | 9 |
| *Micropterus salmoides* | Largemouth Bass | Centrarchidae | LMB | 9 |
| *Pomoxis nigromaculatus* | Black Crappie | Centrarchidae | BLC | 6 |
| *Etheostoma exile* | Iowa Darter | Percidae | IOD | 15 |
| *Etheostoma nigrum* | Johnny Darter | Percidae | JND | 14 |
| *Perca flavescens* | Yellow Perch | Percidae | YEP | 27 |
| *Percina caprodes* | Logperch | Percidae | LGP | 5 |
| *Percina shumardi* | River Darter | Percidae | RVD | 1 |
| *Sander canadensis* | Sauger | Percidae | SAR | 5 |
| *Sander vitreus* | Walleye | Percidae | WAE | 7 |

*This is likely the northern longear sunfish *Lepomis megalotis peltastes* (Porterfield et al. 2012, Gorman et al. 2014).

### *Muskellunge*

Muskellunge (Figure 18) are large-bodied, relatively long-lived fish that can grow in excess of 150 cm and reach weights of 25 kg. They are classified as a cool water species and are ecologically important as an apex predator in systems where they are found. Muskellunge are highly piscivorous (Bozek et al. 1999), but have been known to take ducklings and even mammals such as mice (Family Murinae) and muskrats (*Ondatra zibethicus*) (MDNR 2014a). Muskellunge are typically found at very low densities and are considered by anglers to be a very elusive species. They have been labeled "the fish of 10,000 casts" due to their low angling catch rates in most fisheries (Michigan DNR 2012). Most states and provinces, including MN and ON, manage muskellunge as a trophy fishery with low daily creel limits, low possession limits, and high minimum length limits (i.e., 127 cm [50"]).

**Figure 18.** Adult muskellunge. Available: www2.dnr.cornell.edu.

VOYA is home to a unique genetic strain of muskellunge present in Shoepack and Little Shoepack (Boot) Lakes (Shoepack strain; Miller et al. 2009). Shoepack strain muskellunge were stocked into lakes throughout MN for over 30 years (Younk and Strand 1992). The muskellunge in Shoepack Lake were abundant, but small in size. The small size was assumed to be related to density dependent growth (Wingate and Younk 2007). However, lakes stocked with Shoepack strain muskellunge had very few fish reach lengths >1,016 mm (40"), and size structure in many native systems stocked with Shoepack strain muskellunge appeared to decline (Wingate and Younk 2007). Subsequent studies identified that the Shoepack strain was indeed a small size structure strain of muskellunge (Younk and Strand 1992) and that it represented a unique genetic lineage on the landscape (Miller et al. 2009). One concern regarding this unique genetic strain of muskellunge relates to climate change. Predictive models suggest under current climate change scenarios, muskellunge are not likely to persist in Shoepack and Little Shoepack Lakes past the end of this century (Gorman et al. 2014).

### *Lake Sturgeon*

One of the distinctive species found in VOYA is the lake sturgeon (Figure 19), the largest and longest lived fish in North America (Scott and Crossman 1998). They can reach lengths >215 cm, weights >100 kg, and ages >100 years. Due to their life history characteristics, lake sturgeon are highly vulnerable to overharvest (Peterson et al. 2007). In fact, lake sturgeon populations are believed to only be approx. 1% of their historic levels rangewide (Tody 1974, Peterson et al. 2002).

**Figure 19.** Adult lake sturgeon. Available: www2.dnr.cornell.edu.

Lake sturgeon, like most sturgeon species, have experienced major declines throughout their native range due to overfishing, habitat degradation, and pollution and habitat loss due to the impoundment of rivers (Priegel and Wirth 1978, Auer 1999). This reduction in population abundance has led to lake sturgeon being listed as a species of "special concern" in ON and MN (McLeod 2008) and to the closing of commercial fisheries (such as those in Figure 20) as well as many recreational fisheries. Where present, recreational fisheries have very conservative harvest regulations that include high minimum length limits coupled with low creel and possession limits to prevent overharvest (Johnson 1987, Baker and Borgeson 1999, Bruch 1999). Other lake sturgeon fisheries are limited entry and operate with a harvest quota to prevent overharvest (Bruch 1999).

**Figure 20.** Lake sturgeon commercial harvest from Lake of the Woods (the same practices were used on Rainy and Namakan Lakes). Photo courtesy of Lake of the Woods Historical Society.

The specific life history characteristics that make lake sturgeon vulnerable to overharvest are the late age at maturation and protracted spawning periodicity. Male lake sturgeon typically mature between ages 8–20, while females mature between ages 14–33; males typically spawn every 1–3 years, while females spawn every 3–5 years (Peterson et al. 2007, OMNR 2009, Shaw et al. 2012). Additionally, lake sturgeon are known to undergo long spawning migrations (≥200 km) and are believed to exhibit spawning site fidelity (Peterson et al. 2007). Many biologists believe lake sturgeon experience imprinting as juveniles, and, in turn, the spawning site fidelity equates to natal philopatry (Lyons and Kempinger 1992, Peterson et al. 2007). These life history characteristics are especially critical to the populations within VOYA. Recently, three new hydroelectric dams have been proposed on the Namakan River (Hay Rapids, High Falls, and Myrtle Falls; McLeod 2008). The presence of dams has been known to fragment lake sturgeon (and other fishes) populations (Ferguson and Duckworth 1997). Further, isolation of lake sturgeon populations via the impoundment of riverine systems often results in the loss of genetic diversity and has even resulted in the extirpation of local populations (Ferguson and Duckworth 1997). Specifically, McLeod et al. (2013) documented movement of lake sturgeon through the areas proposed for impoundment within the Namakan River. This suggests that the proposed dams could have negative effects on lake sturgeon within VOYA.

Lake sturgeon populations within VOYA appear to be recovering from historic overharvest. All populations are experiencing low natural mortality (<6%), and natural recruitment appears to be present (Adams et al. 2006, McLeod 2008, Shaw et al. 2012). However, many of the populations have still not met the long-term recovery goals (McLeod 2008). Specifically, in Namakan River, some of the recovery goals that have not yet been achieved include the number of age classes present, the number of female fish over 2,030 mm, and the number of females older than 70 years (McLeod 2008). Shaw et al. (2012) also documented that the majority of lake sturgeon present in the Namakan Reservoir were between 33–59 years of age, with a low percentage of sturgeon older than age 60. Similarly, in Rainy Lake, few lake sturgeon older than 50 years of age were collected (Adams et al. 2006). These results suggest that lake sturgeon populations within VOYA are doing well, but are still vulnerable to environmental perturbations.

### *Lake Trout*

Another fish species found within and native to VOYA is the lake trout (Figure 21), a long-lived, large bodied, cold-water salmonid. Lake trout can live in excess of 50 years, with fish over 20 years of age being common in many populations. Lake trout can reach sizes in excess of 22 kg and 125 cm. They are highly piscivorous when prey fishes are available. Lake trout, like most salmonids, spawn during the fall over cobble, boulder, and rubble substrates when water temperatures drop below 10° C. They are believed to exhibit philopatry or “homing” behavior back to a specific reef to spawn each year (Marsden et al. 1995).

Within VOYA, lake trout are found in Rainy Lake and three interior lakes, Cruiser, Little Trout, and Mukooda Lakes. All three of these lakes are infertile (oligotrophic), soft water lakes that are relatively deep, with maximum depths of 28, 29, and 24 m, respectively.

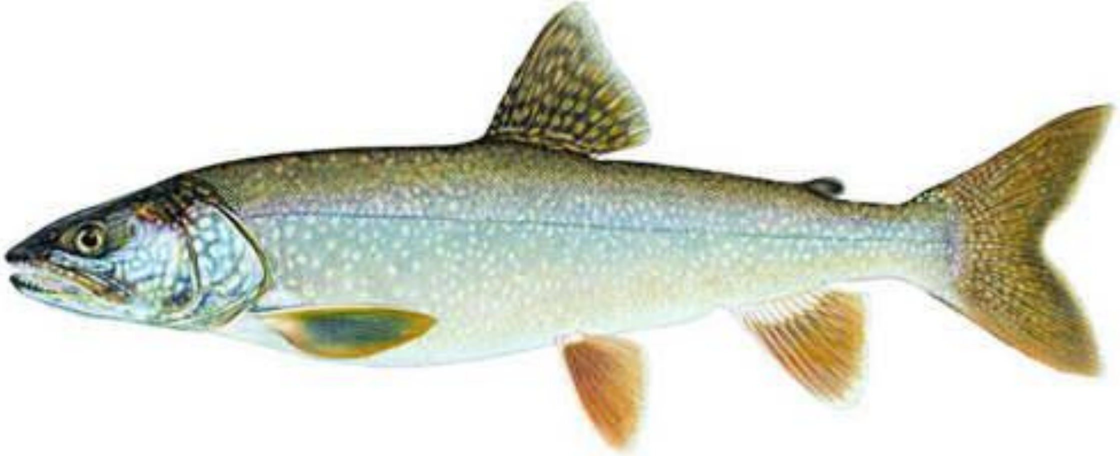

**Figure 21.** Adult lake trout. Photo courtesy of USDA Forest Service. Available: www.fs.usda.gov.

Cruiser Lake (46.5 ha) is located on the Kabetogama Peninsula, approximately 40 km east of International Falls, MN. Currently, no motorized boats, vehicles, or planes are allowed on Cruiser Lake, as Cruiser Lake is in a portion of VOYA designated as proposed wilderness. These restrictions have likely led to a decrease in angler effort on Cruiser Lake. The lake trout stock in Cruiser Lake is believed to have been derived from colonization approx. 10,000 BP, when this lake was isolated (Gorman et al. 2014). Historically, Cruiser Lake was stocked with lake trout fry (1948–1970), fingerlings (1971–1979), and yearlings (1982–1988); however, no stocking has occurred since 1988, and the lake trout population is believed to be sustaining via natural reproduction. Lake trout were sampled in Cruiser Lake during 1970, 1983, 1995, and 2005. Mean catch per unit effort (CPUE) ranged from 3.4 to 6.3 fish per gill net. During the most recent survey (2005), CPUE was 5.8 fish/net which was slightly higher than the historical average of 4.5 fish/net and much higher than other similar water bodies in the region (mean 3.7 fish/net). Cruiser Lake has a relatively simple fish community consisting of yellow perch, white sucker (*Catostomus commersoni*), and various cyprinids (minnow species). However, despite the presence of these prey species, lake trout growth is believed to be reduced due to the lack of cisco (*Corgeonus artedi*) within Cruiser Lake; average size of lake trout in the 2005 sample was 40.4 cm (range 25.9–52.6 cm; Peterson 2007).

Little Trout Lake (96.7 ha) is located near Sand Point Lake and is 14.9 km north of Crane Lake, MN. Access to Little Trout Lake is via a portage trail from Sand Point Lake. Similar to the other interior lakes, access via floatplane has been discontinued following the invasion of spiny water flea (*Bythotrephes longimanus*) within VOYA (MDNR 2013). Lake trout are believed to have colonized Little Trout Lake approximately 3,000 BP (Gorman et al. 2014). Starting in 1965 and continuing through 2006, lake trout of various sizes have been stocked into Little Trout Lake at various densities. Since 1988, Gillis strain lake trout (native to NE MN; Boundary Waters lakes) have been stocked exclusively within Little Trout Lake. It is believed that lake trout were native within Little Trout Lake; however, this cannot be confirmed. Stocking was discontinued in 2006 to determine the level of natural recruitment present in Little Trout Lake.

Little Trout Lake has a more diverse fish community than many of the other interior lakes found within VOYA. At least nine fish species have been captured during MDNR sampling, including yellow perch, white sucker, walleye, cisco, smallmouth bass, sauger, rock bass (*Ambloplites rupestris*), northern pike, and lake trout. Sampling was conducted using gill nets during 1969, 1973, 1983, 1991, 1994, and 1999. Lake trout CPUE has varied from 0.27 to 1.75 fish/gill net during these sampling periods (Figure 22). Additionally, during 2004, 2009 and 2014 gill nets were set in a random stratified manner to encompass both shallow and deep water habitats. During 2004 and 2009, lake trout CPUE in the deep water sets was 1.00 and 0.13 fish/net, respectively. Catch of lake trout during the 2009 sampling was well below the MDNR target of 1.00 fish/net (Peterson 2011). Further, during 2014, no lake trout were captured in the gill net survey (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14). Survey data indicated that most of the lake trout harvested from Little Trout Lake were stocked fish (fin clipped) but also suggested some natural reproduction is occurring (unclipped fish). In fact, 38% of the fish sampled during the 2004 survey were unclipped. Data also indicated that several different year classes were present, growth of lake trout was fast until age-4, and condition was high (Peterson 2011). This was potentially due to both the low abundance of lake trout and the presence of cisco within Little Trout Lake.

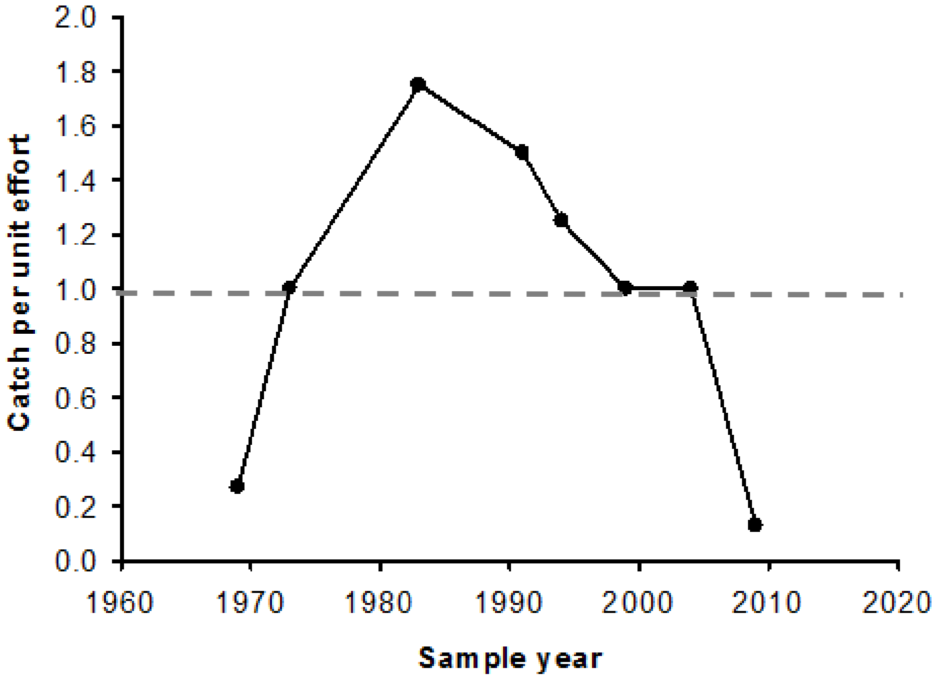

**Figure 22.** Lake trout catch per unit effort (number per gill net) in Little Trout Lake, Voyageurs National Park, during 1969–2009. The 2004 and 2009 data points were only from deep-water sets. Gray dashed horizontal line denotes the management goal of 1 fish/ net. Data from Peterson 2011.

One potential area of concern related to the lake trout population in Little Trout Lake is the increase in both walleye and smallmouth bass since 1983 (Figure 23). Walleye and smallmouth bass are both predatory species, and smallmouth bass have been shown to outcompete lake trout in Canadian lakes (Vander Zanden et al. 1999). Additionally, other top level predators are present within Little Trout

Lake, including northern pike and sauger. The abundance of top level predators could cause competition for food resources between lake trout and the other piscivorous species. Further, an abundance of top level predators could be limiting lake trout recruitment either via direct predation (i.e., northern pike) or competition (i.e., smallmouth bass).

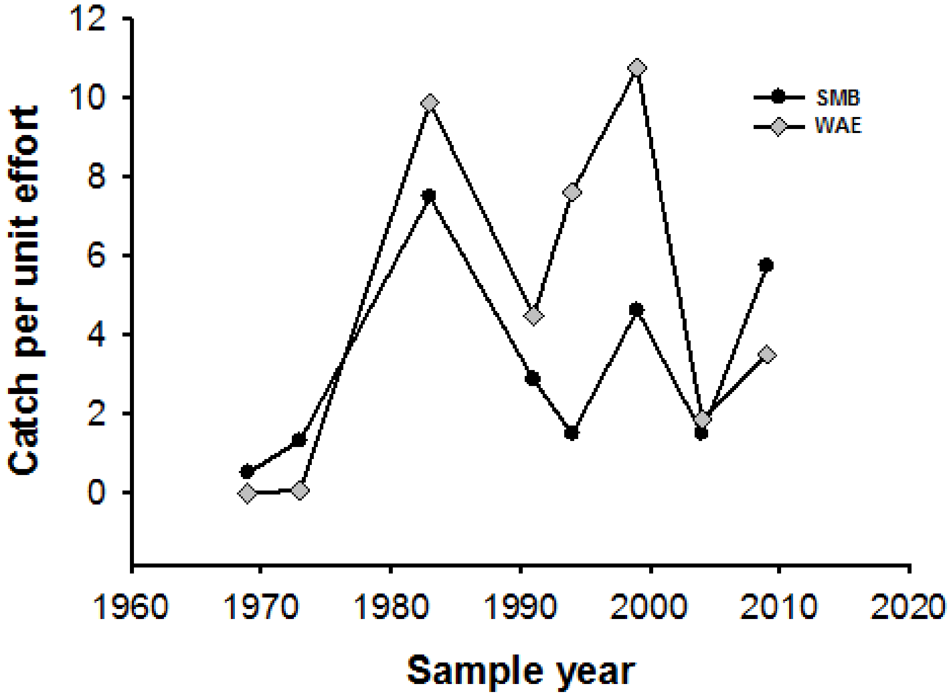

**Figure 23.** Smallmouth bass (SMB) and walleye (WAE) catch per unit effort (number per gill net) in Little Trout Lake, Voyageurs National Park, during 1969–2009. The 2004 data points were only from deep-water sets, while the 2009 data points were only from the shallow water sets. Data from Peterson 2011.

Mukooda Lake (305.1 ha) is the largest and youngest of the interior lakes within VOYA that supports a population of lake trout (Gorman et al. 2014). Like Little Trout Lake, Mukooda Lake is located north of Sand Point Lake and is accessible via a portage from Sand Point Lake. In fact, Mukooda Lake has two small inlets and has an outlet that drains into Sand Point Lake. Mukooda Lake is believed to have been colonized approximately 1,200 BP and includes 15 native species (Gorman et al. 2014). Lake trout were stocked into Mukooda Lake from 1942–2010. The Gillis strain of lake trout was exclusively stocked into Mukooda Lake from 1988–2010; the strain of origin stocked prior to 1988 is unknown. Additionally, smallmouth bass were stocked into Mukooda Lake in 1946. No other stocking of smallmouth was documented, but they have persisted in the system since the original stocking event.

Of the three interior lakes containing lake trout, Mukooda Lake has the most diverse fish community, with 17 different species being captured during MDNR gill net surveys (Peterson 2009). The fish community in Mukooda Lake was sampled in 1969, 1983, 1987, 1991, 1994, 1997, 2002, 2007, and 2012. Lake trout mean CPUE has been relatively low (mean ± SD = 1.1 ± 1.4 fish/net), with only the 1994 and 1997 samples meeting the goal of 2.0 fish/net. However, this goal is for deep water net sets only and prior to 2007, both deep and shallow water sets were included in mean CPUE estimates (Figure 24). No lake trout were collected during annual sampling in 2012; however, anglers did harvest lake trout during the winter fishing season in 2013 (MDNR 2014b). Cisco, an important prey species for lake trout, have had the highest CPUE of any species during every sample year except 1983 and 2012 (Figure 25). Both lake trout and cisco appear to be declining in Mukooda Lake (MDNR 2014b). Due to this decline, the MDNR has put an emergency closure on harvest of lake trout from Mukooda Lake and has proposed a permanent closure of lake trout harvest on both Mukooda and Little Trout Lakes (MDNR 2014c, d).

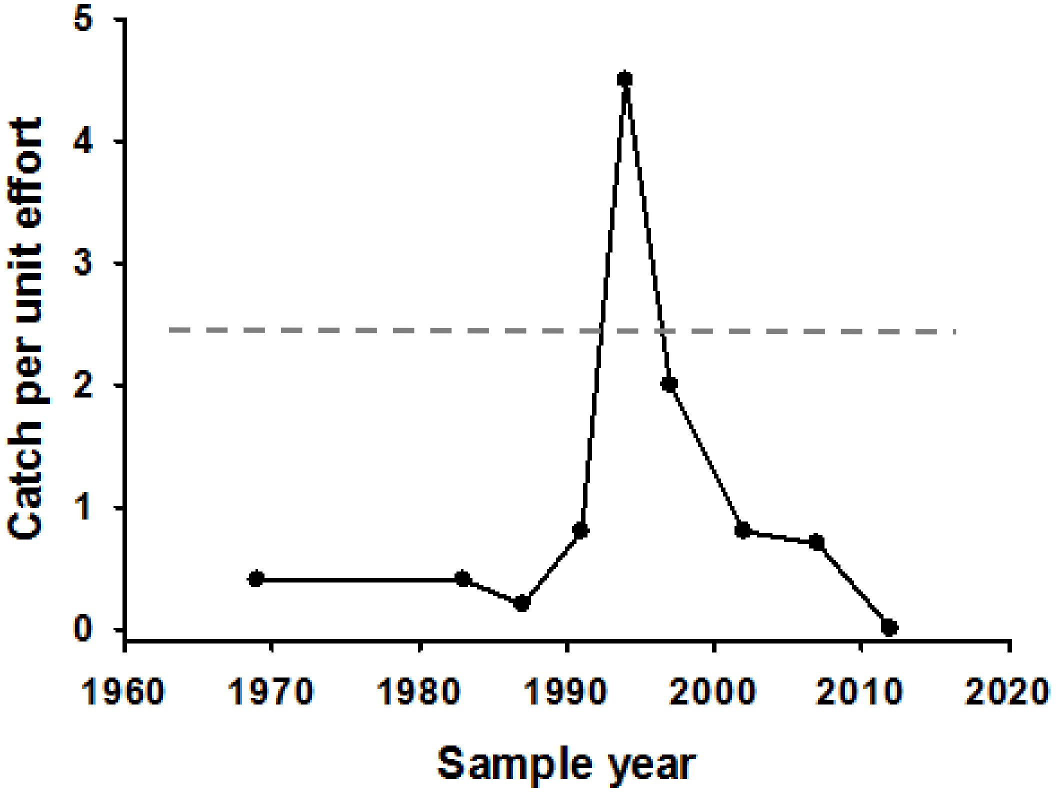

**Figure 24.** Lake trout catch per unit effort (number per gill net) in Mukooda Lake, Voyageurs National Park, during 1969–2012. The 2007 data points were only from deep-water sets. Gray dashed horizontal line denotes the management goal of 2 fish/ net in the deep water gill nets. Data from Peterson 2009 and MDNR 2014b.

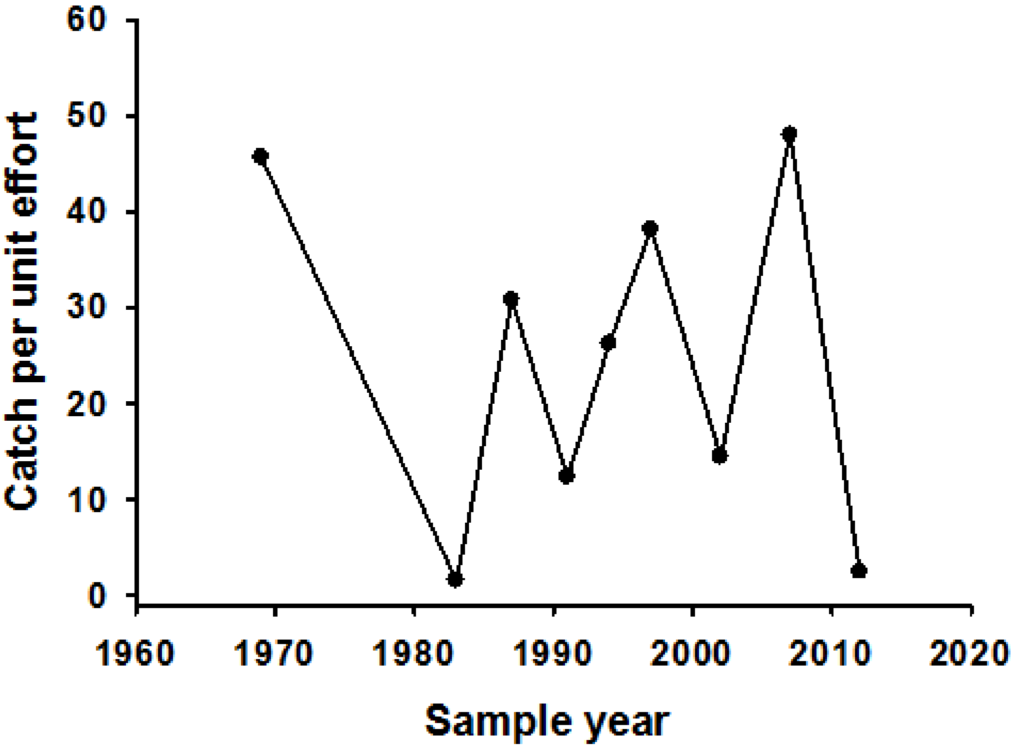

**Figure 25.** Cisco catch per unit effort (number per gill net) in Mukooda Lake, Voyageurs National Park, during 1969–2012. The 2007 data points were only from deep-water sets. Data from Peterson 2009 and MDNR 2014b.

Prior to the presence of the invasive spiny water flea and the new boating regulations (as described above) angler harvest of lake trout in Mukooda Lake was low (Burri 2003), but it exceeded the potential yield estimate based on the morphoedaphic index (Siesennop 2000). However, the projected yields were below values derived from a thermal based model (Kallemeyn et al. 2003). Regardless, harvest of lake trout in Mukooda Lake should be assessed now that artificial bait regulations are in place.

*Cisco*

Cisco (Figure 26) (also called lake herring and tulibee) are a planktivorous, cold water species in the salmonidae family. Cisco feed primarily on zooplankton (cladocerans and copepods) and *Mysis* but also feed on small fishes and benthic macroinvertebrates. However, preferential feeding on the spiny water flea *Bythotrephes longimanus* by cisco has been documented in Harp Lake, ON (Coulas et al. 1998). Cisco, like lake trout, are oxythermally limited and generally reside within the pelagia between 10–100 m of water. Typically they are not present in inland lakes with water temperatures exceeding 18° C (Derosier 2007).

**Figure 26.** Adult cisco. Available: www2.dnr.cornell.edu.

Cisco are a relatively small bodied fish (the MN state record is <3 kg). They can be differentiated from their cousin species (also present in Rainy Lake) the lake whitefish (*Coregonus clupeaformis*) by looking at their snout. The lower jaw on cisco extends up to the tip of the snout (Figure 26), whereas the snout of the lake whitefish overhangs the lower jaw. Cisco spawn in late fall and winter with the eggs hatching the following spring (Scott and Crossman 1998). Currently, cisco can be fished during a fall (Mid October–early December) season using gill nets; however, the number of people participating in this, and the total harvest, is unknown. Cisco are captured as by-catch in the lake whitefish commercial fishery; however, the commercial harvest of lake whitefish is very low (<150 kg annually during the 1990s) and, therefore, by-catch of cisco in this fishery is unlikely to have an effect on their populations within VOYA's large lakes. Cisco are also angled during the winter ice-fishing season on Rainy, Namakan, Kabetogama, and Sand Point Lakes.

Management biologists were concerned about the cisco populations within VOYA following the invasion of the large lakes by rainbow smelt (*Osmerus mordax*). The cisco population in Sparkling Lake, Wisconsin was extirpated in 1990 following the invasion of rainbow smelt; predation on larval cisco by smelt was the most likely cause (Hrabik et al. 1998). Similarly, in Lake Simcoe, ON, catches of cisco and rainbow smelt were inversely related (Evans and Waring 1987).

Cisco are found in four of the interior lakes on the Kabetogama Peninsula within VOYA (Locator, War Club, Mukooda, and Little Trout Lakes). They are also present in Rainy, Namakan, Sand Point, and Kabetogama Lakes. Mean CPUE of cisco during the annual MDNR gill net surveys (1983–2000) was highest in Sand Point Lake (9.14, CV=40) and lowest, but most variable, in Rainy Lake (0.83, CV=99; Kallemeyn et al. 2003). In Rainy Lake, CPUE of cisco has remained relatively stable since the mid-1990s when rainbow smelt populations in Rainy Lake began to decline (see Figure 38 from Kallemeyn et al. 2003).

Locator (57 ha) and War Club (37 ha) Lakes are located on the Kabetogama Peninsula and are connected via a strait; therefore, they function as a single ecosystem. Both lakes have a maximum depth >12 m, with low fertility and soft water. Relative abundance (CPUE) of cisco in these lakes has been variable over time, with the highest catches in War Club Lake occurring during 1983 and the highest catches in Locator Lake occurring in 2000 (Figure 27). Neither of these lakes have lake trout present, and the top level predators in these systems are northern pike and largemouth bass. Based on the life history of these species, it is most likely that the northern pike are the top predator for cisco in these systems. For example, the two highest CPUE estimates for northern pike (1970, 1983) corresponded to the two lowest CPUE estimates for cisco in Locator Lake (r=-0.61). However, this relationship was not present in War Club Lake (r=-0.21).

Cisco are also present in Mukooda Lake, the largest interior lake with the most diverse fish community. Mean CPUE of cisco in Mukooda Lake was also highly variable; however, the catch was much higher than in Locator and War Club Lakes (Figure 25). However, unlike in War Club and Locator, lake trout are likely the top predator structuring the cisco population within Mukooda Lake. No relationship was detected between the CPUE of lake trout and cisco within Mukooda Lake (r=0.05), but it is not uncommon in larger aquatic systems with more complex fish communities for simple predator-prey relationships to be less clear.

The final interior lake with a population of cisco is Little Trout Lake. Like Mukooda Lake, Little Trout Lake also has lake trout present. Cisco CPUE has been variable over the years that Little Trout Lake was sampled (1969–2009); however, catches were typically higher than in Locator and War Club Lakes and lower than in Mukooda Lake. The two highest mean CPUE estimates occurred in 2004 and 2009 (most recent surveys); however, stratified sampling occurred during these two surveys and only the deep water net sets were included for these samples (Figure 28). The use of shallow water sets, where it is likely too warm for cisco, were included in the previous sample years, potentially artificially lowering the CPUE during the 1969–1999 samples.

### *Global climate change and cold-water species in VOYA*

One potentially complicating factor in the future management of lake trout and cisco within VOYA is global climate change. Research has predicted a 2°C–5°C increase in mean annual air temperature by 2090 in the Great Lakes region (Kattenberg et al. 1996, Magnuson et al. 1997, Kling et al. 2003). Increased water temperatures could have large effects on both lake trout and cisco, as they require specific oxythermal conditions (cold, oxygen rich waters) to survive (Steedman and Kushneriuk 2000 and references within). Increased water temperatures stress lake trout and their primary prey species, cisco (where present) (Edsall and Colby 1970, Magnuson and Destasio 1997). Increased water temperature also reduces the amount of oxygen within the water. Lake trout require dissolved oxygen concentrations of >5–6 mg/L for survival (Sellers et al. 1998). Some biologists combine dissolved oxygen and temperature into a single parameter known as TDO3 (temperature at 3 mg $L^{-1}$ of dissolved oxygen; Jacobson et al. 2010, LeDuc and Damstra 2013). This further reduces the amount of suitable habitat within lakes for lake trout. In fact, some climate models predict that 74% of MN and 70% of Wisconsin lakes containing cisco will lose this species by the end of the 21st century (Sharma et al. 2011, Jiang et al. 2012). However, Gorman et al. (2014) hypothesized that based on thermal conditions and physical habitats, Cruiser, Mukooda, and Little Trout Lakes (along with Locator and War Club Lakes) are likely to retain their full complement of cold and coolwater species

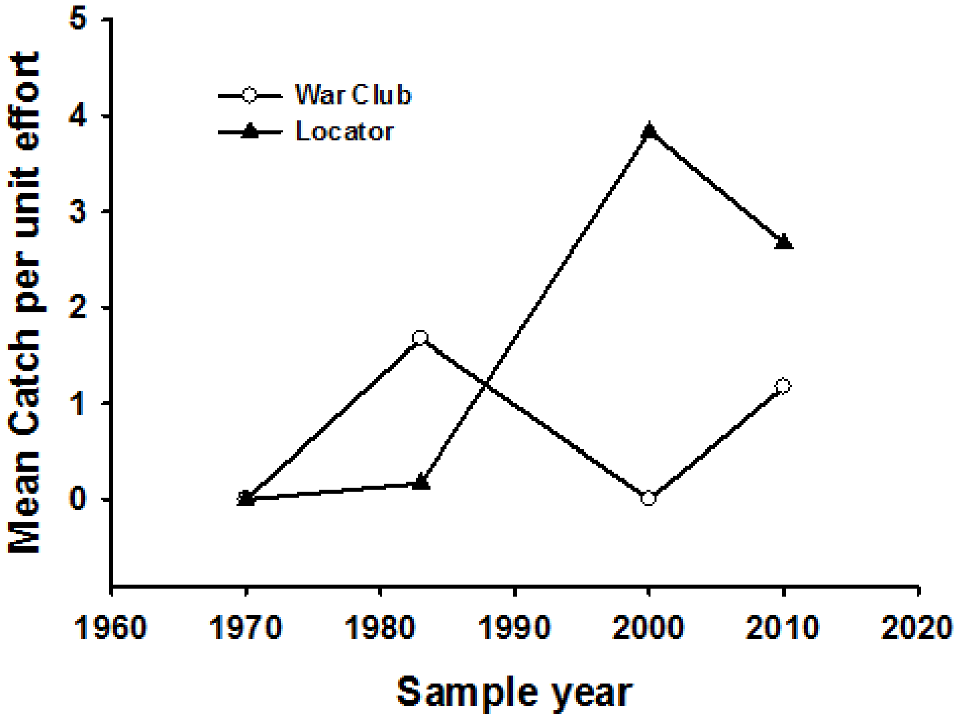

**Figure 27.** Cisco catch per unit effort (number per gill net) in Locator (black triangles) and War Club (white circles) Lakes, Voyageurs National Park, during 1970–2010. Data from Peterson 2012a, 2012b.

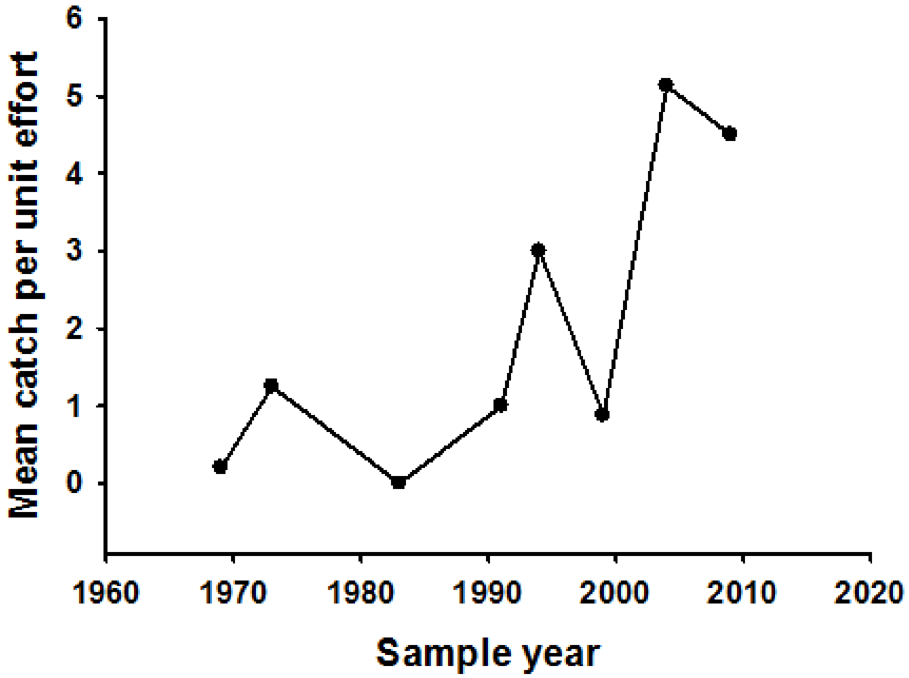

**Figure 28.** Cisco catch per unit effort (number per gill net) in Little Trout Lake, Voyageurs National Park, during 1969–2009. Catch estimates in 2004 and 2009 were only from deep water gill net sets. Data from Peterson 2011.

over the next century. This makes these lakes especially valuable as heritage communities within VOYA. However, the best way for these lakes to maintain their cold, oxythermal habitats is to prevent eutrophication (Fang et al. 2012). Therefore, protection of the lakes' watershed is vital, as this is the best method to prevent eutrophication via nutrient loading and habitat disturbance (Jacobson et al. 2010, 2013, Gorman et al. 2014). Further, careful monitoring of water temperature and oxygen profiles within these systems may be necessary to better understand the potential for maintaining lake trout and cisco populations within VOYA.

### Data and Methods

Kallemeyn et al. (2003) compiled a list of fish species present within VOYA (Table 15). Additional data on fish presence and abundance were obtained from the MDNR and NPS.

Fishes were collected using the following gears: graded mesh gill nets, small mesh gill nets, beach seines, and nighttime boat electrofishing.

### Reference Condition

A true reference condition for VOYA in relation to the fish community is difficult to ascertain. We have chosen the MDNR target levels for fish species populations in VOYA lakes as the reference condition; this is a "least disturbed condition" or "the best of today's existing conditions" (Stoddard et al. 2006).

### Condition and Trend

⇔ Overall, the fish communities within VOYA are in good condition, with a stable trend. Our confidence in this assessment is high. There are few non-native species present, many native species are thriving, and species of special concern (e.g., lake sturgeon) appear to be recovering from historical lows. There is some debate as to whether smallmouth bass are native to these waters, but they do not appear to be outcompeting any native species within VOYA. Rainbow smelt are not native but have been in VOYA since 1990, and their populations are believed to be stable or decreasing.

There are a few exceptions, however. Caution should still be taken to help ensure a full recovery of the lake sturgeon and to prevent future invasions of exotic species. Lake trout within the three interior lakes are below management objectives, and the levels of natural recruitment are still relatively unknown. Additionally, the northern pike populations within some of the interior lakes are below management targets. Further, the long-term effects of the invasive zooplankter *Bythotrephes longimanus* on recruitment of juvenile fishes are still not known. Also, global climate change and eutrophication present ongoing challenges to many fishes with VOYA, especially the cold water species (cisco and lake trout).

### Sources of Expertise

Ryan Maki, Aquatic Ecologist, VOYA; Dr. Justin VanDeHey, Assistant Professor of Fisheries and Water Resources, UWSP; Kallemeyn et al. 2003; MDNR Lake Reports and Management Plans.

Literature Cited

Adams, W. E., L. W. Kallemeyn, and D. W. Willis. 2006. Lake sturgeon population characteristics in Rainy Lake, Minnesota and Ontario. *Journal of Applied Ichthyology* 22:97–102.

Auer, N. A. 1999. Population characteristics and movements of lake sturgeon in the Sturgeon River of Lake Superior. *Journal of Great Lakes Research* 25:282–293.

Baker, E. A., and D. J. Borgeson. 1999. Lake sturgeon abundance and harvest in Black Lake, Michigan 1975–1999. *North American Journal of Fisheries Management* 19:1080–1088.

Bozek, M. A., T. M. Burri, and R. V. Frie. 1999. Diets of muskellunge in northern Wisconsin lakes. *North American Journal of Fisheries Management* 19:258–270.

Bruch, R. M. 1999. Management of lake sturgeon on the Winnebago System – long term impacts of harvest and regulations on population structure. *Journal of Applied Ichthyology* 15:142–152.

Burri, T. 2000. An angler creel survey of Crane, Kabetogama, Little Vermilion, Namakan, and Sand Point Lakes, summer of 1999. Section of Fisheries Completion Report, F-29-R(P)-19, Study 4, Job 484. Minnesota Department of Natural Resources, St. Paul, Minnesota.

Burri, T. 2003. An angler creel survey of Little Trout and Mukooda Lakes, winter of 2002. Section of Fisheries Completion Report, F-29-R(P)-21, Study 4, Job 613. Minnesota Department of Natural Resources, St. Paul, Minnesota.

Capelli, G. M., and B. J. Munjal. 1982. Aggressive interactions and resource competition in relation to species displacement among crayfish of the genus *Orconectes*. *Journal of Crustacean Biology* 2:486–492.

Coulas, R. A., H. J. MacIsaac, and W. Dunlop. 1998. Selective predation on an introduced zooplankter (*Bythotrephes cederstoemi*) by lake herring (*Corgeonus artedii*). *Freshwater Biology* 40:343–355.

Derosier, A. L. 2007. Special animal abstract for *Coregonus artedi* (cisco, lake herring). Michigan Natural Features Inventory. Lansing, Michigan. 3 pp.

Edsall, T. A., and P. J. Colby. 1970. Temperature tolerance of young-of-the-year cisco, *Coregonus artedii*. *Transactions of the American Fisheries Society* 99:526–531.

Evans, D. O., and P. Waring. 1987. Changes in the multispecies, winter angling fishery of Lake Simcoe, Ontario 1961–83: Invasion by rainbow smelt, *Osmerus mordax*, and the roles of intra- and interspecific interactions. *Canadian Journal of Fisheries and Aquatic Sciences* 44 (Supplement 2):187–197.

Fang, X., L. Jiang, P. C. Jacobson, H. G. Stefan, S. R. Alam, and D. L. Pereira. 2012. Identifying cisco refuge lakes in Minnesota under future climate scenarios. *Transactions of the American Fisheries Society* 141:1608–1621.

Ferguson, M. M., and G. A. Duckworth. 1997. The status and distributions of lake sturgeon, *Acipenser fulvescens*, in the Canadian provinces of Manitoba, Ontario and Quebec: a genetic perspective. *Environmental Biology of Fishes* 48:299–309.

Gorman, O., L. Kallemeyn, and R. Maki. 2014. Biogeographic patterns of fish communities of inland lakes of Isle Royale, Voyageurs and Sleeping Bear Dunes National Park units. National Park Service Technical Report.

Hrabik, T. R., J. J. Magnuson, and A. S. McLain. 1998. Predicting the effects of rainbow smelt on native fishes in small lakes: evidence from long-term research on two lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1364–1371.

Jacobson, P. C., H. G. Stefan, and D. L. Pereira. 2010. Coldwater fish oxythermal habitat in Minnesota lakes: influence of total phosphorus, July air temperature, and relative depth. *Canadian Journal of Fisheries and Aquatic Sciences* 67:2002–2013.

Jacobson, P. C., X. Fang, H. G. Stefan, and D. L. Pereira. 2013. Protecting cisco (*Coregonus artedi* Lesueur) oxythermal habitat from climate change: building resilience in deep lakes using a landscape approach. *Advances in Limnology* 64:323–332.

Jiang, L., X. Fang, H. G. Stefan, P. C. Jacobson, and D. L. Pereira. 2012. Oxythermal habitat parameters and identifying cisco refuge lakes in Minnesota under future climate scenarios using variable benchmark periods. *Ecological Modeling* 232:14–27.

Johnson, J. E. 1987. Protected fishes of the United States and Canada. American Fisheries Society, Bethesda, Maryland. 42 pp.

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003–0001. USGS Columbia Environmental Research Center, Columbia, Missouri. 95 pp. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Kattenberg, A., F. Giorgi, H. Grassi, G. A. Meehl, J. F. B. Mitchell, R. J. Stouffer, T. Tokioka, A. J. Weaver, and T. M. L. Wigley. 1996. Climate Models. Projections of future climate. Pages 285–357 *in* J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, editors. Climate Change 1995. The Science of Climate Change. IPCC (Volume 19390). Cambridge University Press, Cambridge, UK.

Kling, G. W., K. Hayhoe, L. B. Johnson, J. J. Magnuson, S. Polasky, S. K. Robinson, B. J. Shuter, M. M. Wander, D. J. Wuebbles, D. R. Zak, R. L. Lindroth, S. C. Moser, and M. L. Wilson. 2003. Confronting climate change in the Great Lakes region: impacts on our communities and ecosystems. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C. Available at http://www.ucsusa.org/greatlakes/ (accessed 30 June 2014).

LeDuc, J., and R. Damstra. 2013. Using moored temperature arrays to understand coldwater fish habitat in lakes at Voyageurs National Park. International Lake of the Woods Water Quality Forum, International Falls, Minnesota.

Lyons, J. D., and J. J. Kempinger. 1992. Movements of adult lake sturgeon in the Lake Winnebago system. Wisconsin Department of Natural Resources Research Report No. 156. Madison, Wisconsin.

Magnuson, J. J., and B. T. Destasio. 1997. Thermal niche of fishes and global warming. Pages 377–408 *in* C. M. Wood, and D. G. McDonald, editors. Global warming: implications for freshwater and marine fish. Society for Experimental Biology Seminar Series 61. Cambridge University Press, UK.

Magnuson, J. J., K. E. Webster, R. A. Assel, C. J. Bowser, P. J. Dillon, J. G. Eaton, H. E. Evans, E. J. Fee, R. I. Hall, L. R. Mortsch, D. W. Schindler, and F. H. Quinn. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian Shield Region. *Hydrological Processes* 11:825–871.

Marsden, J. E., J. M. Casselman, T. A. Edsall, R. F. Elliott, J. D. Fitzsimons, W. H. Horns, B. A. Manny, S. C. McAughey, P. G. Sly, and B. L. Swanson. 1995. Lake trout spawning habitat in the Great Lakes – A review of current knowledge. *Journal of Great Lakes Research* 21 (supplement 1):487–497.

McLeod, D. 2008. A population assessment of lake sturgeon in the Namakan River, Ontario 2006–08. Fort Frances District Report Series No. 81. Ontario Ministry of Natural Resources, Ontario, Canada. Available at http://www.fws.gov/midwest/sturgeon/documents/mcleod-namakan-river-2006-2008.pdf (accessed 1 July 2014).

McLeod, D., S. Katona, and C. Martin. 2013. Movement and seasonal distribution of lake sturgeon in the Namakan River, Ontario. Fort Frances District Report Series No. 93. Ontario Ministry of Natural Resources, Ontario, Canada.

Michigan DNR (Department of Natural Resources). 2012. Muskellunge: A Michigan Resource. Available at http://www.michigan.gov/documents/dnr/Muskellunge_-_A_Michigan_Resource_-_May_2012_386501_7.pdf (accessed 25 June 2014).

Miller, L. M., S. W. Mero, and J. A. Younk. 2009. The genetic legacy of stocking muskellunge in a northern Minnesota lake. *Transactions of the American Fisheries Society* 138:602–615.

MDNR (Minnesota Department of Natural Resources). 2013. Department of Natural Resources designation of infested waters. Available at http://files.dnr.state.mn.us/eco/invasives/infested_waters.pdf (accessed 8 January 2014).

MDNR (Minnesota Department of Natural Resources). 2014a. Muskellunge. Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://www.dnr.state.mn.us/fish/muskellunge/index.html (accessed 27 June 2014).

MDNR (Minnesota Department of Natural Resources). 2014b. Fisheries Lake Survey, Mukooda Lake. Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://www.dnr.state.mn.us/lakefind/showreport.html?downum=69068400 (accessed 18 December 2014).

MDNR (Minnesota Department of Natural Resources). 2014c. Adopted expedited emergency game and fish rules: Mukooda Lake lake trout restrictions. Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/aboutdnr/laws_treaties/emergency_rules/2013-12-mukoda-lk-trout.pdf (accessed 18 December 2014).

