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Report

Assessing Future Ecosystem Services: a Case Study of the Northern Highlands Lake District, Wisconsin

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ABSTRACT. The Northern Highlands Lake District of Wisconsin is in transition from a sparsely settled region to a more densely populated one. Expected changes offer benefits to northern Wisconsin residents but also threaten to degrade the ecological services they rely on. Because the future of this region is uncertain, it is difficult to make decisions that will avoid potential risks and take advantage of potential opportunities. We adopt a scenario planning approach to cope with this problem of prediction. We use an ecological assessment framework developed by the Millennium Ecosystem Assessment to determine key social and ecological driving forces in the Northern Highlands Lake District. From these, we describe three alternative scenarios to the year 2025 in which the projected use of ecological services is substantially different. The work reported in this paper demonstrates how scenarios can be developed for a region and provides a starting point for a participatory discussion of alternative futures for northern Wisconsin. Although the future is unknowable, we hope that the assessment process begun in this paper will help the people of the Northern Highlands Lake District choose the future path of their region.

INTRODUCTION

The 20th century was a period of tumultuous global change. The number of people living on Earth quadrupled. The economy grew 14 times larger, energy use increased 15 times, carbon dioxide emissions increased 17 times, and water use increased nine times. The area of cropland doubled, whereas forested areas declined by 20% (McNeill 2000). Current projections of global population growth estimate that there will be 7.8 x 10^9 people living on the planet by 2025 (Board on Sustainable Development 1999). These people are likely to live in a world that is substantially different from the world today due to changes in climate, disease, technology, trade patterns, societal values, and population structure. Variations in these regional social and ecological characteristics will produce radically different transformations.

Regional transformation offers the potential for human development but also presents a variety of dangers. Many citizens, businesspeople, and civic leaders want to know how they can improve rather than degrade the regions in which they live. How can they produce sustainable development? How can social well-being be increased? How can people improve their lives and those of future generations? How can they produce a world that is peaceful and prosperous?

The services provided by ecosystems are critical to sustaining human societies. Ecological services supply humans with clean water, clean air, climate moderation, pollution dissipation, and desirable things such as beautiful places, game, and wild animals. Unwanted ecological degradation has led people to try to manage the impact they themselves have on the ecology. Management depends on choosing the best approach from a set of alternatives. Evaluating alternatives depends on understanding the future consequences of current actions. That is, managing ecosystems and ecological services depends on ecological prediction. However, ecological predictions have fundamental problems that limit their usefulness (Clark et al. 2001). They are often contingent on drivers that are difficult to predict and include uncertainties such as nonlinearities, unknowns, and surprises that can make prediction nearly impossible. Ecologists rarely, if ever, have enough information to provide accurate predictions of the future (Sherden 1998, Ludwig 2002, Sarewitz et al. 2000).

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The limitations of ecological forecasting and prediction are core problems for ecosystem management. How can we deal with model limitations and uncertainties in a structured way that still allows us to create management plans for sustainable development? One option is to use scenario planning to generate a range of possible futures or scenarios that are consistent with what is known but which contain several potential surprises and cover a wide range of alternative futures. Early scenario planners defined scenarios as hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points (Kahn and Wiener 1967). Each scenario is a description of what the future could be, not a prediction of what the future will be.

Scenario planning uses a set of scenarios, each of which is a plausible example of what could happen under particular assumptions and conditions. Scenarios within a set are not defined in terms of relative probabilities; rather, they are contrasted against one another to provide a tool for thinking about the relationships between choices, dynamics, and alternative futures.

Scenario planning has been used in the business community with great success (van der Heijden 1996). Scenarios allow managers to think about strategies that can be successful across a range of possible futures. They also help managers to focus on the critical decision points. Scenarios are now being used by the ecological community to expand the depth and breadth of environmental decision making (Funtowicz et al. 1999, Greeuw et al. 2000, Wollenberg et al. 2000). In particular, scenario planning has been applied to analyze global sustainability (Hammond 1998, Raskin et al. 1998) and sustainable development in Europe (Rotmans et al. 2000).

One group that uses scenario planning to improve ecological management is the Millennium Ecosystem Assessment. The aim of the Millennium Ecosystem Assessment is to improve the management and understanding of the world's ecosystems by helping to meet the needs of decision makers and the public for peer-reviewed, policy-relevant scientific information on the condition of ecosystems, the consequences of ecosystem change, and potential approaches to ecological management. It plans to use scenario planning to identify key uncertainties and decision variables that will shape the future of regions in transition.

We have used the framework developed by the Millennium Ecosystem Assessment to assess the dynamics of a region in transition. A small team of ecological scientists and managers met in a series of meetings over the course of a year at which we followed the process laid out in Appendix 1. We defined the system we were interested in and characterized its history and current condition prior to focusing our attention on the future of the region's water quality and fish populations. This process involved data collection, analysis, and synthesis as well as discussion with various experts familiar with different aspects of northern Wisconsin. Following this process, we attempted to identify key uncertainties in the northern highlands. After much discussion and analysis of the interactions among various social and ecological issues, we identified two key uncertainties that we used to define a set of scenarios. From these initial scenarios, we drafted and then repeatedly revised a set of scenarios of the future of northern Wisconsin. The results of these efforts are presented in this paper, although they do not represent the end of the scenario planning effort for this region.

The region we examine is Wisconsin's Northern Highlands Lake District (NHLD). This region is in transition from a relatively sparsely settled region to a more densely populated region. The transition will be shaped by many complex variables, including changes in climate, species invasions, human migration patterns, land use regulation, technology, and business. The combination of predictable gradual change and unpredictable, sudden shifts in the NHLD make it an excellent place to attempt scenario planning. Furthermore, the long history of scientific research in the area has led to extensive knowledge about its ecosystems and ecosystem services. By conducting the initial phase of an ecosystem assessment based on the principles of the Millennium Ecosystem Assessment, we sought not only to assess the NHLD but also to evaluate the feasibility of using scenario planning to improve the long-term management of ecosystem services.

NORTHERN HIGHLANDS LAKE DISTRICT

Geographical and historical context

The Northern Highlands Lake District (NHLD) is located in northern Wisconsin, USA, to the south and east of Lake Superior at a latitude of 46°N (Martin 1965). It spans 5330 km^2 and includes most of Oneida and Vilas counties and portions of Forest, Iron, and Price counties. The climate of the NHLD is heavily influenced by its proximity to Lake Superior, leading to cool summers and cold winters. Precipitation occurs all year. The ice-free season extends from late April or early May until November, and the frost-free season from early June until mid-September. As seen in Fig. 1, the NHLD is within the Superior mixed-forest ecoregion (Bailey 1998).

Fig. 1. The location of the Northern Highlands Lake District (NHLD) within a) North America and b) Wisconsin. The NHLD includes all of Vilas County and portions of Iron, Price, Oneida, and Forest counties. As shown in c), the current landcover of the northern highlands lake region is primarily secondary forest, wetlands, and lakes (Wisconsin Department of Natural Resources 1998).