MDNR (Minnesota Department of Natural Resources). 2014d. News Release: DNR fisheries to hold public input meeting for Mukooda, Little Trout lakes. Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://news.dnr.state.mn.us/2014/08/19/dnr-fisheries-to-hold-public-input-meeting-for-mukooda-little-trout-lakes/ (accessed 18 December 2014).

OMNR (Ontario Ministry of Natural Resources). 2009. The lake sturgeon in Ontario. Fish and Wildlife Branch. Peterborough, Ontario.

Peterson, D. L., B. Gunderman, and P. Vecsei. 2002. Lake sturgeon of the Manistee River: A current assessment of spawning stock size, age and growth. Pages 175–182 *In* W. Van Winkle, P. J. Anders, D. H. Secor, and D. A. Dixon, editors. Biology, management, and protection of North American sturgeon. American Fisheries Society, Symposium 28, Baltimore, Maryland.

Peterson, D. L., P. Vecsei, and C. A. Jennings. 2007. Ecology and biology of the lake sturgeon: a synthesis of current knowledge of a threatened North American *Acipenseridae*. *Reviews in Fish Biology and Fisheries* 17:59–76.

Peterson, K. 2007. Lake management plan for Cruiser Lake. Minnesota Department of Natural Resources Report Series NA-01570-01. International Falls, Minnesota.

Peterson, K. 2009. Lake management plan for Mukooda Lake. Minnesota Department of Natural Resources Report Series NA-01570-01. International Falls, Minnesota.

Peterson, K. 2011. Lake management plan for Little Trout Lake. Minnesota Department of Natural Resources Report Series NA-01570-01. International Falls, Minnesota.

Peterson, K. 2012a. Lake management plan for Locator Lake. Minnesota Department of Natural Resources Report Series NA-01570-01. International Falls, Minnesota.

Peterson, K. 2012b. Lake management plan for War Club Lake. Minnesota Department of Natural Resources Report Series NA-01570-01. International Falls, Minnesota.

Porterfield, J., P. Ceas, and J. Hiebert. 2012. Life histories of the northern longear sunfish (*Lepomis megalotis peltastes*) and pugnose shiner (*Notropis anogenus*) in Minnesota, with examinations of other rare non-game fishes. Final Report T-32-R-1 F10AF00108 to the Minnesota State Wildlife Grants Program. Minnesota Department of Natural Resources, St. Paul, Minnesota. Available at http://files.dnr.state.mn.us/eco/nongame/projects/consgrant_reports/2012/swg_2012_porterfield_ceas.pdf (accessed 1 July 2014).

Priegel, G. R., and T. L. Wirth. 1978. Lake sturgeon populations, growth, and exploitation in lakes Poygan, Winneconne, Lake Butte Des Morts, Wisconsin. Technical Bulletin No. 107. Wisconsin Department of Natural Resources, Madison, Wisconsin. Available at http://digital.library.wisc.edu/1711.dl/EcoNatRes.DNRBull107 (accessed 1 July 2014).

Scott, W. B., and E. J. Crossman. 1998. Freshwater fishes of Canada. Galt House Publications, Oakville, Ontario.

Sellers, T. J., B. R. Parker, D.W. Schindler, and W. M. Tonn. 1998. Pelagic distribution of lake trout (*Salvelinus namaycush*) in small Canadian Shield lakes with respect to temperature, dissolved oxygen and light. *Canadian Journal of Fisheries and Aquatic Sciences* 55:170–179.

Sharma, S., M. J. Vander Zanden, J. J. Magnuson, and J. Lyons. 2011. Comparing climate change and species invasions as drivers of coldwater fish population extirpations. PLoS (Public Library of Science) ONE; [online serial] 6(8):e22906. DOI: 10.1371/journal.pone.0022906.

Shaw, S. L., S. R. Chipps, S. K. Windels, M. A. H. Webb, D. T. McLeod, and D. W. Willis. 2012. Lake sturgeon population attributes and reproductive structure in the Namakan Reservoir, Minnesota and Ontario. *Journal of Applied Ichthyology* 28:168–175.

Siesennop, G. D. 2000. Estimating potential yield and harvest of lake trout, *Salvelinus namaycush*, in Minnesota's lake trout lakes, exclusive of Lake Superior. Department of Natural Resources, Section of Fisheries Investigational Report 487. St. Paul, Minnesota. 43 pp.

Steedman, R. J., and R. S. Kushneriuk. 2000. Effects of experimental clearcut logging on thermal stratification, dissolved oxygen, and lake trout (*Salvelinus namaycush*) habitat volume in three small boreal forest lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 57 (Supplement 2):82–91.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

Tody, W. H. 1974. Whitefish, sturgeon and the early Michigan commercial fishery. pp. 45–60 *in* Michigan Fisheries Centennial Report 1873–1973. Michigan Department of Natural Resources, Lansing, Michigan. Available at http://www.michigandnr.com/PUBLICATIONS/PDFS/ifr/ifrlibra/special/reports/SR06.pdf (accessed 1 July 2014).

Underhill, J. C. 1957. The distribution of Minnesota minnows and darters in relation to Pleistocene glaciation. University of Minnesota Museum of Natural History. Paper No. 7. pp. 1–45. University of Minnesota Press.

Vander Zanden, M. J., J. M. Casselman, and J. B. Rasmussen. 1999. Stable isotope evidence for the food web consequences of species invasions in lakes. *Nature* 401:464–467.

Wepruk, R. L., W. R. Darby, D. T. McLeod, and B. W. Jackson. 1992. An analysis of fish stock data from Rainy Lake, Ontario, with management recommendations. Fort Frances District Report 41, Ontario Ministry of Natural Resources, Ontario, Canada. 196 pp.

Wingate, P. J., and J. A. Younk. 2007. A program for successful muskellunge management: a Minnesota success story. *Environmental Biology of Fishes* 79:163–169.

Younk, J. A., and R. F. Strand. 1992. Performance evaluation of four muskellunge *Esox masquinongy* strains in two Minnesota lakes. Division of Fish and Wildlife Investigational Report 418, Minnesota Department of Natural Resources, St. Paul, Minnesota.

### *4.3.9. Zooplankton Communities*

Description

Zooplankton is a broad category of organisms ranging from microscopic protozoans to larger metazoans. However, in the more common use of the term and how it is applied to the aquatic communities within VOYA, zooplankton are a group of small crustaceans which are primary consumers including copepods, cladocerans (Figure 29), and rotifers. Common copepods found in this watershed include the genera *Diaptomus*, *Cyclops*, and *Limnocalanus* and juveniles called nauplii (Kallemeyn et al. 2003, DeSellas et al. 2009). At least 38 different zooplankton species have been collected and described within VOYA from 1978–1996. Hargis (1981) reported that individual lakes within VOYA typically had 6–12 zooplankton species, with most lakes having 10–11 different species present. Zooplankton sampling conducted by the USGS/VOYA showed that the large lakes within VOYA had higher species diversity (typically >20 species) compared to the interior lakes (10–14 species; Kallemeyn et al. 2003).

**Figure 29.** Cladoceran zooplankter *Daphnia mendotae,* a common species found in both the interior and large lakes within Voyageurs National Park (Kallemeyn et al. 2003). Photo courtesy of Center for Freshwater Biology, Department of Biological Sciences, University of New Hampshire. Available at http://cfb.unh.edu/cfbkey/html/Organisms/CCladocera/FDaphnidae/GDaphnia/Daphnia_mendotae/daphniamendotae.html.

Zooplankton abundance has been shown to be related to growth rates and in-turn survival of many larval fishes (Bremigan and Stein 1994, DeVries et al. 1998) including important recreational species in VOYA such as walleye and yellow perch (Francis et al. 1996, Graeb et al. 2004). During the 1983 sample (VOYA/USGS unpublished data), total zooplankton abundances (# $L^{-1}$) in the large lakes (Kabetogama, Namakan, Sand Point, and Rainy) typically ranged from <10 to 40 $L^{-1}$. The highest densities were typically found in Kabetogama Lake and the lowest densities were found in Namakan Lake. During August and early September, densities peaked in Kabetogama Lake and were the highest of any lake sampled (100–120 $L^{-1}$; Kallemeyn et al. 2003). This is to be expected, as Kabetogama Lake is the most productive large lake within VOYA. Perhaps more important than total zooplankton density is the density of selected zooplankton taxa. Cladocerans and copepods are generally the most consumed by fishes like walleye, yellow perch, and cisco (Mathias and Li 1982, Link et al. 1995, Mayer and Wahl 1997, Davis and Todd 1998, Graeb et al. 2004). Larval walleye are shown to prefer cladocerans over copepods and rotifers (Mayer and Wahl 1997, Hoxmeier et al. 2004). Total crustacean (cladoceran and copepod) zooplankton densities ranged from <2 to approx. 35 for Rainy, Sand Point, and Namakan Lakes during both 1983 and 1984, with densities in Kabetogama Lake ranging from approx. 10 to >120 $L^{-1}$ (See Figures 24 and 25 in Kallemeyn et al. 2003).

A major threat to the native zooplankton communities within VOYA is the invasion of some of these waters by the spiny water flea. Currently, these are present in all five large lakes in and near VOYA, with the highest densities being found in Rainy, Kabetogama, and Namakan Lakes. Their presence has caused significant declines in the number and biomass of most cladoceran species within these lakes, and some copepod species have also seen declines (Hobmeier et al. 2013). In fact, total zooplankton densities have declined by approximately 60%, cladocerans have declined by over 80%, and copepods have declined by nearly 40% in Kabetogama, Rainy, and Namakan Lakes following the invasion of the spiny water flea (Hobmeier et al., unpublished data). These declines in cladocerans and copepods could eventually have major effects on the growth, survival, and subsequent recruitment of many recreationally important species within VOYA (e.g., walleye).

### Data and Methods

Zooplankton samples were collected from the large lakes within the park monthly (or bi-weekly) during 1978–1980 (Hargis 1981) and 1996 (VOYA/USGS, unpublished data) using vertical net tows with various mesh sizes (63–153 µm; see Kallemeyn et al. 2003 for more details). Zooplankton samples were also collected monthly from Rainy Lake and Namakan Reservoir lakes using vertical tows with 153 µm mesh size nets with 30 cm openings from 2001–2003, 2007–2010, and 2013–2014 (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14).

### Reference Condition

A true reference for the zooplankton communities in VOYA is difficult to ascertain due to variation in survey methods, taxonomic identification limitations, and the lack of a park-wide comprehensive survey (Kallemeyn et al. 2003). We have chosen the pre-*Bythotrephes* invasion community presented in Hobmeier et al. (2013) as the reference condition; this is a “historic condition” (Stoddard et al. 2006).

### Condition and Trend

We rank the condition of the zooplankton community in VOYA as of significant concern, with a declining trend. Our confidence in this assessment is moderate. Overall, zooplankton abundances and biomass have declined within the five large lakes in and near VOYA, likely due to the invasion of the spiny water flea. Specifically, cladocerans have been affected the most, with declines in Namakan, Rainy and Kabetogama Lakes of approximately 80%. This could ultimately have bottom-up effects on the aquatic food webs and negatively affect recruitment of fishes.

Presently it appears that the only exotic zooplankter present is the spiny water flea. The spiny water flea is a voracious predator of other zooplankters (see section on invasive species) and has been known to shape zooplankton communities where present (Rennie et al. 2011).

Further complicating factors for zooplankton communities include climate change and eutrophication. Climate change can affect phenology of aquatic organisms which could cause “bottom-up effects” on the aquatic food webs (Lindeman 1942, McQueen et al. 1986). Further, eutrophication could have similar effects by increasing phytoplankton abundance, a main food source for many zooplankters (Scheffer 2004). These changes in phenology and abundance could have effects on aquatic food webs and fish communities within VOYA (Cushing 1972).

### Sources of Expertise

Ryan Maki, Aquatic Ecologist, VOYA; Dr. Justin VanDeHey, Assistant Professor of Fisheries and Water Resources, UWSP; Kallemeyn et al. 2003.

### Literature Cited

Bremigan, M. T., and R. A. Stein. 1994. Gape-dependent larval foraging and zooplankton size: implications for fish recruitment across systems. *Canadian Journal of Fisheries and Aquatic Resources* 51:913–922.

Cushing, D. H. 1972. The production cycle and the numbers of marine fish. *Symposium of the Zoological Society of London* 29:213–232.

Davis, B. M., and T. N. Todd. 1998. Competition between larval lake herring (*Coregonus artedi*) and lake whitefish (*Coregonus clupeaformis*) for zooplankton. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1140–1148.

DeSellas, A. M., A. M. Paterson, B. J. Clark, N. G. Baratono, and T. J. Sellers. 2009. State of the basin report for the Lake of the Woods and Rainy River basin. Lake of the Woods Water Sustainability Foundation. Available at http://www.lowwsf.com/sobr-download (accessed 15 July 2014).

DeVries, D. R., M. T. Bremigan, and R. A. Stein. 1998. Prey selection by larval fishes as influenced by available zooplankton and gape limitation. Transactions of the American Fisheries Society 127:1040–1050.

Francis, J. T., S. R. Robillard, and J. E. Marsden. 1996. Essay—yellow perch management in Lake Michigan: a multi-jurisdictional challenge. *Fisheries* 21(2):18–23.

Graeb, B. D. S., J. M. Dettmers, D. H. Wahl, and C. E. Cáceres. 2004. Fish size and prey availability affect growth, survival, prey selection and foraging behavior of larval yellow perch. *Transactions of the American Fisheries Society* 133:504–514.

Hargis, J. R. 1981. Ecological analysis of the plankton communities of Voyageurs National Park. Contract PX-60007-0921. Final report to the National Park Service. University of Minnesota, Duluth, Minnesota. 56 p.

Hobmeier, M. M., J. K. Hirsch, W. C. Kerfoot, F. Yousef, J. F. LeDuc, and R. P. Maki. 2013. Spiny water flea (*Bythotrephes longimanus*) impacts on zooplankton communities of Voyageurs National Park. International Lake of the Woods Water Quality Forum, International Falls, Minnesota.

Hoxmeier, R. J. H., D. H. Wahl, M. L. Hooe, and C. L. Pierce. 2004. Growth and survival of larval Walleyes in response to prey availability. *Transactions of the American Fisheries Society* 133:45–54.

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001. USGS Columbia Environmental Research Center, Columbia, Missouri. 95 pp. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Lindeman, R. L. 1942. The trophic-dynamic aspect of ecology. *Ecology* 23:399–417.

Link, J., J. H. Selgeby, M. H. Hoff, and C. Haskell. 1995. Winter diet of lake herring (*Coregonus artedi*) in Western Lake Superior. *Journal of Great Lakes Research* 21:395–399.

Mathias, J. A., and S. Li. 1982. Feeding habits of Walleye larvae and juveniles: comparative laboratory and field studies. *Transactions of the American Fisheries Society* 111:722–735.

Mayer, C. M., and D. W. Wahl. 1997. The relationship between prey selectivity and growth and survival in larval fish. *Canadian Journal of Fisheries and Aquatic Sciences* 54:1504–1512.

McQueen, D. J., J. R. Post, and E. L. Mills. 1986. Trophic relationships in freshwater pelagic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences* 43:1571–1581.

Rennie, M. D., A. L. Strecker, and M. E. Palmer. 2011. *Bythotrephes* invasion elevates trophic position of zooplankton and fish: implications for contaminant biomagnification. *Biological Invasions* 13:2621–2634.

Scheffer, M. 2004. Ecology of shallow lakes. Kluwer Academic Publishers, Norwell, Massachusetts.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

### *4.3.10. Zoobenthos Communities*

Description

Zoobenthos is a term used to describe benthic (bottom-dwelling) animals. In aquatic systems, these are primarily macroinvertebrates. Benthic macroinvertebrates are an important link in aquatic food webs, with both avian and fish species consuming them for parts or the majority of their lives.

Benthic invertebrates were intensively sampled from the large lakes within VOYA during 1984–1985 (Kraft 1988) and during 2004–2005 (McEwen and Butler 2010). Samples were collected from Harrison Bay and Black Bay in Rainy Lake, Moxie Bay in Kabetogama Lake, Junction Bay in Namakan Lake, and Swanson Bay in Sand Point Lake (See Figure 1 in McEwen and Butler 2010). These sites were originally selected to compare diversity and abundance between the more hydrologically regulated waters of the Namakan Reservoir (composed of Sand Point, Crane, Little Vermilion, Kabetogama, and Namakan Lakes) to the less hydrologically altered Rainy Lake. Water levels in the Namakan Reservoir and Rainy Lake are regulated using rule-curves established by the IJC. Rule-curves essentially dictate the high and low water levels within a system during the year. The first benthic macroinvertebrate study (Kraft 1988) was conducted after the 1970 rule-curve was instituted by the IJC. This rule-curve had an average winter drawdown of 2.5 m in Namakan Reservoir and 1.1 m in Rainy Lake. Winter drawdowns have been shown to negatively affect benthic macroinvertebrates (Kraft 1988, Palomaki 1994). Specifically, in VOYA, Kraft (1988) found that both densities and diversity of macroinvertebrates were higher in Rainy Lake (less drawn down) than Namakan Reservoir (more drawn down). Several taxa were more negatively affected by the drawdowns in Namakan Reservoir, including the isopod genus *Asellus*, phantom midges *Chaoborus*, mayflies *Caenis* and *Hexagenia*, snails (Gastropoda) and the alder fly *Sialis*. Conversely, a more tolerant and ubiquitous family of dipterans, Chironomidae, was found to be more abundant in drawdown-affected sites and hence appeared to be favored by the 1970 rule-curve (Kraft 1988, McEwen and Butler 2008).

At least 128 species of benthic macroinvertebrates from 47 different families and 20 different orders were documented within the large lakes in VOYA (McEwen and Butler 2008). Some of the most commonly found taxa included Oligochaeta (aquatic earthworms), various species within Chironomidae (midges) (Figure 30), and the mayfly *Eurylophella*, all being found at >70 total sites throughout Rainy Lake and Namakan Reservoir. Chironomidae was the most ubiquitous, being found at all 100 sites; however, this is a relatively large family with a variety of tolerant species, so its presence at all sites is not surprising.

**Figure 30.** Four different species of chironomidae (midge) larvae. Chironomidae are some of the most ubiquitous benthic macroinvertebrates found within Voyageurs National Park. Photo courtesy of the North American Benthological Society. Available at www.benthos.org.

In 2000, a new rule-curve was implemented. Namakan Reservoir was drawn down only 1.5 m (as opposed to 2.5 m under the 1970 rule-curve), and the reservoir was allowed to fully refill in mid-May (one month earlier than the 1970 rule-curve). However, water level regulation on Rainy Lake was only minimally changed from the 1970 rule-curve. McEwen and Butler (2008, 2010) revisited the same sites as Kraft (1988) and found that densities of macroinvertebrates were lower in Namakan Reservoir than in Rainy Lake. Additionally, size structure of the benthic macroinvertebrates shifted from small to large-bodied organisms. McEwen and Butler (2008) stated that the largest effects were seen in the sites at 1 and 2 m of depth within Namakan Reservoir, those most likely affected by the winter drawdowns. In fact, depth was one of the most important variables explaining invertebrate densities, especially within Namakan Reservoir (McEwen and Butler 2010). Even the tolerant taxa Chironomidae was found at lower densities in Namakan Reservoir relative to data collected by Kraft (1988). McEwen and Butler (2008, 2010) hypothesized that the observed changes in macroinvertebrate densities, communities, and size structure was likely due to cooler water, lower production, and a more stable environment under the new rule-curve. However, these data were only collected 4–5 years post rule-curve change, and it may take longer than that for this system to “reset” itself from the recent changes in water level management (McEwen and Butler 2008). Currently, zoobenthic samples collected during 2012 and 2013 are being assessed to determine if the changes in the rule curve have affected these benthic communities 12–13 years later. The study is scheduled to be completed in 2015.

Data and Methods

At each of the five sample sites during both studies (Kraft 1988 and McEwen and Butler 2010), samples were collected along depth transects from 1–5 m depths, except in Black Bay where depths >3 m did not occur. A total of three subsamples were collected from each site/depth location using an Ekman grab sampler. Samples were live washed through a 0.59 mm mesh, and then subsamples were pooled to represent a single sample for each depth at each location (bay). All macroinvertebrates were identified to the lowest ‘practicable’ level.

### Reference Condition

Prior to the impoundment of Squirrel and Kettle Falls and at the northwest end of Rainy Lake in the early 1900s, the only natural spillways within the system were found at Bear Portage, at the north-central shore of Namakan Lake, and at Gold Portage, which connects Kabetogama Lake to Black Bay on Rainy Lake. Historically, these lakes fluctuated naturally with climatic conditions. Currently, they function as two large, regulated reservoirs. The reference condition of zoobenthos would be represented by water level management which most closely mimics a natural flow regime with seasonal and annual variability in water levels. This is a “historic condition” (Stoddard et al. 2006).

### Condition and Trend

The condition of zoobenthos within VOYA appears to be good. Our confidence in this assessment is moderate. The trend appears to be stabilizing or possibly improving with the newest rule-curve. However, results from the more recent (2012–2013) monitoring will help determine the condition of the zoobenthos communities now that it is >10 years post the newest water level management rule-curve implementation.

### Sources of Expertise

Ryan Maki, Aquatic Ecologist, VOYA; Dr. Justin VanDeHey, Assistant Professor of Fisheries and Water Resources, UWSP.

### Literature Cited

Kraft, K. J. 1988. The effect of unnatural water level fluctuations on benthic macroinvertebrates in Voyageurs National Park. Research/Resources Management Report MWR-12, U.S. Department of the Interior, National Park Service, International Falls, Minnesota.

McEwen, D. C., and M. G. Butler. 2008. Impacts from water-level regulation on the benthic macroinvertebrate community structure in Namakan Reservoir and Rainy Lake: Voyageurs National Park. Natural Resource Technical Report NPS/NRPC/WRD/NRTR–2008/129 . National Park Service, Fort Collins, Colorado.

McEwen, D. C., and M. G. Butler. 2010. The effects of water-level manipulation on the benthic invertebrates of a managed reservoir. *Freshwater Biology* 55:1086–1101.

Palomaki, R. 1994. Response by macrozoobenthos biomass to water level regulation in some Finnish lake littoral zones. *Hydrobiologia* 286:17–26.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

#### ***4.3.11. Aquatic Invasive Species***

<u>Description</u>

Aquatic invasive species are non-indigenous (non-native) species that adversely affect habitats and native species present. Currently, three aquatic invasive species – rainbow smelt, spiny water flea, and rusty crayfish (*Orconectes rusticus*) – have been documented within VOYA boundaries (MDNR 2013, USGS 2014). Additionally, there is an imminent threat of an additional aquatic invasive species; recently, zebra mussels (*Dreissena polymorpha*) have also been found in the Rainy River watershed, downstream of VOYA (Clark and Sellers 2014).

*Rainbow smelt*

The first aquatic invasive species to be documented within VOYA was the rainbow smelt (Figure 31); smelt were first documented in Rainy and Namakan Lakes during 1990 (Franzin et al. 1994, Kallemeyn et al. 2003). Rainbow smelt are native to the eastern seaboard of the U.S. and Canada, and freshwater rivers and lakes of northeastern states and provinces (Buckley 1989).

**Figure 31.** Adult rainbow smelt (*Osmerus mordax*). Photo credit NOAA, Fish Atlas. Available at http://mapping.fakr.noaa.gov/ShoreZoneMvcServices/FishAtlas/FishDisplayPage?spCode=RBWSMELT.

Rainbow smelt are highly fecund, broadcast spawners that generally spawn during early spring, shortly after ice-out, at temperatures between 4.4°C–10°C (Becker 1983). Rainbow smelt are eurythermal and occupy an intermediate trophic position. They are omnivorous, feeding on zooplankton, including ichthyoplankton (larval fishes). These life history traits often result in ontogenetic diet shifts and segregation of life stages (larval, juvenile, and adults; Evans and Loftus 1997). This consumption of zooplankton can cause interspecific competition with native species such as yellow perch and lake herring (Evans and Loftus 1997, Hrabik et al. 1998, Rooney and Paterson 2009) and can also cause recruitment bottlenecks due to direct consumption of larval fishes by smelt (Evans and Loftus 1997, Mercado-Silva et al. 2007, Rooney and Paterson 2009). Alternatively, rainbow smelt are also excellent prey for top level piscivores, such as the native northern pike and walleye (Jones et al. 1994, Graeb et al. 2008).

In VOYA, rainbow smelt populations are relatively stable or have declined since their introductions. In Rainy Lake, CPUE of rainbow smelt has been consistently higher than in Namakan Lake; however, CPUE of adult smelt has declined since its peak in 1996 (Kallemeyn et al. 2003).

**Figure 32.** Female spiny water flea (*Bythotrephes longimanus*). Photo courtesy of Dave Brenner, Michigan Sea Grant.

*Spiny water flea*

The spiny water flea (Figure 32) is an invasive zooplankter that was first reported in the Rainy River watershed (Namakan and Rainy Lakes) in 2006. Currently, the MDNR designates the following waters within and near the park as being infested: Rainy River, Rainy Lake, Namakan Lake, Kabetogama Lake, Sand Point Lake, Crane Lake, and Little Vermilion Lake (MDNR 2013).

The spiny water flea is native to Europe and Asia. It was likely introduced into the Great Lakes through ballast water discharge (Sprules et al. 1990, Berg et al. 2002), and was first discovered in Lake Huron in 1984 (Bur et al. 1986). The spiny water flea is of concern as it competes with native zooplankton for food resources and preys upon smaller, native zooplankton (Rennie et al. 2011). Its name arises from the long (≥70% of its total length) spine; the spine also reduces predation by gape-limited larval and juvenile fishes (Barnhisel and Harvey 1995). Alternatively, preferential feeding on spiny water flea by cisco, a species native to the park, was documented in Harp Lake, ON (Coulas et al. 1998).

Another concerning life history characteristic of the spiny water flea is its modes of reproduction and rapid reproductive capabilities. The spiny water flea can reproduce both sexually and, in the absence of males, asexually via parthenogenesis. Additionally, during sexual reproduction, females can produce resting eggs which can lie dormant for long periods of time and are believed to be tolerant to harsh conditions such as desiccation, cold temperatures, chlorination, salinity, and even digestion from fishes (Jarnagin et al. 2000, Branstrator et al. 2013).

*Rusty crayfish*

Rusty crayfish (Figure 33) have now established a population in Sand Point Lake (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14) after first being detected there in 2006 (Kissane and LeDuc 2008). They have also been detected in various other water bodies adjacent to the park, including Rainy River (USGS 2014) and Crane and Johnson Lakes (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14). Directed sampling did not detect rusty crayfish in Little Johnson Lake in 2007, Junction Bay of Namakan Lake in 2003 and 2007, or near boat ramps on Kabetogama and Rainy Lakes in 2011 (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14).

Rusty crayfish are native to the Ohio River basin and the states of Ohio, Tennessee, and Kentucky. They likely spread out of their native range through “bait-bucket” transfers by anglers who often use them as fishing bait. Rusty crayfish are generally considered opportunistic feeders and eat aquatic plants, detritus, fish eggs, juvenile and larval fishes, and benthic macroinvertebrates (Minnesota Sea Grant 2014).

**Figure 33.** Rusty crayfish (*Orconectes rusticus*). Photo courtesy USGS.

Rusty crayfish are considered an invasive species due to their larger sizes, aggressive nature, ability to displace native crayfish (Capelli and Munjal 1982), impacts on native aquatic plant and invertebrate communities, and, in some cases, their negative effects on fish communities. Rusty crayfish tend to displace native crayfishes in a variety of ways. First, due to their aggressive nature, they tend to outcompete native crayfish for both shelter and food resources (Hill and Lodge 1994, Garvey et al. 1994). Next, they can hybridize with native crayfishes (Perry et al. 2001). Finally, they can have indirect effects on native crayfish. By outcompeting native crayfish for food and resting habitats, native crayfish are often forced into suboptimal habitats where increased predation by fishes can occur, in turn lowering their abundances (Hill and Lodge 1993, DiDonato and Lodge 1994, Garvey et al. 1994, Roth and Kitchell 2005).

Rusty crayfish can also have negative effects on native fish communities. Due to their larger size and aggressive nature, they are less vulnerable to predation than native crayfishes. Horns and Magnuson (1981) documented the consumption of fish eggs by rusty crayfish. Additionally, other fish species such as pumpkinseed (*Leopomis gibbosus*) and bluegill (*L. machrochirus*), which compete for food resources with rusty crayfish, have been shown to decline over time in the presence of rusty crayfish (Wilson et al. 2004).

While rusty crayfish have negative impacts on native crayfish and even native fish communities, the biggest impact of rusty crayfish is generally seen in the destruction of aquatic vegetation, which has both direct and indirect effects on aquatic food webs (Lodge and Lorman 1987, Olsen et al. 1991, Wilson et al. 2004). Although native crayfishes eat aquatic plants, rusty crayfish tend to eat more due to their larger sizes, increased metabolism, and higher population densities (Stein 1977, Jones and Momot 1983).

## Data and Methods

### *Rainbow smelt*

Rainbow smelt were sampled from Rainy Lake and the waters of the Namakan Reservoir during annual fish surveys for important recreational species (e.g. walleye and northern pike) and during surveys targeting smelt (see Franzin et al. 1994). Gears include graded mesh gill nets (four, 2-m x 38-m panels of 13-mm-bar mesh and one, 2-m x 46-m panel of 10-mm-bar mesh and (or) one 2-m x 61-m panel of 10-mm-bar mesh; Franzin et al. 1994). Additionally, small mesh gill nets (61 m nets containing 30.5 m each of 9.5 and 12.7 mm bar mesh) have been used to sample rainbow smelt (Kallemeyn et al. 2003). Some rainbow smelt were also captured during annual beach seining surveys targeting age-0 fishes. Seining events took place during July and (or) August from 1966 through present. In Rainy Lake, the first rainbow smelt were captured in beach seines during 1992 and none were captured from 2002–2010.

*Spiny water flea*

Zooplankton samples were collected from the large lakes within the park monthly (or bi-weekly) during 1978–1980 (Hargis 1981), and in 1996 (VOYA/USGS, unpublished data), using vertical net tows with various mesh sizes (63–153 µm; see Kallemeyn et al. 2003 for more details). However, no spiny water fleas were captured in these samples. Zooplankton samples were also collected monthly from Rainy Lake and Namakan Reservoir lakes using vertical tows with 153 µm mesh size nets with 30 cm openings from 2001–2003, 2007–2010, and 2013–2014. Spiny water fleas were captured in the samples post-2007. Additionally, diapausing eggs were collected using an Ekman grab sampler (15x15x15 cm; 232 cm$^2$; Kerfoot et al. 2011).

*Rusty crayfish*

Rusty crayfish were collected using modified minnow traps. The entrance to the trap was expanded, and traps were baited with cat food. All traps were fished in the littoral zones of lakes. Specific details can be found in Kissane and LeDuc (2008).

### Reference Condition

The reference condition for Voyageurs National Park in relation to the three aquatic invasive species listed above is that of absence. None of the listed invasive species were documented within the boundaries of the park prior to 1990. Hence, data collected prior to 1990 should represent reference conditions relative to all invasive species (rainbow smelt, spiny water flea, and rusty crayfish). Data collected prior to 2006 should be considered reference conditions relative to spiny water flea and rusty crayfish. This is a “historic condition” (Stoddard et al. 2006).

### Condition and Trend

↔ The condition of VOYA for aquatic invasive species is of significant concern, with a stable trend. Our confidence in this assessment is only moderate, as directed sampling, especially for rusty crayfish, has been limited. However, the limited sampling that has occurred suggests that rusty crayfish are likely spreading and the invasion of zebra mussels into VOYA could occur in the near future.

On a positive note, rainbow smelt have been stable or declining within the large lakes (specifically Rainy Lake) in VOYA. Of the aquatic invasive species currently present in VOYA, the greatest concern to the aquatic ecosystems is likely the spiny water flea. Since its establishment in the five large lakes in and near VOYA, the zooplankton community has experienced an overall decline in zooplankton biomass of between 40%–60%. The zooplankton community has shifted towards larger cladocerans and copepods, and other predacious zooplankters (e.g., *Leptodora kindtii*) have experienced declines (Hobmeier et al. 2013). This is likely having an effect on the fish community via bottom-up food web effects. The presence of zebra mussels downstream of the park is of significant concern as well.

Sources of Expertise
Ryan Maki, Aquatic Ecologist, VOYA; Dr. Justin VanDeHey, Assistant Professor of Fisheries and Water Resources, UWSP.

Literature Cited

Barnhisel, D. R., and H. A. Harvey. 1995. Size-specific fish avoidance of the spined crustacean *Bythotrephes*: field support for laboratory predictions. *Canadian Journal of Fisheries and Aquatic Sciences* 52:768–775.

Becker, G. C. 1983. Fishes of Wisconsin. University of Wisconsin Press. Madison, Wisconsin.

Berg, D. J., D. W. Garton, H. J. MacIsaac, V. E. Panov, and I. V. Telesh. 2002. Changes in genetic structure of North American *Bythotrephes* populations following invasion from Lake Ladoga, Russia. *Freshwater Biology* 47:275–282.

Branstrator, D. K., L. J. Shannon, M. E. Brown, and M. T. Kitson. 2013. Effects of chemical and physical conditions on hatching success of *Bythotrephes longimanus* resting eggs. *Limnology and Oceanography* 58:2171–2184.

Buckley, J. L. 1989. Species profiles: life history and environmental requirements of coastal fishes and invertebrates (North Atlantic) – rainbow smelt. U.S. Fish and Wildlife Service Biological Report 82 (11.106). Washington, D.C.

Bur, M. T., D. M. Klarer, and K. A. Krieger. 1986. First records of a European cladoceran, *Bythotrephes cederstroemi*, in Lakes Erie and Huron. *Journal of Great Lakes Research* 12:144–146.

Capelli, G. M., and B. J. Munjal. 1982. Aggressive interactions and resource competition in relation to species displacement among crayfish of the genus *Orconectes*. *Journal of Crustacean Biology* 2:486–492.

Clark, B. J., and T. J. Sellers, editors. 2014. Rainy-Lake of the Woods State of the Basin Report, 2nd Edition, July 2014. Lake of the Woods Water Sustainability Foundation, Kenora, Ontario. Available at http://ijc.org/files/publications/R-LoW_SOBR_2014_web-res.compressed.pdf (accessed 18 December 2014).

Coulas, R. A., H. J. MacIsaac, and W. Dunlop. 1998. Selective predation on an introduced zooplankter (*Bythotrephes cederstoemi*) by lake herring (*Corgeonus artedii*). *Freshwater Biology* 40:343–355.

DiDonato, G. T., and D. M. Lodge. 1994. Species replacements among *Orconectes* species in Wisconsin Lakes: the role of predation by fish. *Canadian Journal of Fisheries and Aquatic Sciences* 50:14–84.

Evans, D. O., and D. H. Loftus. 1997. Colonization of inland lakes in the Great Lakes region by rainbow smelt, *Osmerus mordax*: their freshwater niche and effects on indigenous fishes. *Canadian Journal of Fisheries and Aquatic Sciences* 44:249–266.

Franzin, W. G., B. A. Barton, R. A. Remnant, D. B. Wain, and S. J. Pagel. 1994. Range extension, present and potential distribution, and possible effects of rainbow smelt in Hudson Bay drainage waters of northwestern Ontario, Manitoba and Minnesota. *North American Journal of Fisheries Management* 14:65–76.

Garvey, J. E., R. A. Stein, and H. M. Thomas. 1994. Assessing how fish predation and interspecific prey competition influence a crayfish assemblage. *Ecology* 75:532–547.

Graeb, B. D. S., S. R. Chipps, D. W. Willis, J. P. Lott, R. P. Hanten, W. Nelson-Stastny, and J. W. Erickson. 2008. Walleye response to a rainbow smelt population decline and liberalized angling regulations in a Missouri River reservoir. Pages 275–291 *in* M. S. Allen, S. Sammons, and M. J. Maceina, editors. Balancing fisheries management and water uses for impounded river systems. American Fisheries Society, Symposium 62. Atlanta, Georgia.

Hargis, J. R. 1981. Ecological analysis of the plankton communities of Voyageurs National Park. Contract PX-60007-0921. Final report to the National Park Service. University of Minnesota, Duluth, Minnesota. 56 p.

Hill, A. M., and D. M. Lodge. 1993. Competition for refugia in the face of predation risk: a mechanism for species replacement among ecologically similar crayfishes. *Bulletin Journal of the North American Benthological Society* 10:120.

Hill, A. M., and D. M. Lodge. 1994. Diel changes in resource demand: competition and predation in species replacement among crayfishes. *Ecology* 75:2118–2126.

Hobmeier, M. M., J. K. Hirsch, W. C. Kerfoot, F. Yousef, J. F. LeDuc, and R. P. Maki. 2013. Spiny water flea (*Bythotrephes longimanus*) impacts on zooplankton communities of Voyageurs National Park. International Lake of the Woods Water Quality Forum, International Falls, Minnesota.

Horns, W.H., and J.J. Magnuson. 1981. Crayfish predation on lake trout eggs in Trout Lake, Wisconsin. *Rapports et Proces-Verbaux des Reunions Conseil International pour l'Exploration de la Mer* 178:299–303.

Hrabik, T. R., J. J. Magnuson, and A. S. McLain. 1998. Predicting the effects of rainbow smelt on native fishes in small lakes: evidence from long-term research on two lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1364–1371.

Jarnagin, S. T., B. K. Swan, and W. C. Kerfoot. 2000. Fish as vectors in the dispersal of *Bythotrephes cederstroemi*: diapausing eggs survive passage through the gut. *Freshwater Biology* 43:579–589.

Jones, M. S., J. P. Goettl, Jr., and S. A. Flickinger. 1994. Changes in Walleye food habits and growth following a rainbow smelt introduction. *North American Journal of Fisheries Management* 14:409–414.

Jones, P. D., and W. T. Momot. 1983. The bioenergetics of crayfish in two pothole lakes. *Freshwater Crayfish* 5:193–209.

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001. USGS Columbia Environmental Research Center, Columbia, Missouri. 95 pp. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Kerfoot, W. C., F. Yousef, M. M. Hobmeier, R. P. Maki, S. T. Jarnagin, and J. H. Churchill. 2011. Temperature, recreational fishing and diapause egg connections: dispersal of spiny water fleas. *Biological Invasions* 13:2516–2531.

Kissane, C., and J. LeDuc. 2008. Rusty crayfish detection in Voyageurs National Park and nearby U.S. waters. National Park Service Internal Report. Voyageurs National Park, International Falls, Minnesota.

Lodge, D. M., and J. G. Lorman. 1987. Reductions in submerged macrophyte biomass and species richness by the crayfish *Orconectes rusticus*. *Canadian Journal of Fisheries and Aquatic Sciences* 44:591–597.

Mayer, C. M., and D. W. Wahl. 1997. The relationship between prey selectivity and growth and survival in larval fish. *Canadian Journal of Fisheries and Aquatic Sciences* 54:1504–1512.

Mercado-Silva, N., G. G. Sass, B. M. Roth, S. Gilbert, and M. J. Vander Zanden. 2007. Impact of rainbow smelt (*Osmerus mordax*) invasion on Walleye (*Sander vitreus*) recruitment in Wisconsin lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 64:1543–1550.

MDNR (Minnesota Department of Natural Resources). 2013. Department of Natural Resources designation of infested waters. Available at http://files.dnr.state.mn.us/eco/invasives/infested_waters.pdf (accessed 8 January 2014).

Minnesota Sea Grant. 2014. Rusty crayfish: a nasty invader. Available at http://www.seagrant.umn.edu/ais/rustycrayfish_invader (accessed 10 January 2014).

Olsen, T. M., D. M. Lodge, G. M. Capelli, and R. J. Houlihan. 1991. Mechanisms of impact of an introduced crayfish (*Orconectes rusticus*) on littoral congeners, snails, and macrophytes. *Canadian Journal of Fisheries and Aquatic Sciences* 48:1853–1861.

Perry, W. L., J. L. Feder, and D. M. Lodge. 2001. Implications of hybridization between introduced and resident *Orconectes* crayfishes. *Conservation Biology* 15:1656–1666.

Rennie, M. D., A. L. Strecker, and M. E. Palmer. 2011. *Bythotrephes* invasion elevates trophic position of zooplankton and fish: implications for contaminant biomagnification. *Biological Invasions* 13:2621–2634.

Rooney, R. C., and M. J. Paterson. 2009. Ecosystem effects of rainbow smelt (*Osmerus mordax*) invasions in inland lakes: a literature review. *Canadian Technical Report of Fisheries and Aquatic Sciences* 2845. Winnipeg, Manitoba. Available at http://www.dfo-mpo.gc.cal-library/338381.pdf (accessed 1 July 2014).

Roth, B. M., and J. F. Kitchell. 2005. The role of size selective predation in the dispersment of *Orconectes* crayfishes following rusty crayfish invasion. *Crustaceana* 78: 297–310.

Sprules, W. G., H. P. Riessen, and E. H. Jin. 1990. Dynamics of the *Bythotrephes* invasion of the St. Lawrence Great Lakes. *Journal of Great Lakes Research* 16:346–351.

Stein, R. A. 1977. Selective predation, optimal foraging and the predator-prey interaction between fish and crayfish. *Ecology* 58:1237–1253.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

USGS (United States Geological Survey) 2014. Nonindigenous aquatic species database. Available at http://nas.er.usgs.gov (accessed 6 January 2014).

Wilson, K. A., J. J. Magnuson, T. K. Kratz, and T. V. Willis. 2004. A long term rusty crayfish (*Orconectes rusticus*) invasion: dispersal patterns and community changes in a north temperate lake. *Canadian Journal of Fisheries and Aquatic Sciences* 61:2255–2266.

## 4.4. Physical and Chemical Condition

The USEPA-SAB framework subdivides chemical and physical characteristics into the categories of nutrient concentrations, trace inorganic and organic chemicals, other chemical parameters, and physical parameters (USEPA 2002). It allows for either reporting the categories separately by environmental medium or displaying integrated information from all environmental compartments (air, water, soil, and sediment). In this section, we describe air quality, water quality, and mercury in the environment.

### *4.4.1. Air*

Description

Air quality is a broad term that includes all compounds, particles, aerosols, gases, and metals in the atmosphere. These substances are considered air pollutants when they enter at rates that clearly exceed the background rates and when they have the potential to affect human health or ecosystem structure, function, or composition. They may originate locally or travel long distances from their sources. Air pollution may affect VOYA resources through atmospheric deposition of contaminants, nutrient enrichment, or vegetation damage, and may affect human uses of the park by limiting visibility and harming human health.

VOYA is designated as a Class I air quality area and is provided with the highest degree of protection under the USEPA Clean Air Act (CAA) and its amendments. New or modified major sources of air emissions must show that the added emissions will not adversely affect air quality related values around VOYA. The CAA also has a goal of preventing any future, and remedying any existing, impairment of visibility in VOYA caused by human-caused air pollution (USEPA 2013c).

Air Quality and Air Quality Related Values (AQRV) are Vital Signs for VOYA and all other parks in the GLKN (NPS 2007). In the prioritized list of Vital Signs for GLKN, air contaminants were ranked 27th of 46 (3.0 on a 5-point scale), and AQRV were ranked 36th of 46 (2.6 on a 5-point scale) (NPS 2007).

The USEPA collects monitoring data and establishes concentration limits for six common air pollutants called criteria pollutants; these are carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), ozone ($O_3$), particulate matter (PM), and lead (Pb) (USEPA 2013a). In order to track the sources of criteria pollutants, USEPA collects emissions data from regulated facilities for CO, $SO_2$, PM, and three ‘precursor/promoters’ of criteria air pollutants: volatile organic compounds (VOC), nitrogen oxides ($NO_x$), and ammonia ($NH_3$) (USEPA 2013a). USEPA also tracks Pb emissions, but reports them as hazardous air pollutants instead of criteria pollutants (USEPA 2013a). Thousands of metric tons of criteria pollutants and precursors (hereafter, criteria pollutants) are emitted from regulated facilities, nonpoint sources, and mobile sources in the vicinity of VOYA each year (Figure 34, Table 16). The dot within the VOYA boundary is the Namakan seaplane base at Junction Bay.

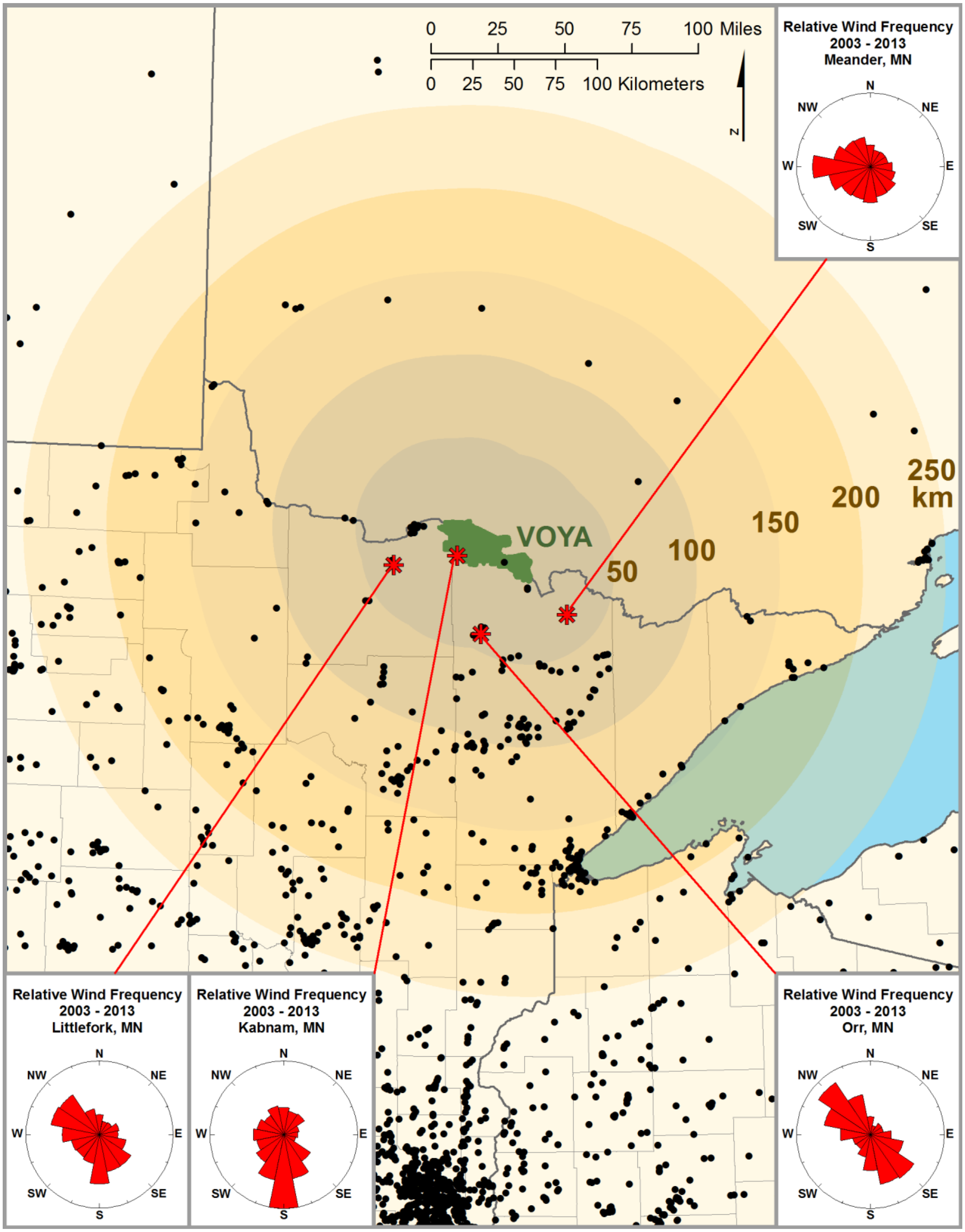

**Figure 34.** Regulated facilities that emit criteria air pollutants within 250 km of Voyageurs National Park and prevailing wind directions (Environment Canada 2012, USEPA 2013b).