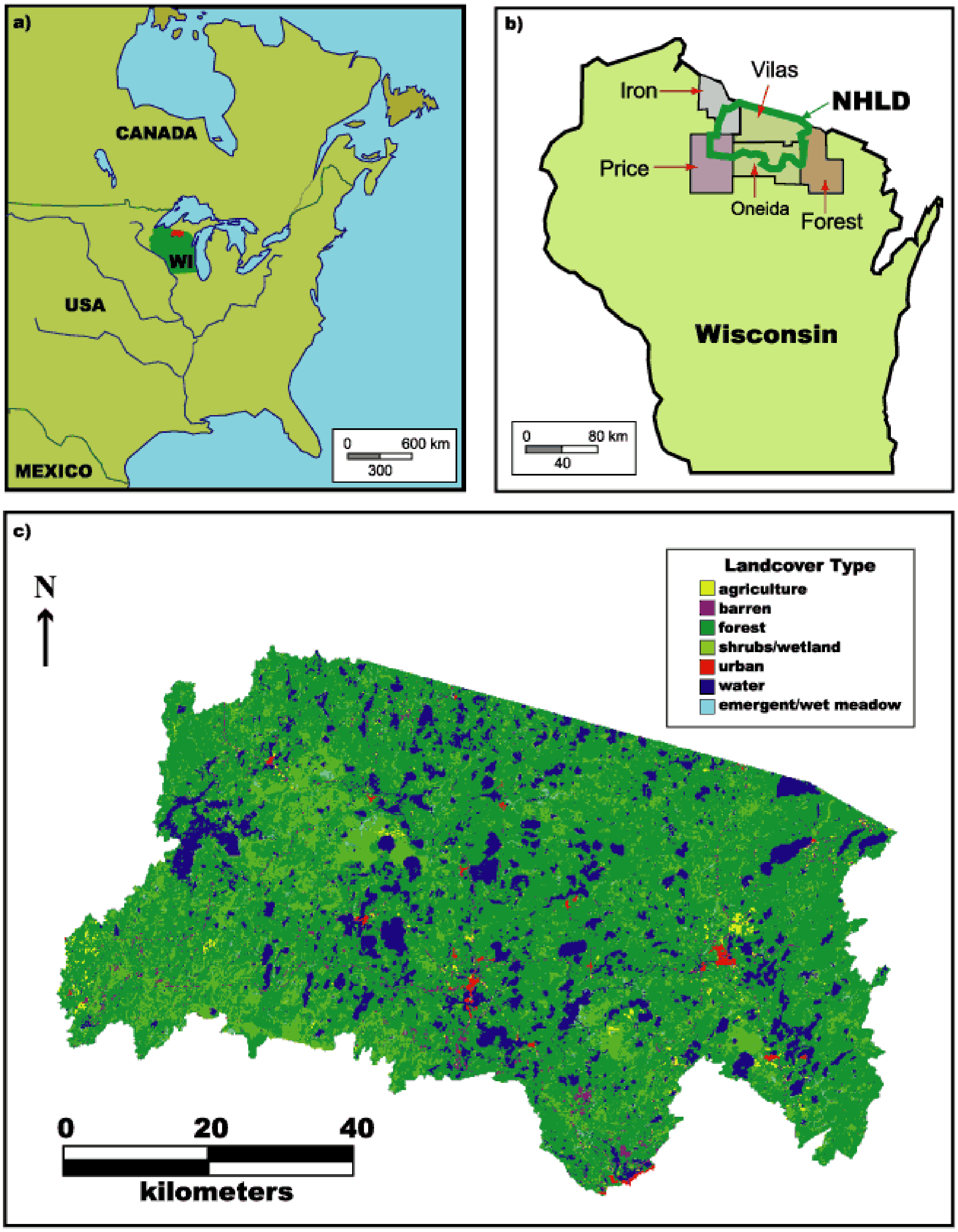
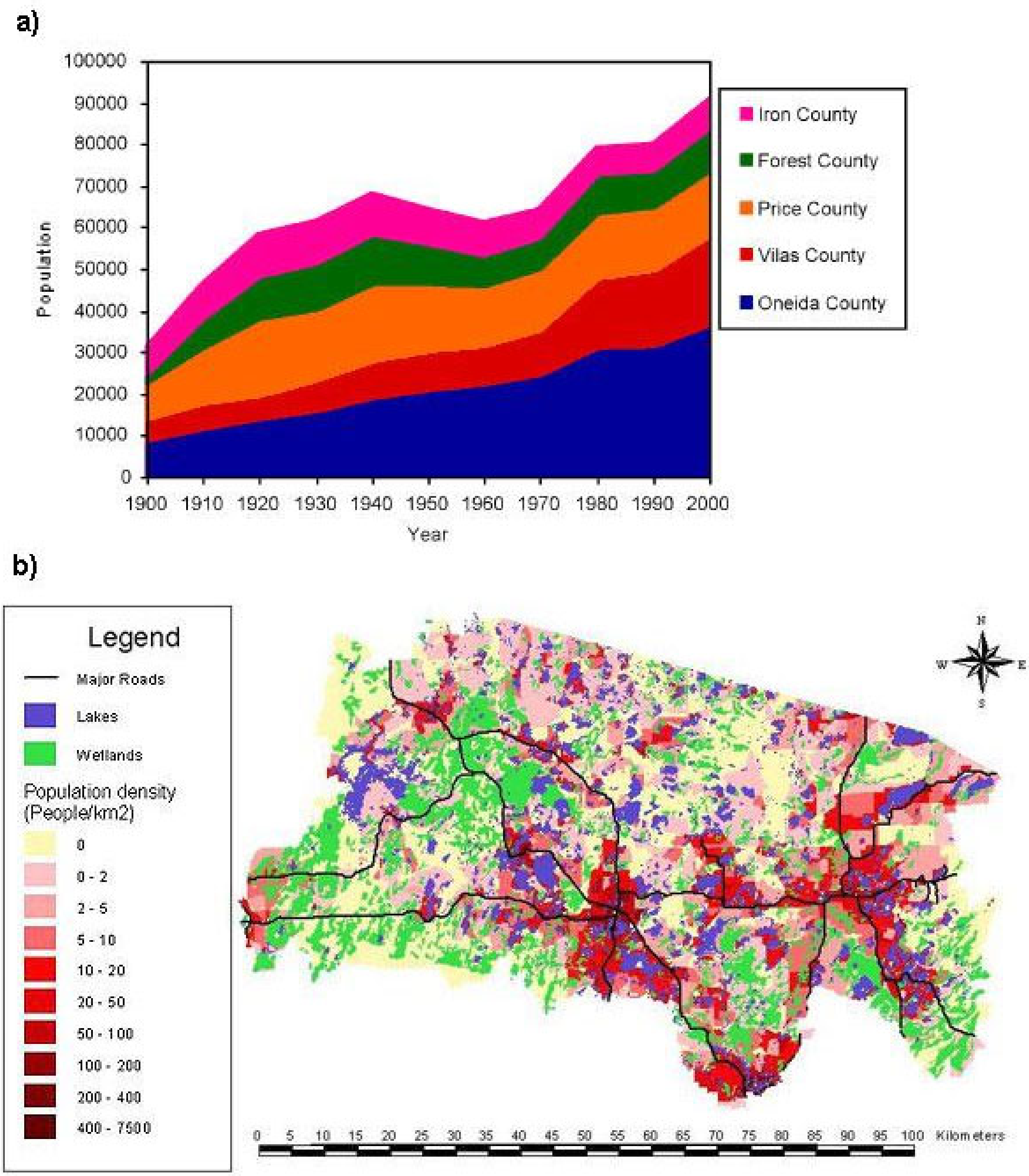


Fig. 2. Population history and distribution in the Northern Highland Lake District (NHLD). a) Historical population of the five counties (Forest, Iron, Oneida, Price, and Vilas) that make up the NHLD. The NHLD consists mainly of Vilas and Oneida counties. Based on deccenial censuses from 1900 to 2000 (U.S. Bureau of the Census 1992, U.S. Bureau of the Census 2001). Most of the population growth occured in Vilas and Oneida counties. b) Spatial distribution of residential population in 2000 (Wisconsin Department of Natural Resources 1999, U.S. Bureau of the Census 2001).



About 13% of the NHLD is open water, and lakes are the region's most conspicuous and distinctive landscape feature. The region has been repeatedly glaciated, producing a relatively flat landscape. When glaciers retreated 12,000 yr ago, many lakes were formed. Some lakes occur in hollows in outwash gravel plains; others formed in depressions in the ground moraine or were created by the melting of buried ice chunks. These lakes range in size from small, temporary ponds and darkly stained "bog" lakes to large lakes covering well over 1000 ha, with depths ranging from 1 to more than 30 m.

The NHLD has been sparsely inhabited for thousands of years. In the 17th century, European fur traders entered the region and transformed the lives of the Native Americans, its original inhabitants. In the 19th century, the expansion of the United States led the First Nations to surrender their sovereignty in exchange for land use, hunting, and fishing rights in a series of treaties in 1837 and 1842 (Loew 2001). The old-growth forest of the NHLD was extensively logged in the late 19th and early 20th centuries (Curtis 1959). By the 1930s, much of the Northern Highlands had been clear-cut. Eighty-one percent of the region has since been reforested. This forest is composed of 40% mixed coniferous-deciduous trees and shrubs, 35% hardwoods, and 25% softwoods (Wisconsin Department of Natural Resources 1998).

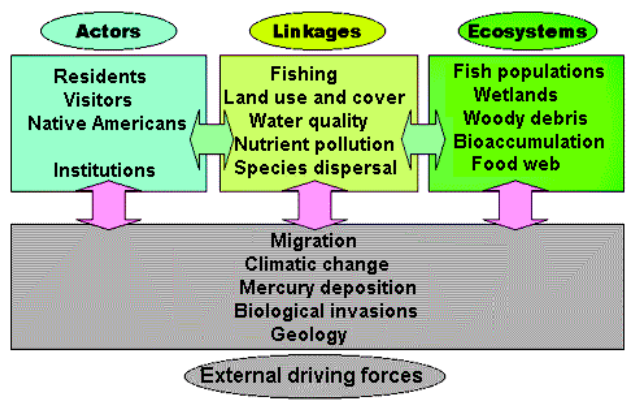
In 1900, the population of Oneida and Vilas counties, which together comprise most of the NHLD, was 12,000 (U.S. Bureau of the Census 1992). Over the past century, their populations increased 4.5-fold, with growth accelerating over the last three decades (Fig. 2). Recreation and tourism are major components of the economy, and there has been substantial development of vacation and retirement homes around local lakes.

Fishing is one of the major tourist attractions of the region, which is one of the main sport fishing areas of Wisconsin. There are approximately 17 x 10^6 people-days of fishing in Wisconsin, with 48 x 10^6 fish caught annually. There are approximatley 565,000 boats registered in Wisconsin, or about one boat for every 10 people (Legislative Reference Bureau 2002). The economic benefit of sport fishing is some \$2.1 x 10^9/yr, representing 1% of the gross state product (Maharaj and Carpenter 1996), and much of this spending and effort occurs in the NHLD. The region lies within a day's drive of several major urban centers, including Chicago, Milwaukee, and Minneapolis-Saint Paul. In recent decades, highway improvements have made the area more accessible by decreasing the travel time from these cities.

Assessment

To assess the sustainability of the ecosystem services within this region, we need to understand how different people use and transform ecosystems, the dynamics of ecosystems, and the external forces that are shaping the region. Whereas the people in the NHLD depend on a variety of ecological services, we focus on those provided by lakes, because they are the defining feature of the NHLD.

Fig. 3. Key attributes and drivers of Wisconsin's Northern Highlands Lake District. Different actors within society use and alter ecosystems in different ways. People use ecological services, extract goods from ecosystems, and dispose of wastes into ecosystems. Key aspects of ecological systems determine the quality of the goods and services that the region's ecosystems produce. Both society and nature are influenced by external driving forces that alter the character and dynamics of human and ecological systems.



To analyze the sustainability of the ecological services provided by its lakes, we considered the NHLD to contain a set of human actors who are linked to ecosystems by the use of services and ecological transformation. The ecological services that people use are regulated by several key ecosystem properties. Social and ecological drivers, such as climate change, influence both the social and the ecological dynamics within the region. The key actors, linkages, ecosystem properties, and drivers that we used to analyze the NHLD are shown in Fig. 3. These human and ecological aspects of the NHLD are summarized below and described in more detail in Appendix 2.

People use ecosystem services in diverse ways. For example, Native Americans have treaty rights to spearfish, whereas non-Native Americans do not. Another major division is between seasonal and year-round residents. The interactions of people with ecosystems are largely influenced by formal and informal regulations defined by the U.S. federal government, the state of Wisconsin, local lake associations, and the people within local communities.

People interact with lakes via fishing and other recreational activities such as canoeing and jet-skiing. People use water for drinking, industrial processes, power generation, and waste disposal. People can also modify local ecological communities by introducing new species either inadvertently or intentionally. Healthy fish populations require the presence of habitat, such as coarse woody debris, and prey. The eutrophication of lakes lowers their water quality for people and can also degrade fishing by producing low oxygen conditions that kill fish. Mercury can contaminate fish populations; methlymercury, which is created in anoxic conditions, bioaccumulates in food webs (Driscoll et al. 1994, Rudd 1995). The trophic position of an animal in a food web and the availability of methlymercury in the environment determine the degree to which methlymercuy bioaccumulates within an animal. Because wetlands are often anoxic, wetland areas can increase the formation of methlymercury.

A variety of external forces is transforming the NHLD. Preeminent among these is the migration of people into the region. Climatic change, mercury deposition, and the invasion of unfamiliar species are also expected to play a role. It is anticipated that climatic change will warm the region and increase rainfall over the next century, although the degree of future change is uncertain. Mercury from the burning of fossil fuels outside the region continues to accumulate within the region's ecosystems. The ever-increasing global movement of material inadvertently relocates species, occasionally with large effects on their receiving environments. Although the arrival of new species in the NHLD is to be expected, the consequences of their arrival are difficult to predict.

The locations of human and ecological change are not independent. The existing spatial pattern of the landscape has constrained ecological processes and human settlement. The topography of the NHLD landscape and resulting flows of water have defined the pattern of lakes (Kratz and Frost 2000). Lakes higher in the landscape tend to be smaller than lakes lower in the landscape (Fig. 4). Precipitation is the main method by which lakes high in the landscape receive water inputs. Lakes lower in the landscape also receive water from precipitation, but this is augmented by surface and groundwater flows from lakes at higher elevations. Overland runoff is affected by the land use pattern and is greater in lakes where the surrounding vegetation has been removed. There has generally been more settlement surrounding the larger, lower lakes.