**Table 16.** 2010 (Canada) and 2011 (US) emissions of criteria air pollutants in metric tons by regulated facilities within a 250 km buffer of Voyageurs National Park (Environment Canada 2012, USEPA 2013b).

| Criteria Pollutant | Emissions, MT $yr^{-1}$ |
|---|---|
| $NH_3$ | 629 |
| CO | 17,861 |
| $NO_X$ | 41,049 |
| $PM_{10}$ | 14,230 |
| $PM_{2.5}$ | 8,808 |
| $SO_2$ | 21,404 |
| VOC | 3,912 |

The NPS Air Resources Division (ARD) assesses the current condition of air quality in NPS units in the categories of $O_3$; wet deposition of $NH_3$, nitrate ($NO_3^-$), and sulfate ($SO_4^{2-}$); and visibility (as PM), all of which are, or are related to, the USEPA criteria pollutants. Ozone affects human health and harms vegetation. Wet deposition affects ecological health through acidification and fertilization of soil and surface waters, and visibility affects how well and how far visitors can see (NPS 2013a).

Data and Methods

Data for criteria air pollutant emissions within 250 km of VOYA were downloaded from the Environment Canada 2010 National Pollutant Release Inventory website (Environment Canada 2012) and the USEPA 2011 National Emissions Inventory Data website (USEPA 2013b). The 250 km radius, which includes northern Minnesota, northwestern Wisconsin, the southern portion of Ontario, and a small part of the southeast corner of Manitoba, was chosen to facilitate comparison with an earlier study done for VOYA by Swackhamer and Hornbuckle (2004). Air quality data for VOYA were acquired from the NPS air quality estimate tables (NPS 2014) as recommended in the Methods for Determining Air Quality Conditions and Trends for Park Planning and Assessments (NPS 2013b).

Wind rose climatology was found for Kabnam, Littlefork, Orr, and Meander, MN at the Western Regional Climate Center (2013) RAWS USA climate archive. Prevailing winds may give some indication of the importance of a particular emission source for VOYA. However, the wind roses on the air monitoring station map reflect the distribution of wind direction over the period of record and may not match well with the movement of emissions if they are timed to certain seasons or times of day.

Numerous air monitoring sites are located in the vicinity of VOYA (Figure 35). A National Atmospheric Deposition Program (NADP) site (http://nadp.sws.uiuc.edu/) that monitors wet deposition is located at VOYA at Sullivan Bay; other nearby sites are located at Fernberg Road in the BWCAW (82 km SE) and Marcell (103 km SSW). Fernberg Road and Marcell also are NADP Mercury Deposition Network (MDN) sites. Dry deposition and ozone are monitored by the national Clean Air Status and Trends Network (CASTNet) (http://epa.gov/castnet/javaweb/index.html) site at VOYA at Sullivan Bay.

VOYA also hosts an Interagency Monitoring of Protected Visual Environments (IMPROVE) (http://vista.cira.colostate.edu/improve/Web/MetadataBrowser/MetadataBrowser.aspx) monitoring site, which measures fine aerosols, particulate matter less than 2.5 microns in size ($PM_{2.5}$), and light extinction and scattering; another is located at Fernberg Road.

A more detailed look at the data from these sites is included as Appendix B.

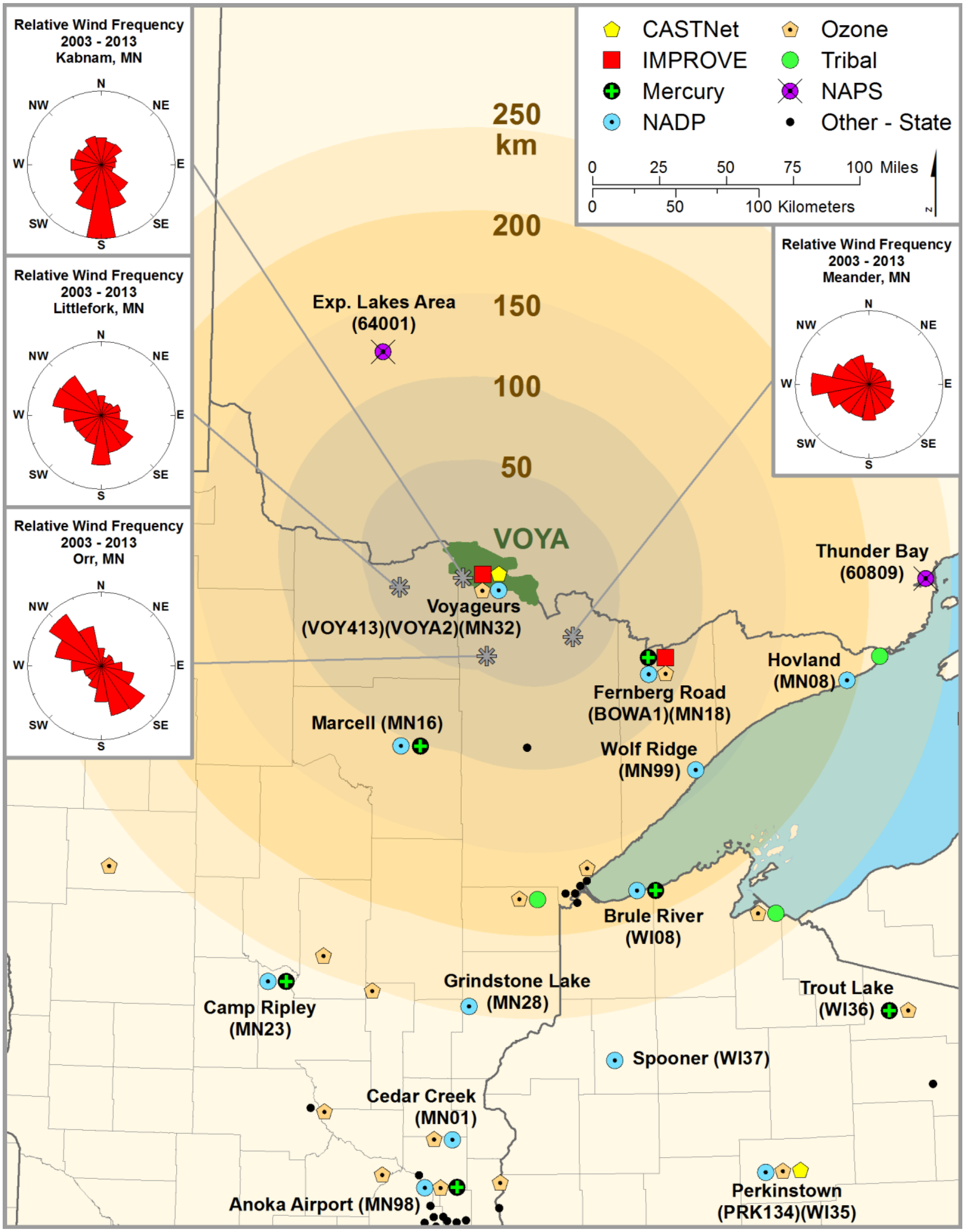

**Figure 35.** Air monitoring sites operated by state and federal agencies in the vicinity of Voyageurs National Park (WDNR 2012, Environment Canada 2013, MPCA 2012, 2014).

Sullivan et al. (2011a, 2011b, 2011c, 2011d) conducted national-scale risk assessments for nitrogen and sulfur deposition in national parks in NPS Inventory and Monitoring networks. They described their work as “construct(ing) a preliminary overall risk assessment to estimate the relative risk… of nutrient enrichment impacts from atmospheric N deposition” and “provid(ing) a first step” in “compil(ing) available information at the national scale to identify park resources that are known or thought to be sensitive to acidification from atmospheric deposition of acidifying S and N compounds.”

### Reference Conditions

For ozone, the NPS metric is the annual 4th highest daily maximum 8-hour ozone concentration (The metric used by USEPA is the *3-year average* of the annual 4th highest daily maximum 8-hour ozone concentration). For visibility, the NPS metric is the difference between the mean of the visibility observations falling within the range of the 40th through 60th percentiles and the estimated values that would be observed under natural conditions. This metric is called the ‘Group 50 visibility minus natural conditions’ and is expressed in deciviews, a unitless measure of light extinction (Malm 1999). For wet deposition of nitrogen (N) and sulfur (S), the NPS metric is expressed in kilograms per hectare per year. Values that represent ‘Good’ condition (Table 17) were used as the reference condition as specified in NPS 2013b. These reference conditions represent “least disturbed conditions” or “the best of today’s existing conditions” (Stoddard et al. 2006).

### Condition and Trend

Overall, air quality at VOYA is of significant concern, based on the NPS weighted calculation using the individual scores for wet deposition, ozone, and visibility (NPS 2013b). The overall score for 2006–2012 is 6.33, with >6 being of significant concern (NPS 2013b). Air quality at VOYA is of moderate concern for ozone and visibility. It is of significant concern for wet deposition of total sulfur and total nitrogen (Table 17) (NPS 2013c, 2014). All air quality metrics had stable trends for 2000–2009 (NPS 2013a). However, there were improving trends for visibility (clear days, a subset of visibility) and wet deposition of nitrate (a subset of total nitrogen) from 2000–2009 (NPS 2013c). These assessments are based on NPS ARD data and have a high level of confidence because the air quality monitoring locations are within the park. In the following sections, the significance and sources of ozone, visibility, and total sulfur and nitrogen deposition will be further discussed.

#### *Ozone*

Ozone is a compound of three oxygen atoms. In the stratosphere, ozone protects life on Earth from harmful ultraviolet radiation, but at ground level, it is the primary constituent of smog. Breathing ozone can trigger a variety of human health problems such as chest pain, coughing, throat irritation, and congestion, and can worsen bronchitis, emphysema, and asthma (USEPA 2003). Ground-level ozone also damages vegetation and ecosystems (USEPA 2003).

Five-year averages of annual 4th highest daily maximum 8-hour ozone concentrations for VOYA range from 61.2 ppb for 2008–2012 to 63.8 ppb for 2005–2009 (Table 17). These values fall within the category of moderate concern, but may be approaching 60 ppb, “good” condition (NPS 2013b). Our confidence in this assessment is high. An assessment of the risk of foliar injury from ozone in

**Table 17.** Air quality conditions for ozone, wet deposition, and visibility in Voyageurs National Park (NPS 2013a, 2014).

| Parameter | Date Range | Metric/Value | Condition | Condition Range |
|---|---|---|---|---|
| Ozone | | 4th highest 8 hr (ppb) | | |
| | 2005–2009 | 63.8 | Moderate Concern | Significant Concern: ≥ 76 |
| | 2006–2010 | 62.7 | Moderate Concern | Moderate Concern: 61–75 |
| | 2008–2012 | 61.2 | Moderate Concern | Good: ≤ 60 |
| Visibility | | Group 50 Visibility minus Natural Conditions (deciviews) | | |
| | 2005–2009 | 4.0 | Moderate Concern | Significant Concern:>8 |
| | 2006–2010 | 3.9 | Moderate Concern | Moderate Concern: 2–8 |
| | 2008–2012 | 3.5 | Moderate Concern | Good: <2 |
| Wet Deposition – Total Nitrogen (TN) | | Kg/ha/year | | |
| | 2005–2009 | 3.1 | Significant Concern | Significant Concern:>3 |
| | 2006–2010 | 3.1 | Significant Concern | Moderate Concern: 1–3 |
| | 2008–2012 | 3.0 | Significant Concern* | Good: <1 |
| Wet Deposition – Total Sulfur | | Kg/ha/year | | |
| | 2005–2009 | 1.5 | Significant Concern* | Significant Concern:>3 |
| | 2006–2010 | 1.4 | Significant Concern* | Moderate Concern: 1–3 |
| | 2008–2012 | 1.2 | Significant Concern* | Good: <1 |

*VOYA is ranked very high in sensitivity to acidification effects from atmospheric deposition relative to all Inventory & Monitoring parks, so the condition category is adjusted to the next worse condition category (NPS 2013b).

VOYA and other GLKN parks listed 13 plant species sensitive to ozone in VOYA, but it concluded that VOYA was at low risk because of low exposure levels (GLKN 2004).

Ground-level ozone (hereafter, ozone) is not emitted directly into the air. It is created by chemical reactions between VOC and $NO_x$ in the presence of sunlight. Ozone levels are generally higher in summer because of the combination of high temperatures and strong sunlight. Industrial emissions, electric utilities emissions, motor vehicle exhausts, gasoline vapors, and chemical solvents are some of the major sources of VOC and $NO_x$ (USEPA 2003).

In the VOYA vicinity in 2010, the largest regulated source of VOC within 250 km is a pulp and paper plant in Thunder Bay, ON (398 MT $yr^{-1}$). Other large VOC point sources within 250 km include a petroleum refinery in Superior, WI (290 MT $yr^{-1}$), a pulp and paper mill in Grand Rapids, MN (242 MT $yr^{-1}$), a pulp and paper mill at Fort Frances, ON (now closed) (236 MT $yr^{-1}$), an engineered wood products plant at Barwick, ON (231 MT $yr^{-1}$), and the paper mill at International Falls (now operating only two of its four paper machines) (157 MT $yr^{-1}$) (Figure 36). US nonpoint sources of VOC in counties within 250 km of VOYA include residential fuel combustion (natural gas, oil, wood, and other fuels) of 15,308 MT $yr^{-1}$, mobile sources (aircraft, commercial, marine

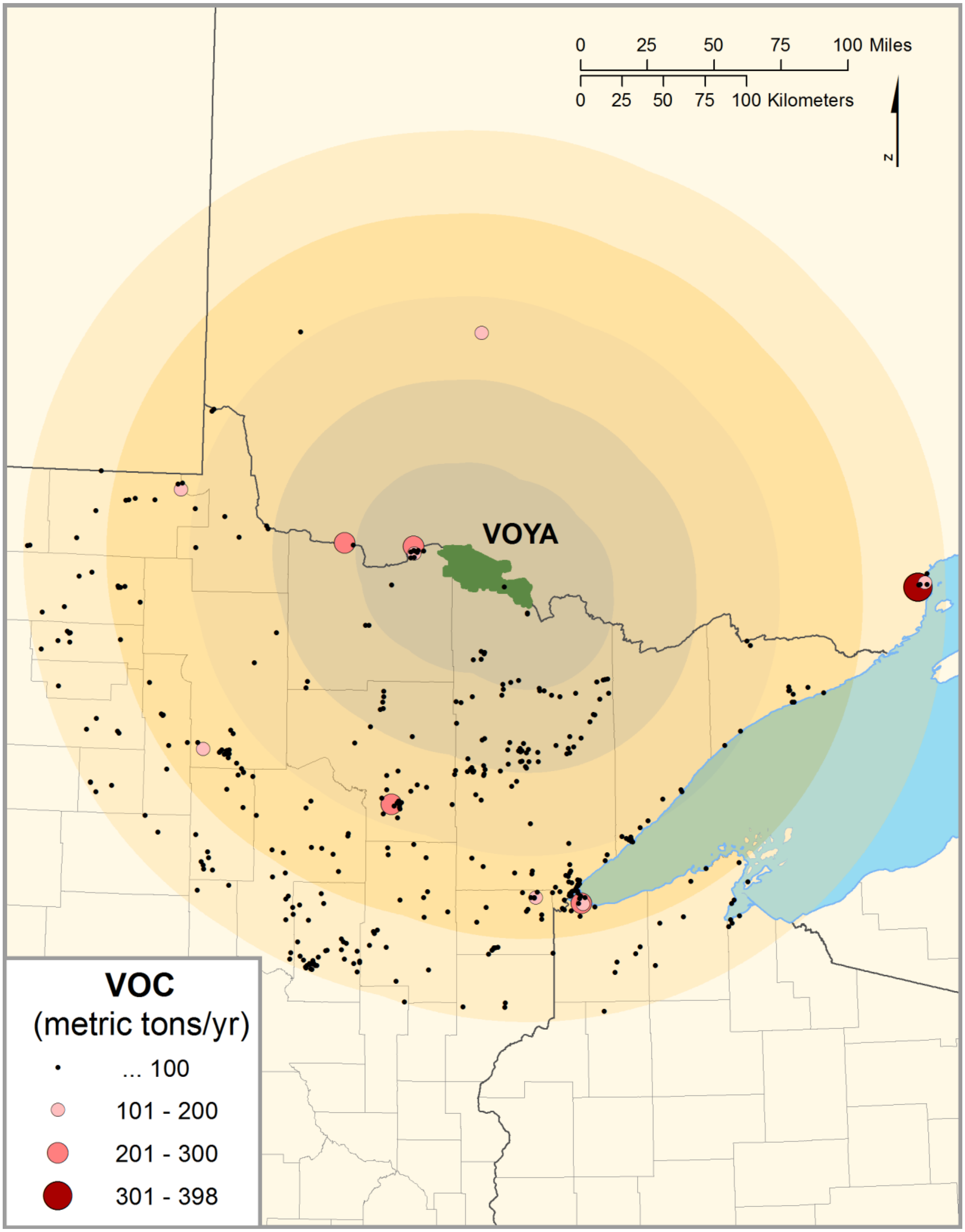

**Figure 36.** Emissions of volatile organic compounds (VOCs) from regulated facilities within 250 km of Voyageurs National Park (Environment Canada 2012, USEPA 2013b).

**Table 18.** 2011 (US) and 2010 (Canada) emissions of criteria air pollutants in metric tons for selected nonpoint and point sources within a 250 km buffer of Voyageurs National Park (Environment Canada 2012, USEPA 2013b).

| | **2011 emissions in metric tons and % of US total emissions** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **U.S.** | ***CO*** | ***%*** | ***$NH_3$*** | ***%*** | ***$NO_x$*** | ***%*** | ***$PM_{10}$*** | ***%*** | ***$PM_{2.5}$*** | ***%*** | ***$SO_2$*** | ***%*** | ***VOC*** | ***%*** |
| ***Selected nonpoint sources*** | | | | | | | | | | | | | | |
| Residential fuel combustion-US* | 87,749 | 30.4 | 791 | 46.1 | 1,995 | 2.5 | 13,597 | 45.4 | 13,592 | 56.2 | 740 | 4.1 | 15,308 | 30.3 |
| Mobile Sources-US** | 78,771 | 27.3 | 20 | 1.2 | 22,965 | 29.1 | 1,586 | 5.3 | 1,494 | 6.2 | 380 | 2.1 | 23,429 | 46.4 |
| On-road sources-US*** | 107,931 | 37.4 | 344 | 20.1 | 17,357 | 22.0 | 1,121 | 3.7 | 721 | 3.0 | 84 | 0.5 | 9,174 | 18.2 |
| Subtotal | | **95.2** | | **67.3** | | 53.5 | | 54.4 | | **65.4** | | 6.7 | | **95.0** |
| ***Point sources*** | | | | | | | | | | | | | | |
| Regulated facilities-US | 13,907 | 4.8 | 560 | 32.7 | 36,726 | 46.5 | 13,664 | 45.6 | 8,372 | 34.6 | 16,700 | **93.3** | 2,530 | 5.0 |

| | **2010 emissions in metric tons** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Canada** | **CO** | **$NH_3$** | **$NO_x$** | **$PM_{10}$** | **$PM_{2.5}$** | **$SO_2$** | **VOC** |
| Regulated facilities-Canada | 3,954 | 69 | 4,324 | 567 | 436 | 4,704 | 1,382 |

*natural gas, oil, wood, and other fuels

**aircraft, commercial marine vessels, locomotives, and non-road equipment (gasoline and diesel)

***diesel and gasoline-powered vehicles

vessels, locomotives, and non-road gasoline and diesel equipment) of 23,429 MT yr$^{-1}$, and on-road sources (diesel and gasoline-powered vehicles) of 9,174 MT yr$^{-1}$ (Table 18). Within 250 km of VOYA in the US, nonpoint sources account for 95% of VOC emissions. These nonpoint sources include the motorized recreational equipment (mainly motorboats and snowmobiles) used within the park. However, given current USEPA reporting, nonpoint emissions within VOYA cannot be separated from emissions in other parts of St. Louis and Koochiching Counties, the two largest counties in MN.

Swackhamer and Hornbuckle (2004) concluded that emissions of VOCs (and CO) within VOYA, primarily from snowmobile use, were similar in magnitude to emissions of those pollutants from major point sources outside the park. Emissions of VOCs by regulated facilities within 250 km of VOYA in the US have decreased from 5,396 MT yr$^{-1}$ in 1996 to 2,530 MT yr$^{-1}$ in 2011 (-53.1%) (Table 19). Emissions of hydrocarbons (much of which is VOC) from new snowmobiles have also decreased from the early 2000s as a result of USEPA regulations, from a maximum of 111 grams per horsepower hour (g/hp-hr) to as few as 7.8 g/hp-hr today (Table 20). Much of the improvement has resulted from a shift from two-stroke to four-stroke engines, which release less unburned fuel.

**Table 19.** Change in emissions from regulated facilities in the US within 250 km of Voyageurs National Park, 1996–2011 (Swackhamer and Hornbuckle 2004, USEPA 2013b).

| | Emissions in metric tons | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | ***CO*** | ***% change*** | ***$NO_x$*** | ***% change*** | ***$PM_{10}$*** | ***% change*** | ***$SO_2$*** | ***% change*** | ***VOC*** | ***% change*** |
| 1996 | 17,322 | | 57,776 | | 57,960 | | 36,699 | | 5,396 | |
| 2011 | 13,907 | -19.7 | 36,726 | -36.4 | 13,664 | -76.4 | 16,700 | -54.5 | 2,530 | -53.1 |

**Table 20.** Emissions of air pollutants from snowmobiles (USEPA 2010, NPS 2011).

| | | | Emissions, g/hp-hr | | | |
|---|---|---|---|---|---|---|
| **Type** | **Cycle** | **Fuel System** | ***HC (VOC)*** | ***CO*** | ***PM*** | ***$NO_x$*** |
| Snowmobile | 2-stroke | Precontrol | 111.00 | 296.00 | 2.70 | 0.86 |
| | | Modified | 53.70 | 146.90 | 2.70 | 0.86 |
| | | Direct Injection | 21.80 | 90.00 | 0.57 | 2.80 |
| | 4-stroke | Closed crankcase | 7.80 | 123.00 | 0.15 | 9.20 |
| | | NPS Best Available Technology | 11.03 | 88.26 | - | - |
| | | Meets 2010+ USEPA standards | 55.16 | 202.26 | - | - |

Recreational boating emissions were outside the scope of the Swackhamer and Hornbuckle (2004) report. However, similar reductions in hydrocarbon emissions have occurred), from a maximum of 109 grams per brake horsepower hour (g/bhp-hr) to as few as 3.5 g/bhp-hr today (Table 21)

Although it is clear that emissions of hydrocarbons from individual snowmobiles and outboard motors have greatly decreased, there are many difficulties in determining the significance of this within VOYA. We do know, for example, the number of snowmobile visits in VOYA in 2013 (8,821) and the number of houseboat visits (31,649), one measure of motorboat use. However, we do

**Table 21.** Emissions of air pollutants from outboard motors (USEPA 2010).

|  |  |  | Emissions, g/bhp-hr* |  |  |  |
|---|---|---|---|---|---|---|
| **Type** | **Cycle** | **Fuel System** | ***HC (VOC)*** | ***CO*** | ***PM*** | ***$NO_x$*** |
| 50–100 hp outboard motor | 2-stroke | Carbureated | 109.11 | 240.34 | 2.20 | 1.34 |
|  |  | Indirect Injection | 92.45 | 204.16 | 1.90 | 1.96 |
|  |  | Direct Injection | 15.55 | 77.32 | 0.22 | 4.32 |
|  | 4-stroke | Carbureated | 4.69 | 114.51 | 0.06 | 5.18 |
|  |  | Indirect Injection | 5.82 | 152.25 | 0.06 | 5.44 |
|  |  | Direct Injection | 3.53 | 127.94 | 0.06 | 5.82 |
|  |  | Meets 2010+ USEPA standards | 6.88 | 125.94 | 0.06 | 4.03 |

*bhp is a reference to the method of calculation; bhp and hp are equivalent.

not know the horsepower of the snowmobile or boat engines, their ages, or which engine technology they use. The USEPA has a model that, with the proper inputs, can be used to refine the estimate of motorized vehicle emissions in VOYA (MOVES, [Motor Vehicle Emission Simulator], http://www.epa.gov/otaq/models/moves/).

The other major component contributing to ozone levels in VOYA is $NO_x$. In 2011, the largest regulated sources of $NO_x$ within 250 km of VOYA were taconite facilities located in Mountain Iron, MN (5,824 MT $yr^{-1}$) and Hibbing, MN (4,316 MT $yr^{-1}$) and an electric generation facility in Cohasset, MN (4,161 MT $yr^{-1}$) (Figure 37). Emissions of $NO_x$ by regulated facilities in the US within 250 km of VOYA have decreased from 57,776 MT $yr^{-1}$ in 1996 to 36,726 MT $yr^{-1}$ in 2011 (-36.4%) (Table 19). US nonpoint sources of $NO_x$ in counties within 250 km of VOYA included residential fuel combustion of 1,995 MT $yr^{-1}$, mobile sources of 22,965 MT $yr^{-1}$, and on-road sources of 17,357 MT $yr^{-1}$ (Table 18). Within 250 km of VOYA in the US, nonpoint sources accounted for 53.5% of $NO_x$ emissions. It should be noted that as emissions of hydrocarbons and VOCs from motorized recreation decrease, emissions of $NO_x$ increase (Table 20 and Table 21); this has been noted as a potential concern in Yellowstone National Park (NPS 2011).

### *Visibility*

Visibility is a measurement of how well and at what distance visitors to VOYA can see the park's natural features. Using the metric called 'Group 50 visibility minus natural conditions' and measured in deciviews, visibility was of moderate concern at VOYA from 2005–2012 (Table 17). Our confidence in this assessment is high.

Particulate matter pollution, especially particles with diameters of 2.5 microns or less, ($PM_{2.5}$) is the major cause of reduced visibility, also called haze (Malm 1999, USEPA 2006). The largest regulated sources of $PM_{2.5}$ in 2011 within 250 km of VOYA were a taconite processing facility in Mountain Iron, MN (2,192 MT $yr^{-1}$) and an electrical generation facility in Cohasset, MN (981 MT $yr^{-1}$) (Figure 38). US nonpoint sources of $PM_{2.5}$ in 2011 in counties within 250 km of VOYA included residential fuel combustion of 13,592 MT $yr^{-1}$, mobile sources of 1,494 MT $yr^{-1}$, and on-road sources of 721 MT $yr^{-1}$; these accounted for 65.4% of all US $PM_{2.5}$ emissions (Table 18). Swackhamer and Hornbuckle (2004) did not report emissions of $PM_{2.5}$ by regulated facilities within 250 km of VOYA, but emissions of $PM_{10}$, which also contribute to visibility issues, have decreased in the US from 57,960 MT $yr^{-1}$ in 1996 to 13,664 MT $yr^{-1}$ in 2011 (-76.4%) (Table 19).

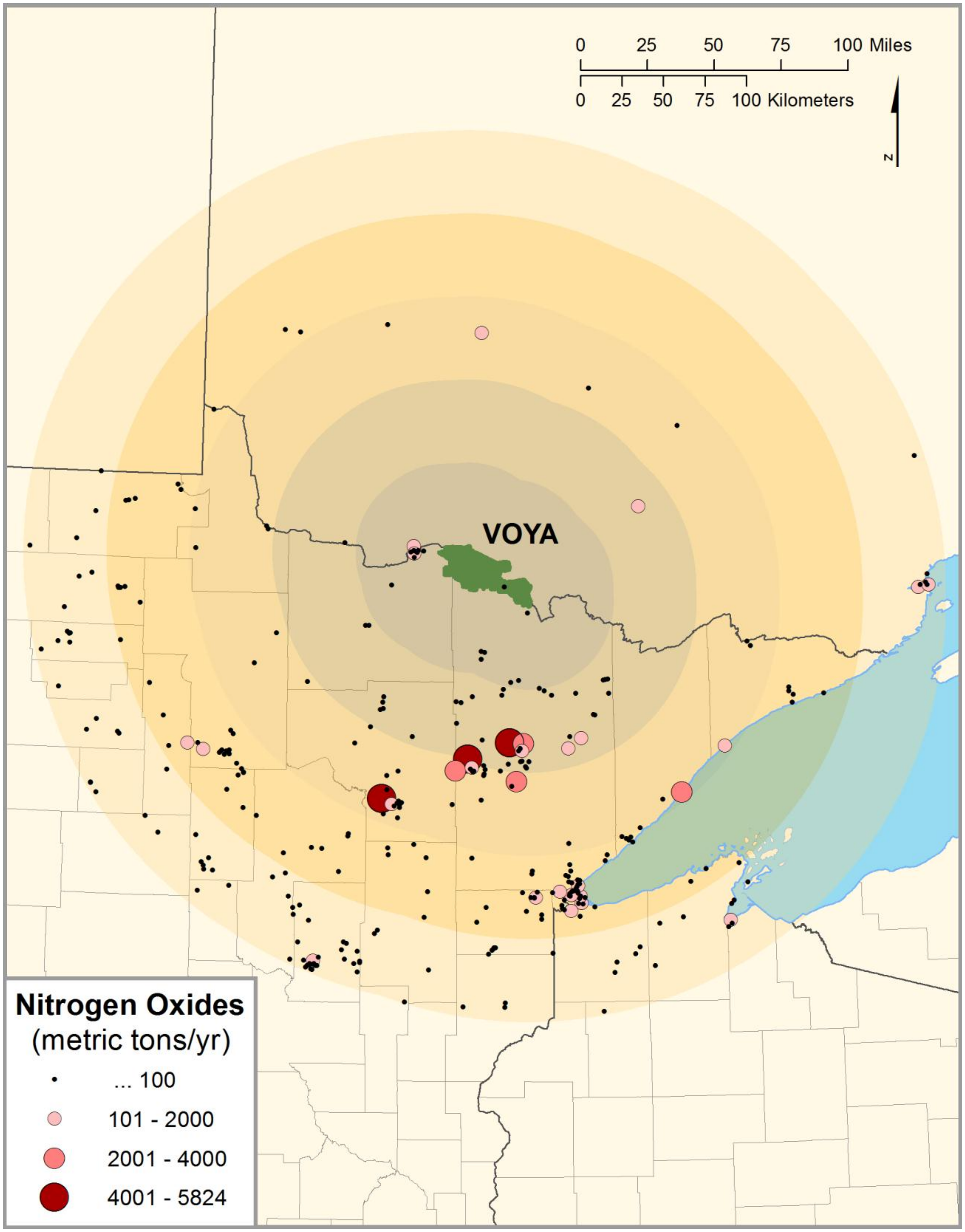

**Figure 37**. Emissions of nitrogen oxides ($NO_x$) from regulated facilities within 250 km of Voyageurs National Park (Environment Canada 2012, USEPA 2013b).

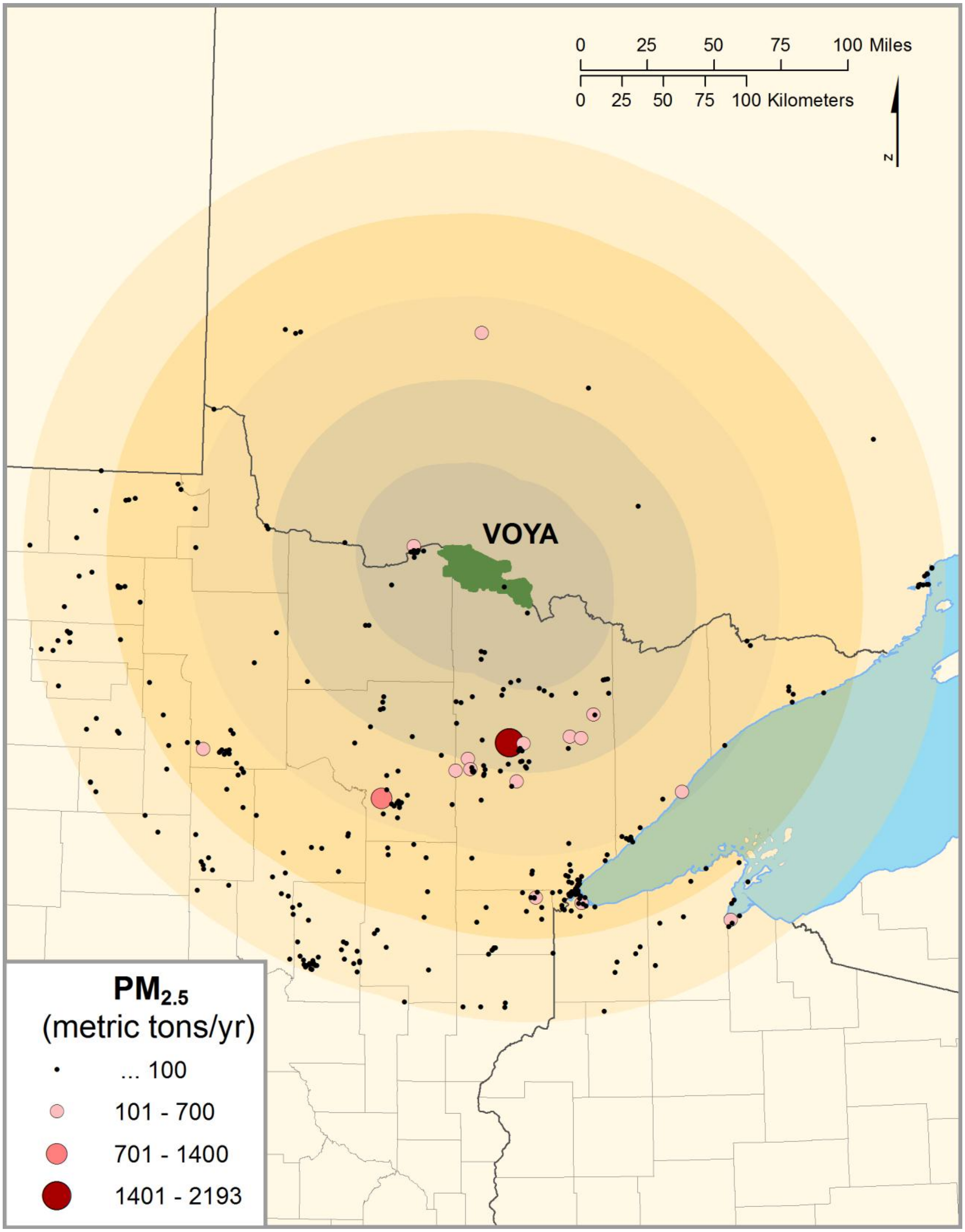

**Figure 38.** Emissions of particulate matter ($PM_{2.5}$) from regulated facilities within 250 km of Voyageurs National Park (Environment Canada 2012, USEPA 2013b).

One study found that at BWCAW, ammonium sulfate was the largest contributor to $PM_{2.5}$ except at $PM_{2.5}$ concentrations above the 95th percentile. On these haziest days, organic carbon from fires became the largest constituent. Other constituents of $PM_{2.5}$ at BWCAW, in order of significance, are ammonium nitrate, elemental carbon, and soil dust (MACTEC 2004).

The state of MN is working on a Regional Haze Plan to reduce visibility impairments at both VOYA and BWCAW (http://www.pca.state.mn.us/sbiz4ca). In 2012, the NPS, USDA Forest Service, and a coalition of Friends groups and environmental organizations commented that the proposed State Implementation Plan was inadequate and would not sufficiently reduce emissions from electrical generating facilities and taconite processing plants to achieve the visibility requirements for these two Class I areas.

*Wet Deposition – Sulfur and Wet Deposition – Nitrogen*

**Total S** **Total N**

The potential effects of wet deposition of nitrogen and sulfur include acidification of ecosystems, both aquatic and terrestrial, and addition of nutrients that can lead to eutrophication. Deposition results from emissions of $SO_2$ and $NO_x$, which also have consequences for human health. These gases create a variety of respiratory problems in people, and they react with other components in the atmosphere to create fine particles that create additional respiratory problems (USEPA 2011a, 2011b). As noted above, sulfate and nitrate also contribute greatly to visibility reductions at high relative humidity levels (Malm 1999).

Wet deposition of total S is of significant concern for VOYA, with 1.2 kg $ha^{-1}$ $yr^{-1}$ from 2008–2012 to 1.5 kg $ha^{-1}$ $yr^{-1}$ for 2005–2009. Wet deposition of total N is also of significant concern for VOYA, with values of 3.0–3.1 kg $ha^{-1}$ $yr^{-1}$ from 2005–2012 (Table 17). Our confidence in this assessment is high.

The largest regulated sources of $SO_2$ within 250 km of VOYA in 2011 were electrical generation facilities in Cohasset, MN (3,599 MT $yr^{-1}$); Schroeder, MN (3,047 MT $yr^{-1}$); and Atikokan, ON (2,299 MT $yr^{-1}$); and an electrical generating and taconite processing facility in Silver Bay, MN (2,042 MT $yr^{-1}$) (USEPA 2013b) (Figure 39). Emissions of $SO_2$ by regulated facilities in the US within 250 km of VOYA have decreased from 36,699 MT $yr^{-1}$ in 1996 to 16,700 MT $yr^{-1}$ in 2011 (-54.5%) (Table 19). Nonpoint sources of $SO_2$ in US counties within 250 km of VOYA include residential fuel combustion of 740 MT $yr^{-1}$, mobile sources of 380 MT $yr^{-1}$, and on-road sources of 84 MT $yr^{-1}$ (Table 18). Within 250 km of VOYA in the US, regulated facilities accounted for 93.3% of $SO_2$ emissions in 2011.

In the region, atmospheric $SO_4^{2-}$ deposition at ISRO exhibited a downward trend from 1985–2005 (Drevnick et al. 2007). Similarly, in New England, the region with the longest deposition record in North America, a decline in $SO_4^{2-}$ input has been documented since the 1970s (Hedin et al. 1994, Likens et al. 1996). This decline extended as far west as MN. Driscoll et al. (2001) reported that a decrease in $SO_4^{2-}$ wet deposition in the eastern US has resulted from the Clean Air Act Amendments (CAAA) of 1990. However, sulfur still remains a concern at VOYA because it plays a role in the methylation of mercury and is a strong driver of acidification of surface waters and soils (NPS 2013d).

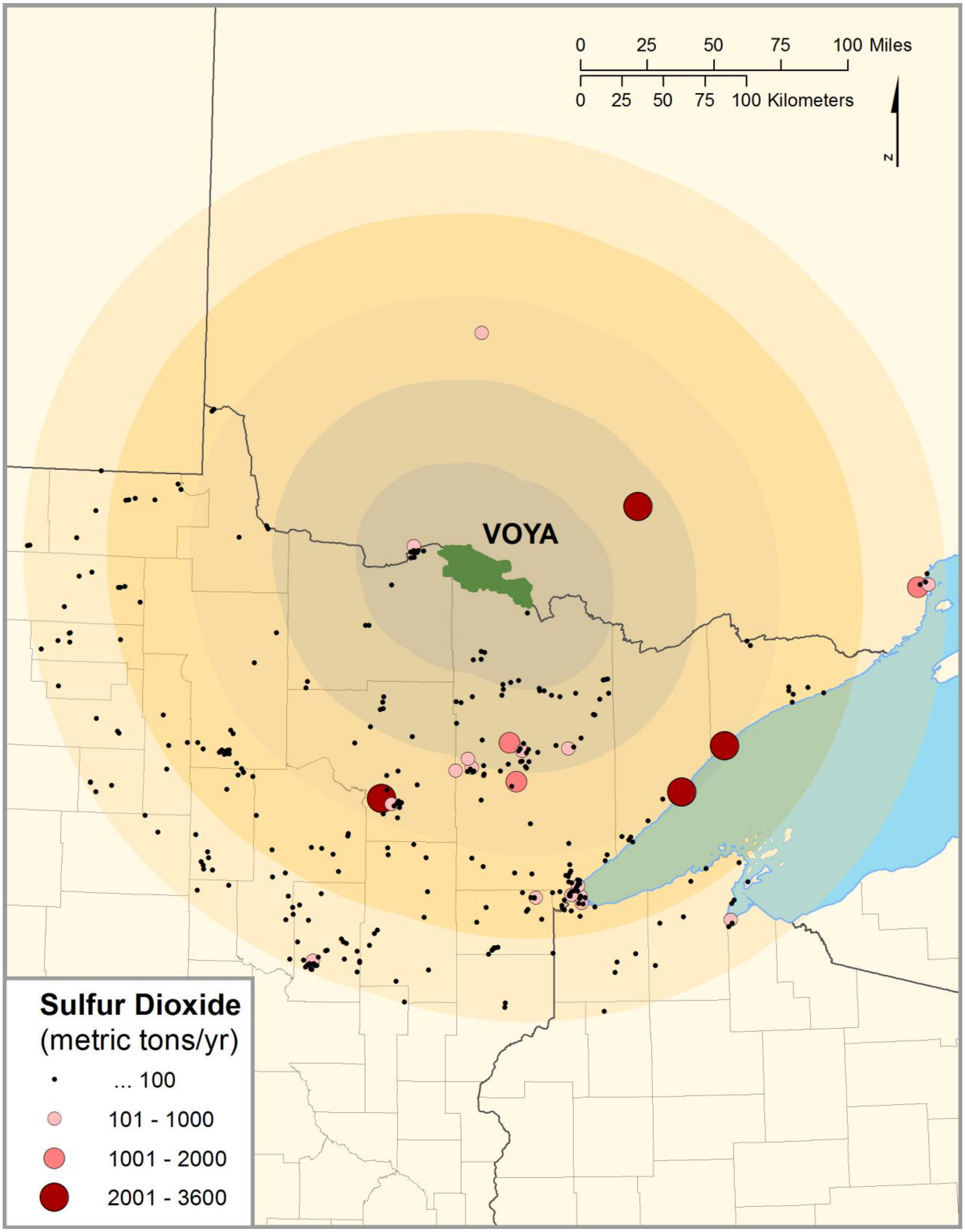

**Figure 39.** Emissions of sulfur dioxide ($SO_2$) from regulated facilities within 250 km of Voyageurs National Park (Environment Canada 2012, USEPA 2013b).

Sources of nitrogen emissions were described in the previous discussion of ozone. Although the 1990 CAAA decreased sulfur deposition in the eastern US, the same effect was not observed for nitrogen deposition (Driscoll et al. 2001). In addition to the wet deposition of nitrogen considered by NPS ARD, dry deposition of total nitrogen (TN) is also a consideration for VOYA. Wet deposition may include $HNO_3$, $NO_3^-$, and $NH_4^+$, while dry deposition includes $HNO_3$, particulate $NO_3^-$, particulate $NH_4^+$, and $NH_3$ (NAPAP 2005). Of TN deposition at VOYA (the closest CASTNet site) from 2008–2010, 86% was wet deposition and 14% was dry deposition (USEPA 2012).

Researchers have attempted to define thresholds below which there are no discernible effects of N deposition, called critical loads (CL). Beyond CLs, N saturation can occur. This level of N deposition may affect forest ecosystem function by increasing nitrification and $NO_3^-$ leaching, with associated acidification of soils and surface waters; depletion of soil nutrient cations and development of plant nutrient imbalances; and forest decline and changes in species composition (Driscoll et al. 2003).

Acid deposition: Wet deposition of reactive forms of sulfur and nitrogen that form or can form acids when in contact with water is a subset of air pollution known as acid deposition. Acid deposition specifically includes gases, particles, rain, snow, clouds, and fog that are composed of sulfuric acid, nitric acid, and ammonium, derived from $SO_2$, $NO_x$, and $NH_3$, respectively.

In a ranking of all national parks by quintile, VOYA is considered to be at very high risk from acidic deposition. This ranking is based on three factors: a moderate pollutant exposure, very high ecosystem sensitivity, and a very high degree of park protection (Sullivan et al. 2011a). We believe this ranking to be valid for VOYA's aquatic ecosystems, but we believe the risk for the terrestrial ecosystems to be less because of a lack of sensitive species of vegetation (defined by Sullivan et al. 2011c as vegetation types expected to contain red spruce (*Picea rubens*) or sugar maple (*Acer saccharum*).

The effect of acid precipitation on aquatic ecosystems is determined largely by the ability of the water and watershed soil to neutralize the acid deposition they receive. Generally, small watersheds with shallow soils and few alkaline minerals are most sensitive to acidification. Low pH levels and higher aluminum levels that result from acidification hinder fish reproduction and decrease fish sizes and population densities (NAPAP 2005). Watersheds that contain alkaline minerals such as limestone, or those with well-developed riparian zones, generally have a greater capacity to neutralize acids. VOYA is located in a region where surface waters have low alkalinity (2.5–5 mg $L^{-1}$ as $CaCO_3$, http://water.usgs.gov/owq/alkus.pdf). As noted in Section 4.4.2., VOYA's index lakes (small interior lakes) on the Kabetogama Peninsula had maximum alkalinities of 7–16 mg $L^{-1}$ as $CaCO_3$ from 2006–2012. Surface waters with alkalinities less than 25 mg $L^{-1}$ as $CaCO_3$ are generally considered susceptible to acidification (Sheffy 1984, Shaw et al. 2004).

Recent efforts to assess CLs for atmospheric deposition of TN have not specifically addressed Midwestern lakes or streams. However, Baron et al. (2011a, 2011b) have indicated that for lakes in the eastern US, the CL for acidity is 9 kg $ha^{-1}$ $yr^{-1}$, within the range derived for forested streams in Europe. Deposition levels at VOYA are below that threshold (Table 17).

The effects of acid precipitation on upland and forest ecosystems include direct and indirect impacts on plants, changes in forest floor and/or soil chemistry, and altered rates of mineral and nutrient accumulation and loss (Ohman and Grigal 1990, Aber et al. 1998, 2003). The possible direct effects on plants (e.g., reducing the integrity of the epidermis) are well-known (McLaughlin 1985), and are all negative, with the possible exception of a fertilization effect. The indirect effects on plants derive largely from changes in chemistry of the system, and include nutritional, toxic, and altered symbiosis effects (Hedin et al. 1994, Aber et al. 1998, Friedland and Miller 1999, Zaccherio and Finzi 2007).

Because N is a common limiting nutrient in temperate forests (Nadelhoffer et al. 1985), N deposition might appear to be beneficial. However, the acidification that accompanies N and S deposition can lead to the loss of cations, which are important nutrients, from the soil. Buffering capacity (the ability to resist acidification) in forest soils is largely a function of four factors: a) surface horizon texture and depth, b) B-horizon texture and depth, c) total cation exchange capacity and base saturation, and d) abundance of fungi and bacteria in the upper soil profile (Johnson et al. 1983, Aber et al. 1998). Generally, buffering capacity is low in systems with coarse, acid soils; soils low in organic matter; and soils that are shallow.

Nutrient deficiency is particularly likely for any upland ecosystem that has low base saturation, which is common on acidic sites. Stottlemyer and Hanson (1989) determined that under conifers, the concentrations of $SO_4^{2-}$, calcium ($Ca^{2+}$), and magnesium ($Mg^{2+}$) were higher in soil solution than in precipitation, and $SO_4^{2-}$ had a flux 2–3 times that of other nutrients. These findings demonstrate how acid deposition could affect a terrestrial system by setting the stage for accelerated loss of cations. The hydrogen ions associated with $SO_4^{2-}$ replace other cations on the soil exchange sites (Tomlinson 2003), and then the cations are leached if water moves down through the soil profile. However, cation loss occurs even on soils with high buffering capacity. The effect is cumulative and continues even after acid deposition is mitigated. In New England, large quantities of $Ca^{2+}$ and $Mg^{2+}$ have been lost from the soil (Likens et al. 1996, Friedland and Miller 1999) even after nitrate and sulfate inputs were reduced and the pH of precipitation increased (Likens et al. 1996).