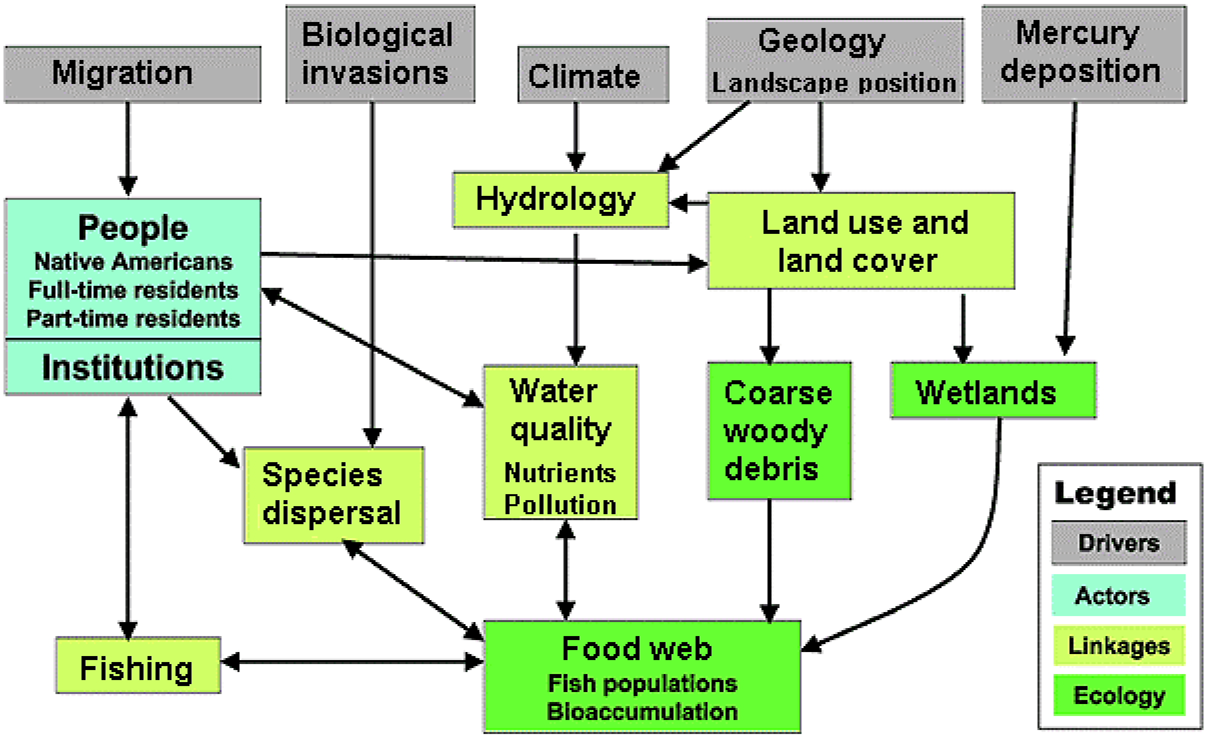
Conceptualizing change

In summary, the NHLD is being transformed by land development, fishing, the invasion of exotic species, and local pollution. Migration is changing the composition of the local population, and climate change and mercury deposition are altering the ecology (Fig. 5). On the landscape, there is a continuum of human use of lakes from the more pristine, less affected lakes to highly impacted lakes (Fig. 6). We characterize the differences between these types of lakes using cartoons that show aspects of the systems that influence the production of important ecological services.

A lake that is relatively unaltered by human use typically contains a variety of native species and physical habitats (Fig. 6). Uses of the lake and its riparian areas include low-impact boating and activities such as bird watching and cross-country skiing. Riparian areas contain coarse woody debris and macrophyte beds that support fish recruitment and productive benthic invertebrate populations. The food web is healthy, and the water quality is high.

A lake that has been greatly affected by human use may have lost some of its native species, and its physical structure has often been simplified (Fig. 6). Smaller fish may dominate fish communities. The riparian areas have been deforested and replaced with buildings and lawns. Problems may include high runoff of polluted water and leaky septic tanks. Other changes to the lake edge include the removal of macrophyte beds and coarse woody debris and the building of docks and piers. On the lake, anglers are common, as are highly polluting speedboats and personal watercraft. Exotic species within the lake are also present, including various fish species (e.g., rainbow smelt), macrophytes (e.g., Eurasian water milfoil and purple loosestrife), and invertebrate species (e.g., rusty crayfish). Many exotic species gain access to previously uninvaded lakes in bait buckets or by attaching to boats. The many uses of the lake can lead to a simplified food web in which the ecological functions provided by large predatory animals are reduced.

Fig. 4. The human use of ecosystem services in Wisconsin's Northern Highlands Lake District depends on the connections among the actors, linkages, ecosystem properties, and drivers within the region. Although people and nature are connected in a diversity of ways, the strongest connections are illustrated in this figure.



Identifying key uncertainties

From this analysis of the forces shaping the NHLD, we identified a number of key processes that were important, uncertain, and difficult to control. Migration is a key force shaping the social organization of the region. The number of people and the number of houses will have a large effect on the future shape of the NHLD. However, where and how people choose to live will also strongly influence their impact on the region. Ecologically, the degree to which anthropogenic transformations drive significant environmental changes is also unknown. A decline in the quality of the water could have a large impact on the region, as could a decline in fishing quality. We used scenario planning to analyze how changes in these key processes could shape the future of the NHLD.

SCENARIOS

We used the two key, weakly controllable uncertainties, migration pattern and ecological vulnerability, to define three scenarios for the Northern Highlands Lake District (NHLD). We present them as examples of the type of scenarios that can be generated for a region and to stimulate discussion leading to the creation of more useful scenarios for the NHLD. The following scenarios are the first step in an ongoing process.

Each of the scenarios is based on the social and ecological processes that are known to take place in the NHLD. Several factors were used to create differences among scenarios (Table 1). These differences illustrate a range of possible consequences from system drivers that are important, yet unpredictable. The factors listed in Table 1 exclude climate change and governance (Nakicenovic and Swart 2000). We chose not to emphasize a range of possible future climates and instead assumed that the future climate would be similar to the most recent projections for the NHLD, i.e., that it will be warmer, with longer growing seasons, generally milder conditions, and more precipitation. We did not consider major changes in governance structure at the national or state level, although our scenarios assume certain changes in the kinds of political conflicts that occur in the region and in the relative importance of lake associations.

Fig. 5. A landscape-scale view of lakes in Wisconsin's Northern Highlands Lake District. The landscape position of a lake affects the pattern of water movement into and out of it. Precipitation is the main method by which lakes high in the landscape receive water inputs. Lakes lower in the landscape receive water from groundwater flow from precipitation and groundwater-fed lakes at higher elevations. Overland runoff is affected by the land use pattern and is common for lakes where the surrounding vegetation has been removed. On the landscape, there is a continuum of human use of lakes from the more pristine, unaffected lakes (click on lake 2 for a closer view) to highly affected lakes (click on the lowest lake to see more).

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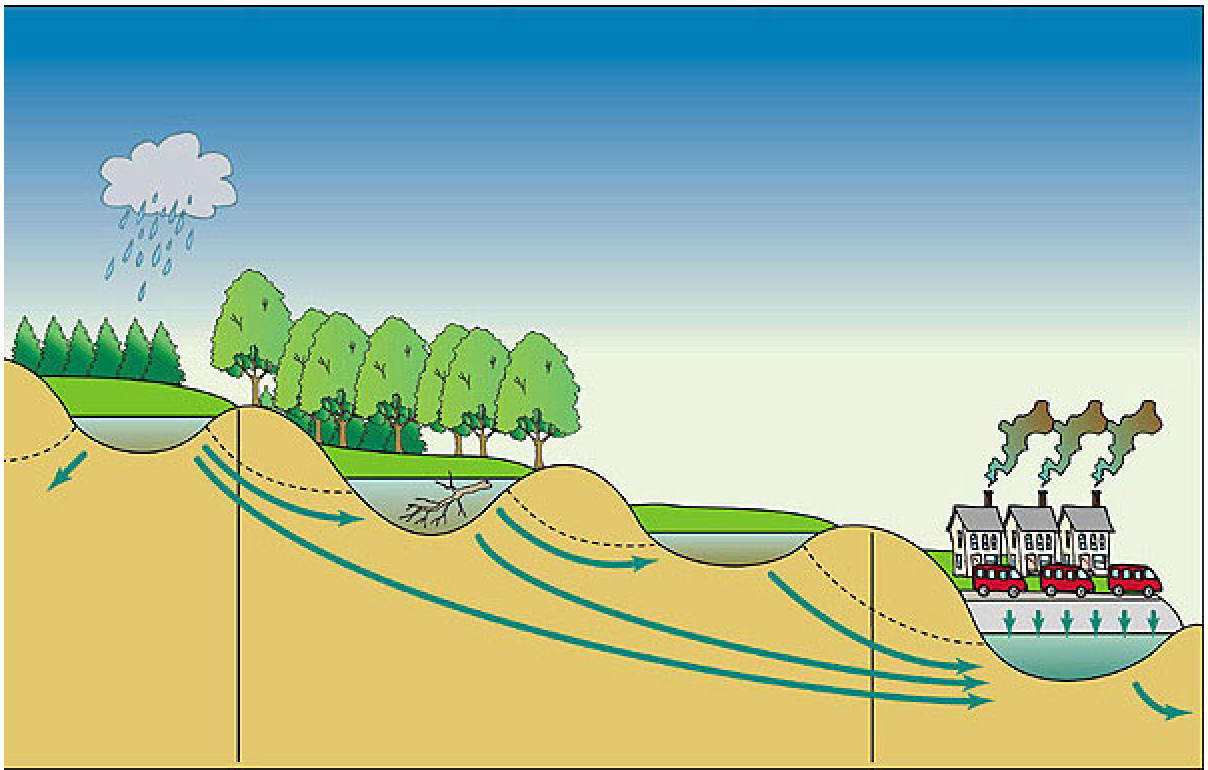

We chose to focus our scenarios on human population change, including the spatial distribution of human use of the landscape, and the effects of human activity on ecological services in the NHLD. For example, does population growth depend on an expansion of industry, or does it depend on people living as retirees or seasonal residents? Will human activities change in ways that tend to stabilize ecosystem services or evoke substantial changes? Changes in these two drivers will have profound and direct impacts on the ecology and human use of the NHLD. We use these two forces to define a scenario space in which we present three radically different scenarios of the future of the northern lakes region (Fig. 7). Narratives describing the unfolding of these scenarios appear in the following three sections and are followed by a comparative summary.

Walleye Commons

In the 2000s, national and global economic growth accelerated due to reforms in energy policy, expanding globalization, and peaceful international relations. As wealth spread worldwide, many regional conflicts were resolved. Terrorist threats declined, and international travel increased sharply. The expansion of high-speed wireless networks increased the ability of people to telecommute and greatly increased the flexibility of the traditional work week. People had more disposable income than previous generations and more time for leisure activities. Global travel became easy, cheap, and common.

Fig. 6. a) A lake at the unimpacted end of the spectrum in Wisconsin's Northern Highlands Lake District. Uses of the lake and its riparian areas include low-impact boating such as canoeing and activities like bird watching and cross-country skiing in the winter. Riparian areas contain coarse woody debris and macrophyte beds that allow for successful fish recruitment and productive benthic invertebrate populations. The food web is healthy, and the water quality is high (click on the food chain to see more about what influences food web structure). b) A highly affected lake representing some common human uses of and threats to lakes in the northern highlands region. The riparian areas have been deforested and replaced with concrete and buildings. Common problems include high runoff of polluted water, leaky septic tanks, and the immigration of animals that have high nutrient deposition rates through waste products. Other changes to the lake edge include the removal of macrophyte beds and coarse woody debris and the building of docks and piers. On the lake, anglers are common, as are highly polluting speedboats and personal watercraft. Exotic species within the lake are also present, including various fish species (e.g., carp and rainbow smelt), macrophytes (e.g., Eurasian water milfoil and purple loosestrife), invertebrate species (e.g., rusty crayfish, zebra mussels). Many exotic species gain access to previously uninvaded lakes by means of human activities like dumping baitfish and by the movement of boats with hitchhiking individuals attached. The many uses of the lake can lead to a less healthy food web in those areas where higher trophic levels are especially reduced or contaminated through the bioaccumulation of toxins like mercury (click on the food chain to see more about the factors that influence the structure of the food web).