Nutrient N enrichment: Sullivan et al. (2011b) ranked VOYA as at very high risk from atmospheric nutrient N enrichment, but reported only moderate pollutant exposure, low ecosystem sensitivity, and a very high degree of park protection. For N enrichment, the particular ecosystem risk factors for VOYA are the presence of "sensitive vegetation types" (defined as arctic, alpine, meadow, wetland, arid, and/or semiarid vegetation, Sullivan et al. 2011b), which total 10% of the terrestrial vegetation at VOYA; and the presence of N-limited boreal lakes, where increased N can affect the biodiversity, algal communities, and water clarity (NPS 2013d).

Nitrogen can cause changes in terrestrial plant communities. Among trees, red pine (*Pinus resinosa*), yellow birch (*Betula alleghaniensis*), trembling aspen, basswood (*Tilia americana*), and northern white cedar, all present at VOYA (NPS n.d.), are among the N-'sensitive' species identified by Pardo et al. (2011) and Gilliam et al. (2011). This group shows reduced growth or survivorship at TN deposition rates above 3 kg $ha^{-1}$ $yr^{-1}$. A synthesis by Pardo et al. (2011) for the Northern Forest ecoregion determined that the ectomycorrhizal community and lichen community had the lowest CLs for nutrient N (4–7 kg $ha^{-1}$ $yr^{-1}$). Similarly, for Eastern Hardwood forests, the lowest CL for nutrient

N was observed for lichens (4–8 kg $ha^{-1}$ $yr^{-1}$) (Gilliam et al. 2011). For wetlands, Greaver et al. (2011 and citations therein) report CLs for TN of 2.7–13 kg $ha^{-1}$ $yr^{-1}$ for peat accumulation and net primary production and 6.8–14 kg $ha^{-1}$ $yr^{-1}$ for pitcher plant community change. TN deposition at VOYA is at the CL for sensitive trees and exceeds the lower end of the range for peat accumulation.

A second undesirable effect that might manifest from N deposition is simplification of composition. That is, a subset of species is favored under the changed nutrient conditions and is able to outcompete other species. Simplification has not been documented in a boreal forest, but has been demonstrated in some forest fertilization trials (Rainey et al. 1999).

A recent study (Clark et al. 2013) estimated losses of plant biodiversity in the US from N deposition that occurred from 1985–2010, without distinguishing between acidification and nutrient enrichment effects. The authors concluded that millions of hectares in the US (including 222.1 million ha in the Eastern Forest ecoregion) have N deposition levels exceeding the "common" CL of 10 kg $ha^{-1}$ $yr^{-1}$. Species losses varied considerably by ecosystem types. They urged greater research in refining CLs and questioned the adequacy of current CL estimates in providing protection to terrestrial plant biodiversity.

Increased nitrate leaching is one of the probable indicators that N saturation has occurred (Aber et al. 2003, Pardo et al. 2011). A compilation of many studies in the eastern hardwood forests of the northeast (Aber et al. 2003) concluded that an increase in nitrate leaching to surface waters is likely to occur if the N deposition rate exceeds approximately 8 kg $ha^{-1}$ $yr^{-1}$ for an extended period of time. Baron et al. (2011a, 2011b) indicated that for lakes in the eastern US, this level of N deposition is a CL for eutrophication.

Because streams and rivers integrate the deposition on land and deposition directly to the aquatic system, the N concentration in water has been suggested as a suitable sentinel of N deposition problems (Williamson et al. 2008). However, the magnitude of nitrate leaching was highly variable among sites; it was hypothesized that this variability is due to the large number of factors (plant composition, soil type, land use, hydrology, and climate) that affect leaching (Pardo et al. 2011). The complexity of the situation is highlighted by the fact that very large differences between evergreen and broadleaved species often occur (Stottlemyer and Hanson 1989, Reich et al. 1997, Ollinger et al. 2002), and that N deposition rates are only weakly related to nitrogen cycling processes (Pardo et al. 2011). Other components of the system (such as foliar N concentration or the fungal community discussed above) may change prior to nitrate leaching and thus provide an earlier 'warning.'

### Sources of Expertise

USEPA air quality website (http://www.epa.gov/air); NPS ARD; Jen McNelly, James Cook, Christine Mechenich, UWSP.

### Literature Cited

Aber, J., W. McDowell, K. Nadelhoffer, A. Magill, G. Berntson, M. Kamakea, S. McNulty, W. Currie, L. Rustad, and I. Fernandez. 1998. Nitrogen saturation in temperate forest ecosystems. *Bioscience* 48:921–933.

Aber, J. D., C. L. Goodale, S. V. Ollinger, M. Smith, A. H. Magill, M. E. Martin, R. A. Hallett, and J. L. Stoddard. 2003. Is nitrogen deposition altering the nitrogen status of northeastern forests? *Bioscience* 53:375–388.

Baron, J. S., C. T. Driscoll, and J. L. Stoddard. 2011a. Inland surface waters, chapter 18. Pages 209–227 *in* L. H. Pardo, M. J. Robin-Abbott, and C. T. Driscoll, editors. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. General Technical Report NRS-80. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at http://treesearch.fs.fed.us/pubs/38129 (accessed 25 August 2014).

Baron, J. S., C. T. Driscoll, J. L. Stoddard, and E. E. Richer. 2011b. Empirical critical loads of atmospheric nitrogen deposition for nutrient enrichment and acidification of sensitive US lakes. *BioScience* 61:602–613.

Clark, C. M., P. E. Morefield, F. S. Gilliam, and L. H. Pardo. 2013. Estimated losses of plant biodiversity in the United States from historical N deposition (1985–2010). *Ecology* 94:1441–1448.

Drevnick, P. E., D. E. Canfield, P. R. Gorski, A. C. Shinneman, D. R. Engstrom, D. C. G. Muir, G. R. Smith, P. J. Garrison, L. B. Cleckner, J. P. Hurley, R. B. Noble, R. R. Otter, and J. T. Oris. 2007. Deposition and cycling of sulfur controls mercury accumulation in Isle Royale fish. *Environmental Science and Technology* 41:7266–7272.

Driscoll, C. T., G. B. Lawrence, A. J. Bulger, T. J. Butler, C. S. Cronan, C. Eagar, K. F. Lambert, G. E. Likens, J. L. Stoddard, and K. C. Weathers. 2001. Acid rain revisited: advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments. Science Links™ Publication. Vol. 1, no.1. Hubbard Brook Research Foundation, North Woodstock, New Hampshire. Available at http://hubbardbrookfoundation.org/wp-content/uploads/2010/12/acid-rain-revisited.pdf (accessed 25 August 2014).

Driscoll, C. T, D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. L. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence, and S. Ollinger. 2003. Nitrogen pollution in the northeastern United States: sources, effects, and management options. *BioScience* 53:357–374.

Environment Canada. 2012. National Pollutant Release Inventory: 2010 facility-reported data (Pollutant releases and transfers). Gatineau, Quebec, Canada. Available at http://www.ec.gc.ca/inrp-npri/ (accessed 3 October 2012).

Environment Canada. 2013. 10 years of data from the National Air Pollution Surveillance (NAPS) network: data summary from 1999 to 2008. Gatineau, Quebec, Canada. Available at www.ec.gc.ca/rnspa-naps/default.asp?lang=En&n=77FECF05-1#reports (accessed 20 August 2014).

Friedland, A. J., and E. K. Miller. 1999. Major-element cycling in a high-elevation Adirondack forest: patterns and changes, 1986–1996. *Ecological Applications* 9:958–967.

Gilliam, F. S., C. L. Goodale, L. H. Pardo, L. H. Geiser, and E. A. Lilleskov. 2011. Eastern temperate forests, chapter 10. Pages 99–116 *in* L. H. Pardo, M. J. Robin-Abbott, and C. T. Driscoll, editors. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. General Technical Report NRS-80. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at http://treesearch.fs.fed.us/pubs/38121 (accessed 25 August 2014).

GLKN (Great Lakes Inventory and Monitoring Network). 2004. Assessing the risk of foliar injury from ozone on vegetation in parks in the Great Lakes Network. National Park Service Great Lakes Inventory and Monitoring Network, Ashland, Wisconsin. Available at http://nature.nps.gov/air/Pubs/pdf/03Risk/glknO3RiskOct04.pdf (accessed 25 August 2014).

Greaver, T. L., L. Liu, and R. Bobbink. 2011. Wetlands, chapter 17. Pages 193–208 *in* L. H. Pardo, M. J. Robin-Abbott, and C. T. Driscoll, editors. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. General Technical Report NRS-80. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at http://treesearch.fs.fed.us/pubs/38128 (accessed 25 August 2014).

Hedin, L. O., L. Granat, G. E. Likens, T. A. Buishand, J. N. Galloway, T. J. Butler, and H. Rodhe. 1994. Steep declines in atmospheric base cations in regions of Europe and North America. *Nature* 367:351–354.

Johnson, D. W., D. D. Richter, H. Van Miegroet, and D. W. Coles. 1983. Contributions of acid deposition and natural processes to cation leaching from forest soils: a review. *Journal of the Air Pollution Control Association* 33:1036–1041.

Likens, G. E., C. T. Driscoll, and D. C. Buso. 1996. Long-term effects of acid rain: response and recovery of a forest ecosystem. *Science* 272:244–246.

MACTEC Engineering and Consulting, Inc. 2004. Analysis of air quality data collected near tribal lands in Minnesota, Wisconsin, and Michigan. MACTEC, Jacksonville, Florida. Available at http://www.ladco.org/reports/rpo/data_analysis/tribal_data_anaysis_final_report_maltec.pdf (accessed 29 November 2011).

Malm, W. C. 1999. Introduction to visibility. Cooperative Institute for Research in the Atmosphere (CIRA) NPS Visibility Program, Colorado State University, Fort Collins, Colorado. Available at http://www.epa.gov/air/visibility/pdfs/introvis.pdf (accessed 25 August 2014).

McLaughlin, S. B. 1985. Effects of air pollution on forests. *Journal of the Air Pollution Control Association* 35:512–534.

MPCA (Minnesota Pollution Control Agency). 2012. Annual air monitoring network plan for Minnesota 2013. Document number aq10-07a. MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/view-document.html?gid=17855 (accessed 16 July 2013).

MPCA (Minnesota Pollution Control Agency). 2014. Draft 2015 annual air monitoring network plan—Appendix A: 2014 air monitoring site descriptions. MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/view-document.html?gid=21126 (accessed 20 August 2014).

Nadelhoffer, K. J., J. D. Aber, and J. M. Melillo. 1985. Fine roots, net primary production and soil nitrogen availability: a new hypothesis. *Ecology* 66:1377–1390.

NAPAP (National Acid Precipitation Assessment Program). 2005. National Acid Precipitation Assessment Program Report to Congress: an integrated assessment. Available at http://www.esrl.noaa.gov/csd/aqrs/reports/napapreport05.pdf (accessed 25 August 2014).

NPS (National Park Service). n.d. A checklist of plants and animals in Voyageurs National Park. Voyageurs National Park, International Falls, Minnesota. Available at http://www.nps.gov/voya/planyourvisit/loader.cfm?csModule=security/getfile&PageID=359900 (accessed 14 August 2014).

NPS (National Park Service). 2007. Long-term ecological monitoring plan: Great Lakes Inventory and Monitoring Network. Natural Resource Report NPS/GLKN/NRR—2007/001. National Park Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/645523 (accessed 28 October 2013).

NPS (National Park Service). 2011. Scientific assessment of Yellowstone National Park winter use, March 2011. Available at http://www.nps.gov/yell/parkmgmt/upload/yell_sci_assessment_deis_release_2011.pdf (accessed 7 July 2014).

NPS (National Park Service), Air Resources Division. 2013a. Air quality in national parks: trends (2000–2009) and conditions (2005–2009). Natural Resource Report NPS/NRSS/ARD/NRR—2013/683. National Park Service, Denver, Colorado. Available at http://www.nature.nps.gov/air/Pubs/pdf/gpra/AQ_Trends_In_Parks_2013.pdf (accessed 25 August 2014).

NPS (National Park Service). 2013b. Methods for determining air quality conditions and trends for park planning and assessments. NPS Air Resources Division, Natural Resource Program Center, Denver, Colorado. Available at http://www.nature.nps.gov/air/Planning/docs/AQ_ConditionsTrends_Methods_2013.pdf (accessed 25 August 2014).

NPS (National Park Service). 2013c. Additional trends and conditions information: Air quality in national parks: trends (2000–2009) and conditions (2005–2009). NPS Air Resources Division, Natural Resource Program Center, Denver, Colorado. Available at http://nature.nps.gov/air/Pubs/pdf/gpra/AQ_Trends_In_Parks_2013_508appendix.pdf (accessed 25 August 2014).

NPS (National Park Service). 2013d. Air pollution impacts – Voyageurs National Park. Webpage. Available at http://www.nature.nps.gov/air/permits/aris/voya/impacts.cfm (accessed 25 August 2014).

NPS (National Park Service). 2014. NPS air quality estimate tables. NPS Air Resources Division, Denver, Colorado. Available at http://www.nature.nps.gov/air/Maps/AirAtlas/IM_materials.cfm (accessed 20 August 2014).

Ohman, L. F., and D. F. Grigal. 1990. Spatial and temporal patterns of sulfur and nitrogen in wood of trees across the north central United States. *Canadian Journal of Forest Research* 20:508–513.

Ollinger, S. V., M. L. Smith, M. E. Martin, R. A. Hallett, C. L. Goodale, and J. D. Aber. 2002. Regional variation in foliar chemistry and N cycling among forests of diverse history and composition. *Ecology* 83:339–355.

Pardo, L. H., C. L. Goodale, E. A. Lilleskov, and L. H. Geiser. 2011. Northern forests, chapter 7. Pages 61–73 *in* L. H. Pardo, M. J. Robin-Abbott, and C. T. Driscoll, editors. Assessment of nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. General Technical Report NRS-80. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, Pennsylvania. Available at http://treesearch.fs.fed.us/pubs/38116 (accessed 25 August 2014).

Rainey, S. M, K. J. Nadelhoffer, W. L. Silver, and M. R. Downs. 1999. Effects of chronic nitrogen additions on understory species in a red pine plantation. *Ecological Applications* 9:949–957.

Reich, P. B., D. G. Grigal, J. D. Aber, and S. T. Gower. 1997. Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology* 78:335–347.

Shaw, B., C. Mechenich, and L. Klessig. 2004. Understanding lake data. Publication G3582. University of Wisconsin-Extension, Madison, Wisconsin. Available at http://www3.uwsp.edu/cnr-ap/weal/Documents/G3582.pdf (accessed 2 September 2014).

Sheffy, T. 1984. Interpreting acid rain research findings in Wisconsin: what does it all mean? *Wisconsin Natural Resource* 8:29–32.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

Stottlemyer, R., and D. G. Hanson, Jr. 1989. Atmospheric deposition and ionic concentrations in forest soils of Isle Royale National Park, Michigan. *Soil Science Society of America Journal* 53:270–274.

Sullivan, J. T., G. T. McPherson, T. C. McDonnell, S. D. Mackey, and D. Moore. 2011a. Evaluation of the sensitivity of inventory and monitoring national parks to acidification effects from atmospheric sulfur and nitrogen deposition: Great Lakes Network (GLKN). Natural Resource Report NPS/NRPC/ARD/NRR—2011/356. National Park Service, Denver, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2170582 (accessed 25 August 2014).

Sullivan, J. T., T. C. McDonnell, G. T. McPherson, S. D. Mackey, and D. Moore. 2011b. Evaluation of the sensitivity of inventory and monitoring national parks to nutrient enrichment effects from atmospheric nitrogen deposition: Great Lakes Network (GLKN). Natural Resource Report NPS/NRPC/ARD/NRR—2011/309. National Park Service, Denver, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2168660 (accessed 25 August 2014).

Sullivan, T. J., G. T. McPherson, T. C. McDonnell, S. D. Mackey, and D. Moore. 2011c. Evaluation of the sensitivity of inventory and monitoring national parks to acidification effects from atmospheric sulfur and nitrogen deposition: main report. Natural Resource Report NPS/NRPC/ARD/NRR—2011/349. National Park Service, Denver, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2170555 (accessed 2 September 2014).

Sullivan, J. T., T. C. McDonnell, G. T. McPherson, S. D. Mackey, and D. Moore. 2011d. Evaluation of the sensitivity of inventory and monitoring national parks to nutrient enrichment effects from atmospheric nitrogen deposition: main report. Natural Resource Report NPS/NRPC/ARD/NRR—2011/313. National Park Service, Denver, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2168692 (accessed 2 September 2014).

Swackhamer, D. L., and K. C. Hornbuckle. 2004. Assessment of air quality and air pollutant impacts in Isle Royale National Park and Voyageurs National Park. National Park Service, Fort Collins, Colorado. Available at www.nature.nps.gov/air/Pubs/pdf/SwackHorn20040901.pdf (accessed 11 November 2013).

Tomlinson, G. H. 2003. Acidic deposition, nutrient leaching and forest growth. *Biogeochemistry* 65:51–81.

USEPA (United States Environmental Protection Agency) Science Advisory Board. 2002. A framework for assessing and reporting on ecological condition: an SAB report. EPA-SAB-EPEC-02-009. USEPA, Washington, D.C. Available at www.epa.gov/sab/pdf/epec02009.pdf (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2003. Ozone – good up high bad nearby. EPA-451/K-03-001. USEPA, Washington, D.C. Available at http://www.epa.gov/airquality/gooduphigh/ (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2006. How air pollution affects the view. EPA-456/F-06-001. USEPA, Research Triangle Park, North Carolina. Available at http://www.epa.gov/air/visibility/pdfs/haze_brochure_20060426.pdf (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2010. Exhaust emission factors for nonroad engine modeling--spark ignition. Report No. NR-010f. USEPA Office of Transportation and Air Quality, Washington, D. C. Available at http://www.epa.gov/otaq/models/nonrdmdl/nonrdmdl2010/420r10019.pdf (accessed 21 August 2014).

USEPA (United States Environmental Protection Agency). 2011a. Sulfur dioxide webpage. http://www.epa.gov/air/sulfurdioxide/index.html (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2011b. Nitrogen dioxide – health webpage. http://www.epa.gov/airquality/nitrogenoxides/health.html (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2012. Composition of N deposition for 2008-2010-VOY413. Webpage. Available at http://www.epa.gov/castnet/javaweb/charts/VOY413_pctn.png (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2013a. Basic information – air emission sources webpage. Available at http://www.epa.gov/air/emissions/basic.htm (accessed 25 August 2014).

USEPA (United States Environmental Protection Agency). 2013b. The 2011 national emissions inventory website. Available at http://www.epa.gov/ttn/chief/net/2011inventory.html (accessed 16 December 2013).

USEPA (United States Environmental Protection Agency). 2013c. The Clean Air Act in a nutshell: how it works. USEPA, Washington, D. C. Available at http://www.epa.gov/air/caa/pdfs/CAA_Nutshell.pdf (accessed 20 August 2014).

WDNR (Wisconsin Department of Natural Resources). 2012. Wisconsin Department of Natural Resources/Air Monitoring Network Plan 2013. WDNR, Madison, Wisconsin. Available at http://dnr.wi.gov/topic/airquality/documents/2013networkplanfinal.pdf (accessed 8 April 2013).

Western Regional Climate Center. 2013. RAWS (Remote Automatic Weather Stations) USA climate archive website. Available at http://www.raws.dri.edu/ (accessed 24 July 2013).

Williamson, C. E., W. Dodds, T. K. Kratz, and M. A. Palmer. 2008. Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. *Frontiers in Ecology and the Environment* 6:247–254.

Zaccherio, M. T., and A. C. Finzi. 2007. Atmospheric deposition may affect northern hardwood forest composition by altering soil nutrient supply. *Ecological Applications* 17:1929–1941.

### *4.4.2. Surface Water Quality*

Description

The water resources of VOYA are dominated by its four major lakes, Rainy, Kabetogama, Namakan, and Sand Point, and also include streams, rivers, 26 small interior lakes, and numerous wetlands and beaver ponds (Kallemeyn et al. 2003). These surface waters are generally considered to be of high quality (Kallemeyn et al. 2003). All surface waters within VOYA are designated as "Outstanding Resource Value Waters" by the state of MN (MPCA Ch. 7050.0180, MPCA 2013).

In the Water Resources Scoping Report for VOYA, Weeks and Andrascik (1998) described water issues at VOYA as both numerous and complex, with both widespread and local threats having the potential to degrade the park's water resources. Intense public usage at cabins, resorts, campsites, houseboat mooring sites, and day-use sites has resulted in improper sewage treatment, improper garbage disposal, the release of petroleum byproducts, and erosion. VOYA's vulnerability is enhanced by its size and location, including an international boundary, and water levels in the large lakes manipulated for human needs.

### Data and Methods

The water quality of VOYA has been summarized in numerous agency reports. In 1995, the NPS Water Resources Division and Servicewide Inventory and Monitoring Program conducted a *Baseline Water Quality Data Inventory and Analysis* (NPS 1995). This report includes the results of surface water quality data retrievals from five USEPA national databases. It provides a complete inventory of all retrieved water quality parameter data, stations, and collecting agencies; descriptive statistics and graphical representation of data; comparisons of data to applicable standards; and inventory data evaluation and analysis (IDEA) to determine what servicewide inventory and monitoring program level 1 water quality parameters have been measured within the area. The report identified 15 sites at VOYA with at least one exceedance of a USEPA water quality criterion. Acute criteria for the protection of freshwater life were exceeded for dissolved oxygen, pH, alkalinity, and the metals cadmium, copper, lead, and zinc. USEPA drinking water criteria for one or more of cadmium, lead, and nickel were exceeded at 12 of the 15 sites. One site exceeded the NPS screening limit for coliform bacteria related to whole body contact recreation.

As noted above, in 1998 Weeks and Andrascik completed a Water Resources Scoping Report. In July of 1999, Payne (2000) conducted a study which included collecting water samples from selected lakes, bays, and the mouths of two rivers within VOYA. Water samples collected in 1999 were compared to samples collected from 1977–1983 and evaluated for changes in specific conductance, alkalinity, nutrients, trace metals, bacteria, and trophic state. Among the findings was that concentrations of the trace metals reported in NPS (1995) were below the method detection limits in 1999.

Kallemeyn et al. (2003) of the USGS completed an in-depth aquatic synthesis of VOYA in 2003. The purpose of the synthesis was to 1) provide a complete and integrated account of what is known about the aquatic ecosystems of VOYA, 2) provide pertinent comparisons from other areas to help park managers better understand the results of research and monitoring within the park, and 3) identify needs and potential opportunities for expanding the existing knowledge base.

The GLKN VOYA water quality monitoring program began in 2006 because water quality was highly ranked as a Vital Sign across Network parks and monitoring was mandated by the NPS Water Resources Division (Elias and VanderMeulen 2008). A series of reports (Elias and VanderMeulen

2008, Elias 2009, Elias and Damstra 2011, 2012, and Damstra et al. 2014) summarized the yearly monitoring data collected by the GLKN on eight index lakes (and additional lakes in 2006, 2009, and 2010) in VOYA. Sampling was conducted three times per year from June to October, although some parameters were sampled only annually. Results were compared to those of other GLKN parks and to USEPA and MN reference criteria.

For this assessment, we will focus on data from eight interior index lake sites (Locator, Shoepack, Ek [Leif], Brown, Peary, Ryan, Cruiser, and Little Trout Lakes). The latter two lakes have populations of lake trout. Data for index lakes was downloaded from the USEPA STORET website (http://www.epa.gov/storet/) on January 8, 2014. In addition, we will examine data provided by Ryan Maki, aquatic ecologist at VOYA, for seven large lakes in and near VOYA (Namakan, Kabetogama, Crane, Little Vermilion, Sand Point, and Rainy Lakes and Black Bay of Rainy Lake) that have multiple monitoring sites on the lake (Figure 40, Table 22). These, in recent years, have had twice-monthly sampling from May–October; their period of record goes back to 1976/1977, and the data are suitable for long term trend analysis.

At each of the interior index lakes, water quality sampling is conducted at the deepest part of each index lake three times during the open water season. Samples are collected at approximately the same location on each site visit; details of sample collection are in Elias and VanderMeulen (2008).

Data from the large lake water quality monitoring sites in VOYA is an ongoing collection from multiple studies and monitoring programs; we used data for samples 2 m or less in depth from 1977–2012. Multiple sampling procedures and locations were used for each lake; we combined the data to generate an annual mean for each lake for each parameter. To minimize seasonal differences in the data and to coincide with NPS interior lakes data, our use of large lake data was limited to the May–October sampling period. We have chosen a subset of GLKN core water quality parameters (specific conductance, dissolved oxygen [DO], water clarity [Secchi depth] as well as a subset of nutrients (total phosphorus [TP] and total nitrogen [TN]), indicators of human activity (chloride) and vulnerability to acidification (alkalinity), and an indicator of trophic state (chlorophyll-*a*) for our analyses.

Our analysis at all sites involved averaging sampling data for each year and comparing these yearly means to the chosen reference conditions. A Mann-Kendall test (significance level $\alpha$=0.05) was used to examine temporal trends in all the water quality parameters for each site with enough data, using the method of Helsel and Hirsch (2002). The non-parametric Mann-Kendall test determines whether $y$ (water quality) values tend to increase or decrease with time. The test requires at least ten observations for the normal approximation to be appropriate, and only observations from July and August of each sample year were used to eliminate variations due to seasonality. Due to these restrictions, only certain parameters for the index lake sites and large lakes had enough observations to run the Mann-Kendall trend test. Because quantitation limits were not always available and were

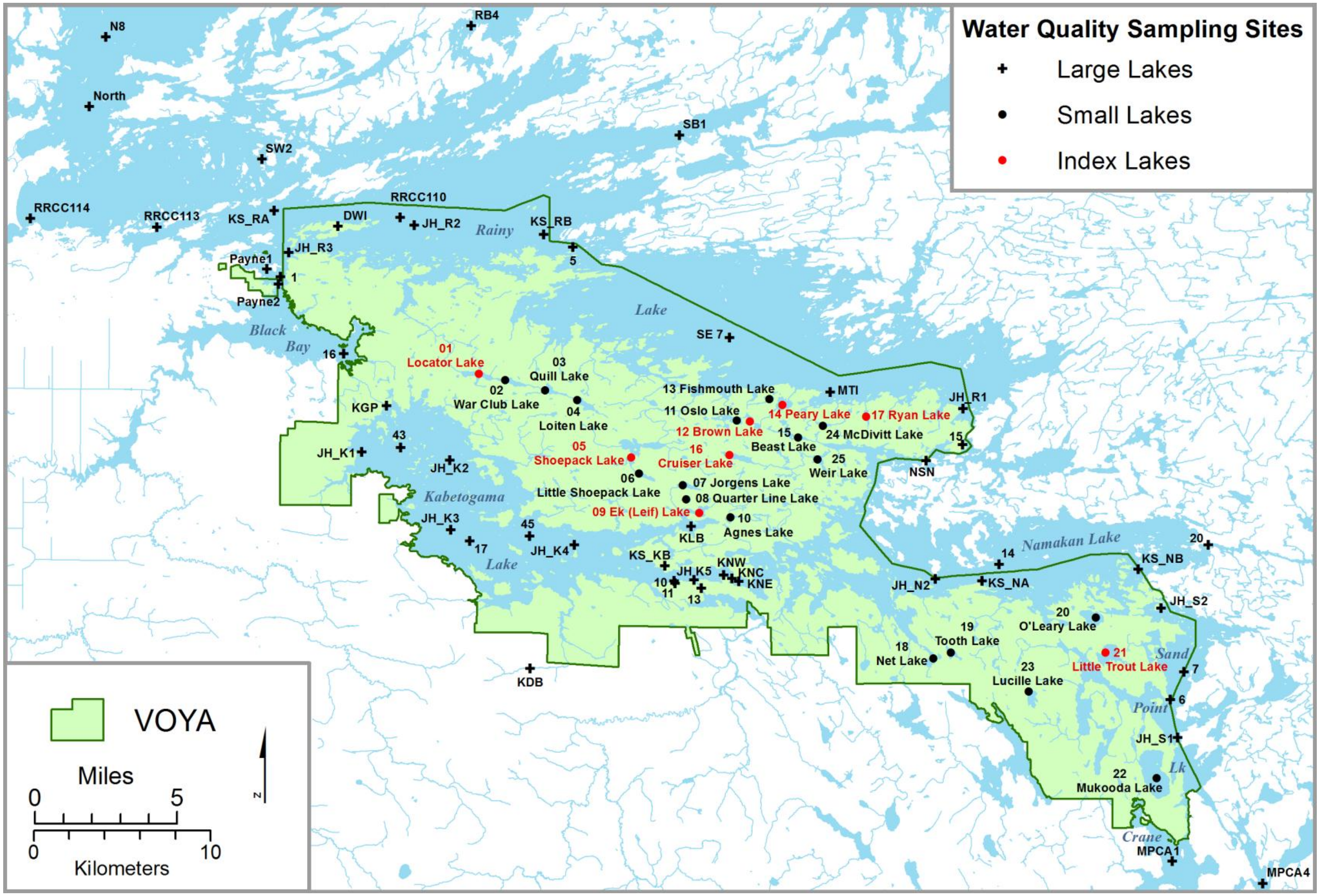

**Figure 40.** Location of water quality monitoring sites in and near Voyageurs National Park. Large lake sites with unknown latitude/longitude: Kabetogama, 18; Namakan, NJB, NMI, NMYI, NN1, NN2; Sand Point, Payne 7; Black Bay, 44; Rainy, 3, 4, EMI. KS_RB moved to 92° 57’ 15” to match mapped location in Kepner and Stottlemyer 1988.

**Table 22.** Dates of collection of field data and lab samples for large lakes in and near Voyageurs National Park.

| | | **Field Profiles** | | **Lab Samples** | |
|---|---|---|---|---|---|
| **Lake** | **Site** | ***Dates*** | ***# Observations*** | ***Dates*** | ***# Samples*** |
| Rainy | DWI | 5/96–10/04 | 100 | 7/83–7/06 | 113 |
| | EMI | 5/96–9/98 | 32 | 5/96–9/98 | 31 |
| | JH_R1 | 7/78–7/80 | 5 | 7/78–7/80 | 5 |
| | JH_R2 | 7/78–7/80 | 5 | 7/78–7/80 | 5 |
| | JH_R3 | 7/78–7/80 | 5 | 7/78–7/80 | 5 |
| | KS_RA | - | - | 5/85–10/86 | 12 |
| | KS_RB | - | - | 5/85–10/86 | 11 |
| | MTI | 5/96–9/02 | 72 | 5/96–9/02 | 69 |
| | North | 5/06–9/06 | 3 | 5/06–9/06 | 5 |
| | RB4 | 5/05–10/07 | 17 | 5/05–10/07 | 16 |
| | RRCC110 | 5/05–6/13 | 88 | 5/05–9/13 | 100 |
| | RRCC113 | - | - | 6/05 | 1 |
| | RRCC114 | - | - | 6/05 | 1 |
| | SB1 | 5/05–10/07 | 16 | 5/05–10/07 | 16 |
| | SE7 | 5/05–10/12 | 44 | 5/05–9/13 | 51 |
| | SW2 | - | - | 5/05–8/05 | 4 |
| | 3 | 8/77–8/79 | 5 | - | - |
| | 4 | 5/78–8/79 | 6 | - | - |
| | 5 | 5/78–8/83 | 13 | 5/80–8/83 | 8 |
| | 5 | 5/01–10/12 | 133 | 7/99–9/13 | 146 |
| Black Bay- Rainy | Payne 1 | 8/77–8/79 | 6 | 7/99 | 1 |
| | Payne 2 | 8/77–8/81 | 7 | - | - |
| | 1 | 5/96–6/13 | 156 | 6/96–6/11 | 168 |
| | 16 | 5/80–8/83 | 8 | 5/80–8/83 | 8 |
| | 16 | 5/01–6/03 | 27 | 5/01–6/03 | 26 |
| | 44 | 5/01–9/03 | 34 | 5/01–9/03 | 35 |
| Namakan | JH_N2 | 7/78–7/80 | 5 | 7/78–7/80 | 5 |
| | KS_NA | - | - | 5/85–10/86 | 12 |
| | KS_NB | - | - | 5/85–10/86 | 12 |
| | NJB | 5/96–10/97 | 18 | 5/96–10/97 | 22 |
| | NMI | 5/91–10/91 | 11 | - | - |
| | NMYI | 5/91–10/91 | 10 | - | - |
| | NN1 | 5/91–10/91 | 11 | - | - |
| | NN2 | 5/91–10/91 | 12 | 5/91–10/91 | 12 |
| | NSN | 5/96–10/97 | 22 | 5/96–10/97 | 22 |
| | NSN | 7/08 | 1 | - | - |
| | 14 | 5/79–5/13 | 364 | 5/91–9/13 | 359 |
| | 15 | 8/77–8/83 | 9 | 5/82–8/83 | 4 |
| | 20 | - | - | 5/82–8/82 | 2 |
| | 20 | 5/96–10/97 | 22 | 5/97–7/99 | 12 |
| Kabetogama | JH_K1 | - | - | 7/78–7/80 | 5 |
| | JH_K2 | - | - | 7/78–7/80 | 5 |
| | JH_K3 | - | - | 7/78–7/80 | 5 |
| | JH_K4 | - | - | 7/78–7/80 | 5 |
| | JH_K5 | - | - | 7/78–7/80 | 5 |
| | KDB | 8/08 | 1 | - | - |
| | KGP | 6/08–7/09 | 5 | - | - |
| | KLP | 5/09 | 1 | - | - |
| | KS_KB | - | - | 5/85–10/86 | 12 |

**Table 22 (continued).** Dates of collection of field data and lab samples for large lakes in and near Voyageurs National Park.

| | | **Field Profiles** | | **Lab Samples** | |
|---|---|---|---|---|---|
| **Lake** | **Site** | ***Dates*** | ***# Observations*** | ***Dates*** | ***# Samples*** |
| Kabetogama | 10 | 8/77–8/79 | 7 | - | - |
| (continued) | 11 | 5/78–8/83 | 12 | 5/80–8/83 | 8 |
| | 11 | 5/01–9/03 | 35 | 5/01–9/03 | 35 |
| | 11 | 6/08–8/12 | 8 | - | - |
| | 13 | 5/79–8/83 | 10 | 5/80–8/83 | 8 |
| | 13 | 6/08–7/09 | 5 | - | - |
| | 17 | 5/80–8/83 | 8 | 5/85–10/86 | 11 |
| | 17 | 5/11–8/12 | 4 | 8/99 | 1 |
| | 18 | 5/80–8/83 | 8 | 5/80–8/83 | 8 |
| | 19 | 8/80–8/81 | 2 | | |
| | 43 | 5/01–9/03 | 35 | 5/01–9/03 | 35 |
| | 43 | 6/08–7/09 | 4 | - | - |
| | 45 | - | - | 5/83–9/13 | 339 |
| Sand Point | JH_S1 | 7/78–7/80 | 5 | 7/78–7/80 | 5 |
| | JH_S2 | 7/78–7/80 | 5 | 7/78–7/80 | 5 |
| | Payne 7 | 5/78–8/83 | 12 | - | - |
| | 6 | 8/77–8/80 | 8 | - | - |
| | 7 | 5/84–6/13 | 319 | 5/84–9/13 | 318 |
| Little Vermilion | MPCA4 | 5/05–5/13 | 39 | 5/05–9/13 | 44 |
| Crane | MPCA1 | 5/05–5/13 | 40 | 5/05–9/13 | 49 |

said to be variable, we calculated annual means by setting both “non detect” and “present below quantitation limit” values to zero for total phosphorus and chlorophyll-*a* for interior index lakes.

### Reference Conditions

It is important to define some terms related to water quality conditions. USEPA establishes water quality “criteria,” scientific assessments of ecological and human health effects, under the Clean Water Act (e.g., USEPA 1976, 1986, 2006). It recommends these criteria to states and tribes so they can establish water quality “standards,” which provide a basis for them to control discharges of pollutants (USEPA 2000). “Reference conditions” as used by USEPA (2000) refer to a ranking process in which water quality data from waterbodies in an ecoregion are ordered in a database; the value representing the 25th percentile is called the “reference condition” and is considered to represent an undisturbed condition for that ecoregion. Therefore, for a parameter whose harmful effects increase with concentration, the value for that parameter would be expected to be less than the reference condition in 25% of the waterbodies and more than the reference condition in 75% of the waterbodies. Our use of the term “reference condition” may encompass a standard, criterion, or USEPA reference condition, and we specify this in the discussion of each parameter.

The state of MN has assigned seven designated use classes to surface waters of the state; those that pertain to the selected monitoring sites in VOYA are in the categories of drinking water (class 1), aquatic life and recreation (class 2), industrial uses (class 3), agricultural and wildlife uses (class 4), aesthetics and navigation (class 5), and other uses and protection of border waters (class 6) (http://www.revisor.leg.state.mn.us/arule/7050/). The classes and subclasses for each monitoring site are shown in Table 23. The state has established water quality standards for some water quality parameters based on the designated use classes and their subclasses. We use these unless a more stringent federal criterion or draft standard was found. In addition, all monitoring sites within VOYA fall within the Northern Lakes and Forests (VIII/50) USEPA nutrient ecoregion (USEPA 2000).

### Condition and Trend for Individual Parameters

#### *Specific Conductance*

Specific conductance is the measure of the capacity of water to conduct an electric current; waterbodies with higher concentrations of ions will have higher specific conductance. Its magnitude is largely controlled by watershed geology, with the size of the watershed relative to the waterbody also an important factor (Elias et al. 2008). In VOYA, waterbodies in areas covered by clay deposits from Glacial Lake Agassiz (e.g., Kabetogama Lake, Sullivan Bay, and Black Bay) have higher specific conductance, pH, and alkalinity than those with extensive granitic bedrock exposure (Kallemeyn et al. 2003). A trend of increasing specific conductance may indicate polluted runoff, which could contain excess nutrients, organic matter, pathogenic microbes, heavy metals, and organic contaminants. If waters are soft, these contaminants can be a major stressor to shoreline and nearshore plants and other aquatic organisms (Elias et al. 2008).

#### Reference Condition

There are currently no specific conductance standards associated with any of the water use designations for any of the index lakes or large lakes in or near VOYA.

#### Condition and Trend

◌ The condition of VOYA lakes for specific conductance is unranked because there is no reference condition. Interior lake monitoring sites within VOYA had annual (2006–2012) means ranging from 17–66 µmhos cm$^{-1}$ (Table 24). Large lake monitoring site annual means ranged from 28–175 µmhos cm$^{-1}$ (Table 25). Using July and August data for index lakes from 2006–2012 (Figure 41) and large lakes from 1977 or 2005 to 2013 (Figure 42), an upward trend in specific conductance was detected at Cruiser, Little Trout, Kabetogama, Namakan, Sand Point, Little Vermilion, and Rainy Lakes and at Black Bay. Based on diatom analysis, Edlund et al. (2012) suggested that specific conductance had increased slightly in Cruiser, Little Trout, Ek, and Jorgens Lakes from 2006–2010. The evidence suggests that the ionic strength, or mineral content, of these waters is increasing, but whether this is human-induced or natural, and the implications, cannot be determined without further investigation.

**Table 23.** Minnesota designated use classes that apply to selected surface water monitoring sites in and near Voyageurs National Park (MPCA 2013).

| **Minnesota Designated Use Classification** | **Definition** | **VOYA_01 Locator** | **VOYA_05 Shoepack** | **VOYA_09 Ek** | **VOYA_12 Brown** | **VOYA_14 Peary** | **VOYA_16 Cruiser** | **VOYA_17 Ryan** | **VOYA_21 Little Trout** | **Kabetogama** | **Namakan** | **Rainy** | **Sand Point** | **Crane*** | **Little Vermilion*** | **Vermilion River*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1B | Surface and ground waters with a moderately high degree of natural protection | | | | | | X | | X | X | X | X | X | | | |
| 2A | Cold water fisheries protected for drinking water | | | | | | X | | X | | | | X | X | | |
| 2B | Cool and warm water fisheries not protected for drinking water | X | X | X | X | X | | X | | | | | | | X | X |
| 2Bd | Cool and warm water fisheries protected for drinking water | | | | | | | | | X | X | X | | | | |
| 3A | Use without chemical treatment for most industrial purposes | | | | | | | | | X | X | X | X | X | | |
| 3B | General industrial purposes | X | X | X | X | X | X | X | X | | | | | | X | X |
| 3C | Industrial cooling and materials transport without high degree of treatment | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 4A | Agriculture and wildlife use – irrigation | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 4B | Agriculture and wildlife use – livestock and wildlife | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5 | Aesthetic enjoyment and navigation | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 6 | Other uses and protection of border waters | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |

*outside park boundary

**Table 24.** Minimum and maximum value for annual means and individual samples for selected water quality parameters in interior lakes at Voyageurs National Park, 2006–2012.

| Parameter and Units of Measurement | Minimum Annual Mean | Maximum Annual Mean | Standard Deviation of Annual Means | Minimum Individual Sample, Location, and Year | Maximum Individual Sample, Location, and Year** |
|---|---|---|---|---|---|
| Specific conductance<br>(µmhos cm$^{-1}$) | 17 | 66 | ± 9.5 | 8<br>VOYA_10 (Agnes)<br>2006 | 66<br>VOYA_20 (O'Leary)<br>2007 |
| pH<br>(pH units) | 6.3 | 8.7 | ± 0.5 | 3.6<br>VOYA_21 (Little Trout)<br>2012 | 8.7<br>VOYA_20 (O'Leary)<br>2007 |
| Dissolved oxygen<br>(mg L$^{-1}$) | 6.8 | 11.3 | ± 0.7 | 6.3<br>VOYA_10 (Agnes)<br>2006 | 11.3<br>VOYA_24 (McDivitt)<br>2007 |
| Alkalinity<br>(mg L$^{-1}$) | Non-Detect | 28 | * | Non-Detect<br>(various) | 28<br>VOYA_20 (O'Leary)<br>2006 |
| Chloride<br>(mg L$^{-1}$) | Present below Quantitation Limit | 1.1 | * | Present below Quantitation Limit<br>(various) | 1.1<br>VOYA_18 (Net), 2006 and VOYA_05 (Shoepack)<br>2008 & 2011 |
| Total phosphorus<br>(µg L$^{-1}$) | Non-Detect | 49.7 | * | Non-Detect<br>(various) | 190<br>VOYA_16 (Cruiser)<br>2009 |
| Inorganic nitrogen<br>(µg L$^{-1}$) | Non-Detect | 60 | * | Non-Detect<br>(various) | 102<br>VOYA_01 (Locator)<br>2006 |
| Total nitrogen<br>(µg L$^{-1}$) | 174 | 855 | ± 153 | 153<br>VOYA_16 (Cruiser)<br>2008 | 1,100<br>VOYA_05 (Shoepack)<br>2012 |
| Chlorophyll-*a*<br>(µg L$^{-1}$) | Non-Detect | 10.3 | * | Non-Detect<br>(various) | 17<br>VOYA_18 (Net)<br>2006 |
| Secchi Depth<br>(m) | 0.7 | 9.2 | ± 1.9 | 0.7<br>VOYA_10 (Agnes)<br>2010 | 9.45<br>VOYA_16 (Cruiser)<br>2011 |

*not calculated because of the number of samples that were labeled "no detect" or "present below quantitation limit"

**excluding outliers

**Table 25.** Minimum and maximum value for annual means and individual samples for selected water quality parameters in large lakes in and near Voyageurs National Park, 1977-2013.

| Parameter and Units of Measurement | Minimum Annual Mean | Maximum Annual Mean | Standard Deviation of Annual Means | Minimum Individual Sample, Location, and Year* | Maximum Individual Sample, Location, and Year* |
|---|---|---|---|---|---|
| Specific conductance<br>(µmhos cm$^{-1}$) | 28 | 175 | ± 27 | 25<br>Little Vermilion, 2008-2009; Rainy 2010 | 110<br>various |
| pH<br>(pH units) | 6.38 | 8.38 | ± 0.38 | 6.00<br>Little Vermilion 2005, 2008; Rainy 2003 | 9.00<br>Kabetogama, 1984, 2001 |
| Dissolved oxygen<br>(mg L$^{-1}$) | 7.88 | 16.28 | ± 0.92 | 2.65<br>Rainy, 2012 | 13.71<br>Kabetogama, 2011 |
| Alkalinity<br>(mg L$^{-1}$) | 7.65 | 42.5 | ± 9.45 | 5.50<br>Little Vermilion, 2008 | 70.50<br>Kabetogama, 2002 |
| Total phosphorus<br>(µg L$^{-1}$) | 1.0 | 66 | ± 11.5 | 1.0<br>Namakan, 1983 | 89.0<br>Black Bay, 2003 |
| Chlorophyll-*a*<br>(µg L$^{-1}$) | 1.1 | 21.5 | ± 4.0 | 0.08<br>Kabetogama, 2003 | 69.2<br>Kabetogama, 1981 |
| Secchi Depth<br>(m) | 1.52 | 3.74 | ± 0.43 | 0.4<br>Rainy, 2010 | 4.0<br>various |

*excluding outliers

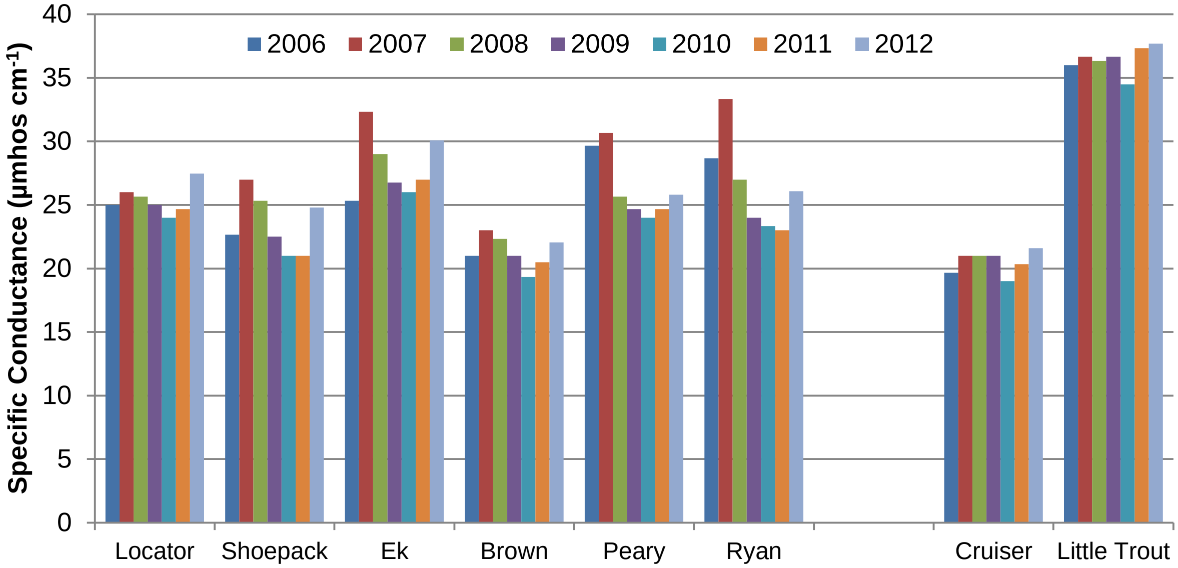

**Figure 41.** Annual mean specific conductance values for interior index lake water quality monitoring sites at Voyageurs National Park, 2006–2012.