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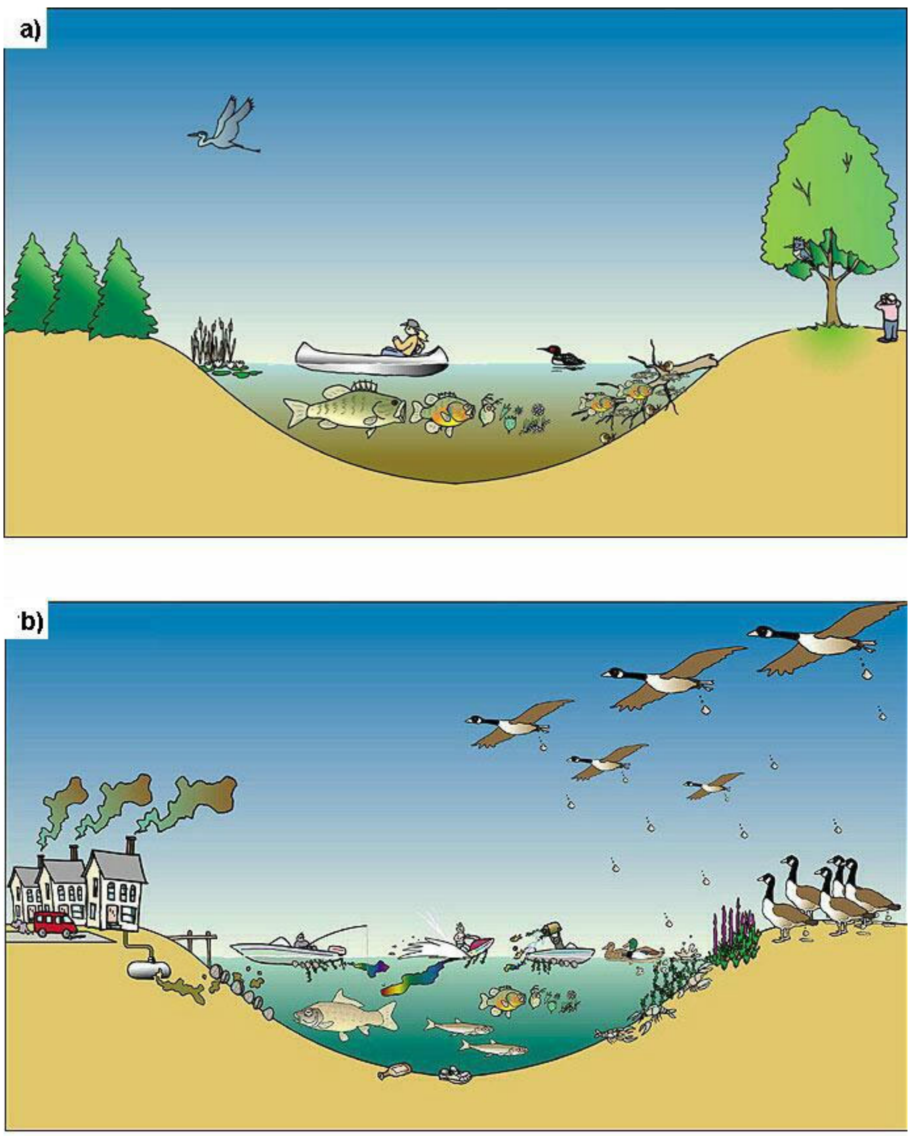
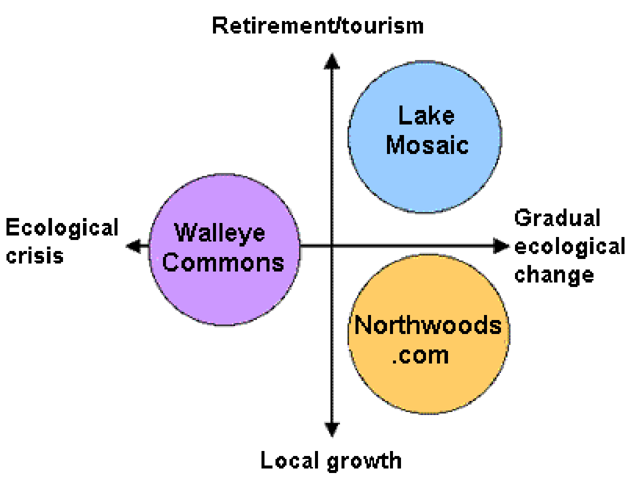


Life in Wisconsin's northern highlands, however, has taken a turn for the worse. Climate change brought longer summers and milder weather. As expected, warming reduced opportunities for snowmobiling, cross-country skiing, and other winter sports. At the same time, quite unexpectedly, climate warming also contributed to the spread of disease. A deadly walleye pathogen, which was amplified in hatcheries, quickly spread and forced the closure of several valuable walleye fisheries in the NHLD. Even worse, a water-borne protozoan introduced from South America created a new human health hazard in the region. The protozoan easily moved from lake water through open cuts to infect the human nervous system. Over a period of years, victims of protozoan infection suffered gradual and debilitating nervous system disorders. Although the disease was usually not lethal, the quality of life of those infected was severely reduced during the multiyear recovery period.

Fig. 7. Scenarios in relationship to key drivers.



The coincidence of easy global travel, substantial disposable income, limited fishing opportunities, and fear of disease had a substantial impact on life in the NHLD. People from urban centers who had once flocked to the region due to its accessibility, charming beauty, and relaxed atmosphere now chose to vacation or retire to other, safer locations. The decline in tourism and the sale of many second homes, along with the fear of living with a mysterious and dangerous disease, led many local business owners to follow their former customers to other regions. These initial emigrations set in motion a downward spiral. Declining property values, bankrupt businesses, and school closures led more people to leave the area and accelerated the decline. Small towns lost almost all of their businesses. Larger towns, such as Minocqua and Eagle River, became small, poor, and dilapidated. When they couldn't be sold, many summer homes and cabins were seldom visited or simply boarded up and abandoned.

During this emigration, however, few people left Lac du Flambeau. Despite unemployment and declines in casino revenue, people began to take advantage of low land prices to purchase land. Due to the construction of new casinos in southern Wisconsin, the Lac du Flambeau Tribe in cooperation with a consortium of other Native American groups was able to purchase land in northern Wisconsin. The State of Wisconsin and The Nature Conservancy also took advantage of cheap land to expand existing nature reserves. The net result was an increase in the size of protected areas and tribal lands and a decrease in the amount of land held in small private plots.

Ecologically, this series of events had both predictable and surprising consequences. Wetlands greatly expanded as riparian vegetation reclaimed once-manicured lawns. Wildlife proliferated due to reduced exploitation and increased available habitat. The reduction in fishing and boating slowed the spread of invasive species, especially into small isolated lakes. Reduced human activity increased overall water quality and improved fish populations in the region. However, erosion from poorly maintained roads and lawns increased turbity in a number of lakes. Size and age distributions of fish populations shifted toward older, bigger fish, i.e., those typically targeted by anglers. In lakes affected by the hatchery-borne walleye disease, walleyes did not recover, but other fishes such as smallmouth bass and muskellunge established robust stocks. A few larger lakes became eutrophic as the septic systems of abandoned lakefront homes failed and leaked. However, there was less pollution in the area in general, and the increase in wetland area provided more filtering and buffering capacity for the pollutants that remained.

Surprisingly, mercury pollution in lakes became an increasingly severe problem. Coal burning upwind of the NHLD continued to deposit mercury across the region, and the increased wetland area exacerbated the bioaccumulation of mercury. The increase in wetlands caused an increase in anoxia and dissolved organic carbon (DOC) in lakes. Increased anoxia increased the generation of methylmercury, and increased DOC reduced the ability of light to degrade methylmercury. The presence of large, old fish, which bioaccumulate more mercury than do the smaller fish lower on the food chain, in combination with the increased amounts of methlymercury led to high levels of mercury in many fish. For Native Americans heavily dependent on spearfishing walleye, which selects for larger, more mercury-laden fish, this presented a health risk, but an innovative system that combined lake rotation with pulsed harvesting was invented to reduce mercury exposure.

In 2025, there were roughly 12,000 people living in the NHLD district, which represented a fourfold population decline from 2000 to near 1900 levels. However, the Native American population had grown from less than 10% of the population to roughly 40%. People living in the area were not much better off than they were in 2000 and relatively much worse off than in Wisconsin as a whole. With the exception of walleye, fish populations were healthy. The lakes looked good, but the water was dangerous. However, the people of the NHLD now say that the wealth they receive from nature more than compensates for their low incomes. Those who disagree left long ago.

Northwoods.com

In the 2000s, concerned that the robust growth of the U.S. economy would leave Wisconsin behind, the state government, business leaders, academics, and community groups created state-wide economic and community development plans that would allow Wisconsin to thrive in the 21st century. A program that combined venture capital with university and community partnerships lead to the establishment of a new University of Wisconsin campus and business park in Rhinelander. The goal of this university was to retain young people in Wisconsin. The university emphasized local community and business development. With the establishment of the university campus and the influx of faculty, staff, and students, the regional economy gradually diversified away from tourism toward an economy that included a number of branch or back offices for a wide variety of businesses. Some initial local successes combined with the high quality of life led to the rapid expansion of these branch offices.

Young people were drawn to the area by the low cost of living and the high quality of life in the North Woods. Companies found the area attractive because they could recruit talented people for relatively low wages. Some companies even argued that the residents of the NHLD received two paychecks: one from their jobs and the other from life in a region that offered remarkable opportunities for outdoor recreation. As young people remained in the region, the Rhinelander and Minocqua areas began to urbanize. The young residents tended to cluster near the social life of the university. As the area developed and property values rose, this area gradually expanded along the Wisconsin River from Rhinelander to Merrill.

The fresh waters in the Wisconsin River corridor from Eagle River to Merrill became highly urbanized and heavily used. The lakes closest to this corridor sustained major ecological impacts from urban development and heavy human recreation. Most nearby wetlands were drained for lakeshore development, more pollutants entered these lakes from the watershed, blue lakes turned green from increased nutrient runoff, increased fishing pressure caused fish stocks to decline, boat traffic accelerated the dispersal of invading species, and polycyclic aromatic hydrocarbons increased 100-fold in the lakes.

A series of fish kills in the Wisconsin River caused widespread concern about the costs of development. Economic growth around Rhinelander had increased the tax base of cities and towns, which increased the relative political power of urban residents. These fish kills mobilized the urban residents to protect the aquatic resources of the surrounding areas. City governments and then county governments and businesses all supported new land use policies to appeal to their new constituents. However, businesspeople in the NHLD preferred market-based policies to strict regulation, and, in cooperation with the University of Wisconsin faculty, they created an innovative and profitable market for quality riparian habitats and a variety of ecosystem services provided by pristine lakes. Acquiring conservation lands became a major goal of the local government. Zoning ordinances and conservation easement plans, funded by a steep horsepower tax on boat motors and riparian development, were enacted to preserve the lakes in the surrounding region.

Although many landowners profited from these policies, other residents grew angry as development costs for lakefront property soared, as did the cost of utilities, wells, and fishing. Some rural constituents took advantage of the cost-sharing programs and capitalized on the increased value of their property for tourism, whereas some urban residents still wanted to use large motorboats on pristine lakes. However, regardless of this opposition, the majority agreed that, if the inhabitants wanted to degrade ecosystem services, they would have to pay to replace them.

Although the Lac du Flambeau casino did not do as well as hoped, the influx of new job and training opportunities into the NHLD greatly improved job, educational, and cultural opportunities for Native Americans. In two decades, they went from having a per capita income less than half that of other northern residents to one as high as the state mean. Despite some conflicts with the new town-oriented environmental regulations, these regulations increased the value of much of the Lac du Flambeau land. The tribe, controversially, limited access to a number of reservation lakes to produce highly profitable, high-quality fishing lakes.

In 2025, the population of the region had grown to nearly 65,000 people, a 50% increase over the population in 2000. Most of the population growth occurred near the Wisconsin River. Household income in the region was now about equal to that of Wisconsin as a whole. Rather than being older than the rest of Wisconsin, the population of the region was slightly younger. In general, the conservation policies caused most of the lakes in the region, specifically those further away from the urban corridor, to improve in quality. Overall, the region was providing more ecosystem services than in the past. More riparian habitat improved fish recruitment and growth, and more trophy fish were caught. Lakes that previously had experienced a lot of motorboat activity and associated pollution improved in water quality. Wetland area increased, adding to the improvement of the water quality in many lakes. Increased wetland area also increased DOC inputs to some lakes, and, through methylation-light penetration feedback, mercury problems were exacerbated in some areas. However, because few people depended on fish for food, mercury was not considered a serious health problem.

Lake Mosaic

Economic growth in the late 20th and early 21st centuries created many wealthy baby boomers. Despite a generally robust economy, international tensions, terrorism, and warfare greatly reduced international travel. Their ready cash and reluctance to travel led many families to consider either buying a vacation home in, or retiring to, the NHDP. Furthermore, the milder climate resulting from global warming made northern Wisconsin a more desirable location to live in year-round. These changes, combined with the expansion of high-speed wireless networking, increased the number of people who could alternate their lives between two homes. All these factors increased the number of households that decided to move, full- or part-time, to the NHLD. Most of these new residents wanted lakeshore property and homes in the woods away from the hustle and bustle of city life.

Lakeshore development proceeded rapidly. The residents, most of whom moved to the area because of a love of the outdoors, spent lots of time on lakes or in the nearby wooded areas. Consequently, they chose locations that were not highly developed. As the number of cabins on an individual lake began to climb, that lake became less attractive to new arrivals, and new developments began on other, less developed lakes. As a result, almost all lakes in the region became moderately developed.

Most residents were very attached to their lakes. Often people were attracted to a particular lake because of its features and the attitudes of the other people living around it. These people frequently organized themselves into lake associations. Many existing lake associations became quite powerful organizations and implemented a wide variety of activities intended to improve life around their lakes. However, the scope and ultimate goals of these activities varied greatly. Some people improved their lakes by removing all hazards to boat navigation and importing sand for beaches, whereas others tried to improve fishing; still others added woody debris to their lakes in an effort to return them to a past wild state.

The great variability among lakes and the diverse interests of the people settling around them led to considerable variety in lakeshore development patterns. Some lake associations advocated the rights of residents to build "dockominiums," modify habitat, and intensify boating activity. Other lake associations worked to ban personal watercraft, severely restrict loss of habitat, limit access, and improve fishing.

With the increased population of the region, fishing quality generally declined despite ever-stricter regulation by the Wisconsin Department of Natural Resources. This led several groups of people, including some fishing clubs, to purchase the entire perimeter of a lake to allow them high-quality fishing. On these lakes and a few lakes in government-maintained wilderness areas with "trophy-only" regulations, fishing quality was excellent. Some private landowners were able to profit handsomely by selling extraordinary fishing opportunities at premium prices. However, in most lakes accessible to the public, fishing quality continued to decline because of increased fishing pressure and the continual removal of the larger individual fish. Whenever one lake had a particularly good year, mobile anglers would quickly descend on it and reduce the quality of its fishing to the level of the other lakes in the region.

The decline in public fishing opportunities combined with the improvement in private fishing was only one of many initially subtle, but increasingly open conflicts among people living on different lakes. Tourist operators complained about how the new residents, through overfishing, limited their ability to attract tourists. Lake residents were often unfriendly to outsiders, and conflicts over noisy boats, roads, land use, and the deterioration in water quality sometimes led to nasty and long-running feuds. Ecological management decisions were frequently court-mandated. There were many irate letters to the editors of local papers, more intense influence peddling, more acrimonious County Board meetings, and increasingly frequent acts of vandalism.

This gradual spread of low-density residential development across the landscape had variable and lake-specific ecological effects. These depended on the preferences of the lakeshore owners and the characteristics of the individual lakes. For example, a "swimming lake" might have less coarse woody debris, better or at least stabilized water quality, and decreased motorboat traffic. In other lakes, especially small lakes or lakes with only a few property owners, habitat, water quality, and fishing quality remained high.

In 2025, the population of the NHLD was 55,000 people, a population increase of 25% from 2000. The region's inhabitants were generally older and richer than in Wisconsin as a whole. However, there was a lot of inequality. Whereas a number of rich people owned huge homes that they occupied for only a few weeks a year, many local residents earned minimum wages for cleaning and security companies. Everyone could agree, however, that the North Woods had become more like the suburban environments found commonly throughout the United States. There were many suburban features, ranging from extensive lawns to strip malls. Local politics were more contentious and divisive. Although many people were unhappy with the ways that the NHLD had changed, there were conflicts that prevented effective organization to improve the situation. There was a sense of quiet resignation that the North Woods would inevitably follow the path of suburbanized counties "down south." Some long-term residents even sold their homes to relocate to quiet, wild, undeveloped lakes in Canada.