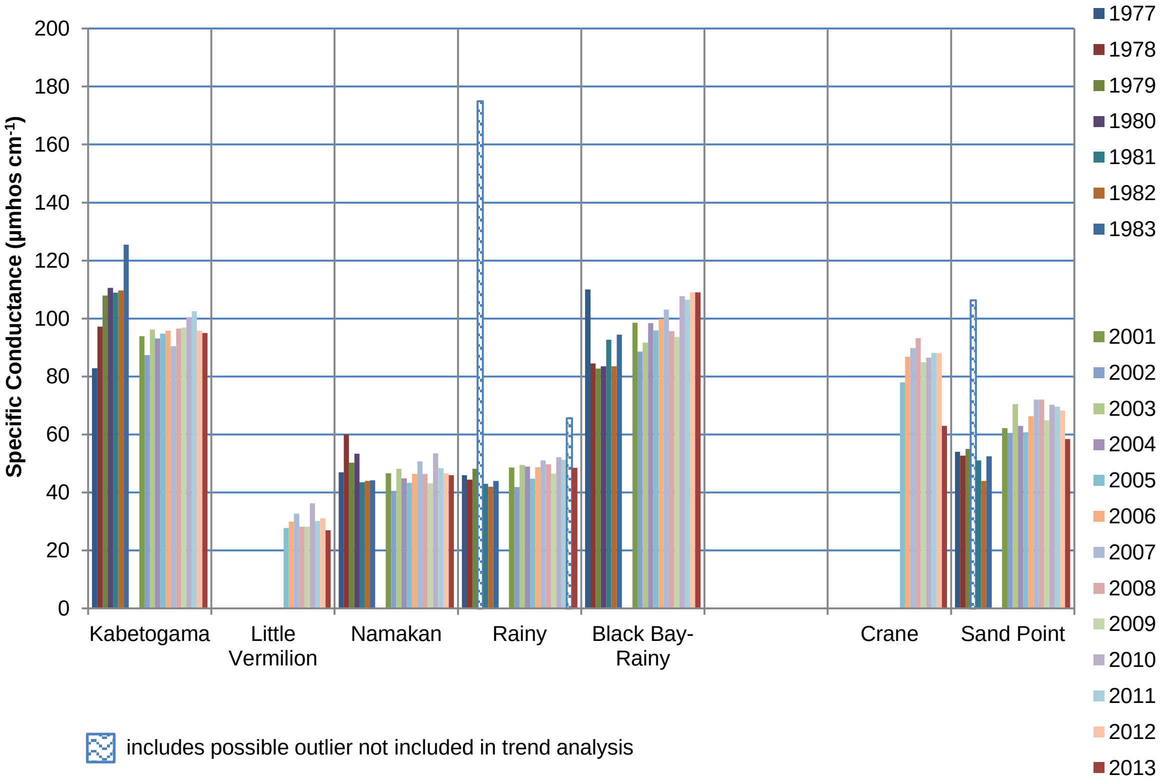

**Figure 42.** Annual mean specific conductance values for large lake water quality monitoring sites in and near Voyageurs National Park, 1977–2013 (data gap between 1983 and 2001 not to scale).

### *pH*

The pH value is the negative logarithm of the hydrogen ion (H+) activity in the water, a measure of acidity. It is important as a determinant of the solubility and biological availability of nutrients essential for growth as well as potentially toxic heavy metals (Elias et al. 2008). Aquatic macroinvertebrates and some salmonids can be adversely affected at certain stages of their life cycles when pH is above 9.0 or below 6.5 (Elias et al. 2008). Lakes at the low end of the pH scale in VOYA are likely naturally acidic, and these lakes can have distinctly different aquatic communities than lakes with a more neutral pH (Elias and Damstra 2011).

#### Reference Condition

The MN water quality standard (MnRule 7050.0220) of an optimal pH range of 6.5–8.5 pH units applies to designated use classification 2A (MnRule 7050.0200) (MPCA 2013). This is our chosen reference condition for Cruiser, Little Trout, Sand Point, and Crane Lakes. Similarly, an optimal pH range of 6.5–9 pH units applies to classes 2B and 2Bd and is the chosen reference condition for Locator, Shoepack, Ek, Brown, Peary, Ryan, Kabetogama, Namakan, Rainy, and Little Vermilion Lakes. These represent a "least disturbed condition" or "the best of today's existing conditions" (Stoddard et al. 2006).

#### Condition and Trend

We rate the condition of the interior index lakes in VOYA for pH as good, with a stable trend. Our confidence in this assessment is high. The annual means (2006–2012) for pH ranged from 6.3–8.7 (Table 24) and were within the range of the reference condition for all interior index lakes except for Shoepack Lake, which periodically fell below the desirable range, and Little Trout, which fell below the range in 2012 (Figure 43). Using July and August data from 2006–2012, only Ek Lake exhibited a trend; a statistically significant decrease in pH was observed. This analysis does not agree with the qualitative observation of Damstra et al. (2014) about Ek Lake.

We rate the condition of the large lakes in VOYA for pH as good, but with no clear trend. Our confidence in this assessment is high. The annual means for pH (1977–2012) ranged from 6.38–8.38, excluding outliers (Table 25). Only Sand Point Lake in 1978 had an annual mean (samples at two locations collected on the same date) outside the range of the reference condition (Figure 44). However, this is likely an outlier (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14). Using July and August data, an upward trend or statistically significant increase in pH was observed in Little Vermilion Lake from 2005–2012 and a downward trend was observed at Black Bay, 1977 and 2001–2012. No trend was observed at the remaining large lakes (Kabetogama, Namakan, and Sand Point 1977–2012; Rainy, 1977–1980 and 2001–2012; and Crane, 2005–2012).

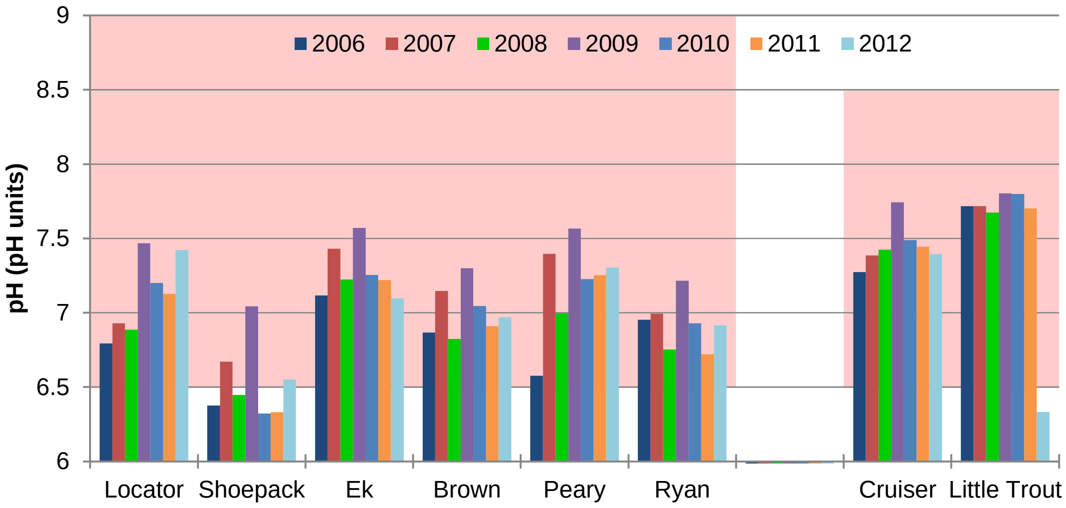

**Figure 43.** Annual mean pH values for interior index lake water quality monitoring sites in Voyageurs National Park, 2006–2012 (reference condition 6.5–9.0 and 6.5–8.5).

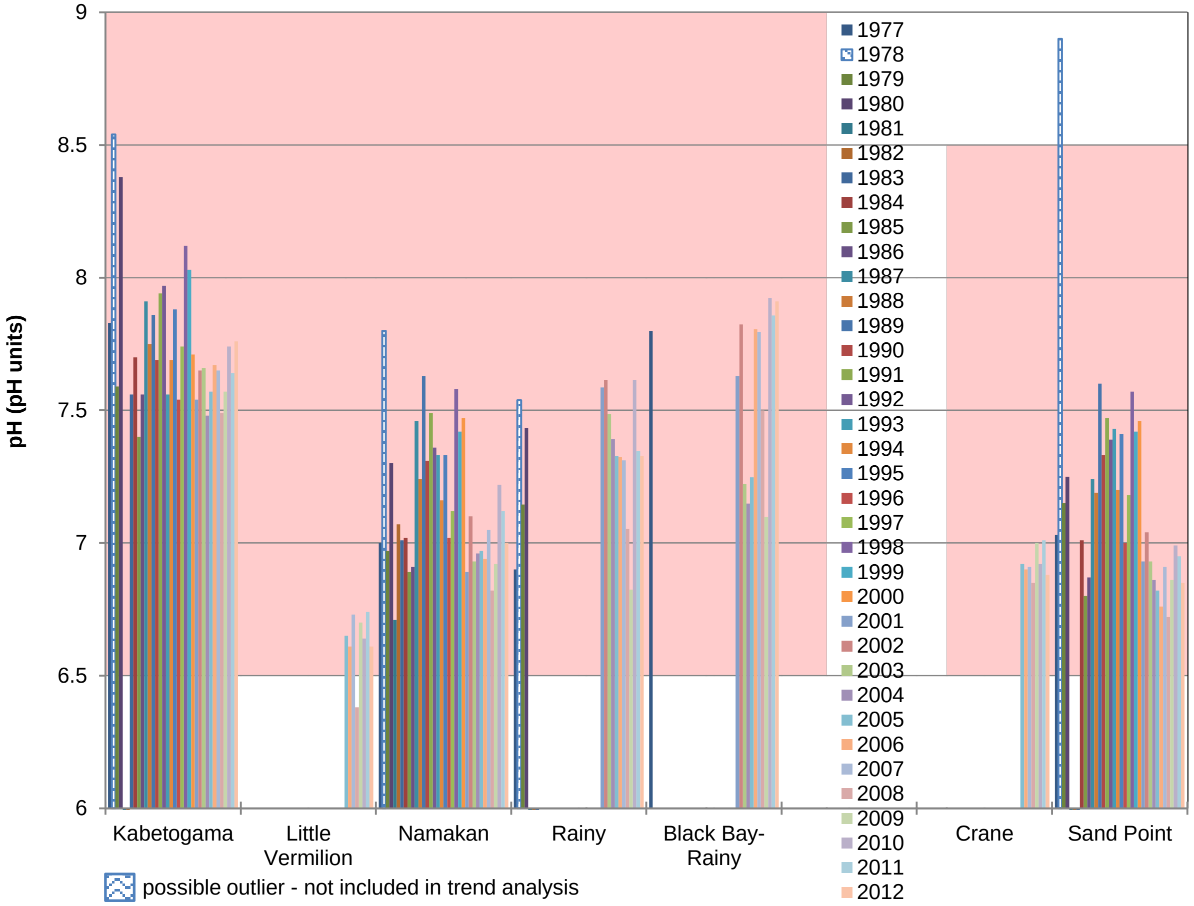

**Figure 44.** Annual mean pH values for large lake water quality monitoring sites in and near Voyageurs National Park, 1977–2012 (reference condition 6.5–9.0 and 6.5–8.5).

### *Alkalinity*

Alkalinity is a measure of the ability of a waterbody to buffer, or resist, a change in pH. A lake's alkalinity is affected by the type of minerals (primarily calcium and magnesium carbonate and bicarbonate) in the soil and watershed bedrock and by how much the lake water comes into contact with these minerals.

#### Reference Condition

Our chosen reference condition for both the interior index lakes and the large lakes is the USEPA minimum criterion of 20 mg $L^{-1}$ as calcium carbonate ($CaCO_3$) for the protection of aquatic life "except where natural conditions are less" (USEPA 1986). This represents a "least disturbed condition" or "the best of today's existing conditions" (Stoddard et al. 2006).

It should be noted that in its sampling of the inland lakes at VOYA, the GLKN (Elias et al. 2008) uses the term "alkalinity" to refer to results from unfiltered samples. The USEPA also uses this terminology. However, the USGS restricts the term "alkalinity" to filtered samples and uses the term "acid neutralizing capacity" for unfiltered samples. Some of the samples in the large lakes database may be filtered, but the majority are not (review comments, Ryan Maki, aquatic ecologist, VOYA, 12/10/14). Thus, we are using the term "alkalinity" to refer to unfiltered samples and a small (uncertain) number of filtered samples.

#### Condition and Trend

🔴 We rate the condition of the interior index lakes for alkalinity as of significant concern. Data were insufficient to calculate trends. Our confidence in this assessment is high. Of 22 interior lakes sampled, all but O'Leary and Mukooda Lakes had values for alkalinity below the 20 mg $L^{-1}$ minimum from 2006–2012, with ranges of non-detectable to 17 mg $L^{-1}$, indicating poorly-buffered waters. (Since lakes were sampled only once a year for alkalinity in recent years, the concept of annual mean is not useful here). Although this condition is naturally occurring, it is of significant concern because it highlights the susceptibility of these lakes to acid precipitation.

🟡 We rate the condition of the large lakes for alkalinity as of moderate concern, with a mixed trend. Our confidence in this assessment is high. The large lake monitoring site annual means ranged from 7.65–42.5 mg $L^{-1}$ (Table 25). Only Kabetogama and Crane Lakes and Black Bay had annual means that consistently exceeded the 20 mg $L^{-1}$ minimum (Figure 45). Using July and August data from 1978–2012, upward trends in alkalinity were observed in Kabetogama and Sand Point Lakes and a downward trend was observed in Rainy Lake. The other large lakes did not exhibit trends.

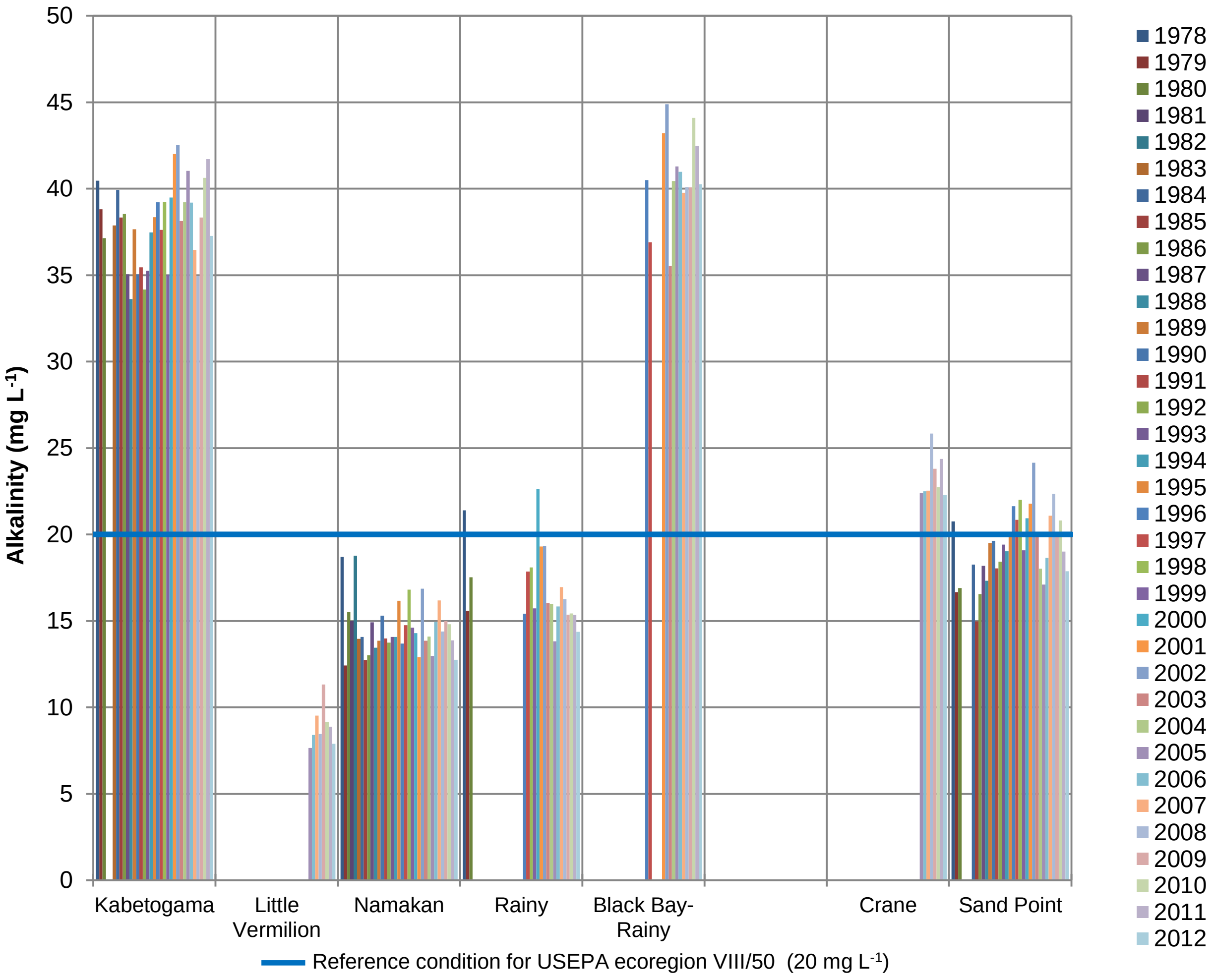

**Figure 45.** Annual mean alkalinity values for large lake water quality monitoring sites in and near Voyageurs National Park, 1978–2012 (reference condition 20 mg $L^{-1}$).

*Chloride*

Chloride is often used as a tracer of wastewater plumes and an indicator of road salt runoff into surface waters. Chloride can come from a mixture of natural sources such as the weathering of rocks and soils and human inputs such as fertilizers and runoff from urban and industrial areas (Elias et al. 2008).

Reference Condition

Our chosen reference condition for chloride is the MN water quality standard of 230 mg $L^{-1}$ for chronic exposure for aquatic life in all class 2A, 2B, and 2Bd waters (MPCA 2013). This represents a “least disturbed condition” or “the best of today’s existing conditions” (Stoddard et al. 2006).

Condition and Trend

We rate the condition of the interior index lakes for chloride as good. Data were insufficient to calculate trends. Our confidence in this assessment is high. All interior lake sites had annual means far below the standard of 230 mg $L^{-1}$ from 2006–2012, with ranges of “present below quantitation limit” to 1.1 mg $L^{-1}$ (Table 24).

Chloride data were not available for the large lakes in VOYA. Such data might be valuable as an early indicator of contamination from wastewater discharges.

### *Dissolved Oxygen*

Dissolved oxygen (DO) is a measure of the amount of oxygen in solution in water. The atmosphere is the largest source of DO, although phytoplankton and macrophytes produce DO during photosynthesis. Respiration by animals, plants, and microbes consumes DO (Elias et al. 2008). The MPCA water quality standard for DO is based on the maintenance of a healthy community of fish and associated aquatic life (MPCA 2013).

#### Reference Condition

Our chosen reference condition is the MN water quality standard for DO of 5 mg $L^{-1}$ for designated use classes 2B and 2Bd and 7 mg $L^{-1}$ for designated use class 2A (MPCA 2013). This represents a “least disturbed condition” or “the best of today’s existing conditions” (Stoddard et al. 2006).

#### Condition and Trend

We rate the condition of the interior index lakes in VOYA for DO as good, with a stable trend. Our confidence in this assessment is high. All interior lake sites had annual (2006–2012) DO means ranging from 6.8–11.3 mg $L^{-1}$ (Table 24), exceeding the respective minimum standards of 5 mg $L^{-1}$ and 7 mg $L^{-1}$ (MPCA 2013) (Figure 46). Using July and August data from 2006–2012, no trend in DO levels were observed at any of the interior index lake sites.

We rate the condition of the large lakes in VOYA for DO as good, with an improving trend. Our confidence in this assessment is high. All large lake sites had annual (1977–2012) DO means ranging from 7.9–16.3 mg $L^{-1}$ (Table 25), exceeding the respective minimum standard of 5 mg $L^{-1}$ and 7 mg $L^{-1}$ (MPCA 2013) (Figure 47). Using July and August data from 1977–2012, an upward trend in DO levels was observed in Kabetogama, Namakan, Rainy, and Sand Point Lakes. No trend was observed at Crane and Little Vermilion Lakes or at Black Bay.

### *Nutrients—Total Nitrogen (TN) and Total Phosphorus (TP)*

Nitrogen and phosphorus are the two most important nutrients regulating phytoplankton and aquatic macrophyte growth in lakes and streams. Excessive nutrient inputs can lead to excessive algal growth and eutrophication and are the most important threat to lakes in the upper Midwest (Elias et al. 2008 and citations therein). Nutrients enter bodies of water primarily through surface and subsurface runoff and groundwater, although concern has been expressed about atmospheric deposition of nitrogen (NPS 2013).

Most of the interior index lakes in VOYA do not receive direct anthropogenic inputs (i.e., fertilizer runoff, failing septic systems, or sewage effluent) because of their remote locations within the park. The major sources of phosphorus and nitrogen in these lakes is most likely re-suspension of lake sediment during mixing (Elias and Damstra 2011).

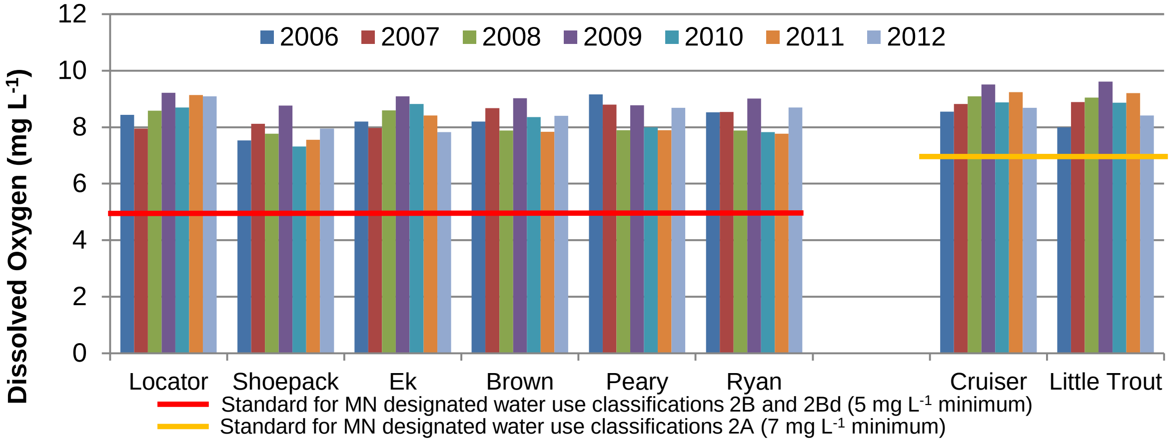

**Figure 46.** Annual mean dissolved oxygen values for interior index lake water quality monitoring sites in Voyageurs National Park, 2006–2012 (reference condition 5.0 and 7.0 mg $L^{-1}$).

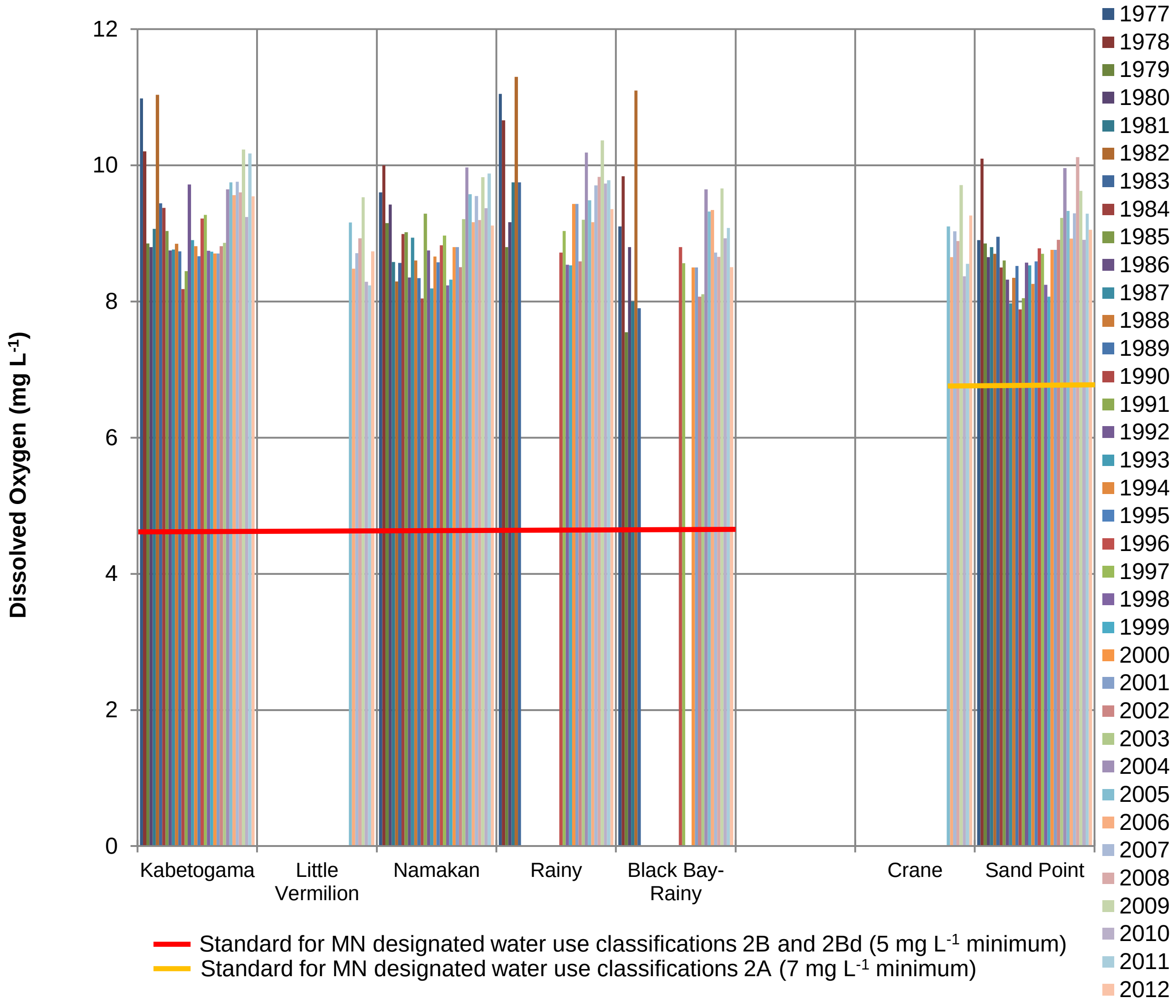

**Figure 47.** Annual mean dissolved oxygen values for large lake water quality monitoring sites in and near Voyageurs National Park, 1977–2012 (reference condition 5.0 and 7.0 mg $L^{-1}$).

The large lakes within VOYA are affected by the origin of their inflow. Kabetogama Lake and Black Bay of Rainy Lake receive inflow from richer geological substrates, which results in higher nutrient concentrations (Kallemeyn et al. 2003).

*Total Nitrogen (TN)*

Reference Condition

The chosen reference condition for TN for the interior index lake sites in VOYA is the USEPA reference condition for nutrient ecoregion VIII/50 (400 µg L$^{-1}$) (USEPA 2000). This represents a "minimally disturbed condition" or "the condition of systems in the absence of significant human disturbance" (Stoddard et al. 2006).

Condition and Trend

We rate the condition of interior index lakes in VOYA for TN as good, with a stable trend. Our confidence in this assessment is high. For all interior lake sites, annual TN means ranged from 174–855 µg L$^{-1}$ from 2006–2012 (Table 24). Individual TN values ranged from 153 µg L$^{-1}$ in Cruiser Lake in 2008 to 1,100 µg L$^{-1}$ in Shoepack Lake in 2012 (Table 24). Annual mean TN exceeded the USEPA reference condition at all the interior index lakes except Cruiser and Little Trout Lakes (Figure 48), indicating that the water quality for TN is not within the best 25% of sites in the nutrient ecoregion. However, no water quality criterion has been established for TN in lakes in MN. Using July and August data from 2006–2012, no trend was observed at any index lake site. No TN data are available for the large lakes.

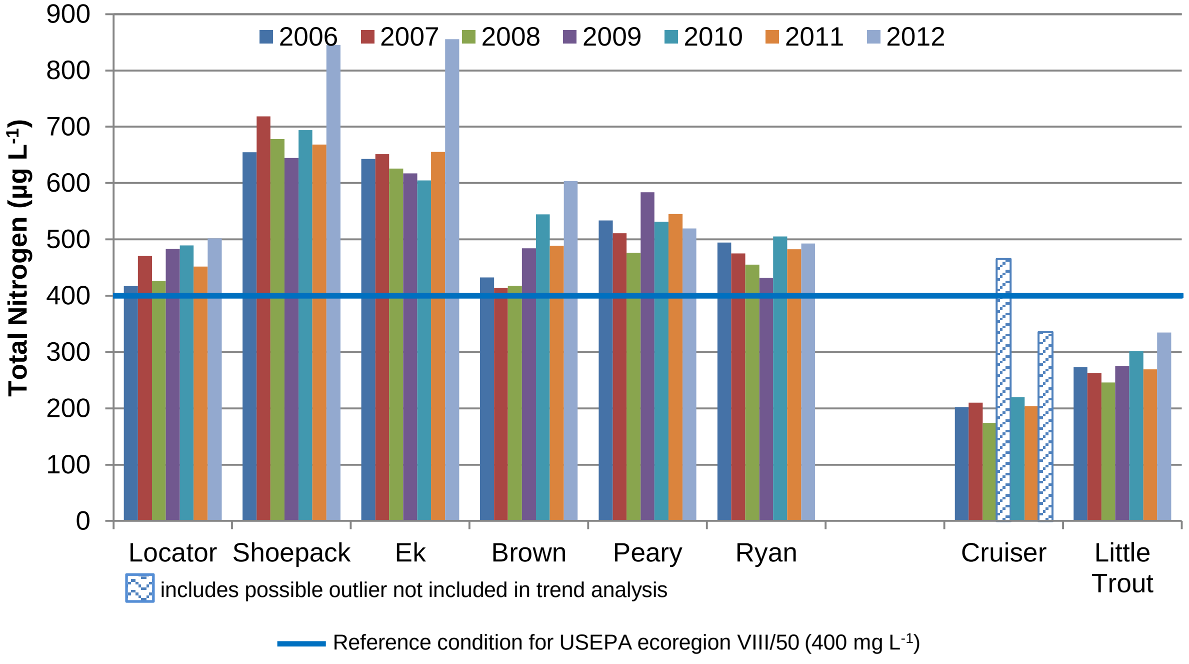

**Figure 48.** Annual mean total nitrogen values for interior index lake water quality monitoring sites in Voyageurs National Park, 2006–2012 (reference condition 400 µg L$^{-1}$).

Calculation of ratios of TN:TP (generally >15) indicate that the growth of phytoplankton in VOYA interior index lakes is limited by phosphorus, not nitrogen, levels (Shaw et al. 2004), although other researchers (e.g., Sterner 2008) have stated that this simple ratio ignores the importance of micronutrients and other factors important to phytoplankton growth.

### *Total Phosphorus (TP)*

#### Reference Condition

Our chosen reference condition is the MN water quality standard for total phosphorus of 30 µg L$^{-1}$ for designated use classes 2B and 2Bd and 12 µg L$^{-1}$ for designated use class 2A (MPCA 2013). These represent a “least disturbed condition” (Stoddard et al. 2006). TP values were also compared to the reference condition for USEPA nutrient ecoregion VIII/50 (USEPA 2000), which represents a “minimally disturbed condition” (Stoddard et al. 2006).

#### Condition and Trend

We rate the condition of the interior index lakes in VOYA for TP as good, with a stable trend. Our confidence in this assessment is high. For all interior lake sites, annual TP means ranged from non-detect to 49.7 µg L$^{-1}$ from 2006–2012 (Table 24). All the interior index lakes except Cruiser had annual TP means consistently below the water quality standard for their designated water use class from 2006–2012 (Figure 49). Individual samples of 190.04 µg L$^{-1}$ in 2006 and 57.51 µg L$^{-1}$ in 2012 helped raise the annual means for Cruiser Lake. All except Little Trout exceeded the USEPA reference condition for the ecoregion. Using July and August data from 2006–2012, no trend in TP concentrations was observed at any of the interior index lake sites.

Diatom analyses performed on sediment cores from three VOYA index lakes (Ek, Peary, and Cruiser) (Edlund et al. 2011) indicate that modern TP levels in these lakes are not significantly different from those pre-European settlement. Thus, the lakes may not have met the USEPA reference condition even at that time (Damstra et al. 2014). Diatom inference models developed for VOYA lakes suggest slight increases in TP from 2006–2010 (Edlund et al. 2012).

We rate the condition of the large lakes in VOYA for TP as of moderate concern, with a stable trend. Our confidence in this assessment is high. All the large lakes have exceeded both the water quality standard for their designated water use class and the USEPA reference condition (Figure 50), with annual (1983–2012) TP means ranging from 1–66 µg L$^{-1}$ (Table 25). In recent years, Kabetogama, Namakan, and Rainy Lakes seem to be meeting the water quality standard of 30 µg L$^{-1}$. However, using July and August data from 1983–2012, no trend in TP concentrations was observed at any of the large lake sites, except for an upward trend at Sand Point Lake from 2005–2013. Payne (2000) noted significant decreases in TP concentrations in Kabetogama Lake and Black Bay between 1977–1983 and 1999. Kallemeyn et al. (2003) observed a decrease in TP in Kabetogama Lake after 1990 and attributed it to water level fluctuations. Christensen and Maki (2014) did not find a significant change in TP in Sand Point, Namakan, Kabetogama, or Rainy Lakes or Black Bay between 1977–1999 and 2000–2011.

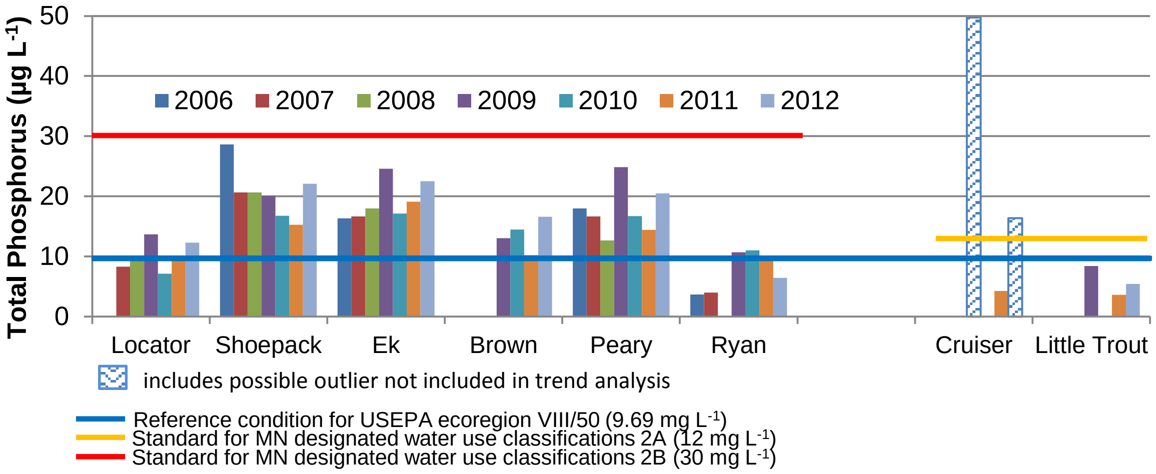

**Figure 49.** Annual mean total phosphorus values for interior index lake water quality monitoring sites in Voyageurs National Park, 2006–2012 (reference condition 9.69, 12, and 30 µg $L^{-1}$; missing bars indicate means below quantitation limit).

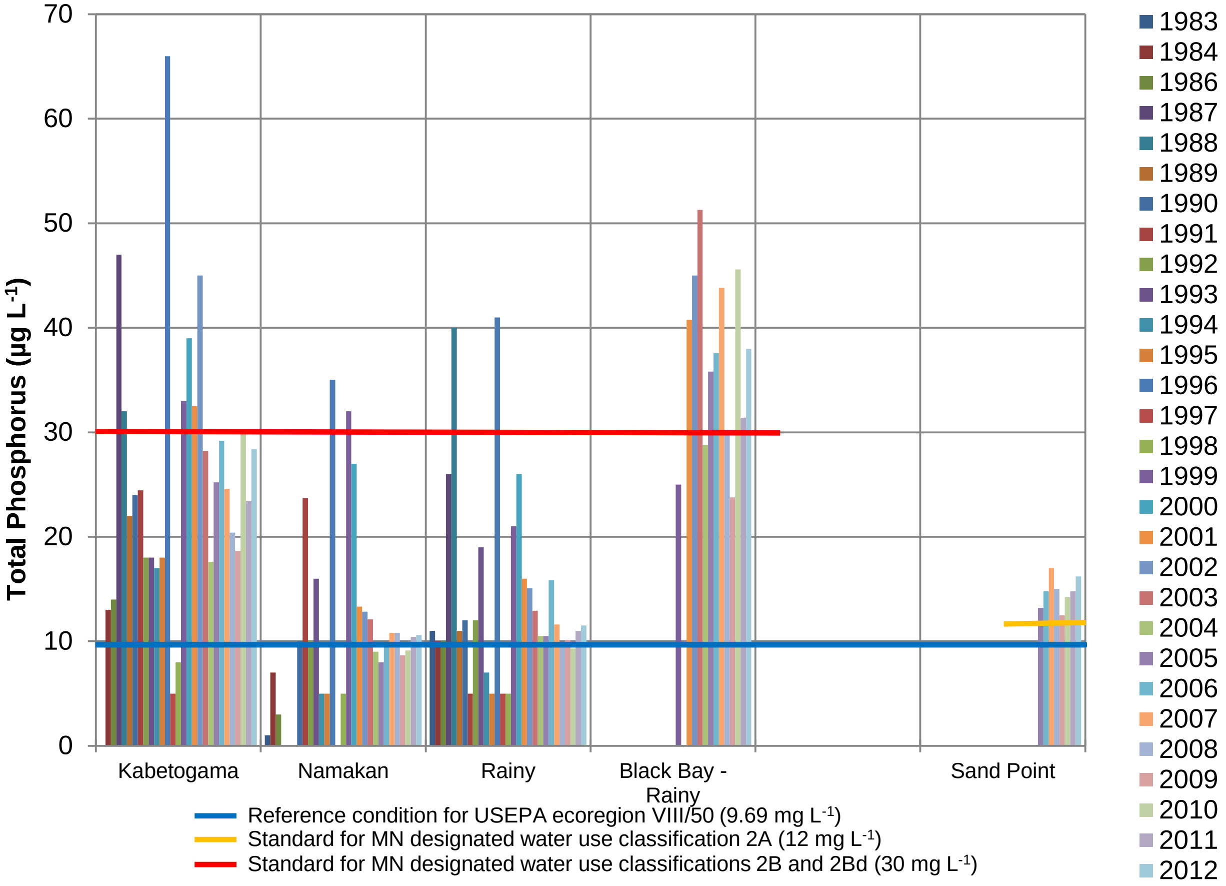

**Figure 50.** Annual mean total phosphorus values for large lake water quality monitoring sites in and near Voyageurs National Park, 1983–2012 (reference condition 9.69, 12, and 30 µg $L^{-1}$).

*Water Clarity*

While water clarity is not a mandated parameter for monitoring, it is included in the GLKN core suite because of its ease to monitor and its importance to whole lake ecology. Water clarity, which is a substitute for light penetration in a lake, is an important determining factor in the rate of primary production and the aquatic plant community composition. Water clarity has also has a long history of being used as an indicator of trends in phytoplankton biomass (Elias et al. 2008). It has been shown that there is a negative relationship between light penetration in a lake and chlorophyll-*a* concentrations in VOYA. However, in both the large lakes and interior lakes, light penetration is limited not by chlorophyll-*a* concentrations or algal productivity but rather by naturally occurring stain or color associated with organic materials (Kallemeyn et al. 2003).

<u>Reference Condition</u>

Our chosen reference conditions are the MN water quality standard for water clarity of 2 m for designated use classes 2B and 2Bd and 4.8 m for designated use class 2A (MPCA 2013). These represent “least disturbed conditions” or “the best of today’s existing conditions” (Stoddard et al. 2006). Water clarity values were also compared to the reference condition for USEPA nutrient ecoregion VIII/50 (4.2 m) (USEPA 2000), which represents a “minimally disturbed condition” or “the condition of systems in the absence of significant human disturbance” (Stoddard et al. 2006).

<u>Condition and Trend</u>

↔ We rate the condition of the interior index lakes for water clarity as good, with a stable trend. Our confidence in this assessment is high. Annual Secchi depth means ranged from 0.7–9.2 m from 2006–2012 (Table 24). Locator, Brown, Peary, Ryan, Cruiser, and Little Trout Lakes all had annual mean Secchi depths that exceeded the MN minimum standards for their designated water use classes (Figure 51). However, Shoepack and Ek Lakes did not consistently meet the MN minimum standard, and only Cruiser and Little Trout Lakes met the USEPA reference condition. Payne (1991) reported that Ek Lake is highly colored, which likely accounts for its lower Secchi depth readings. Using July and August data from 2006–2012, an upward trend in water clarity was observed in Ek Lake and a downward trend was observed in Peary Lake; trends were not observed in the other interior index lakes.

↔ We also rate the condition of the large lakes for water clarity as good, with a stable trend. Our confidence in this assessment is high. Annual Secchi depth means ranged from 1.52–3.74 m from 1981–2012 (Table 25). Kabetogama, Namakan, and Rainy Lakes had annual mean Secchi depths that exceeded the MN minimum standard for their designated water use class, but Little Vermilion Lake did only occasionally, and Black Bay did not. Crane and Sand Point Lakes, with a higher MN minimum standard, also did not (Figure 52). None of the large lakes met the USEPA reference condition. Payne (1991) reported that Secchi depth in Sand Point, Namakan, and Rainy Lakes was limited by color caused by the presence of natural organic materials from bogs, fens, and peatlands. Kallemeyn et al. (2003) reported that light penetration, which is related to water clarity, in Kabetogama Lake was reduced by “significant” mid to late summer algal blooms. Using July and August data from 1981–2012, an upward trend in water clarity was observed in Kabetogama and Rainy Lakes; the other large lakes and Black Bay did not exhibit trends. Christensen and Maki

(2014) did not find a significant change in water clarity in Sand Point, Namakan, Kabetogama, or Rainy Lakes or Black Bay between 1977–1999 and 2000–2011.

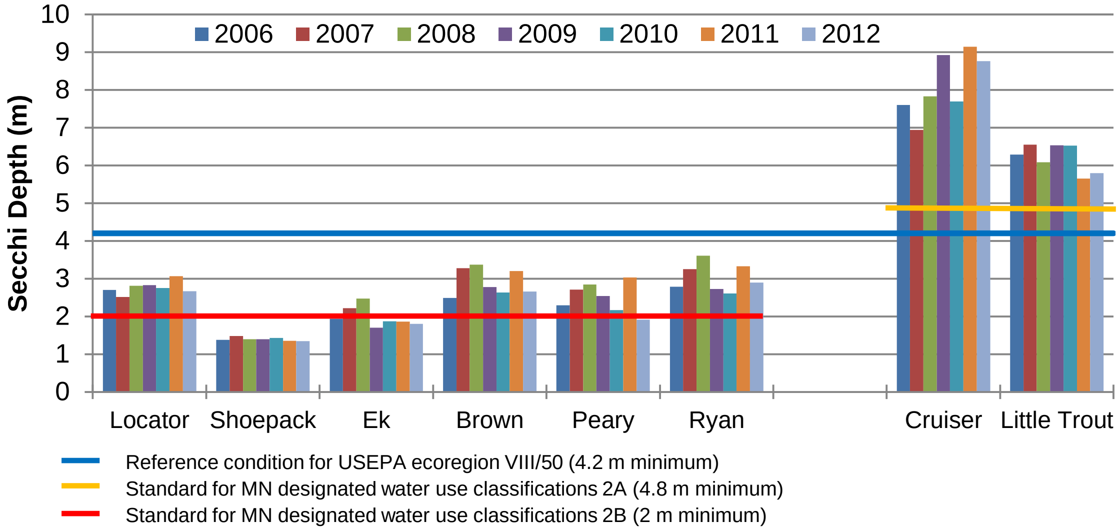

**Figure 51.** Annual mean Secchi depth values for interior index lake water quality monitoring sites in Voyageurs National Park, 2006–2012 (reference condition 2, 4.2, and 4.8 m).

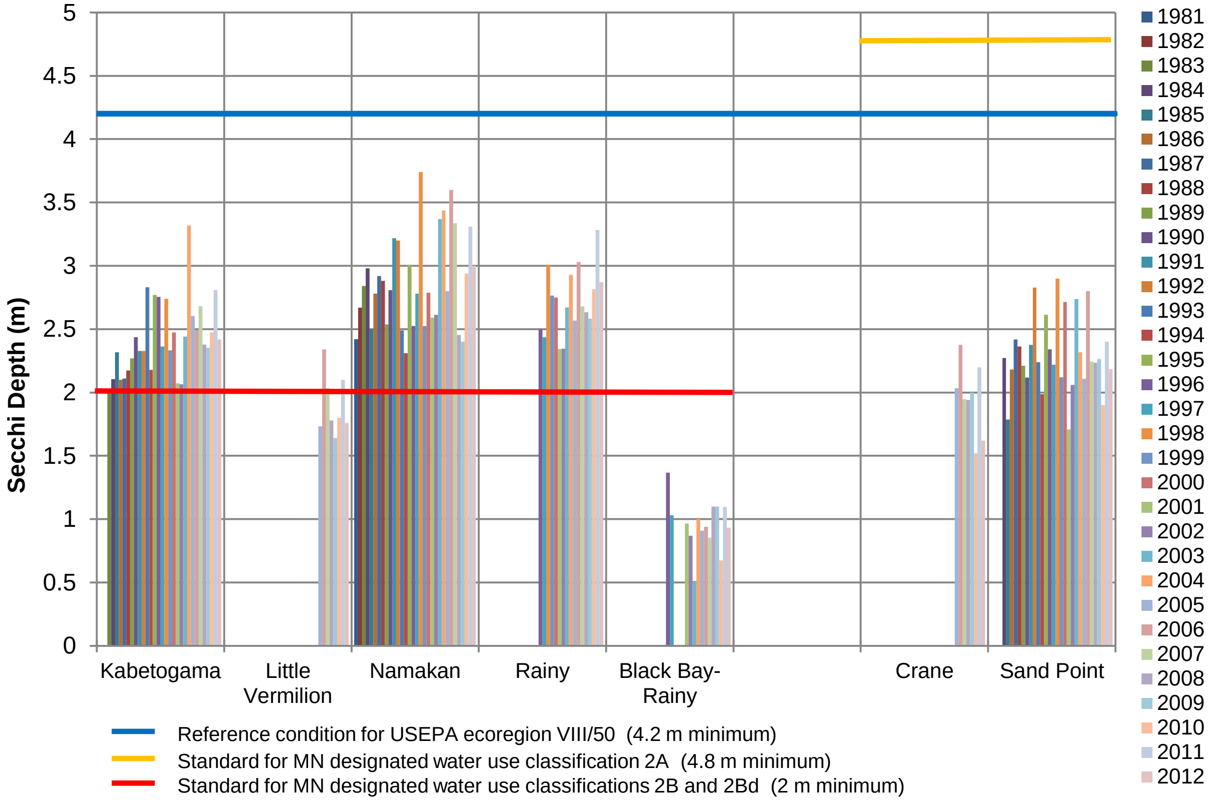

**Figure 52**. Annual mean Secchi depth values for large lake water quality monitoring sites in and near Voyageurs National Park, 1981–2012 (reference condition 2, 4.2, and 4.8 m).

### *Chlorophyll-a (Chl-a)*

Chl-*a* is the primary photosynthetic pigment in all green plants, including phytoplankton, and is nearly universally accepted as a measure of algal biomass in the open waters of lakes (Elias et al. 2008 and citations therein). However, some inaccuracy arises because different algal groups have different proportions of chl-*a* versus other pigments, and the mix of species may affect management decisions for lakes (Elias et al. 2008). Consistent and directional trends in chl-*a* concentrations are good indicators of change in a lake's trophic status (Elias et al. 2008 and citations therein).

#### Reference Condition

Our chosen reference condition is the MN water quality standard for chl-*a* of 9 µg L$^{-1}$ for designated use classes 2B and 2Bd and 3 µg L$^{-1}$ for designated use class 2A (MPCA 2013). These represent a "least disturbed condition" (Stoddard et al. 2006). Chl-*a* values were also compared to the reference condition for USEPA nutrient ecoregion VIII/50 (1.38 µg L$^{-1}$) (USEPA 2000), which represents a "minimally disturbed condition" (Stoddard et al. 2006).

#### Condition and Trend

⇔ We rate the condition of the interior index lakes in VOYA for chl-*a* as good, with a stable trend. Our confidence in this assessment is good. Annual mean chl-*a* values ranged from non-detected to 10.3 µg L$^{-1}$ from 2006–2012 (Table 24). Only Ek Lake in 2008 exceeded its chl-*a* water quality standard for its designated use (Figure 53). All sites, except Little Trout Lake, exceeded the USEPA reference condition. However, this standard is extremely stringent, and there is concern that the data used to develop the criteria was insufficient (only two lakes were used) and could bias the criterion (Elias and Damstra 2012). Using July and August data from 2006–2012, no trends in chl-*a* concentrations were observed except for a statistically significant downward trend in Cruiser Lake.

⇧ We rate the condition of the large lakes in VOYA for chl-*a* as of moderate concern, with an improving trend. Our confidence in this assessment is high. Annual mean chl-*a* concentrations ranged from 1.1–21.5 µg L$^{-1}$ from 1978–2012 (Table 25). Only Namakan, Rainy, and Little Vermilion Lakes had annual means consistently below the water quality standard for their designated use class. Crane and Sand Point Lakes had similar chl-*a* values to Namakan, Rainy, and Little Vermilion, but have a more stringent standard applied to them. Kabetogama Lake and Black Bay regularly exceeded the standard in the earlier period of record (Figure 54). Using July and August data from 1978–2012, downward trends in chl-*a* concentrations were observed in Kabetogama, Rainy, and Sand Point Lakes; however, no trend was observed in Rainy Lake when the 1978 data point was removed as a possible outlier. No trends were observed in Little Vermilion, Namakan, or Crane Lakes or in Black Bay. Payne (2000) reported a decrease of 10%–13% in chl-*a* levels in Kabetogama Lake from 1977–1983 to 1999, and Kallemeyn et al. (2003) reported a similar decrease after 1990. Christensen and Maki (2014) reported a decrease in chl-*a* in Kabetogama Lake and Black Bay, but not in Namakan or Rainy Lakes, after 2000.

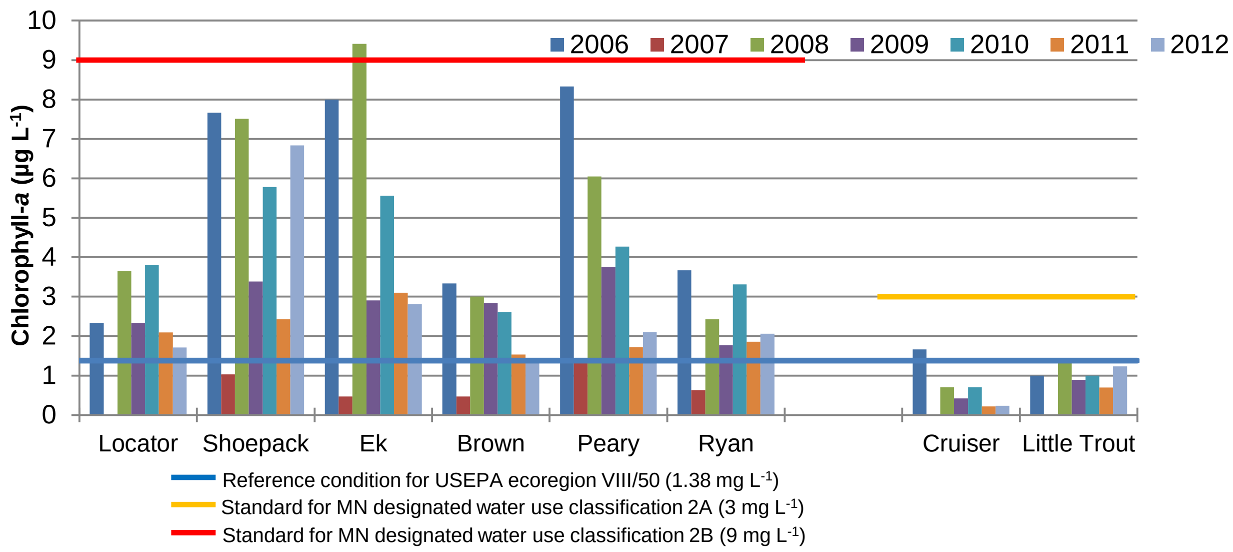

**Figure 53**. Annual mean chlorophyll-*a* values for interior index lake water quality monitoring sites in Voyageurs National Park, 2006–2012 (missing bars indicate means below quantitation limit).

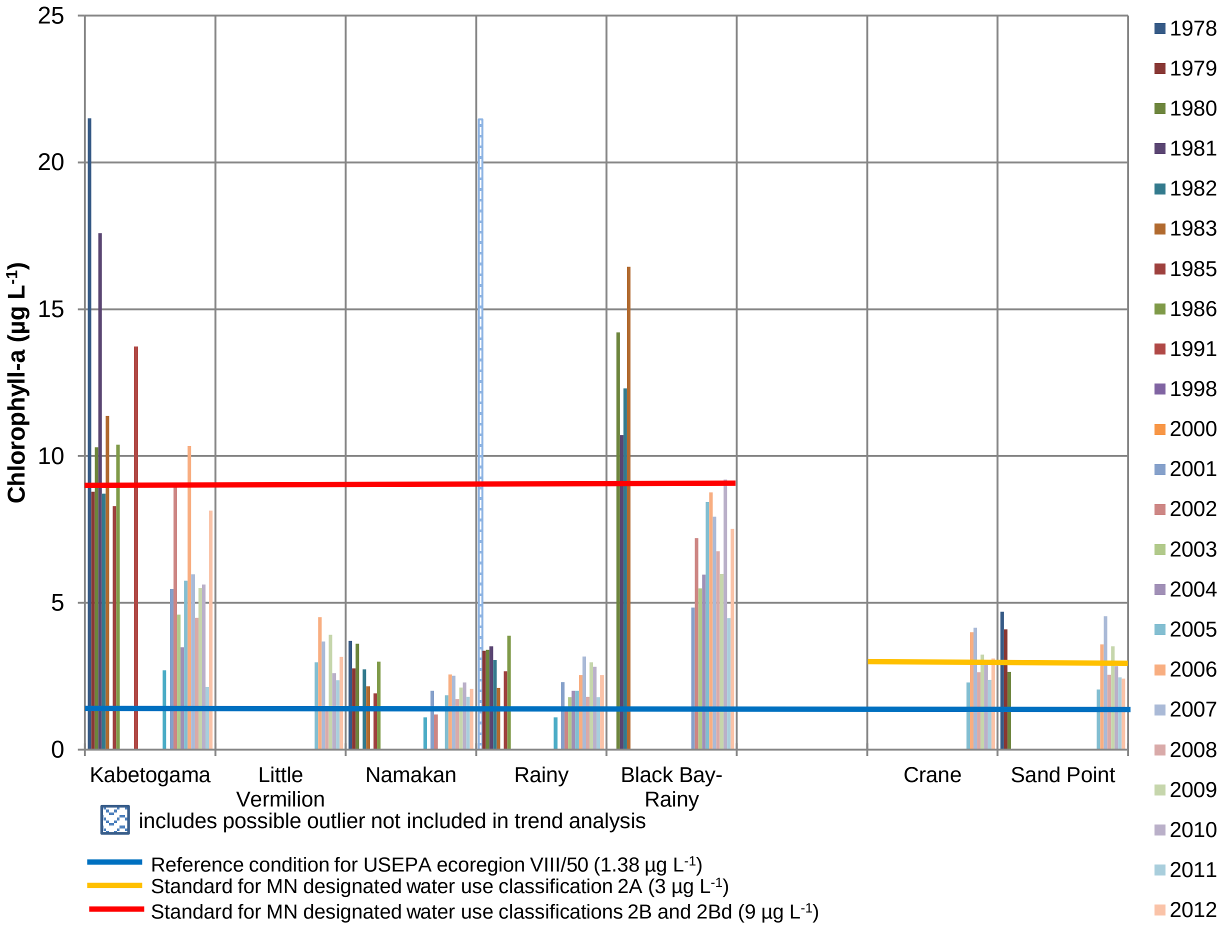

**Figure 54**. Annual mean chlorophyll-*a* values for large lake water quality monitoring sites in and near Voyageurs National Park, 1978–2012.

Algal productivity (which can be measured by chl-*a*) is of particular concern in Kabetogama Lake because of its history of blue-green algal (cyanobacterial) blooms. Cyanobacteria such as *Anabaena* and *Aphanizomenon* fix their own nitrogen; thus, their growth can be stimulated by increasing phosphorus. Compared to the other large lakes in VOYA, Kabetogama is shallower and polymictic (mixes more frequently than twice a year), which may lead to increased internal phosphorus recycling. Since the southwest shore of Kabetogama is not within VOYA, it has numerous homes, cabins, and resorts that may also contribute phosphorus to the lake through inadequate sewage treatment and lawn fertilization practices (Christensen et al. 2011). Cyanobacteria in Kabetogama Lake in 2008–2009 produced the cyanotoxin microcystin at levels exceeding World Health Organization guidelines for drinking water and, in some cases, for body contact recreation. Both Christensen et al. (2011) and Christensen and Maki (2014) found decreases in chl-*a* concentrations in Kabetogama since 2000, when the rules concerning the operation of dams on the Namakan Reservoir and Rainy Lake were changed (see Section 4.6 for details).

#### *Trophic state*

Trophic state is another indicator of water quality; it is based on the total weight of living biologic material at a specific location and time (Carlson and Simpson 1996). Carlson's trophic state indices (TSIs) use algal biomass as the basis for trophic state classification. Three variables (chlorophyll pigments, Secchi depth, and TP) independently estimate algal biomass, with chlorophyll being the best predictor (Carlson 1977). Both the GLKN (Damstra et al. 2014) and the VOYA aquatic ecologist (Christensen and Maki 2014) recommend using the chl-*a* TSI for the interior lakes and the large lakes, respectively.

In the 1996 version of Carlson's work (Carlson and Simpson 1996), the authors indicate that TSI values <30 indicate oligotrophy, while those between 40 and 50 indicate mesotrophy. In the range between 30–40, the waters are oligotrophic, but there is a tendency for hypoxia in the hypolimnions of shallower lakes. By this standard, the annual means of chl-*a* TSIs for the interior index lakes fell into the oligotrophic range, with a few instances of mesotrophy, and Cruiser and Little Trout Lakes being clearly more oligotrophic than the others (Figure 55).

We calculated annual mean chl-*a* TSIs for the large lakes, using all data from each lake (Figure 56), and found that Namakan and Rainy Lakes were in the oligotrophic range for the most recent time period (2005–2012). Little Vermilion, Crane, and Sand Point Lakes generally fell into the oligotrophic to lower mesotrophic range. Black Bay of Rainy Lake and Kabetogama Lake had the highest values overall, and Kabetogama, Namakan, and Rainy Lakes and Black Bay appeared to have experienced a reduction in their chl-*a* TSIs over the period of record. Using a more rigorous approach that eliminated samples without clear locational data, Christensen and Maki (2014) found that based on August chl-*a* TSIs, Sand Point, Namakan, and Rainy Lakes were oligotrophic from 2001–2012, Kabetogama Lake was mesotrophic to eutrophic, and Black Bay was eutrophic.

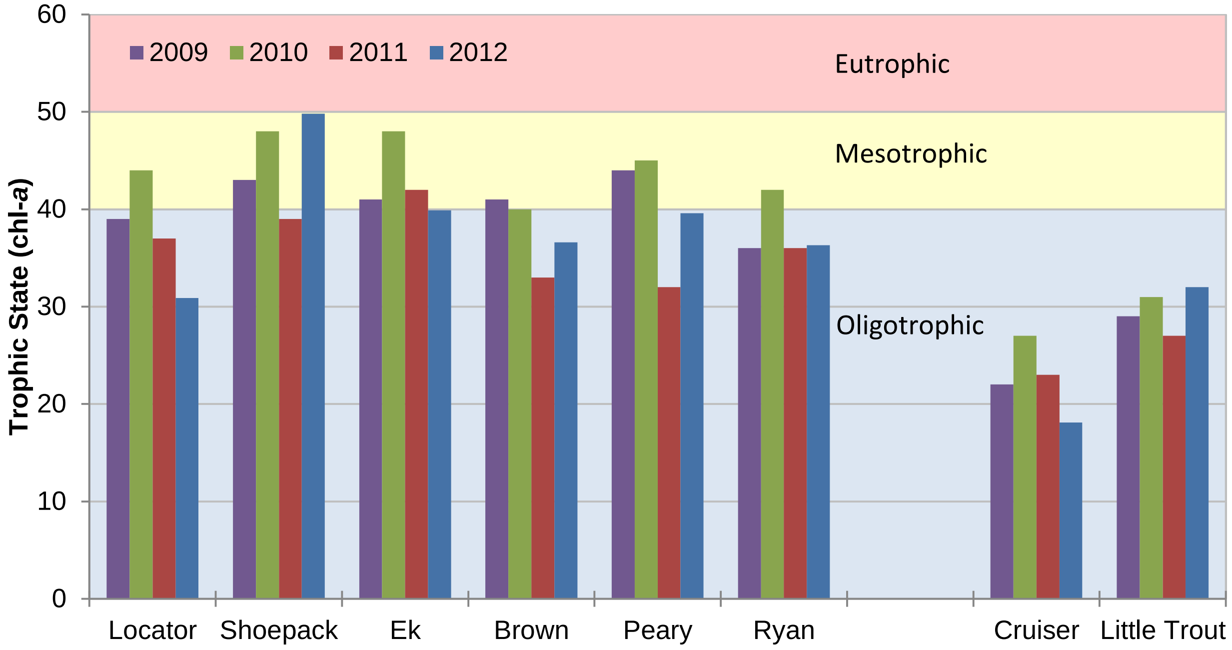

**Figure 55.** Annual mean chlorophyll-*a* trophic state index values for interior index lakes in Voyageurs National Park, 2009–2012 (Elias and Damstra 2011, 2012, Damstra et al. 2014).

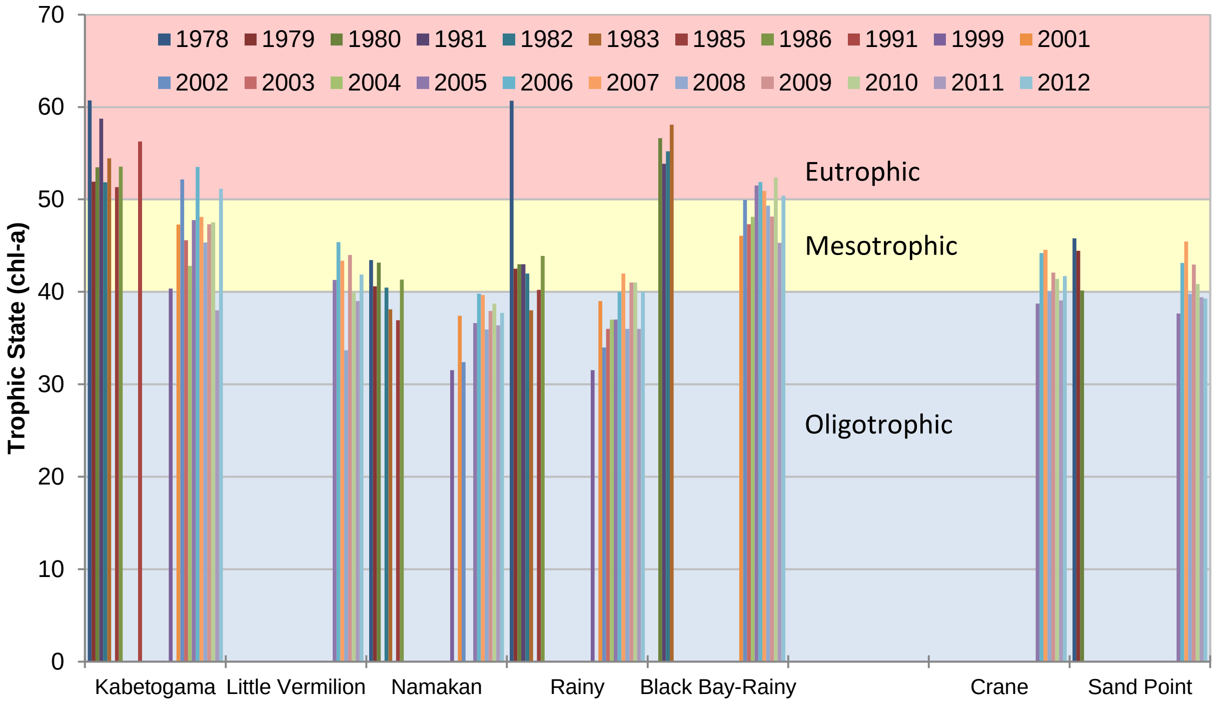

**Figure 56.** Annual mean chlorophyll-*a* trophic state index values for large lakes in and near Voyageurs National Park, 1978–2012.

### *Endocrine Disruptors*

Writer et al. (2010) conducted a study of concentrations of endocrine disrupting chemicals and endocrine disruption in fish in 11 MN lakes, including Kabetogama Lake, in 2008. Molecular tracers associated with wastewater, including boron, anthropogenic gadolinium, coprostanol, ethylenediaminetetra acetic acid (EDTA), cholesterol, and steroidal hormones were recovered from Kabetogama Lake water and sediment. Levels of five anthropogenic organic compounds in sediment, (bisphenol A, cholesterol, coprostanol, 17β estradiol, and estrone) which indicate chronic inputs, were 5th, 2nd, 2nd, 3rd, and 1st highest, respectively, in Kabetogama compared to the other 10 lakes in the study, including those with much greater population densities and densities of onsite sewage disposal systems.

Endocrine disruption in wild-caught fish in Kabetogama was lower than the median value for the 11 lakes, but higher than the median for caged fathead minnows. The results indicate that any of a variety of nonpoint sources, including land-applied biosolids, stormwater runoff, row crop production, animal feeding operations, onsite wastewater disposal systems, recreational activities, transportation, and atmospheric deposition, are contributing these contaminants to Kabetogama Lake. Further study is needed to determine the presence of sources in the watershed, the magnitude of contributions from each source, and the extent to which these contributions are historic or ongoing.

### Sources of Expertise

Kallemeyn et al. 2003; Elias and VanderMeulen 2008 and subsequent GLKN interior lake water quality reports; Dr. Katherine Clancy, Jen McNelly, Christine Mechenich, UWSP.

### Literature Cited

Carlson, R. E. 1977. A trophic state index for lakes. *Limnology and Oceanography* 22:361–369.

Carlson, R. E., and J. Simpson. 1996. A coordinator's guide to volunteer lake monitoring methods. 96 pp. North American Lake Management Society. Kent State University, Kent, Ohio. Available at http://www.secchidipin.org/tsi.htm (accessed 23 September 2014).

Christensen, V. G., and R. P. Maki. 2014. Trophic state in Voyageurs National Park lakes before and after implementation of a revised water level management plan. *Journal of the American Water Resources Association.* Published online 12 AUG 2014 | DOI: 10.1111/jawr.12234.

Christensen, V. G., R. P. Maki, and R. L. Kiesling. 2011. Relation of nutrient concentrations, nutrient loading, and algal production to changes in water levels in Kabetogama Lake, Voyageurs National Park, northern Minnesota, 2008–09: U.S. Geological Survey Scientific Investigations Report 2011–5096. USGS, Reston, Virginia. Available at http://pubs.usgs.gov/sir/2011/5096/pdf/sir2011_5096.pdf (accessed 23 September 2014).

Damstra, R. A., D. VanderMeulen, and J. Elias. 2014. Monitoring water quality of inland lakes, Great Lakes Network, 2012: data summary report. Natural Resource Data Series NPS/GLKN/NRDS—2014/629. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2208297 (accessed 3 September 2014).

Edlund, M. B., J. M. Ramstack, D. R. Engstrom, J. E. Elias, and B. Moraska Lafrancois. 2011. Biomonitoring using diatoms and paleolimnology in the western Great Lakes national parks. Natural Resource Technical Report NPS/GLKN/NRTR—2011/447. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2170717 (accessed 22 September 2014).

Edlund, M. B., J. Ramstack Hobbs, and D. R. Engstrom. 2012. Biomonitoring using diatoms and paleolimnology in the western Great Lakes national parks. Natural Resource Technical Report NPS/GLKN/NRTR—2012/644. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2191475 (accessed 3 September 2014).

Elias, J. E., and D. VanderMeulen. 2008. Monitoring water quality of inland lakes, 2007: annual summary report. GLKN/2008/05. Great Lakes Inventory and Monitoring Network. Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/660550 (accessed 3 September 2014).

Elias, J. E, R. Axler, and E. Ruzycki. 2008. Water quality monitoring protocol for inland lakes. Version 1.0. National Park Service, Great Lakes Inventory and Monitoring Network. Natural Resources Technical Report NPS/GLKN/NRTR—2008/109. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/653784 (accessed 9 September 2014).

Elias, J. 2009. Monitoring water quality of inland lakes, 2008: annual summary report. GLKN/2009/01. Great Lakes Inventory and Monitoring Network. Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/662762 (accessed 3 September 2014).

Elias J. E., and R. A. Damstra. 2011. Monitoring water quality of inland lakes, Great Lakes Network, 2009 and 2010: data summary report. Natural Resource Data Series. NPS/GLKN/NRDS—2011/163. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2170874 (accessed 3 September 2014).

Elias J. E., and R. A. Damstra. 2012. Monitoring water quality of inland lakes, Great Lakes Network, 2011: data summary report. Natural Resource Data Series. NPS/GLKN/NRDS—2012/363. National Park Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2189073 (accessed 3 September 2014).

Helsel, D. R., and R. M. Hirsch. 2002. Statistical methods in water resources techniques of water resources investigations, book 4, chapter A3. U.S. Geological Survey, Reston, Virginia. Available at http://pubs.usgs.gov/twri/twri4a3/ (accessed 2 October 2012).

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001. USGS Columbia Environmental Research Center, Columbia, Missouri. 95 pp. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Kepner, R. L., and R. R. Stottlemyer. 1988. Physical and chemical factors affecting primary production in the Voyageurs National Park lake system (final report). GLARSU Technical Report #29. Great Lakes Area Resources Studies Unit—Michigan Technological University, Houghton, Michigan. Available at https://irma.nps.gov/App/Reference/Profile/92258 (accessed 29 June 2015).

MPCA (Minnesota Pollution Control Agency). 2013. Waters of the state: water quality standards for protection of waters of the state. Minnesota Administrative Rules Chapter 7050. MPCA, St. Paul, Minnesota. Available at https://www.revisor.mn.gov/rules/?id=7050&version=2014-01-18T07:06:14-06:00&format=pdf (accessed 4 August 2014).

NPS (National Park Service). 1995. Baseline Water Quality Inventory, Voyageurs National Park. Project-2173811. NPS, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2173811 (accessed 3 September 2014).

NPS (National Park Service). 2013. Air pollution impacts – Voyageurs National Park. Webpage. Available at http://www.nature.nps.gov/air/permits/aris/voya/impacts.cfm (accessed 25 August 2014).

Payne, G. A. 1991. Water quality of lakes and streams in Voyageurs National Park, northern Minnesota, 1977–84. United States Geological Survey Water-Resources Investigations Report: 88-4016. USGS, Denver, Colorado. Available at http://pubs.usgs.gov/wri/1988/4016/report.pdf (accessed 16 September 2014).

Payne, G. A. 2000. Water quality of lakes in Voyageurs National Park, Northern Minnesota, 1999. United States Geological Survey Water-Resources Investigations Report. 00-4281. USGS, Mounds View, Minnesota. Available at https://irma.nps.gov/App/Reference/Profile/2206988 (accessed 3 September 2014).

Shaw, B., C. Mechenich, and L. Klessig. 2004. Understanding lake data. Publication G3582. University of Wisconsin-Extension, Madison, Wisconsin. Available at http://www3.uwsp.edu/cnr-ap/weal/Documents/G3582.pdf (accessed 2 September 2014).

Sterner, R. W. 2008. On the phosphorus limitation paradigm for lakes. *International Review of Hydrobiology* 93:433–445. doi: 10.1002/iroh.200811068.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

USEPA (United States Environmental Protection Agency). 1976. Quality criteria for water, 1976. EPA 440-9-76-023, Environmental Protection Agency, Office of Water Regulations and Standards, Washington, D.C.

USEPA (United States Environmental Protection Agency). 1986. Quality criteria for water, 1986. EPA 440/5-86-001, Environmental Protection Agency, Office of Water Regulations and Standards, Washington, D.C.

USEPA (United States. Environmental Protection Agency). 2000. Ambient water quality criteria recommendations: Information supporting the development of state and tribal nutrient criteria for rivers and streams in nutrient ecoregion VIII. EPA-822-B-00-010. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, Washington, D.C. Available at http://www2.epa.gov/sites/production/files/documents/lakes8.pdf (accessed 4 September 4 2014).

USEPA (United States Environmental Protection Agency). 2006. National recommended water quality criteria. Environmental Protection Agency, Office of Science and Technology, Washington, D.C. Available at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1003R9X.txt (accessed 25 March 2013).

Weeks, D. P., and R. J. Andrascik. 1998. Voyageurs National Park, Minnesota: Water Resources Scoping Report. NPS/NRWRS/NRTR—98/201 (D-119). National Park Service, Water Resources Division. Denver, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/134264 (accessed 29 September 2014).

Writer, J. H., L. B. Barber, G. K. Brown, H. E. Taylor, R. L. Kiesling, M. L. Ferrey, N. D. Jahns, S. E. Bartell, and H. L. Schoenfuss. 2010. Anthropogenic tracers, endocrine disrupting chemicals, and endocrine disruption in Minnesota lakes. *Science of the Total Environment* 409:100–111.

### *4.4.3. Mercury*

Description

Mercury (Hg) is a persistent, bioaccumulative toxic pollutant with harmful health consequences for both humans and animals. Although it is naturally occurring, human activities have facilitated its spread throughout the environment. Most of the Hg that is found in MN lakes, rivers, and fishes has been deposited from the atmosphere (MPCA 2013). Atmospheric deposition of Hg in rural MN increased steadily from the mid-1800s to approximately 1990, with a net three-fold increase (Engstrom and Swain 1997, Engstrom et al. 2007). Since that time, the deposition rate has decreased, yet Hg levels in many lakes and fish are still at unsafe levels (Hall et al. 2005, Wiener et al. 2006).

Hg occurs in four forms in the atmosphere: the gas-phase elemental form (Hg[0]), a gaseous inorganic form (Hg[II]) formed in photochemical reactions, the particulate form (Hg[P]), and methylmercury (MeHg). Ninety-five percent of the total in the atmosphere is in the elemental form (Grigal 2002), but the inorganic form is more soluble and is the dominant form in precipitation. In aquatic ecosystems, particularly in anaerobic environments such as wetlands and lake sediments, microbes transform deposited inorganic Hg into methylmercury (MeHg), which biomagnifies in food webs, resulting in high concentrations in fish (Morel et al. 1998, Drevnick et al. 2007 and citations therein). For example, in Lake Superior, a small amount (< 6%) of the total Hg deposited is MeHg;

this occurs mainly during low-volume rain events where it is “washed out” of the atmosphere. Sources of this MeHg may include lake-effect cloud and fog and nearby wetlands (Hall et al. 2005).

In 2005, 56% of the Hg emissions in MN were related to energy production (mostly burning coal). Taconite production accounted for 21%, and the use and disposal of products containing Hg accounted for 22% (MPCA 2013). MPCA (2013) estimates that Hg emissions within MN account for only 10% of atmospheric Hg deposition in MN; the remainder is attributed to natural emissions (30%) and anthropogenic global and regional emissions (30% and 40%, respectively).

However, deposition is not evenly distributed across MN, and local sources may be significant in local deposition. Engstrom and Swain (1997) suggested that a variety of regional sources, including non-ferrous smelting in Ontario, taconite processing on the Iron Range in MN, a steel mill in Duluth, and volatilization of mercuric fungicides from paper mills, all affected lakes in northeastern MN but had minimal impact on western MN lakes. Engstrom et al. (2007) suggested that the paper mill in International Falls likely used mercuric fungicides through the 1970s, and that these likely volatilized to the atmosphere. At the peak of their use, potential Hg emissions from fungicides exceeded those from coal combustion by an order of magnitude (Engstrom et al. 2007).

Air emissions of Hg within 250 km of VOYA are shown in Figure 57; within 50 km of VOYA, 8.3 kg $yr^{-1}$ of Hg are emitted from 10 facilities. Within 250 km of VOYA, 139 facilities emit 620 kg $yr^{-1}$ of Hg. The sources nearest VOYA are a paper mill at International Falls (now operating only two of its four paper machines) and a pulp and paper mill at Fort Frances (now closed); their emissions were 6.1 kg $yr^{-1}$ in 2011 and 1.8 kg $yr^{-1}$ in 2010, respectively. The three facilities in the 80.1–110.0 kg $yr^{-1}$ category are a power plant (109 kg $yr^{-1}$) and two taconite processing facilities (103 and 84 kg $yr^{-1}$), and the two in the 40.1–80 kg $yr^{-1}$ category are taconite processing facilities (61 and 48 kg $yr^{-1}$).

### Data and Methods

Hg air emissions data were obtained and mapped from the 2011 National Emissions Inventory (USEPA 2013) and the 2010 National Pollutant Release Inventory (Environment Canada 2012).

Data for Hg in precipitation at the MDN stations at Fernberg, MN (MN 18), 82 km SE of VOYA, and Marcell, MN (MN 16), 103 km SSW of VOYA, were downloaded from the Mercury Deposition Network of the National Atmospheric Deposition Program (NADP) http://nadp.sws.uiuc.edu/ on July 3, 2014. Data for Hg in the GLKN index lakes at VOYA were downloaded from the USEPA STORET warehouse at http://www.epa.gov/storet/ on January 8, 2014.

Extensive investigation has been conducted on Hg deposition and accumulation in VOYA; in particular, see Brigham et al. (2014). These authors found decreases in atmospheric deposition of Hg at VOYA from 1998–2012 along with decreases in epilimnetic aqueous MeHg and Hg in small yellow perch in two of four studied lakes. Counter to these trends, a third lake showed increases in both MeHg in water and Hg in fish, and a fourth lake lacked overall trends. They concluded that their study lakes “exemplify the complexity of ecosystem responses to decreased loads of atmospheric pollutants.”

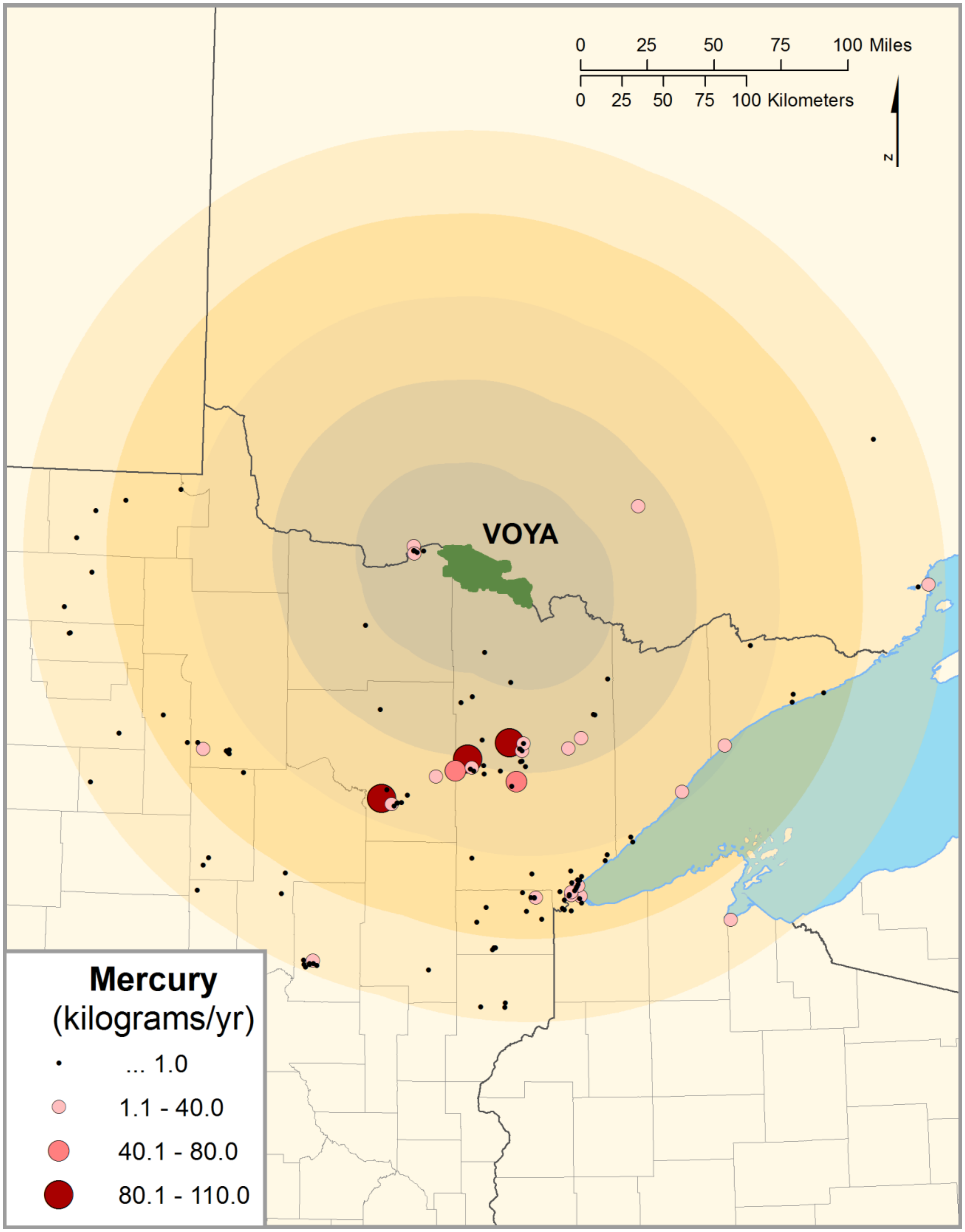

**Figure 57.** Mercury emissions to the air within 250 km of Voyageurs National Park for 2010 (Canada) and 2011 (Minnesota) (Environment Canada 2012, USEPA 2013).

## Reference Condition

### *Precipitation*

A modeling study in Sweden indicated that in humic lakes in the boreal ecosystem, the maximum Hg concentration in precipitation to maintain the regional mean Hg concentrations in 1-kg northern pike below 0.5 mg kg$^{-1}$ fresh weight was approximately 2 ng L$^{-1}$ (Meili et al. 2003). The authors also suggested that 2 ng L$^{-1}$ or less may be the global pre-industrial level of Hg in precipitation. Thus, this reference condition represents both a "historic condition" and a "least disturbed condition" (Stoddard et al. 2006).

### *Fish Tissue*

MN has established a statewide fish tissue criterion of 0.2 mg kg$^{-1}$ for Hg (MPCA 2009) and places water bodies in which less than 90% of sampled fish meet this criterion on the impaired waters list (MPCA 2013). (This differs slightly from the Minnesota Department of Health (MDH) criterion of 0.22 mg kg$^{-1}$ for protection of sensitive populations, which takes into account consumption of marine as well as freshwater fish [MPCA 2013]).

Sandheinrich and Wiener (2011) reported a threshold of 500 ppb for Hg in muscle tissue in fish; beyond this level, laboratory studies have indicated damage to cells and tissues, altered biochemical processes, and reduced reproduction.

### *Surface Water*

The USEPA has developed a surface water quality criterion for total Hg of 1.3 ng L$^{-1}$ for wildlife to "…protect mammals and birds from adverse impacts from that chemical due to consumption of food 58attainable conditions," or the condition that today's sites might achieve if they were better managed (Stoddard et al. 2006). Reference conditions for Hg are summarized in Table 26.

**Table 26.** Reference conditions used in evaluating mercury contamination at Voyageurs National Park.

| Medium | Source | Reference condition | Units | Equivalents (ppm) |
|---|---|---|---|---|
| Precipitation | Meili et al. 2003 | 2 | ng L$^{-1}$ | 0.000002 |
| Fish tissue (human consumption) | MPCA 2009 | 0.2 | mg kg$^{-1}$ | 0.2 |
| Fish tissue (reproductive biology) | Sandheinrich and Wiener 2011 | 500 | ppb | 0.5 |
| Surface water (wildlife) | USEPA 1995 | 1.3 | ng L$^{-1}$ | 0.0000013 |

## Condition and Trend

### *Precipitation*

Hg concentrations in precipitation at VOYA are of significant concern, but with an improving trend. Our confidence in this assessment is high. Hg concentrations in precipitation at Fernberg and Marcell, MN consistently exceed the reference condition of 2 ng L$^{-1}$ (Table 27). Of 646 weekly samples for which data were recorded from 1996–2013 at Fernberg, the closest MDN station to VOYA, only 24 (3.7%) met the reference criterion; 527 (81.6%) were up to an order of magnitude higher, in the 2–20 ng L$^{-1}$ range, and 95 (14.7%) exceeded 20 ng L$^{-1}$. For Marcell, with 719 weekly samples collected from 1996–2013, 34 (4.7%) samples met the reference condition.

**Table 27.** Data from Mercury Deposition Network for precipitation at Fernberg and Marcell, Minnesota (NADP 2014).

|  | Fernberg (MN18) |  | Marcell (MN16) |  |
|---|---|---|---|---|
| **Hg in precipitation (ng L$^{-1}$)** | ***Samples*** | ***%*** | ***Samples*** | ***%*** |
| 0–2 | 24 | 3.7 | 34 | 4.7 |
| 2.1–20 | 527 | 81.6 | 577 | 80.3 |
| 20.1–100 | 93 | 14.4 | 105 | 14.6 |
| >100 | 2 | 0.3 | 3 | 0.4 |
| Total number of observations | 646 |  | 719 |  |
| Date range | 3/5/1996–12/31/2013 |  | 2/27/1996–12/31/2013 |  |
| Maximum and date | 396.57 ng L$^{-1}$, 11/27/2001 |  | 374.89 ng L$^{-1}$, 2/20/2001 |  |

Engstrom et al. (2007) suggest that Hg deposition had declined in the vicinity of VOYA by 20%–30% since the mid-1970s. Brigham et al. (2014), using a subset of the data depicted in Figure 58, found that rates of wet deposition of Hg declined 32% at both MN16 and MN18 from 1998–2012.

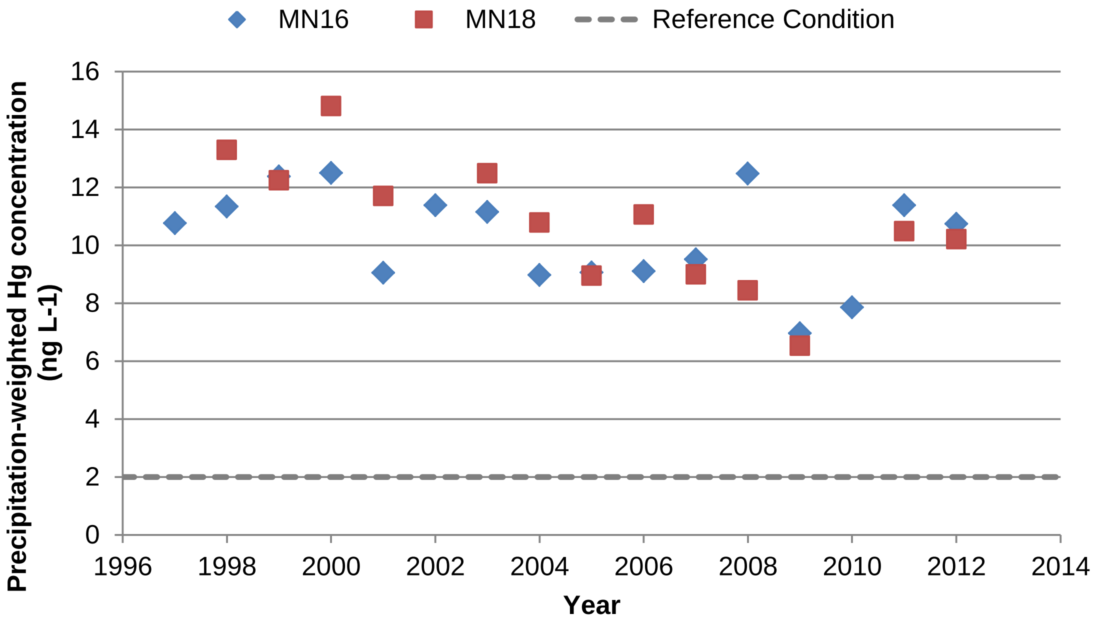

**Figure 58.** Precipitation-weighted annual average mercury concentrations for two MDN sites near Voyageurs National Park, 1997–2013 (NADP 2014).

### *Fish tissue*

🔴 Hg concentrations in fish tissue for human consumption are of significant concern, with an uncertain trend. Our confidence in this assessment is moderate. MDH (2013) has issued fish consumption advisories for the Rainy River and all VOYA lakes which have been sampled for fish tissue Hg concentrations. MPCA (2014) has listed the Rainy River and Cruiser, Ek, Kabetogama, Little Trout, Mukooda, and Peary Lakes on its proposed list of waters impaired for Hg in fish tissue for 2014. Two lakes within VOYA, Tooth and Ryan Lakes, have the highest fish tissue Hg levels measured within the state of MN (Goldstein et al. 2003). As previously noted, Brigham et al. (2014) observed decreasing Hg levels in whole age-1 yellow perch in two VOYA lakes (Peary and Ryan), with decreases of 37% and 32%, respectively, from 2000–2012. However, they also observed no significant change in Shoepack Lake, and an increase of 80% in Brown Lake, in that same time period.

Monson et al. (2011) found a biphasic downward trend in walleye and northern pike Hg concentrations in lakes in MN from 1982 to the mid-1990s, followed by an upward trend through 2006. The authors noted that researchers in the Canadian arctic have found increasing Hg concentrations in fish and attributed them to a warming climate (Carrie et al. 2010, Kirk et al. 2011 in Monson et al. 2011). They also suggested changes in the aquatic food web caused by invasive species as a possible contributing factor to changing growth rates, and thus, changing Hg concentrations in fish.

● Hg concentrations in fish tissue are also of significant concern in VOYA as they relate to fish health and reproductive biology. The trend is unknown, and our confidence in this assessment is high. Hg levels in 67% of northern pike analyzed in recent years exceeded 500 ppb wet weight, a level that has been associated with tissue and cell damage and altered biochemical processes (NPS 2013). These levels also exceed the thresholds where sublethal reproductive effects have been documented (Sandheinrich and Wiener 2011). For example, Hg, at levels found within VOYA, appears to suppress testosterone and 11-ketotestosterone levels in northern pike (NPS 2013).

The accumulation and biomagnification of MeHg in aquatic food webs is especially important for piscivores (aquatic, avian and terrestrial; Wiener et al. 2003). For example, in Rainy Lake, the Hg loads in northern pike, a top-level piscivore, were approximately 10 times higher than levels in cisco, a planktivorous species, and nearly 1,000 times higher than levels in plankton (see Figure 39 in Kallemeyn et al. 2003). Hg continues to be a concern for biologists and managers within VOYA, and continued monitoring and research will aid in management decisions related to Hg in fishes and aquatic systems.

### *Water Quality*

● Hg concentrations in surface water in interior lakes in VOYA is of significant concern, with an uncertain trend. Our confidence in this assessment is moderate. Only five of 85 samples collected by the GLKN from 2006–2012 in six VOYA interior lakes met the reference condition of 1.3 ng L$^{-1}$; all these were from Peary Lake (Figure 59). The data were insufficient for trend analysis. Brigham et al. (2014) observed no significant trends in total Hg concentrations in epilimnetic water in Brown, Peary, and Ryan Lakes in VOYA from 2000–2012, but detected a significant upward trend (27% increase) in Shoepack Lake.

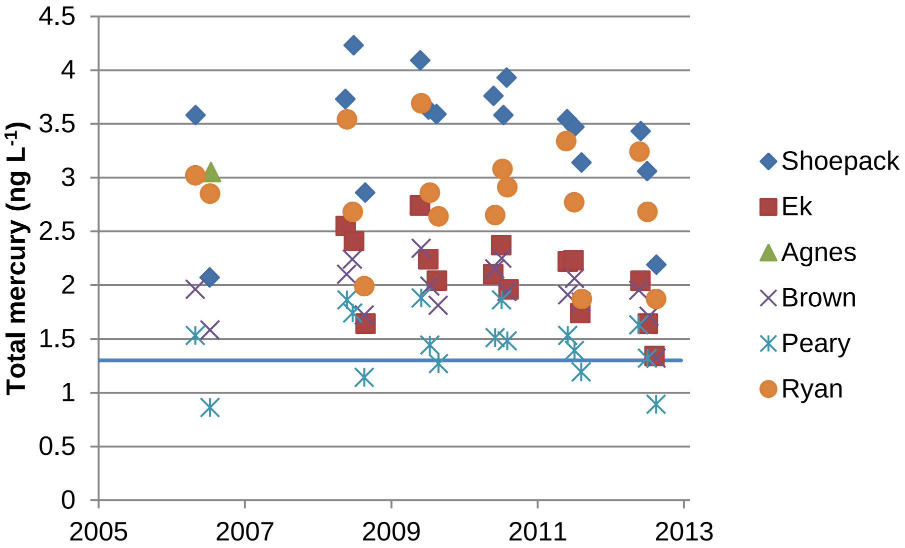

**Figure 59.** Concentrations of total mercury in water samples from six interior lakes in Voyageurs National Park, 2006–2012 (USEPA 2014).

*Terrestrial systems*

The study of Hg in terrestrial systems at VOYA is limited. Such study is warranted because Hg can bioaccumulate in the MeHg form and because of the intimate process connections between terrestrial and aquatic systems. The high percentage of the VOYA landscape that is aquatic or wetland points to the importance of Hg export from terrestrial (mostly forested) systems. Studies have shown that between 5% and 25% of deposited Hg will reach associated lakes (Grigal 2002). Thus, the land is an important contributor to the Hg status of lakes, and a strong majority of the incoming Hg stays in the terrestrial system for some period of time. This suggests that bioaccumulation needs to be examined, as well as direct effects on organisms in the soil.

The fate of Hg in the terrestrial system is not well understood. It is subject to volatilization at ambient temperatures and readily adheres to most forms of organic matter. For this reason, the concentration of Hg in the organic horizon on the forest floor is six times that of the mineral soil, though the total mass in the mineral soil is five times higher (Nater and Grigal 1992, Grigal 2002).