Comparison of scenarios

Collectively, the scenarios span a great diversity of possible futures for the NHLD (Table 2). We do not think that any of these scenarios is likely to occur, although aspects of each scenario may occur. We also believe that these scenarios are prototypes that can and should be improved through wider discussions among the people of the NHLD.

One important use of scenarios is to identify the traps and opportunities that the future may bring. Our prototype scenarios differ in this respect. Walleye Commons shows that climate mitigation may not be a boon, and that the spread of exotic species and widespread fish stocking may exact a heavy toll. On the other hand, economic decline provides the opportunity to develop extensive private, public, and tribal ecological reserves that greatly improve the natural resource base of the region and could lead to economic restructuring. Northwoods.com suggests one pathway for the development of a more autonomous economic base for the NHLD, while at the same time maintaining a large number of high-quality ecological services. The potential traps in the Northwoods.com scenario derive from the growing conflict between rural and urban citizens, the deterioration of the environment in the urban corridor, and possible long-term changes in the values of the urban residents. Lake Mosaic depicts the trap of developing lakeshore after lakeshore, which Gene Likens (1992) has called "leapfrog degradation." People are attracted to the North Woods for its natural features, but in the process of development they convert the North Woods into the suburbia they were trying to escape from in the first place. On the other hand, there is opportunity to improve individual lakes, vested in the local power of lake associations. Moreover, the great diversity of lake types on the landscape offers the potential for experimentation and innovation. These scenarios enable decision makers to consider their choices in view of possible traps or opportunities that might develop in the future.

Unlike statistical models disciplined by past data, scenarios can explore surprises and their consequences. In Walleye Commons, the surprise is the diseases linked to environmental change and fish stocking. In Northwoods.com, the surprise is a rapid political shift driven by the development of the Wisconsin River valley. In Lake Mosaic, the surprise is fraying social interactions derived from the suburbanization of the lake shore. All of these surprises occur as consequences of slow, predictable changes that set the stage for rapid, unexpected ones. This is a type of change that is extremely difficult to anticipate (Dörner 1996). Scenarios can help frame possible futures of this nature.

Scenarios are not predictions. In contrast to statistical forecasting, in which a particular model or set of models provides the optimal out-of-sample prediction, there is no uniquely optimal set of scenarios. Instead, we seek scenarios that expose a wide range of possible outcomes, are consistent with available scientific information, and evoke creative, forward-looking plans. The primitive set of scenarios offered in this paper meets the first two criteria. The last criterion can be evaluated only after the scenarios are replaced with new ones developed by people who live in the NHLD, and even those scenarios must be tested in the crucible of practice. An initial step toward this was taken via a workshop in early 2002, in which stakeholders defined the key issues facing the NHLD and assessed the vulnerabilities of the region. This meeting will be followed by a stakeholder scenario workshop in the fall of 2002, at which stakeholders will use the results of the previous workshop and this paper to develop a new set of stakeholder scenarios for the region.

CONCLUSIONS

The Northern Highlands Lake District (NHLD) is in some respects an ideal test bed for assessment methodologies. The region is well defined geologically, and its political boundaries pose few complications. Because of extensive prior research, we were able to draw on a rich body of data for the region. Access to data was essential; without the resources of a major state university, the state government, and a Long-Term Ecological Research site, largely shared on the Internet, our task would have been much more difficult. Because of these resources, we were able to rapidly assemble a scientific assessment, determine important uncertainties and uncontrollable drivers, and design zero-order scenarios. This suggests that the approach of the Millennium Ecosystem Assessment is feasible, at least in this case. It awaits further work to see how well this approach succeeds in regions for which data are unavailable, social and ecological change are poorly understood, and there is little research to build upon.

Scenarios have long been used for business and military planning (Kahn and Weiner 1967, van der Heijden 1996, Hammond 1998). Global scenarios have addressed a number of environmental issues (Hammond 1998, Raskin et al. 1998, Nakicenovic and Swart 2000). There is less experience with scenarios for regional or local conservation problems (Greeuw et al. 2000, Rotmans et al. 2000, Wollenberg et al. 2000), although global scenarios are often built upward from regional analyses (Raskin et al. 1998). The Millennium Ecosystem Assessment plans to develop scenarios at multiple scales. The process of translating information across scales is unexplored, at least so far. Different scales pose different challenges. For example, global projections of human population, although difficult, are more certain than local projections because of the unpredictability of human migrations. Comparison of global scenarios with our scenarios for the NHLD illustrates some of the differences that may arise. For example, the Stockholm Environment Institute scenarios (Raskin et al. 1998) emphasize the openness of societies, the globalization of economy, the distribution of wealth, and global biogeophysical changes, whereas our NHLD scenarios emphasize the spatial distribution of population and land ownership and a region-specific set of biogeophysical conditions. If global scenarios are used as the context for local scenarios, it seems likely that the coupling across scales must be informal and flexible. Site-specific considerations are likely to introduce many issues to local scenarios that are not addressed in global ones.

Despite the creation of preliminary scenarios, the work described here is largely an academic exercise that must be grounded in local practice to be useful. It is the first step in an ongoing process of assessment and planning for the NHLD. We hope that this paper will serve as the initial cornerstone document of a process that will continue for many years to come. Although the future path of the NHLD is unknowable, we hope that the assessment process begun here will help the people of the region choose the most desirable route.

Responses to this article can be read online at:
http://www.consecol.org/vol7/iss3/art1/responses/index.html

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APPENDIX 1

Proposed steps for analysis of the Northern Highlands Lake District based on guidelines for the Millennium Ecosystem Assessment.

1. Define the geographical scope.
2. Define the ecosystem subdivisions or units of analysis.
3. Characterize the ecosystem.
4. Characterize the human demands on, or uses of, the ecosystem.
5. Characterize the state or condition of the ecosystem.
6. Develop plausible future descriptions of the driving forces influencing the system.
7. Assess the impact of these plausible futures on the goods and services provided by the ecosystem. Assess the economic and public health impact of those futures.
8. Identify the policies, technologies and tools that would help to address any negative impacts of ecosystem change, or increase the aggregate benefits provided by ecosystems.
9. Identify the monitoring, research, institutional, and human needs to enable better assessments of ecosystem condition and better capability to act on those assessments.

APPENDIX 2.
PROCESSES OF THE
NORTHERN HIGHLANDS LAKES DISTRICT

Northern Highlands Lake District

This appendix presents a synthetic summary of current scientific understanding of the structure and dynamics of the actors, linkages, and ecosystems in Wisconsin's Northern Highlands Lake District (NHLD). This synthesis was conducted for the purpose of understanding the use and production of aquatic ecosystem services. It was used to develop the scenarios presented in the main text by 1) refining the key variables that were considered, 2) defining the key uncertainties that the scenarios would explore, and 3) qualitatively supporting the development of the scenarios.

The 2000 census estimated that about 43,000 people reside in the NHLD (U.S. Bureau of the Census 2