Hg(0) and Hg(II) are the more common forms in the soil (MeHg is about 0.6% of the total), and both forms go into solution and adhere to soil adsorption sites (Grigal 2003). The movement of Hg from the terrestrial to an aquatic system can occur in solution (groundwater flow), and through overland flow (dissolved or adsorbed to organic matter or clay particles); Grigal (2002) stated that the amount of dissolved organic matter is ‘critically important’ to the movement of Hg in the environment. Thus, Hg decreases with depth in the soil profile.

There is a close positive relationship between percent of a watershed in wetland and the flux of MeHg into the aquatic system (Grigal 2002). Under certain conditions, Hg is converted to the MeHg form by sulfate-reducing bacteria (Grigal 2003, Drevnick et al. 2007), and thus sulfate availability influences Hg methylation. These microbes are most abundant under anoxic conditions and in places where carbon accumulates. This explains why wetland area around a lake is a critical determinant of

Hg concentration in lakes, and why beaver ponds have higher levels of Hg than lake sediments (Grigal 2003).

The amount of Hg in the soil and in soil solution is highly variable (Grigal 2002), but in general VOYA sits in a part of the region with one of the lower levels of soil Hg (Nater and Grigal 1992). Wiener et al. (2006) indicated that geologic sources within VOYA have contributed little Hg to the watersheds they studied. It was recently determined that the fire history of a site has a strong effect on the amount of Hg in the O- and A-horizons of soils. Woodruff and Cannon (2010) found a statistically significant trend of increasing Hg concentration with forest age at BWCAW; the sites varied by 217 years, and all were of fire origin. An additional sample of a 2004 fire in VOYA pinned down the presumed mechanism for this trend: fire volatilizes Hg, and as the severity of the fire increases, so does the amount of Hg lost. Thus, the age of a forest would be one determinant of the potential for Hg movement from a watershed into the aquatic systems it contains, and thus as the average age of forests increases (i.e., as fire frequency goes down), this potential will increase.

Published values indicate that the concentration of Hg in "plants" is: herbs < trees + shrubs < aquatic macrophytes < sphagnum moss < mosses < lichens < fungi (Moore et al. 1995). In Ontario, the lowest concentrations of total Hg and MeHg were found in the leaves of trees and shrubs, and the highest in bryophytes (feathermoss, *Sphagnum*). Thus, herbivores that feed on forbs or upland woody plants get a very low dose of Hg, but those that utilize bryophytes get a much higher concentration. This basic difference might manifest among community types at VOYA because the 'southern boreal' types have a greater abundance of bryophytes than the other community types. Though top predators often have higher concentrations than herbivores, there appears to be little biomagnification in terrestrial food chains of temperate zone communities (Grigal 2002).

The roots of plants act as both an adsorption site and a natural barrier to Hg, and thus there is limited uptake (Grigal 2003). The review of inputs and outputs by Grigal (2002) concluded that less than 10% of the Hg in plants is from the soil. The gas-phase elemental form adsorbs to leaf surfaces and enters the plant through open stomates. It binds to mesophyll tissues readily and is easily oxidized, and thus 'captured,' in the leaves. Consequently, litterfall is the dominant flux between the atmosphere and the terrestrial system, and is the primary pathway by which Hg gets to the soil sub-system. This fact explains why characteristics of the surface are an important part of the movement of Hg; the length of the growing season, the longevity of leaves, and the amount of leaf surface area all play a critical role in determining how much Hg is deposited on an annual basis. Though Hg(0) is the most abundant form, approximately 1.5% of the Hg in litterfall is MeHg.

Sources of Expertise

Brigham et al. 2014; James Cook, Justin VanDeHey, Christine Mechenich, UWSP.

Literature Cited

Brigham, M. E., M. B. Sandheinrich, D. A. Gay, R. P. Maki, D. P. Krabbenhoft, and J. G. Wiener. 2014. Lacustrine responses to decreasing wet mercury deposition rates—results from a case study in northern Minnesota. *Environmental Science & Technology* 48:6115–6123.

Carrie, J., F. Wang, H. Sanei, R. W. Macdonald, P. M. Outridge, and G. A. Stern. 2010. Increasing contaminant burdens in an arctic fish, burbot (*Lota lota*), in a warming climate. *Environmental Science and Technology* 44:316–322.

Drevnick, P. E., D. E. Canfield, P. R. Gorski, A. C. Shinneman, D. R. Engstrom, D. C. G. Muir, G. R. Smith, P. J. Garrison, L. B. Cleckner, J. P. Hurley, R. B. Noble, R. R. Otter, and J. T. Oris. 2007. Deposition and cycling of sulfur controls mercury accumulation in Isle Royale fish. *Environmental Science and Technology* 41:7266–7272.

Engstrom, D. R., and E. B. Swain. 1997. Recent declines in atmospheric mercury deposition in the Upper Midwest. *Environmental Science & Technology* 31:960–967.

Engstrom, D. R., S. J. Balogh, and E. B. Swain. 2007. History of mercury inputs to Minnesota lakes: influences of watershed disturbance and localized atmospheric deposition. *Limnology and Oceanography* 52:2467–2483.

Environment Canada. 2012. National Pollutant Release Inventory: 2010 facility-reported data (Pollutant releases and transfers). Gatineau, Quebec, Canada. Available at http://www.ec.gc.ca/inrp-npri/ (accessed 3 October 2012).

Goldstein, R. M., M. E. Brigham, L. Steuwe, and M. A. Menheer. 2003. Mercury data from small lakes in Voyageurs National Park, Northern Minnesota, 2000–02. USGS Open-File Report 2003-480, USGS, Mounds View, Minnesota. Available at http://pubs.er.usgs.gov/publication/ofr2003480 (accessed 5 August 2014).

Grigal, D. F. 2002. Inputs and outputs of mercury from terrestrial watersheds: a review. *Environmental Reviews* 10(1): 1–39.

Grigal, D. F. 2003. Mercury sequestration in forests and peatlands: a review. *Journal of Environmental Quality* 32(2): 393–405.

Hall, B. D., H. Manolpoulos, J. P. Hurley, J. J. Schauer, V. L. St. Louis, D. Kenski, J. Graydon, C. L. Babiarz, L. B. Cleckner, and G. J. Keeler. 2005. Methyl and total mercury in precipitation in the Great Lakes region. *Atmospheric Environment* 39:7557–7569.

Kallemeyn, L. W., K. L. Holmberg, J. A. Perry, and B. Y. Odde. 2003. Aquatic synthesis for Voyageurs National Park. U.S. Geological Survey Information and Technology Report 2003-0001. USGS Columbia Environmental Research Center, Columbia, Missouri. 95 pp. Available at http://www.cerc.usgs.gov/pubs/center/pdfdocs/ITR2003-0001.pdf (accessed 30 June 2014).

Kirk, J. L., D. C. M. Muir, D. Antoniades, M. S. V. Douglas, M. S. Evans, T. A. Jackson, H. Kling, S. Lamoureux, D. S. S. Lim, R. Pienitz, J. P. Smol, K. Stewart, X. Wang, and F. Yang. 2011. Climate change and mercury accumulation in Canadian high and subarctic lakes. *Environmental Science and Technology* 45:964–970.

MDH (Minnesota Department of Health). 2013. Fish consumption guidelines for women who are or may become pregnant and children under age 15, rivers. Minnesota Department of Health, St. Paul, Minnesota. Available at http://www.health.state.mn.us/divs/eh/fish/eating/specpoprivers.pdf (accessed 5 August 2014).

Meili, M., K. Bishop, L. Bringmark, K. Johansson, J. Muthe, H. Sverdrup, and W. de Vries. 2003. Critical levels of atmospheric pollution: Criteria and concepts for operational modelling of mercury in forest and lake ecosystems. *The Science of the Total Environment* 304:83–106.

Monson, B. A., D. F. Staples, S. P. Bhavsar, T. M. Holsen, C. S. Schrank, S. K. Moses, D. J. McGoldrick, S. M. Backus, and K. A. Williams. 2011. Spatiotemporal trends of mercury in walleye and largemouth bass from the Laurentian Great Lakes Region. *Ecotoxicology* 20:1555–1567.

Moore, T. R., J. L. Bubier, A. Heyes, and R. J. Flett. 1995. Methyl and total mercury in boreal wetland plants, Experimental Lakes Area, northwestern Ontario. *Journal of Environmental Quality* 24(5):845–850.

Morel, F. M. M., A. M. L. Kraepiel, and M. Amyot. 1998. The chemical cycle and bioaccumulation of mercury. *Annual Review of Ecology & Systematics* 29:543–566.

MPCA (Minnesota Pollution Control Agency). 2008. Estimated mercury emissions in Minnesota for 2005 to 2018. MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/view-document.html?gid=11652 (accessed 11 December 2012).

MPCA (Minnesota Pollution Control Agency). 2009. Implementation plan for Minnesota’s statewide mercury Total Maximum Daily Load. MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/view-document.html?gid=11481 (accessed 22 March 2012).

MPCA (Minnesota Pollution Control Agency). 2013. Sources of mercury pollution and the methylmercury contamination of fish in Minnesota. Publication p-p2s4-06. MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/view-document.html?gid=288 (accessed 27 June 2014).

MPCA (Minnesota Pollution Control Agency). 2014. 2014 Proposed Impaired Waters List (wq-iw1-47). MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/water/water-types-and-programs/minnesotas-impaired-waters-and-tmdls/impaired-waters-list.html (accessed 4 August 2014).

NADP (National Atmospheric Deposition Program [(NRSP-3]). 2014. NADP Program Office, Illinois State Water Survey, Champaign, Illinois. Available at http://nadp.sws.uiuc.edu/sites/sitemap.asp?net=mdn&state=mn (accessed 3 July 2014).

Nater, E. A., and D. F. Grigal. 1992. Regional trends in mercury distribution across the Great Lakes states, north central USA. *Nature* 358:139–141.

NPS (National Park Service). 2013. Effects of mercury on northern pike at Voyageurs NP. Great Lakes Network Monitoring Brief. GLKN, Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/2196643 (accessed 11 August 2014).

Sandheinrich, M. B., and J. G. Wiener. 2011. Methylmercury in freshwater fish: recent advances in assessing toxicity of environmentally relevant exposures. Pages 169–190 *in* W. N. Beyer and J.P. Meador, editors. Environmental Contaminants in Biota: Interpreting Tissue Concentrations, 2nd edition. Taylor and Francis Publishers, Boca Raton, Florida.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* 16:1267–1276.

USEPA (United States Environmental Protection Agency). 1995. Final water quality guidance for the Great Lakes system: 40 CFR Parts 9, 122, 123, 131, and 132. Federal Register 60 (56) (March 23, 1995): 15366–15424. Available at http://www.epa.gov/gliclearinghouse/docs/usepa_fr_notice_2.pdf (accessed 22 March 2012).

USEPA (United States Environmental Protection Agency). 2013. The 2011 national emissions inventory website. Available at http://www.epa.gov/ttn/chief/net/2011inventory.html (accessed 16 December 2013).

USEPA (United States Environmental Protection Agency). 2014. Data from STORET data warehouse. Available at http://www.epa.gov/storet/dbtop.html (accessed 8 January 2014).

Wiener, J. G., D. P. Krabbenhoft, G. H. Heinz, and A. M. Scheuhammer. 2003. Ecotoxicology of mercury. Pages 409–463 *in* D.J. Hoffmann, B. A. Rattner, G. A. Barton Jr., and J. Cairns Jr. editors. Handbook of Ecotoxicology. CRC Press, Boca Raton, Florida.

Wiener, J. G., B. C. Knights, M. B. Sandheinrich, J. D. Jeremiason, M. E. Brigham, D. R. Engstrom, L. G. Woodruff, W. F. Cannon, and S. J. Balogh. 2006. Mercury in soils, lakes, and fish in Voyageurs National Park (Minnesota): Importance of atmospheric deposition and ecosystem factors. *Environmental Science & Technology* 40:6261–6268.

Woodruff, L. G., and W. F. Cannon. 2010. Immediate and long-term fire effects on total mercury in forests soils of northeastern Minnesota. *Environmental Science and Technology* 44:5371–5376. Available at http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5193070.pdf (accessed 20 March 2012).

## 4.5. Ecological Processes

The EPA-SAB framework lists energy flow and material flow as the two primary subdivisions of ecological processes (USEPA 2002). These categories and their respective subcategories describe how an ecosystem is functioning, and if followed over time, how it is developing. Within VOYA, these flows might be measured within terrestrial or aquatic systems. Adequately characterizing these flows requires the development of energy and material budgets rather than just monitoring of concentrations. Process measurements have inherently higher variability than static measurements and are more costly to obtain, so they are used less often in environmental reporting (USEPA 2002). If these aspects of ecosystem function and their respective subcategories are tracked over time, they may indicate the trajectory of the ecosystem and provide an indication of proximity to an unimpaired, healthy state. Given the natural variation at broad and local scales, and the length of time that most landscapes have been disrupted by humans, it is difficult to determine the function of an “unimpaired, healthy state.”

Energy flow is the movement of carbon into, among compartments (or trophic levels) within, and out of a system. In terrestrial systems, all carbon comes from carbon dioxide in the atmosphere and enters the system via the primary producers (is autochthonous). Thus, carbon is rarely a limiting factor to a terrestrial ecosystem. In contrast, for lakes, streams, and rivers, a significant portion of the carbon used is allochthonous; that is, the organic matter originates in the surrounding terrestrial ecosystems (Wetzel 2001, Allan and Castillo 2007). Therefore, vegetative cover and land use in the riparian zone, and sometimes the floodplain, have a pronounced influence on productivity in lakes, streams, and rivers.

Because a substantial amount of the carbon fixed by primary producers is used internally (well over 50% in a mature forest [Barnes et al. 1998, Megonigal et al. 1997, Valett et al. 2005, Cross et al. 2006]), primary production is divided into gross (GPP) and net (NPP) primary production. To measure the activity of all organisms (i.e., to add in the heterotrophs), net ecosystem production and growth efficiency can be determined. In forests, the rates of GPP and NPP follow predictable trajectories with age (Barnes et al. 1998, Cain et al. 2008), if there is no major disturbance. However, the specific rates of GPP and NPP, and the inflection points along the curves, vary among forest and soil types within a climatic region. The length of the growing season is the most important constraint on growth in the boreal region (Bonan and Shugart 1989). Weather and short-term climatic patterns have pronounced effects on key ecosystem processes and organism metabolism, and thus can constrain or enhance the production rates. For example, NPP increases with increases in net annual radiation (Hare and Ritchie 1972 in Bonan and Shugart 1989). Furthermore, the extremes in weather may exert as much influence on plant processes as the average values (Bonan and Shugart 1989). A severe disturbance will re-start the trajectory but will usually not lead to a novel trajectory. Though human actions alter GPP and NPP, it is rare for one of these actions to result in a truly unique trajectory (though it has occurred due to radiation, heavy metal concentrations from mine tailings, and severe over-grazing, for example).

The terrestrial ecosystems in VOYA historically had a wide range of fire return intervals (see Section 4.1.1). The majority of these fires were moderate to high severity, and thus each had a considerable impact on productivity and its temporal pattern, nutrient cycling, the environmental conditions at the soil litter interface, and on key processes within the nutrient cycle (Bonan and Shugart 1989, Barnes et al. 1998). Some of these effects were direct (i.e., the loss of nutrients due to volatilization) and others indirect (e.g., ash or soil being washed into an aquatic system). The net sum of these effects were large and sudden changes in the productivity, rates of nutrient loss, and rates of decomposition in all terrestrial ecosystems that burned. This magnitude of change compounds the challenge of defining what is the ‘typical’ level of productivity in, or nutrient loss from, these ecosystems.

The interior lakes in VOYA can be compared to lakes studied in the southern boreal forest in northern Michigan by Bade et al. (2007), who found a relationship between dissolved organic carbon (DOC) sources, lake water color, and chl-*a* production by phytoplankton. In a nutrient-enriched lake, up to 40% of DOC was contributed by algal photosynthesis, but only 5% was so produced in a humic lake. Lakes with chl-*a* concentrations <5 µg $L^{-1}$ (e.g., five of VOYA’s eight index lakes) had DOC that was mostly terrestrial in origin (90%–95%), while those with the lowest color values (<1 $m^{-1}$) had a significant contribution from algal DOC.

The large lakes in VOYA are part of a regulated river and reservoir system and so can be considered riverine. The energy base of riverine systems is either organic input from the riparian and floodplain zones, algae (phytoplankton) in the system, or aquatic vascular plants rooted in the stream channel or along the bank (Zeug and Winemiller 2008). The relative importance of these often varies from high order streams (which have a much higher level of dependence on detritus) to low gradient and braided rivers (Cross et al. 2006). Rivers with dams, floodplains with large backwaters, or large amounts of woody debris have more autochthonous production than those without such features (NPS 2007 and citations therein). Rates of GPP and NPP vary among hydrologic regimes and climatic regions (e.g., Benke et al. 2000). Disturbance, in the form of floods, nutrient and sediment subsidy, and local topographic/edaphic factors, leads to differences among streams and rivers within a region (Day et al. 1988, Benke et al. 2000). The degree of disruption in hydrologic regime by human activity is a key factor; changes in flood frequency, timing, and extent have strong effects on the level of production (Valett et al. 2005, Zeug and Winemiller 2008), as does nitrogen and phosphorus input from the watershed (Ice and Binkley 2003, Slavik et al. 2004, Craig et al. 2008).

A measure of the flow of organic material through aquatic ecosystems is their trophic state. VOYA’s interior index lakes are generally oligotrophic (low in productivity), although a few tend toward mesotrophy (Figure 55). They are located in a nutrient-poor environment with little human input except for some recreational use and atmospheric deposition. VOYA’s large lakes, which are part of the Rainy Lake watershed, are more heavily used for recreation, have their water levels regulated, and are influenced by a large watershed area upgradient of the park. They are generally at the upper end of the oligotrophic range (tending toward mesotrophy); Kabetogama, the shallowest and most heavily developed, is mesotrophic and tending toward eutrophy (high productivity), as is Black Bay of Rainy Lake (Figure 56). The trophic state of the large lakes is also influenced by the parent material in the watershed; Kabetogama Lake, Sullivan Bay of Kabetogama Lake, and Black Bay receive inflow from an area overlain by calcareous drift. Thus, they have higher nutrients, chlorophyll-*a*, specific conductance, alkalinity, and pH, a lower Secchi depth, and a higher trophic state index than Sand Point and Namakan Lakes and the remainder of Rainy Lake (Kallemeyn et al. 2003).

The information needed to put together an energy flow budget is extensive, time consuming to collect, and quite costly to obtain (Cain et al. 2008). To use such ecosystem characteristics to gauge ‘health’ would require detailed, highly accurate, site specific measurements over an extended period of time. Thus, it is highly unlikely that such an investment would produce information, or an indicator, that is better than others that are more readily obtainable.

The flow of materials (nitrogen, phosphorus, and other essential minerals) into, through, and out of a system is more complex and less well understood than primary production. For forest systems at higher latitudes, decomposition and mineralization are limited by temperature (and moisture at times), so that nitrogen and other macronutrients commonly limit plant growth (Van Cleve et al. 1983, Bonan and Shugart 1989). In streams, productivity is influenced by nutrient concentrations, particularly phosphorus and nitrogen, but in low-order streams light limitation may be more important (Giller and Malmqvist 2002). One conceptual model of the processes of decomposition and recycling in a flowing river is a “nutrient spiral,” in which nutrients are assimilated from the water column into benthic biomass, temporarily retained, and mineralized back into the water column in a downgradient direction; this concept was first described by Webster (1975). Damming a river, or otherwise slowing its flow, has a sizeable effect on this nutrient cycling. In a reservoir, sediment is trapped, and oxygen levels are lower; these factors lead to the retention of phosphorus on particles that settle, and the loss of nitrogen in the nitrate form to denitrification (Stanley and Doyle 2002 and citations therein).

The processes carried out by a specific trophic level or functional group of a system are well known, but how long a given quantity of carbon or molecule of a nutrient stays in that trophic level is quite variable and not easy to predict. The difficulty is especially acute for all below-ground processes. This is true because of the difficulty of measuring processes accurately *in situ;* the vast, but unknown, number of organisms involved in decomposition; and the rapid changes in fine roots, microorganisms, and invertebrates in the soil (Cain et al. 2008). Thus, the situation for material flow is virtually identical to energy flow – a useful assessment would require a large commitment of time and money to produce the level of accuracy and sensitivity needed.

There are a few situations where the ‘flow’ of nutrients into and/or out of a system is itself the source of impairment. For aquatic systems, the most widespread case is the eutrophication of rivers and littoral zones caused by nutrient-laden runoff. Similarly, high levels of atmospheric deposition of acid-causing compounds (sulfur and nitrogen), or simply excessive amounts of nitrogen, can alter the typical functioning of any aquatic or terrestrial systems (see Section 4.4.1).

The GLKN has identified four monitoring categories related to ecosystem processes (NPS 2007). These are succession, trophic relations, nutrient dynamics, and primary productivity. They are 22nd, 26th, 39th, and 42nd, respectively, in the list of 46 vital signs (see Table 4). Only succession is currently scheduled for the development of a monitoring protocol.

Sources of Expertise

James Cook, Christine Mechenich, UWSP.

Literature Cited

Allan, J. D., and M. M. Castillo. 2007. Stream Ecology: Structure and Function of Running Waters, Second Edition. Springer, The Netherlands. 436 pp.

Bade, D. L., S. R. Carpenter, J. J. Cole, M. L. Pace, E. Kritzberg, M. C. Van de Bogert, R. M. Cory, and D. M. McKnight. 2007. Sources and fates of dissolved organic carbon in lakes as determined by whole-lake carbon isotope additions. *Biogeochemistry* 84:115–129.

Barnes, B. V., D. R. Zak, S. R. Denton, and S. H. Spurr. 1998. Forest Ecology, Fourth Edition. John Wiley and Sons, New York, New York. 792 pp.

Benke, A. C., I. Chaubey, G. M. Ward, and E. L. Dunn. 2000. Flood pulse dynamics of an unregulated river floodplain in the southeastern U.S. coastal plain. *Ecology* 81:2730–2741.

Bonan, G. B., and H. H. Shugart. 1989. Environmental factors and ecological processes in boreal foersts. *Annual Review of Ecology and Systematics* 20:1–18.

Cain, M. L., W. D. Bowman, and S. D. Hacker. 2008. Ecology. Sinauer Associates, Sunderland, Massachusetts. 544 pp.

Craig, L. S., M. A. Palmer, D. C. Richardson, S. Filoso, E. S. Bernhardt, B. P. Bledsoe, M. W. Doyle, P. M. Groffman, B. A. Hassett, S. S. Kaushal, P. M. Mayer, S. M. Smith, and P. R. Wilcock. 2008. Stream restoration strategies for reducing river nitrogen loads. *Frontiers in Ecology and the Environment* 6:529–538.

Cross, W. F., J. B. Wallace, A. D. Rosemond, and S. L. Eggert. 2006. Whole-system nutrient enrichment increases secondary production in a detritus-based ecosystem.(author abstract). *Ecology* 87:1556–1565.

Day, R. T., P. A. Keddy, J. McNeill, and T. Carleton. 1988. Fertility and disturbance gradients: A summary model for riverine marsh vegetation. *Ecology* 69:1044–1054.

Giller, P. S., and B. Malmqvist. 2002. The Biology of Streams and Rivers. Oxford University Press, New York, New York. 296 pp.

Hare, F., and J. C. Ritchie. 1972. The boreal bioclimates. *Geography Review* 62:333–365.

Ice, G., and D. Binkley. 2003. Forest streamwater concentrations of nitrogen and phosphorus—A comparison with EPA’s proposed water quality criteria. *Journal of Forestry* 101:21–28.

Kallemeyn, L., K. Holmberg, J. Perry, and B. Odde. 2003. Aquatic synthesis for Voyageurs National Park. Information and Technology Report USGS/BRD/ITR-2003-0001, U.S. Geological Survey, International Falls Biological Station, International Falls, Minnesota. Available at http://www.nature.nps.gov/water/cooperative_reports/VOYSYNTH.pdf (accessed 26 August 2014).

Megonigal, J. P., W. H. Conner, S. Kroeger, and R. R. Sharitz. 1997. Aboveground production in southeastern floodplain forests: a test of the subsidy-stress hypothesis. *Ecology* 78:370–384.

NPS (National Park Service). 2007. Long-term ecological monitoring plan: Great Lakes Inventory and Monitoring Network. Natural Resource Report NPS/GLKN/NRR—2007/001. National Park Service. Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/645523 (accessed 23 September 2013).

Slavik, K., B. J. Peterson, L. A. Deegan, W. B. Bowden, A. E. Hershey, and J. E. Hobbie. 2004. Long-term responses of the Kuparuk River ecosystem to phosphorus fertilization. *Ecology* 85:939–954.

Stanley, E. H., and M. W. Doyle. 2002. A geomorphic perspective on nutrient retention following dam removal. *BioScience* 52:693–701.

USEPA (United States Environmental Protection Agency) Science Advisory Board. 2002. A framework for assessing and reporting on ecological condition: an SAB report. EPA-SAB-EPEC-02-009. USEPA, Washington, D.C. Available at www.epa.gov/sab/pdf/epec02009.pdf (accessed 23 September 2013).

Valett, H. M., M. A. Baker, J. A. Morrice, C. S. Crawford, M. C. Molles, Jr., C. N. Dahm, D. L. Moyer, J. R. Thibault, and L. M. Ellis. 2005. Biogeochemical and metabolic responses to the flood pulse in a semiarid floodplain. *Ecology* 86:220–234.

Van Cleve, K., L. Oliver, R. Schlentner, L. A. Viereck, and C. T. Dyrness. 1983. Productivity and nutrient cycling in taiga forest ecosystems. *Canadian Journal of Forest Research* 13:747–766.

Webster, J. 1975. Analysis of potassium and calcium dynamics in stream ecosystems on three Southern Appalachian watersheds of contrasting vegetation. Dissertation. University of Georgia, Athens, Georgia.

Wetzel, R. G. 2001. Limnology: Lake and River Ecosystems, 3rd ed. Academic Press, San Diego, California. 1,006 pp.

Zeug, S. C., and K. O. Winemiller. 2008. Evidence supporting the importance of terrestrial carbon in a large-river food web. *Ecology* 89:1733–1743.

### 4.6. Hydrology of the Rainy Lake Watershed

The USEPA-SAB framework considers hydrology and geomorphology an essential ecological attribute because it reflects "the dynamic interplay of water flow and landforms" (USEPA 2002). Water flow patterns, both natural and human-influenced, and the interactions of water, riverbed, and riparian areas influence the natural diversity of habitats and species. Sediment and other material transport patterns are critical to a variety of underwater, riparian, and wetland habitats.

As previously noted, approximately 40% of VOYA is covered by water. This includes 26 interior lakes, 19 of which are located on the Kabetogama Peninsula, part of Rainy Lake, and parts or all of three of the five lakes that make up the Namakan Reservoir (Kabetogama, Crane, Sand Point, Little Vermilion, and Namakan). Kabetogama Lake is entirely within VOYA, as are parts of Namakan and Sand Point Lakes (Kallemeyn et al. 2003).

Thirteen of VOYA's interior lakes drain directly to Rainy Lake; these are the chains of Loiten-Quill-War Club-Locator, Little Shoepack-Shoepack, and Oslo-Brown-Peary, as well as Fishmouth, Beast, McDevitt, and Ryan. The remainder of the lakes on the Kabetogama Peninsula, as well as those south of Namakan Lake, drain to the Namakan Reservoir. The Namakan Reservoir drains into Rainy Lake through two natural spillways (Bear Portage and Gold Portage) and two stop-log sluice dams completed in 1914 at the once-natural rock sill outlets at Kettle Falls and Squirrel Falls (USACE 1999). The water level in Rainy Lake is controlled by a hydroelectric dam at Fort Frances – International Falls, downstream (west) of VOYA, completed in 1909 (Figure 60) (USACE 1999, Kallemeyn et al. 2003, Clark and Sellers 2014) and influenced by outflow through the Kettle Falls and Squirrel Falls dams.

Because Rainy Lake is part of the US-Canada border, it is subject to the Boundary Waters Treaty of 1909. In 1949, the International Rainy Lake Board of Control, established in 1941, issued an Order that established a single rule curve (target elevation that varied seasonally) for Rainy Lake and another for Namakan Lake as a method of precluding "emergency conditions" (high or low water levels that might affect power generation or the property of riparian owners) (USACE 1999). Supplementary Orders were issued in 1957 and 1970; the 1957 Order established an upper and lower rule curve for most of the year (excluding summer) on Namakan Lake, and the 1970 Order defined an upper and lower rule curve for both lakes, as well as a minimum outflow (IJC 2001). Under the 1970 Order, larger-than-natural fluctuations on Namakan Reservoir continued to be used to maintain less-than-natural fluctuations on Rainy Lake (Kallemeyn et al. 2003). Although concerns about the effects of the regulated lake levels on aquatic biota were expressed ever since the dams were constructed, the establishment of VOYA heightened concerns about the effects on the natural environment (Kallemeyn et al. 2003 and citations therein). Today, VOYA describes water level management in Rainy Lake and the Namakan Reservoir as the "most significant natural resource issue for Voyageurs National Park" (NPS 2013). In 2000, another Supplementary Order was issued; this specifies water level fluctuations more similar to pre-dam hydrology (NPS 2013). Seasonal variations and target variations are 2.0 m and 1.5 m in Namakan Reservoir and 1.05 m and 0.80 m in Rainy Lake (Clark and Sellers 2014).

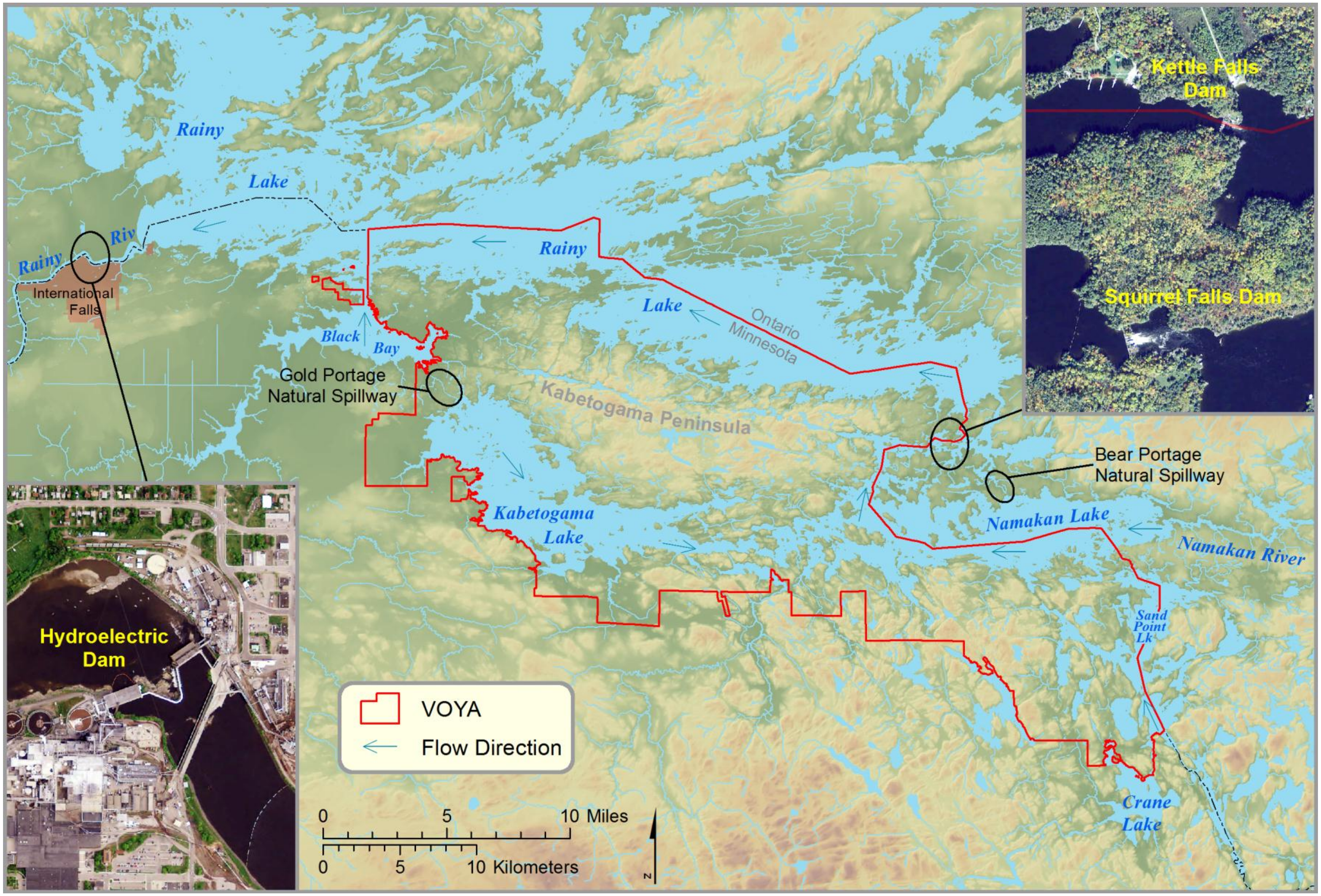

**Figure 60.** The hydrologic system and controls of the major lakes in Voyageurs National Park (USACE 1999, USDA 2010)

Edlund et al. (2014) undertook a study of sediment cores in four large lakes (Rainy, Namakan, and Kabetogama in VOYA and Lac La Croix, an upstream undammed site on the Rainy River). Historical diatom communities and biogeochemistry were examined. The authors noted that while water level changes have been a primary resource concern in border waters, they are not a dominant variable explaining historical changes in diatom communities. Land use explained the greatest portion of the variance, with logging being an important component of land use change, but the interaction of climate, water level, and land use created large, highly significant effects.

In 2007, the International Joint Commission began a process that resulted in the execution of a Plan of Study (Kallemeyn et al. 2009) to evaluate the effectiveness of the 2000 Rule Curves in preparation for providing a recommendation to maintain them or further adjust them in 2015. Eighteen studies, including cultural resources studies, economic studies, and natural resources studies on fish, aquatic vegetation, mussels, the benthic community, herptiles, and birds, are underway and are listed in Table 28.

Sources of Expertise
Christine Mechenich, UWSP.

Literature Cited

Clark, B. J., and T. J. Sellers, editors. 2014. Rainy-Lake of the Woods State of the Basin Report, 2nd Edition, July 2014. Lake of the Woods Water Sustainability Foundation, Kenora, Ontario. Available at http://ijc.org/files/publications/R-LoW_SOBR_2014_web-res.compressed.pdf (accessed 26 August 2014).

Edlund, M. B., C. A. Serieyssol Bleser, L. W. Kallemeyn, and D. R. Engstrom. 2014. Determining the historical impact of water-level management on lakes in Voyageurs National Park. Natural Resource Technical Report NPS/VOYA/NRTR—2014/920. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2217009 (accessed 8 July 2015).

Holmberg, K. L., B. Y. Odde, and J. Perry. 2005. Water resource management plan – Voyageurs National Park . National Park Service, Fort Collins, Colorado. Available at http://www.nature.nps.gov/water/planning/management_plans/voya_wrmp_final.pdf (accessed 26 August 2014).

IJC (International Joint Commission). 2001. In the matter of emergency regulation of the level of Rainy Lake and of other boundary waters in the Rainy Lake Watershed. Consolidation of the Order prescribing method of regulating the levels of boundary waters, dated 8 June, 1949, as amended by Supplementary Order dated 1 October, 1957, by Supplementary Order dated 29 July, 1970, and by Supplementary Order dated 5 January, 2000. IJC, Washington, D. C. Available at http://www.ijc.org/conseil_board/rainy_lake/docs/2001-01-18_IJC_Order.pdf (accessed 8 July 2015).

Kallemeyn, L., K. Holmberg, J. Perry, and B. Odde. 2003. Aquatic synthesis for Voyageurs National Park. Information and Technology Report USGS/BRD/ITR-2003-0001, U.S. Geological Survey,

**Table 28.** Description and status of studies being conducted to assess the effects of the 2000 Rule Curve for Rainy Lake and Namakan Reservoir (Table 3 in Clark and Sellers 2014, modified by Ryan Maki, VOYA aquatic ecologist, 12/10/2014).

| Study | Completion Date | Information Produced |
|---|---|---|
| Reservoirs - develop reservoir hydrologic model & reservoir PHABSIM habitat model | Complete | Model and descriptive text comparing flows and levels for Rainy Lake and Namakan Reservoir under 1970 and 2000 Rule Curve scenarios |
| | Anticipated 2015 | Models and descriptive text comparing habitat available for selected fish and wildlife species under 1970 and 2000 Rule Curve scenarios |
| Characterize the natural hydrology of Rainy River (HECRAS Model) vs. Rule Curves | Complete | Models and descriptive text comparing Rainy River hydrology under 1970 Rule Curve, 2000 Rule Curve, and pre-dam conditions |
| Measure changes in benthic community in relation to curves, in the reservoirs | Anticipated 2015 | Comparison of Rainy Lake and Namakan Reservoir benthic macroinvertebrate communities present under 1970 and 2000 Rule, Curves and assessment of aquatic macroinvertebrate communities present in vegetation beds and on coarse woody debris |
| Aquatic vegetation (replicate Meeker and Harris 2009) | Complete | Comparison of Rainy Lake and Namakan Reservoir aquatic vegetation communities present under 1970 and 2000 Rule Curves |
| Reservoirs – northern pike spawning habitat and reproductive success | Anticipated 2015 | Comparison of Rainy Lake and Namakan Reservoir northern pike spawning and nursery habitat available under 1970 and 2000 Rule Curves |
| Rainy River – critical spawning and nursery habitats | Anticipated 2015 | Comparison of upper Rainy River lake sturgeon, walleye, and log perch spawning habitat available under 1970 and 2000 Rule Curve conditions |
| Economic survey of impact of Rule Curves on tourist resorts on reservoirs | Anticipated 2015 | Assess tourism impacts of 1970 and 2000 Rule Curves on Rainy Lake and Namakan Reservoir resorts |
| Relate Rule Curve changes to flooding and ice effects on reservoirs | Anticipated 2015 | Comparison of Rainy Lake and Namakan Reservoir property damage due to flooding and ice under 1970 and 2000 Rule Curve conditions |
| Synthesis of four studies | Complete | Model and descriptive text comparing Rainy Lake and Namakan Reservoir common loon reproductive success under 1970 and 2000 Rule Curve scenarios |
| Detailed bathymetric mapping of the littoral zone of selected reservoir locations | Anticipated 2015 | Detailed bathymetric maps of selected nearshore areas of Rainy Lake and Namakan Reservoir to support assessments of habitat available under the 1970 and 2000 Rule Curves |
| Assess effects on cultural resources at a small number of sites on the reservoirs | Anticipated 2015 | Assessment of which set of Rule Curves (1970 or 2000) produce less damaging hydrologic conditions for cultural resources near Rainy Lake and Namakan Reservoir |
| Assess effects on cultural resources at benchmark sites on the Rainy River | Anticipated 2015 | Assessment of which set of Rule Curves (1970 or 2000) produce less damaging hydrologic conditions for cultural resources near the Rainy River |
| Assess effects on reservoir habitats for marsh-nesting birds/herps at selected sites | Completed | Comparison of marsh nesting bird and herptile habitat available under 1970 and 2000 Rule Curves |
| Identify critical river benthic habitats at X-sections; model effects of curve change | Will not be funded | Comparison of Rainy River benthic macroinvertebrate communities present under 1970 and 2000 Rule Curves |
| Measure unionid (mussel) diversity and abundance in the Rainy River re: effects | Anticipated 2016 | Assessment of 1970 and 2000 Rule Curve effects on Rainy River mussel community |
| Measure changes in fish community health (Index Biotic Integrity) re: effects | Anticipated 2015 | Assessment of 1970 and 2000 Rule Curve effects on Rainy River fish community health by using Index of Biotic Integrity |
| Measure critical spawning habitat for walleye on Namakan Reservoir re: effects | Anticipated 2015 | Assessment of effects of 1970 and 2000 Rule Curves on Namakan Reservoir walleye spawning habitat quantity and quality |
| Examine municipal water treatment and hatchery data for Rainy River re: effects | Anticipated 2015 | Assessment of whether the change from the 1970 Rule Curves to the 2000 Rule Curves affected the use of water from the Rainy River for municipal purposes or Manitou Rapids fish hatchery operation |

USDA (United States Department of Agriculture). 2010. National Agricultural Imagery Program (NAIP) Digital Orthorectified Images (DOQ), Minnesota, 2010. Minnesota Geospatial Information Office, (MnGeo), St. Paul, Minnesota. Available at http://www.mngeo.state.mn.us/chouse/airphoto/naip10.html (accessed 26 August 2014).

USEPA (United States Environmental Protection Agency) Science Advisory Board. 2002. A framework for assessing and reporting on ecological condition: an SAB report. EPA-SAB-EPEC-02-009. USEPA, Washington, D.C. Available at http://www.epa.gov/sab/pdf/epec02009.pdf (accessed 19 September 2013).

Weeks, D., and R. Andrascik. 1998. Voyageurs National Park, Minnesota, water resources scoping report. Technical report NPS/NRWRS/NRTR—98/2021, National Park Service, Fort Collins, Colorado.

# 5. Discussion

Of the 39 natural resource condition indicators evaluated for VOYA in this NRCA, 17 were in "good" condition, eight were in condition of "moderate concern," 11 were in condition of "significant concern," and the condition of the remaining three was "unknown." Three had an improving trend, 21 were stable, one showed a deteriorating trend, and the trend for 14 was uncertain. Confidence in the assessment was high for 24 indicators, moderate for 12, and unknown for three.

## 5.1. Disturbance Regimes

The dominant component of the natural disturbance regime in the southern boreal forest at VOYA is fire; though generally infrequent, most fires are moderate-to-high severity and thus have major influences on the vegetation. Of secondary importance are low-severity wind, herbivory, and other small-scale disturbances. There are also occasional-to-very infrequent moderate-to-severe disturbances; most commonly these are wind events. Reference conditions were not established for these. The eastern spruce budworm and the forest tent caterpillar are the two herbivores that present the most significant threats to the trees in VOYA, especially balsam fir and aspen. Human disturbance in the form of logging affected the Kabetogama Peninsula through the 1960s. Kirschbaum and Gafvert (2010) found that from 2002–2007, the dominant forms of disturbance in VOYA were fire (0.33% of the VOYA land area was disturbed by fire from 2002–2007), beaver activity (0.18%), and blowdown (0.15%).

## 5.2. Landscape Condition

Landscape condition for VOYA was assessed in the categories of land cover, impervious surfaces, landscape pattern and structure, road density, lightscapes, and soundscapes (Table 29). Using the metric of annual land cover change, VOYA is in good condition, with a stable trend. Land cover change at VOYA is within the range of values for the nearby lower Lake Superior basin. Compared to other NPS units in the region, it is higher than at APIS, ISRO, or MISS, but lower than at SACN (Kirschbaum and Gafvert 2010, 2013 and citations therein). The 2011 NLCD (USGS 2011, Jin et al. 2013) shows that from 2001–2006 and 2006–2011, land cover change was 0.33% and 0.44%, respectively, and all changes were from one natural category to another. Because a six-year window may not capture infrequent, moderate to severe natural disturbances, the LandTrendr analyses of Kirschbaum and Gafvert (2010) should be compared over longer time frames as the GLKN cycle continues.

VOYA is in good and stable condition for the extent of impervious surfaces and road density (USGS 2011, NPS 2014). Because of the lack of severe fire in recent times, the current level of dominant to intact forest cover (94%, NPS 2012) is likely at the upper end of or outside of the historic range of variability. VOYA lightscapes are considered to be in good condition, although recent data are qualitative. The condition of VOYA's soundscapes is unknown but likely of moderate concern because of the popularity of motorized recreation in the park.

## 5.3. Biotic Condition

The composition and structure of the landscape and the structure and abundance of forest and woodland communities at VOYA are probably outside their historic range of variability and are of moderate concern. All assessments indicate less area dominated by pine and more dominated by aspen-birch. Regarding terrestrial exotic plants, VOYA is in good condition based on extent, but several problematic species have become established. plants. Exotic earthworms and their effects have been documented in the aspen-fir forest at VOYA (Hale and Host 2005). The population of moose is considered to be stable in the short term, but of significant concern because it is only about half that of 1991–1992 (Windels 2014).

In the aquatic ecosystem of VOYA, the fish community is generally in good and stable condition, with most species reaching their MDNR target population levels. The zoobenthic community appears to be stabilizing in the large lakes in equilibrium with the water management regime (rule curve) established in 2000. However, aquatic invasive species are of significant concern at VOYA; the spiny water flea invasion has reduced the abundance and biomass of the zooplankton community in the five large lakes in and near VOYA, creating a condition of significant concern.

## 5.4. Physical and Chemical Condition

Overall, air quality at VOYA is of significant concern, based on the individual assessments of significant concern for wet deposition of total nitrogen and total sulfur and moderate concern for ozone and visibility (Table 29) (NPS 2013a, 2013b). Both regulated facilities and nonpoint pollution sources emit tens of thousands of metric tons of criteria air pollutants within 250 km of VOYA each year (Environment Canada 2012, USEPA 2013). Trends for all assessed air pollutants are stable.

Water quality in the interior lakes in VOYA, as measured by pH, chloride, dissolved oxygen, total nitrogen, total phosphorus, water clarity, and chlorophyll-*a*, is good, with generally stable trends. These lakes have small watersheds and are not greatly affected by human activities within the park. Alkalinity is naturally low in the interior lakes, but is of significant concern because it creates a susceptibility to acidification in the presence of acid precipitation.

The large lakes at VOYA receive input from the large Rainy River watershed, and their quality is affected by land use both locally and regionally and by the manipulation of water levels that occurs at the dams. They are in good condition for pH, dissolved oxygen, and water clarity, but are in a condition of moderate concern for alkalinity, total phosphorus, and chlorophyll-*a*. Trends for both dissolved oxygen and chlorophyll-*a* are improving in the large lakes.

Mercury is a pollutant of significant concern in the precipitation, fish tissue, and surface water of VOYA. Only mercury in precipitation shows an improving trend.

## 5.5. Ecological Processes

Energy flow and material flow, the two primary categories of ecological processes, are of great importance in ecosystems but are costly and time consuming to measure. No specific assessments were found for the terrestrial ecosystems in VOYA. Trophic states have been calculated for the aquatic ecosystems in VOYA; the interior lakes are generally oligotrophic, with a few tending toward mesotrophy. The large lakes are generally at the upper end of the oligotrophic range to the lower end of the mesotrophic range, with Kabetogama, the shallowest and most heavily developed, and Black Bay tending toward eutrophy. The GLKN lists four monitoring categories related to ecosystem processes (succession, trophic relations, nutrient dynamics, and primary productivity), but only succession is currently scheduled for the development of a monitoring protocol.

### 5.6. Hydrology of the Rainy Lake Watershed

VOYA managers have designated water level management in Rainy Lake and the Namakan Reservoir as the most significant natural resource issue for the park (NPS 2013d). Water levels in this system are manipulated using sluice dams at Kettle Falls and Squirrel Falls and the hydroelectric dam at Fort Frances-International Falls. The rule curves (bands of allowable high and low water levels throughout the year) have been adjusted by the International Rainy Lake Board of Control over time. The 2000 rule curves specify water level fluctuations more similar to pre-dam hydrology than those in the past (NPS 2013d). Seventeen studies have been completed or are currently underway to evaluate the effects of the new rule curves on natural resources, cultural resources, and economics; most results should be available in 2015 or 2016.

Literature Cited

Brigham, M. E., M. B. Sandheinrich, D. A. Gay, R. P. Maki, D. P. Krabbenhoft, and J. G. Wiener. 2014. Lacustrine responses to decreasing wet mercury deposition rates—results from a case study in northern Minnesota. *Environmental Science & Technology* 48:6115–6123.

Environment Canada. 2012. National Pollutant Release Inventory: 2010 facility-reported data (Pollutant releases and transfers). Gatineau, Quebec, Canada. Available at http://www.ec.gc.ca/inrp-npri/ (accessed 3 October 2012).

Goldstein, R. M., M. E. Brigham, L. Steuwe, and M. A. Menheer. 2003. Mercury data from small lakes in Voyageurs National Park, Northern Minnesota, 2000–02. USGS Open-File Report 2003-480, USGS, Mounds View, Minnesota. Available at http://pubs.er.usgs.gov/publication/ofr2003480 (accessed 5 August 2014).

Hale, C. M., and G. E. Host. 2005. Assessing the impacts of European earthworm invasions in beech-maple hardwood and aspen-fir forests of the western Great Lakes Region. National Park Service Great Lakes Inventory & Monitoring Network Report GLKN/2005/11. National Park Service, Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/592019 (accessed 18 August 2014).

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment* 132:159–175. Available at http://www.mrlc.gov/nlcd2011.php (accessed 13 May 2014).

**Table 29.** Natural Resource Condition Assessment summary table.

**Landscape Condition**

| Priority Resource or Value | Indicator of Condition | Specific Measures | Condition Status/Trend | Rationale |
|---|---|---|---|---|
| **Current Land Cover** | Stability over 5–10 year timeframes, comparison to rate of change in other Great Lakes Network parks or in the Lake Superior basin (0.32% $yr^{-1}$, Stueve et al. 2011). | Rate of change per year, 2002–2007 | 🟢↔ | The rate of change from 2002–2007 was 0.01%–0.25% $yr^{-1}$ (Kirschbaum and Gafvert 2010), meeting the reference condition at VOYA but not in the Minnesota AOA (0.72 $yr^{-1}$) or the Canadian AOA (1.15% $yr^{-1}$). VOYA had a higher rate of disturbance over a six-year period than APIS, ISRO, or MISS. |
| **Landscape Pattern and Structure** | Impervious surfaces | % impervious cover in watershed | 🟢↔ | Within VOYA, 99.9% of the land area is 0% impervious, and the mean impervious value for the park is 0.02% (USGS 2011). |
| | Forest density | Historic range of variability | 🟡 | The current level of forest categorized as dominant to intact (93.9%) is likely at the upper end of or outside the historic range of variability. |
| | Forest morphology | Historic range of variability | ◌ | No data were available to quantify historic forest morphology. |
| | Road density | Road density in km $km^{-2}$ and areas at least 10 $km^2$ and at least 500 m from roads. | 🟢↔ | Road density in VOYA met each of the reference conditions for black bear, gray wolf, and moose habitat. |
| **Lightscapes** | Natural night sky condition | | 🟢 | A 2012 report characterized the natural lightscape of VOYA as “undisturbed” but did not provide quantitative data. |
| **Soundscapes** | Natural ambient sound levels | | ◌ | No data were found, but VOYA likely experiences sound pollution from motorized recreational vehicle (watercraft and snowmobile) use. |

**Table 29 (continued).** Natural Resource Condition Assessment summary table.

| **Biotic Condition** | | | | |
|---|---|---|---|---|
| **Priority Resource or Value** | **Indicator of Condition** | **Specific Measures** | **Condition Status/Trend** | **Rationale** |
| **Vegetation** | Natural range of variation of structure and composition | Presettlement terrestrial vegetation | 🟡 ↔ | All assessments indicate a larger amount of aspen-birch dominated area and less pine-dominated area than what existed historically. |
| | Presence of terrestrial exotic plants | % of land requiring treatment for invasives | 🟢 | Less than 1% of the total area of VOYA has been documented as requiring inventory or treatment for terrestrial invasive plants. |
| **Earthworms** | Presence | Types and numbers present. | 🟡 | Hale and Host (2005) have documented the presence and effects of earthworms in the aspen-fir forest at VOYA. |
| **Moose** | Presence | Numbers in relation to historic density | 🔴 ↔ | The moose population is moderately stable in recent times but only about half that of 1991–1992 (Windels 2014). |
| **Fish Community** | Composition of fish community and abundance of fish | MDNR target levels for fish species populations | 🟢 ↔ | With a few exceptions, native species are thriving, species of special concern appear to be recovering, and few non-native species are present. |
| **Zooplankton Community** | Composition and abundance | Types and numbers present | 🔴 ↓ | Zooplankton abundances and biomass have declined within the five large lakes in VOYA, likely due to the invasion of the spiny water flea. |
| **Zoobenthic Community** | Composition and abundance | Types and numbers present | 🟢 ↔ | The community appears to be stabilizing in the large lakes in equilibrium with the new rule curve (water management regime). |
| **Aquatic Invasive Species** | Presence and abundance | Types and numbers present | 🔴 ↔ | Rainbow smelt have been stable or declining; spiny water flea is having impact; rusty crayfish are present but surveys have been limited; zebra mussels are present downstream. |

**Table 29 (continued).** Natural Resource Condition Assessment summary table.

| **Physical and Chemical Condition** | | | | |
|---|---|---|---|---|
| **Priority Resource or Value** | **Indicator of Condition** | **Specific Measures** | **Condition Status/Trend** | **Rationale** |
| **Air Quality** | Overall | Weighted calculation | 🔴 | Overall, air quality at VOYA is of significant concern, based on the individual scores for wet deposition, ozone, and visibility. Using the NPS weighted calculation method, its overall score is 6.33 for 2006-2012, with >6 being of significant concern (NPS 2013b). |
| | Ozone | Annual 4th highest daily maximum 8-hour ozone concentration | 🟡 | Five-year averages of annual 4th highest daily maximum 8-hour ozone concentrations for VOYA range from 61.2 ppb for 2008–2012 to 63.8 ppb for 2005–2009. These are below the level of significant concern, 76 ppb. |
| | Visibility | Deciviews | 🟡 | Five-year averages for visibility were of moderate concern at VOYA from 2005–2012, with a range of 3.5–4.0 deciviews. |
| | Wet deposition of nitrogen | Kilograms N per hectare per year | 🔴 | Five-year averages for wet deposition of total N exceeded the level of significant concern of 3 kg $ha^{-1}$ $yr^{-1}$ at VOYA, with values of 3.0–3.1 kg $ha^{-1}$ $yr^{-1}$ from 2005–2012. Nitrogen deposition may cause acidification of both aquatic and terrestrial ecosystems and adds nutrients that can lead to eutrophication. |
| | Wet deposition of sulfur | Kilograms S per hectare per year | 🔴 | Five-year averages of wet deposition of total S ranged from 1.2–1.5 kg $ha^{-1}$ $yr^{-1}$ from 2005–2012. These are rated as of significant concern because VOYA is ranked as very high in sensitivity to acidification. Like nitrogen deposition, sulfur deposition may cause acidification of ecosystems. |

**Table 29 (continued).** Natural Resource Condition Assessment summary table.

| **Physical and Chemical Condition** | | | | |
|---|---|---|---|---|
| **Priority Resource or Value** | **Indicator of Condition** | **Specific Measures** | **Condition Status/Trend** | **Rationale** |
| **Water Quality** | Specific conductance | µmhos cm$^{-1}$ | ◌ | Annual means for specific conductance for interior lakes ranged from 17–66 µmhos cm$^{-1}$ from 2006–2012. The range of annual means for large lakes was 27–145 µmhos cm$^{-1}$ from 1977–2013. Upward trends were noted in both some interior and large lakes. There is no water quality standard for specific conductance. |
| | pH | pH units | 🟢 ⇔<br>interior lakes<br>🟢<br>large lakes | Both interior index lakes and large lakes met their reference condition of 6.5–8.5 or 6.5–9 pH units, based on annual means, with a few exceptions. pH showed an increasing trend over the period of record at Ek and Little Vermilion Lakes. |
| | Alkalinity | mg L$^{-1}$ as calcium carbonate | 🔴<br>interior lakes<br>🟡<br>large lakes | All but two interior lakes had annual (2006–2012) means for alkalinity below the minimum standard of 20 mg L$^{-1}$. The large lakes had annual means from 7.65–42.5 mg L$^{-1}$, but only Kabetogama and Crane Lakes consistently met the standard. Upward trends were noted in Kabetogama and Sand Point Lakes and a downward trend was observed in Rainy Lake. |
| | Chloride | mg L$^{-1}$ | 🟢<br>interior lakes | Annual means for chloride in the interior lakes (2006–2012) were far below the maximum standard of 230 mg L$^{-1}$, with a maximum of 1.1 mg L$^{-1}$. Data were insufficient to calculate a trend. Chloride data were not available for the large lakes. |

**Table 29 (continued).** Natural Resource Condition Assessment summary table.

**Physical and Chemical Condition**

| Priority Resource or Value | Indicator of Condition | Specific Measures | Condition Status/Trend | Rationale |
|---|---|---|---|---|
| **Water Quality** (continued) | Dissolved oxygen | mg L$^{-1}$ | 🟢↔<br>interior lakes<br>🟢↑<br>large lakes | Annual DO means for the interior lakes (2006–2012) and large lakes (1977–2012) ranged from 6.8–11.3 and 7.9–16.3 mg L$^{-1}$, respectively, exceeding the applicable minimum standards of 5 and 7 mg L$^{-1}$, and an increasing trend was detected in four of the large lakes. |
| | Total nitrogen | µg L$^{-1}$ | 🟢↔<br>interior lakes | Annual mean TN (2006–2012) exceeded the USEPA reference condition of 400 µg L$^{-1}$at all the interior index lakes except Little Trout and Cruiser, indicating that water quality for TN is not within the best 25% of sites in its nutrient ecoregion. However, there is no MN standard for TN. No TN data were available for the large lakes. |
| | Total phosphorus | µg L$^{-1}$ | 🟢↔<br>interior lakes<br>🟡↔<br>large lakes | Annual (2006–2012) means for TP in the interior index lakes, except for Cruiser Lake, met their standard of 12 or 30 µg L$^{-1}$ TP. All the large lakes had some annual TP means above their respective standard between 1983 and 2012. (Crane Lake was not included in the analysis). TP levels appear to be dropping in the large lakes, but statistically significant decreases were not found. |
| | Water clarity | Secchi depth | 🟢↔ | Annual (2006–2012) mean water clarity in the interior index lakes, except for Shoepack and Ek, met their respective standards of 2 and 4.8 m. Kabetogama, Namakan, and Rainy Lakes met their minimum standard of 2 m, but Crane and Sand Point did not meet their 4.8 m. standard. Kabetogama and Rainy Lakes had an improving trend in water clarity from 1981–2012. |

**Table 29 (continued).** Natural Resource Condition Assessment summary table.

| **Physical and Chemical Condition** | | | | |
|---|---|---|---|---|
| **Priority Resource or Value** | **Indicator of Condition** | **Specific Measures** | **Condition Status/Trend** | **Rationale** |
| **Water quality** (continued) | Chlorophyll-*a* | µg L$^{-1}$ | 🟢 ↔<br>interior lakes<br>🟡 ↑<br>large lakes | All interior index lake annual means (2006–2012) for chl-*a* generally met their designated standard of 3 or 9 µg L$^{-1}$. Only Cruiser Lake had a trend; chl-*a* was decreasing. In recent years, Kabetogama has rarely exceeded its 9 µg L$^{-1}$ standard, and Crane and Sand Point have occasionally exceeded their more stringent 3 µg L$^{-1}$ standard. Kabetogama and Sand Point Lakes showed improving chl-*a* trends from 1978–2012. |
| **Mercury** | Precipitation | ng L$^{-1}$ | 🔴 ↑ | Hg concentrations in precipitation at Fernberg and Marcell, MN consistently exceed the reference condition of 2 ng L$^{-1}$. At Fernberg, the closest MDN station to VOYA, 14.7% of samples exceeded 20 ng L$^{-1}$. |
| | Fish tissue for human consumption | Fish consumption advisories | 🔴 | MDH (2013) has issued fish consumption advisories for the Rainy River and all VOYA lakes that have been sampled for fish tissue Hg concentrations. Rainy River and Cruiser, Ek, Kabetogama, Little Trout, Mukooda, and Peary Lakes are on the proposed list of waters impaired for Hg in fish tissue (MPCA 2014). Tooth and Ryan Lakes have the highest fish tissue Hg levels measured within the state of MN (Goldstein et al. 2003). |
| | Fish tissue for fish health | ppb in fish tissue | 🔴 | Hg levels in 67% of northern pike analyzed in recent years exceeded 500 ppb wet weight, a level that has been associated with tissue and cell damage and altered biochemical processes (NPS 2013c) and exceeds the thresholds where sublethal reproductive effects have been documented (Sandheinrich and Wiener 2011). |

**Table 29 (continued).** Natural Resource Condition Assessment summary table.

| **Physical and Chemical Condition** | | | | |
|---|---|---|---|---|
| **Priority Resource or Value** | **Indicator of Condition** | **Specific Measures** | **Condition Status/Trend** | **Rationale** |
| **Mercury** (continued) | Surface water | ng $L^{-1}$ | 🔴 | Of six interior lakes monitored from 2006–2012, only Peary Lake met the reference condition of 1.3 ng $L^{-1}$. Brigham et al. (2014) observed no significant trends in total Hg concentrations in Brown, Peary, and Ryan Lakes from 2000–2012 but detected a significant upward trend in Shoepack Lake. |

Kirschbaum A. A., and U. B. Gafvert. 2010. Landsat-based monitoring of landscape dynamics at Voyageurs National Park, 2002–2007. Natural Resource Technical Report. NPS/GLKN/NRTR—2010/356. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2124866 (accessed 5 May 2014).

Kirschbaum, A. A., and U. B. Gafvert. 2013. Landsat-based monitoring of landscape dynamics at Mississippi National River and Recreation Area, 2005–2010. Natural Resource Technical Report NPS/GLKN/NRTR—2013/745. National Park Service, Fort Collins, Colorado. Available at https://irma.nps.gov/App/Reference/Profile/2195280 (accessed 28 October 2013).

MDH (Minnesota Department of Health). 2013. Fish consumption guidelines for women who are or may become pregnant and children under age 15, rivers. Minnesota Department of Health, St. Paul, Minnesota. Available at http://www.health.state.mn.us/divs/eh/fish/eating/specpoprivers.pdf (accessed 5 August 2014).

MPCA (Minnesota Pollution Control Agency). 2014. 2014 Proposed Impaired Waters List (wq-iw1-47). MPCA, St. Paul, Minnesota. Available at http://www.pca.state.mn.us/index.php/water/water-types-and-programs/minnesotas-impaired-waters-and-tmdls/impaired-waters-list.html (accessed 4 August 2014).

NPS (National Park Service). 2012. NPS Natural Resource Stewardship and Science Inventory and Monitoring Division. NPScape Metric GIS Data—Landscape pattern. Geospatial Dataset-2184565. Available at https://irma.nps.gov/App/Reference/Profile/2184565 (accessed 11 December 2013 for NLCD and 31 March 2014 for NALC).

NPS (National Park Service), Air Resources Division. 2013a. Air quality in national parks: trends (2000–2009) and conditions (2005–2009). Natural Resource Report NPS/NRSS/ARD/NRR—2013/683. National Park Service, Denver, Colorado. Available at http://www.nature.nps.gov/air/Pubs/pdf/gpra/AQ_Trends_In_Parks_2013.pdf (accessed 25 August 2014).

NPS (National Park Service). 2013b. Methods for determining air quality conditions and trends for park planning and assessments. NPS Air Resources Division, Natural Resource Program Center, Denver, Colorado. Available at http://www.nature.nps.gov/air/Planning/docs/AQ_ConditionsTrends_Methods_2013.pdf (accessed 25 August 2014).

NPS (National Park Service). 2013c. Effects of mercury on northern pike at Voyageurs NP. Great Lakes Network Monitoring Brief. GLKN, Ashland, Wisconsin. Available at https://irma.nps.gov/App/Reference/Profile/2196643 (accessed 11 August 2014).

NPS (National Park Service). 2013d. Restoring and maintaining water quality and aquatic ecosystem health at Voyageurs National Park through bi-national cooperation (webpage). Available at http://www.nature.nps.gov/water/homepage/WorldWaterDay_VOYA.cfm (accessed 28 August 2014).

NPS (National Park Service). 2014. NPScape standard operating procedure: Roads measure –road density, distance from roads, and areas without roads. Version 2014-01-06. National Park Service, Natural Resource Stewardship and Science. Fort Collins, Colorado. Available at http://science.nature.nps.gov/im/monitor/npscape/methods_sops.cfm (accessed 6 May 2014).

Sandheinrich, M. B., and J. G. Wiener. 2011. Methylmercury in freshwater fish: recent advances in assessing toxicity of environmentally relevant exposures. Pages 169–190 *in* W. N. Beyer and J.P. Meador, editors. Environmental Contaminants in Biota: Interpreting Tissue Concentrations, 2nd edition. Taylor and Francis Publishers, Boca Raton, Florida.

USEPA (United States Environmental Protection Agency). 2013. The 2011 national emissions inventory website. Available at http://www.epa.gov/ttn/chief/net/2011inventory.html (accessed 16 December 2013).

USGS (United States Geological Survey). 2011. National Land Cover Database 2006. USGS, Sioux Falls, South Dakota. Available at http://www.mrlc.gov/nlcd2006.php (accessed 28 November 2011).

Windels, S. K. 2014. 2014 Voyageurs National Park moose population survey report. Natural Resource Data Series NPS/VOYA/NRDS—2014/645. National Park Service, Fort Collins, Colorado.

# Appendix A. GIS Layers, Datasets for Base Maps, and Summary/Analysis Files

All maps and associated geoprocessing were done with the ArcGIS 10.2 software by Environmental Systems Research Institute, Inc., Redlands, CA (2014). Map layouts and source data layers are generally in the NAD 1983 UTM Zone 15N coordinate system (NLCD, NALC and NPScape metric related layers, including forest density and morphology, roads, population, and areas of analysis, are Albers Conical Equal Area). See metadata for details. Spatial data obtained in other datums or coordinate systems were reprojected using ArcGIS.

All GIS datasets are contained in the VOYA.gdb geodatabase along with associated metadata. The geodatabase, map document files, layer definition files, and png/pdf versions of the report figures were packaged on a DVD submitted with the report. Map documents use relative pathnames to data sources and therefore should open properly if kept in the same directory as the geodatabase.

References for specific map content are included in the map caption or are described in the report text that refers to the figure. All base map layers and metadata are included in the geodatabase but are generally not referenced in the report. These layers include:

Voyageurs National Park (VOYA) boundary (and other NPS units):
National Park Service. 2012. Current Administrative Boundaries of National Park System Units – Voyageurs National Park (accessed through the NPS IRMA Portal on 13 December 2012).

Elevation layers (and related hillshading created with ArcGIS):
U.S. Geological Survey. 2011. 1-Arc Second National Elevation Dataset. Available at http://nationalmap.gov/viewer.html (accessed 17 May 2013).

Surface water features (NHDs) and watershed boundary datasets (WBDs):
U.S. Geological Survey. 2012. NHD…Flowline/NHD…Area/NHD…Waterbody/WBD_HU... Available at http://nhd.usgs.gov/data.html (accessed 13 December 2012).

Counties and States basemap layers, International Boundary layer – created in ArcGIS from:
Environmental Systems Research Institute, Inc. (ESRI). 2002. Canada Provinces, U.S. Detailed County Boundaries. ESRI Data & Maps 2002 CD.

Minnesota Municipalities:
Minnesota Department of Transportation (MnDOT). 2002. Municipal Boundaries. Available at http://deli.dnr.state.mn.us (accessed 14 November 2012).

Various background/work layers were created in ArcGIS (see metadata for details), including VOYA buffers (50–250 km) for air emission maps, various areas of analysis (AOAs) for NPScape metrics, and conversion of NLCD2006 to a polygon overlay.

The DVD also includes a Spreadsheets subdirectory with Excel spreadsheets for air, landscape, mercury, vegetation, water quality and other topics with source and/or summary data.

# Appendix B. Parameters Measured at Air Quality Monitoring Sites in Voyageurs National Park

During the scoping meeting at VOYA in June 2013, VOYA resource managers expressed a need for a better understanding of the data collected at the air monitoring sites in the park. Therefore, we have prepared this brief summary and provided links to the data for further analysis.

As indicated in Chapter 4.4.1., VOYA has the following air monitoring sites that are part of national air quality monitoring networks:

- A National Atmospheric Deposition Program (NADP) site (MN 32) (http://nadp.sws.uiuc.edu/) that monitors wet deposition of major cations (hydrogen, calcium, magnesium, potassium, sodium, and ammonium) and anions (nitrate, chloride, and sulfate).
- A national Clean Air Status and Trends Network (CASTNet) site (VOY413) (http://epa.gov/castnet/javaweb/index.html) that monitors ozone and dry deposition of nitrogen and sulfur compounds. CASTNet also incorporates wet deposition data from the NADP site into its databases and graphics found on its website.
- An Interagency Monitoring of Protected Visual Environments (IMPROVE) site, (http://vista.cira.colostate.edu/improve/Web/MetadataBrowser/MetadataBrowser.aspx), which measures the concentration of fine aerosols, particulate matter less than 2.5 microns in size ($PM_{2.5}$) and 10 microns in size ($PM_{10}$), and light extinction and scattering.

These monitoring sites are located within VOYA south of Sullivan Bay, approximately 2.9 km southeast of the Ash River Visitor Center (Figure B-1).

NADP Mercury Deposition Network (MDN) sites are located at Fernberg Road in the BWCAW (82 km SE) and Marcell (103 km SSW).

These sites are also described in the MPCA 2015 Annual Air Monitoring Network Plan (http://www.pca.state.mn.us/index.php/view-document.html?gid=21126).

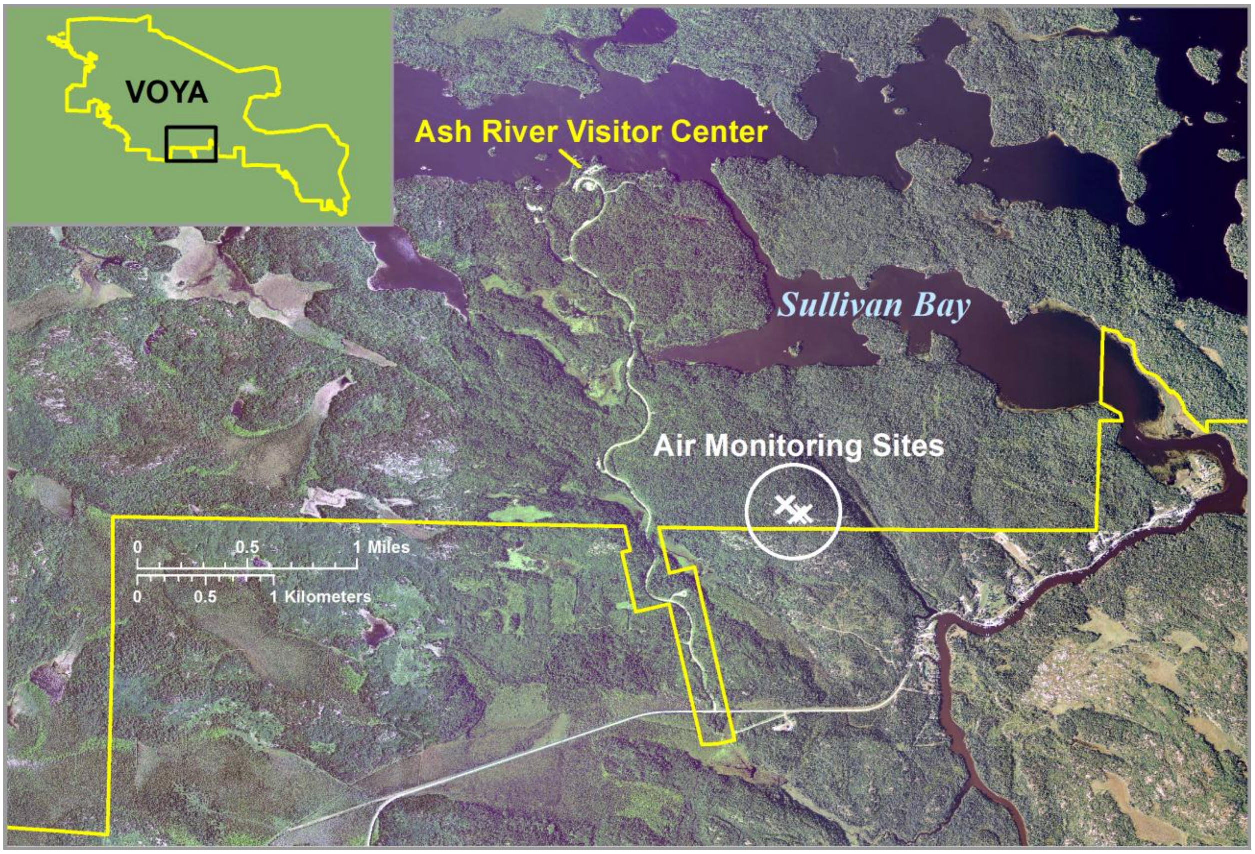

**Figure B-1**. Location of air monitoring sites within Voyageurs National Park (based on coordinates given at individual websites, but all considered to be at one location by MPCA).

**Table B-1**. Annual wet deposition data and basic statistics for 2001–2013 for the NADP site MN 32 in Voyageurs National Park. Weekly data are available from 30 May 2000 to present.

| Year | Precipitation (cm) | Calcium | Magnesium | Potassium | Sodium | Ammonium ($NH_4$-N) | Nitrate ($NO_3$-N) | Inorganic N | Chloride | Sulfate ($SO_4$-S) | H+(Lab) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (kg ha$^{-1}$) | | | | | | | | | |
| 2000 (½ year) | 48.09 | 0.66 | 0.087 | 0.096 | 0.087 | 0.824 | 0.909 | 1.73 | 0.17 | 0.917 | 0.04 |
| 2001 | 92.94 | 1.33 | 0.195 | 0.112 | 0.149 | 2.176 | 1.916 | 4.09 | 0.33 | 1.820 | 0.06 |
| 2002 | 70.63 | 1.49 | 0.198 | 0.177 | 0.226 | 2.479 | 1.921 | 4.40 | 0.30 | 1.853 | 0.04 |
| 2003 | 52.34 | 0.77 | 0.115 | 0.089 | 0.079 | 1.298 | 1.225 | 2.53 | 0.17 | 1.060 | 0.04 |
| 2004 | 78.63 | 1.02 | 0.149 | 0.118 | 0.149 | 2.176 | 1.577 | 3.75 | 0.29 | 1.846 | 0.05 |
| 2005 | 79.05 | 1.26 | 0.190 | 0.126 | 0.087 | 2.191 | 1.539 | 3.73 | 0.24 | 1.766 | 0.04 |
| 2006 | 55.52 | 1.04 | 0.167 | 0.133 | 0.117 | 1.841 | 1.205 | 3.05 | 0.23 | 1.363 | 0.02 |
| 2007 | 63.64 | 0.80 | 0.115 | 0.115 | 0.134 | 1.841 | 1.202 | 3.04 | 0.24 | 1.393 | 0.04 |
| 2008 | 78.73 | 1.12 | 0.157 | 0.157 | 0.142 | 1.873 | 1.236 | 3.11 | 0.26 | 1.567 | 0.04 |
| 2009 | 85.42 | 1.32 | 0.205 | 0.120 | 0.137 | 1.873 | 1.236 | 3.11 | 0.25 | 1.337 | 0.03 |
| 2010 | 88.58 | 1.32 | 0.177 | 0.142 | 0.115 | 1.958 | 1.094 | 3.05 | 0.26 | 1.210 | 0.03 |
| 2011 | 57.35 | 1.34 | 0.218 | 0.126 | 0.132 | 1.562 | 0.972 | 2.53 | 0.24 | 0.900 | 0.02 |
| 2012 | 77.82 | 1.48 | 0.202 | 0.187 | 0.187 | 2.494 | 1.257 | 3.75 | 0.27 | 1.133 | 0.01 |
| 2013 | 81.84 | 1.36 | 0.213 | 0.147 | 0.123 | 2.510 | 1.211 | 3.72 | 0.25 | 1.097 | 0.02 |
| Mean (2001–2013) | 74.04 | 1.20 | 0.177 | 0.135 | 0.137 | 2.021 | 1.353 | 3.37 | 0.26 | 1.411 | 0.03 |
| Minimum (2001–2013) | 52.34 | 0.77 | 0.115 | 0.089 | 0.079 | 1.298 | 0.972 | 2.53 | 0.17 | 0.900 | 0.01 |
| Maximum (2001–2013) | 92.94 | 1.49 | 0.218 | 0.187 | 0.226 | 2.510 | 1.921 | 4.40 | 0.33 | 1.853 | 0.06 |
| Std. Dev (2001–2013) | 13.08 | 0.24 | 0.035 | 0.027 | 0.038 | 0.365 | 0.297 | 0.58 | 0.04 | 0.331 | 0.01 |

The NADP data provides information about deposition of acidic compounds (ammonium, nitrate, sulfate, and hydrogen ions) and base cations (calcium, magnesium, potassium, and sodium) that can counteract the effects of acidic deposition. All the monitored compounds are also plant nutrients; the deposition of nitrogen is of particular concern because it can change plant composition in terrestrial systems and cause eutrophication in aquatic systems.

**Table B-2.** Annual wet and dry deposition of nitrogen and sulfur compounds at the CASTNet site in Voyageurs National Park (wet deposition taken from the NADP data and modified by CASTNet). Weekly data are available from 6/1/1996 to present. Hourly measurements are available for ozone and some trace gases.

| | | **Nitrogen (kg N ha$^{-1}$)** | | | | | | | | **Sulfur (kg S ha$^{-1}$)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **YEAR** | **PRECIP (cm)** | ***WET NH$_4$-N*** | ***WET NO$_3$-N*** | ***WET N TOTAL*** | ***DRY HNO$_3$-N*** | ***DRY NO$_3$-N*** | ***DRY NH$_4$-N*** | ***DRY N TOTAL*** | ***TOTAL N*** | ***WET SO$_4$-S*** | ***DRY SO$_2$-S*** | ***DRY SO$_4$-S*** | ***DRY S TOTAL*** | ***TOTAL S*** |
| 1997 | 57.64 | 1.120 | 1.251 | 2.371 | 0.673 | 0.026 | 0.132 | 0.831 | 3.202 | 1.320 | 0.266 | 0.164 | 0.430 | 1.750 |
| 1998 | 59.58 | 1.874 | 1.526 | 3.401 | 0.572 | 0.027 | 0.117 | 0.717 | 4.118 | 1.923 | 0.226 | 0.148 | 0.374 | 2.297 |
| 1999 | 84.32 | 2.652 | 2.107 | 4.759 | 0.580 | 0.038 | 0.132 | 0.750 | 5.509 | 2.550 | 0.298 | 0.155 | 0.453 | 3.003 |
| 2000 | 60.43 | 1.711 | 1.490 | 3.201 | 0.576 | 0.034 | 0.125 | 0.735 | 3.936 | 1.713 | 0.248 | 0.146 | 0.394 | 2.107 |
| 2001 | 74.50 | 1.836 | 1.608 | 3.443 | 0.526 | 0.032 | 0.126 | 0.684 | 4.128 | 1.763 | 0.278 | 0.141 | 0.419 | 2.182 |
| 2002 | 67.74 | 2.209 | 1.610 | 3.819 | 0.518 | 0.025 | 0.118 | 0.661 | 4.480 | 1.750 | 0.220 | 0.142 | 0.362 | 2.112 |
| 2003 | 52.34 | 1.299 | 1.228 | 2.527 | 0.510 | 0.039 | 0.137 | 0.687 | 3.214 | 1.063 | 0.226 | 0.153 | 0.380 | 1.443 |
| 2004 | 78.63 | 2.201 | 1.581 | 3.782 | 0.501 | 0.030 | 0.111 | 0.641 | 4.423 | 1.860 | 0.239 | 0.126 | 0.365 | 2.225 |
| 2005 | 79.05 | 2.217 | 1.535 | 3.752 | 0.592 | 0.022 | 0.126 | 0.740 | 4.492 | 1.767 | 0.270 | 0.158 | 0.428 | 2.195 |
| 2006 | 51.44 | 1.633 | 1.152 | 2.785 | 0.462 | 0.022 | 0.101 | 0.585 | 3.370 | 1.367 | 0.217 | 0.124 | 0.341 | 1.708 |
| 2007 | 69.87 | 2.302 | 1.364 | 3.666 | 0.456 | 0.027 | 0.116 | 0.599 | 4.265 | 1.753 | 0.221 | 0.138 | 0.359 | 2.113 |
| 2008 | 78.73 | 1.874 | 1.235 | 3.110 | 0.393 | 0.034 | 0.123 | 0.550 | 3.659 | 1.567 | 0.229 | 0.135 | 0.364 | 1.931 |
| 2009 | 85.42 | 1.874 | 1.235 | 3.110 | 0.307 | 0.033 | 0.113 | 0.453 | 3.563 | 1.337 | 0.194 | 0.125 | 0.319 | 1.656 |
| 2010 | 88.58 | 1.960 | 1.093 | 3.053 | 0.344 | 0.026 | 0.089 | 0.459 | 3.512 | 1.210 | 0.143 | 0.097 | 0.241 | 1.451 |
| 2011 | 57.35 | 1.563 | 0.971 | 2.534 | 0.321 | 0.025 | 0.092 | 0.437 | 2.972 | 0.900 | 0.113 | 0.097 | 0.210 | 1.110 |
| 2012 | 71.14 | 2.411 | 1.289 | 3.700 | 0.346 | 0.030 | 0.086 | 0.462 | 4.163 | 1.243 | 0.103 | 0.088 | 0.191 | 1.435 |
| **AVG** | **69.80** | **1.921** | **1.392** | **3.313** | **0.480** | **0.029** | **0.115** | **0.624** | **3.938** | **1.568** | **0.218** | **0.134** | **0.352** | **1.920** |
| **MIN** | **51.44** | **1.120** | **0.971** | **2.371** | **0.307** | **0.022** | **0.086** | **0.437** | **2.972** | **0.900** | **0.103** | **0.088** | **0.191** | **1.110** |
| **MAX** | **88.58** | **2.652** | **2.107** | **4.759** | **0.673** | **0.039** | **0.137** | **0.831** | **5.509** | **2.550** | **0.298** | **0.164** | **0.453** | **3.003** |
| **STD DEV** | **12.154** | **0.406** | **0.273** | **0.612** | **0.110** | **0.005** | **0.016** | **0.123** | **0.646** | **0.403** | **0.056** | **0.023** | **0.077** | **0.458** |

This subset of the CASTNet data focuses on the deposition of nitrogen and sulfur compounds and whether they fall as wet deposition (with precipitation) or dry deposition (dust and particulate matter). From 2010–2012, 87% of nitrogen deposition and 84% of sulfur deposition at VOY413 was wet deposition (http://www.epa.gov/castnet/javaweb/site_pages/VOY413.html).

**Table B-3**. Description of CASTNet parameters in Table B-2.

| **COLUMN NAME** | **DESCRIPTION** |
|---|---|
| YEAR | Calendar year of measurement, using standard Tuesday–Tuesday weeks |
| PRECIP | Precipitation amount; cm. |
| WET $NH_4$ | Wet ammonium ($NH_4$) deposition; kg N $ha^{-1}$. |
| WET $NO_3$ | Wet nitrate ($NO_3$) deposition; kg N $ha^{-1}$. |
| WET N TOTAL | Wet nitrogen (N) deposition; kg N $ha^{-1}$. |
| DRY $HNO_3$ | Dry nitric acid ($HNO_3$) flux; kg N $ha^{-1}$. |
| DRY $NO_3$ | Dry particulate nitrate ($NO_3$) flux; kg N $ha^{-1}$. |
| DRY $NH_4$ | Dry particulate ammonium ($NH_4$) flux; kg N $ha^{-1}$. |
| DRY N TOTAL | Dry nitrogen (N) flux; kg N $ha^{-1}$. |
| TOTAL N | Total nitrogen (N) deposition; kg N $ha^{-1}$. |
| WET $SO_4$ | Wet sulfate ($SO_4$) deposition; kg S $ha^{-1}$. |
| DRY $SO_2$ | Dry sulfur dioxide ($SO_2$) flux; kg S $ha^{-1}$. |
| DRY $SO_4$ | Dry particulate sulfate ($SO_4$) flux; kg S $ha^{-1}$. |
| DRY S TOTAL | Dry sulfur (S) flux; kg S $ha^{-1}$. |
| TOTAL S | Total sulfur (S) deposition; kg S $ha^{-1}$. |

**Table B-4.** A subset of data (ammonium sulfate and ammonium nitrate concentrations in air and their light extinction effects) from the IMPROVE site in Voyageurs National Park.

| | **Ammonium Sulfate (PM$_{2.5}$) (µg m$^{-3}$)** | | | | **Ammonium Sulfate light extinction Mm$^{-1}$ (inverse megameters)** | | | | **Ammonium Nitrate (PM$_{2.5}$) (µg m$^{-3}$)** | | | | **Ammonium Nitrate light extinction Mm$^{-1}$(inverse megameters)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | ***Avg.*** | ***Min.*** | ***Max.*** | ***Std. Dev.*** | ***Avg.*** | ***Min.*** | ***Max.*** | ***Std. Dev.*** | ***Avg.*** | ***Min.*** | ***Max.*** | ***Std. Dev.*** | ***Avg.*** | ***Min.*** | ***Max.*** | ***Std. Dev.*** |
| 2000 | 1.478 | 0.261 | 6.957 | 1.100 | 10.866 | 1.750 | 53.432 | 8.678 | 0.705 | 0.027 | 7.173 | 1.257 | 5.783 | 0.207 | 67.167 | 11.480 |
| 2001 | 1.488 | 0.108 | 4.009 | 0.818 | 10.688 | 0.724 | 32.409 | 6.238 | 0.787 | 0.014 | 6.722 | 1.324 | 6.412 | 0.088 | 64.940 | 11.576 |
| 2002 | 1.625 | 0.320 | 11.433 | 1.305 | 12.146 | 2.360 | 112.183 | 12.221 | 0.679 | 0.021 | 5.892 | 1.140 | 5.454 | 0.151 | 54.028 | 9.860 |
| 2003 | 1.616 | 0.217 | 10.836 | 1.345 | 32.409 | 1.561 | 87.839 | 11.318 | 0.777 | 0.000 | 8.934 | 1.525 | 64.940 | 0.000 | 91.282 | 14.409 |
| 2004 | 1.330 | 0.072 | 5.885 | 0.991 | 9.594 | 0.479 | 55.887 | 7.748 | 0.662 | 0.019 | 9.678 | 1.478 | 5.430 | 0.141 | 86.224 | 13.020 |
| 2005 | 1.985 | 0.275 | 15.054 | 2.343 | 0.000 | 2.077 | 176.830 | 24.243 | 0.514 | 0.010 | 6.787 | 0.946 | 0.000 | 0.081 | 62.906 | 8.267 |
| 2006 | 1.798 | 0.125 | 9.164 | 1.550 | 13.561 | 0.777 | 85.404 | 13.681 | 0.611 | 0.001 | 10.260 | 1.405 | 5.153 | 0.009 | 103.927 | 13.352 |
| 2007 | 1.555 | 0.012 | 10.601 | 1.349 | 13.557 | 0.078 | 102.295 | 12.077 | 0.613 | 0.002 | 9.861 | 1.571 | 37.228 | 0.017 | 103.064 | 15.427 |
| 2008 | 1.417 | 0.174 | 5.785 | 0.946 | 10.335 | 1.295 | 52.283 | 7.599 | 0.703 | 0.000 | 9.641 | 1.514 | 5.870 | 0.000 | 96.182 | 14.289 |
| 2009 | 1.575 | 0.040 | 9.275 | 1.262 | 7.521 | 0.269 | 95.797 | 11.728 | 0.769 | 0.003 | 9.812 | 1.684 | 38.112 | 0.023 | 87.730 | 14.984 |
| 2010 | 1.258 | 0.068 | 5.636 | 1.074 | 8.946 | 0.549 | 41.588 | 7.861 | 0.456 | 0.000 | 7.875 | 1.008 | 3.575 | 0.000 | 67.421 | 8.417 |
| 2011 | 1.265 | 0.043 | 5.513 | 0.988 | 8.270 | 0.288 | 46.498 | 7.693 | 0.525 | 0.000 | 5.358 | 1.009 | 8.499 | 0.000 | 42.327 | 8.359 |
| 2012 | 1.113 | 0.066 | 5.663 | 0.824 | 7.926 | 0.506 | 42.268 | 6.190 | 0.682 | 0.009 | 8.599 | 1.328 | 5.570 | 0.077 | 74.443 | 11.647 |
| **2000–2012** | **1.500** | **0.012** | **15.054** | **1.223** | **8.626** | **0.078** | **176.830** | **10.560** | **0.653** | **0.000** | **10.260** | **1.322** | **1.826** | **0.000** | **103.927** | **11.930** |

Ammonium sulfate and ammonium nitrate are the two largest contributors to fine particulate matter (PM$_{2.5}$) in nearby BWCWA. Their effects on light extinction are calculated by the IMPROVE program using formulas found at http://vista.cira.colostate.edu/improve/tools/reconbext/reconbext.htm, which take into account concentrations of the compounds and relative humidity. At VOYA, these compounds have a wide range of effects on light extinction. For individual sampling dates, light extinction caused by ammonium sulfate was 0.6%–78.0% of total light extinction and light extinction caused by ammonium nitrate was <0.1%–74.3%.

**Table B-5.** Data available for the IMPROVE site in Voyageurs National Park at a three-day interval since 2 March 1988.

| Parameter | Code | Type | Units |
|---|---|---|---|
| Air Temperature | AT | | Deg C |
| Aluminum (Fine) | ALf | PM2.5 | µg/m$^3$ |
| Ammonium Ion (Fine) | NH4f | PM2.5 | µg/m$^3$ |
| Ammonium Nitrate (Fine) | ammNO3f | PM2.5 | µg/m$^3$ |
| Ammonium Nitrate Extinction (Fine) | ammNO3f_bext | CALC | Mm$^{-1}$ |
| Ammonium Sulfate (Fine) | ammSO4f | PM2.5 | µg/m$^3$ |
| Ammonium Sulfate Extinction (Fine) | ammSO4f_bext | CALC | Mm$^{-1}$ |
| Arsenic (Fine) | ASf | PM2.5 | µg/m$^3$ |
| Bromine (Fine) | BRf | PM2.5 | µg/m$^3$ |
| Calcium (Fine) | CAf | PM2.5 | µg/m$^3$ |
| Carbon, Elemental Extinction (Fine) | Ecf_bext | CALC | Mm$^{-1}$ |
| Carbon, Elemental Fraction 1 (Fine) | EC1f | PM2.5 | µg/m$^3$ |
| Carbon, Elemental Fraction 2 (Fine) | EC2f | PM2.5 | µg/m$^3$ |
| Carbon, Elemental Fraction 3 (Fine) | EC3f | PM2.5 | µg/m$^3$ |
| Carbon, Elemental Total (Fine) | ECf | PM2.5 | µg/m$^3$ |
| Carbon, Organic Fraction 1 (Fine) | OC1f | PM2.5 | µg/m$^3$ |
| Carbon, Organic Fraction 2 (Fine) | OC2f | PM2.5 | µg/m$^3$ |
| Carbon, Organic Fraction 3 (Fine) | OC3f | PM2.5 | µg/m$^3$ |
| Carbon, Organic Fraction 4 (Fine) | OC4f | PM2.5 | µg/m$^3$ |
| Carbon, Organic Mass (Fine) (1.4*OC) | OMCf_1_4 | CALC | µg/m$^3$ |
| Carbon, Organic Pyrolized (Fine) | OPf | PM2.5 | µg/m$^3$ |
| Carbon, Organic Total (Fine) | OCf | PM2.5 | µg/m$^3$ |
| Chloride (Fine) | CHLf | PM2.5 | µg/m$^3$ |
| Chlorine (Fine) | CLf | PM2.5 | µg/m$^3$ |
| Chromium (Fine) | CRf | PM2.5 | µg/m$^3$ |
| Coarse Mass Extinction | CM_bext | CALC | Mm$^{-1}$ |
| Copper (Fine) | CUf | PM2.5 | µg/m$^3$ |
| Deciview | dv | CALC | |
| Hydrogen (Fine) | Hf | PM2.5 | µg/m$^3$ |
| Internal instrument temperature | TPINT | PM2.5 | Deg C |
| Iron (Fine) | FEf | PM2.5 | µg/m$^3$ |
| Lead (Fine) | PBf | PM2.5 | µg/m$^3$ |
| Light scattering coefficient | bsp | PM2.5 | Mm$^{-1}$ |
| Magnesium (Fine) | MGf | PM2.5 | µg/m$^3$ |
| Manganese (Fine) | MNf | PM2.5 | µg/m$^3$ |
| Mass, PM10 (Total) | MT | PM2.5 | µg/m$^3$ |
| Mass, PM2.5 - PM10 (Coarse) | CM_calculated | COARSE | µg/m$^3$ |
| Mass, PM2.5 (Fine) | MF | PM2.5 | µg/m$^3$ |
| Mass, PM2.5 Reconstructed (Fine) | RCFM | PM2.5 | µg/m$^3$ |
| Molybdenum (Fine) | Mof | PM2.5 | µg/m$^3$ |
| Nickel (Fine) | NIf | PM2.5 | µg/m$^3$ |
| Nitrate (Fine) | NO3f | PM2.5 | µg/m$^3$ |
| Nitrite (Fine) | N2f | PM2.5 | µg/m$^3$ |
| Organic Mass (Fine) (1.8*OC) | OMCf | PM2.5 | µg/m$^3$ |
| Organic Mass Extinction (Fine) | OMCf_bext | CALC | µg/m$^3$ |
| Phosphorus (Fine) | Pf | PM2.5 | µg/m$^3$ |
| Potassium (Fine) | Kf | PM2.5 | µg/m$^3$ |
| Relative Humidity (Climatological Monthly) | Rhgrid | CALC | % |
| Relative Humidity Factor (Climatological Monthly) | fRHgrid | CALC | % |
| Relative Humidity (Station Hourly) | RH | PM2.5 | % |
| Rubidium (Fine) | RBf | PM2.5 | µg/m$^3$ |
| Sea Salt (Fine) | SeaSaltf | PM2.5 | µg/m$^3$ |
| Selenium (Fine) | SEf | PM2.5 | µg/m$^3$ |
| Silicon (Fine) | SIf | PM2.5 | µg/m$^3$ |
| Sodium (Fine) | NAf | PM2.5 | µg/m$^3$ |
| Soil (Fine) | SOILf | PM2.5 | µg/m$^3$ |
| Soil Extinction (Fine) | SOILf_bext | CALC | Mm$^{-1}$ |
| Strontium (Fine) | SRf | PM2.5 | µg/m$^3$ |
| Sulfate (Fine) | SO4f | PM2.5 | µg/m$^3$ |
| Sulfur (Fine) | Sf | PM2.5 | µg/m$^3$ |
| Sulfur Dioxide | SO2 | PM2.5 | µg/m$^3$ |
| Titanium (Fine) | TIf | PM2.5 | µg/m$^3$ |
| Total Aerosol Extinction | aerosol_bext | CALC | Mm$^{-1}$ |
| Vanadium (Fine) | Vf | PM2.5 | µg/m$^3$ |
| Zinc (Fine) | ZNf | PM2.5 | µg/m$^3$ |
| Zirconium (Fine) | ZRf | PM2.5 | µg/m$^3$ |

NPS 172/129525. August 2015

**National Park Service**
**U.S. Department of the Interior**

**Natural Resource Stewardship and Science**
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov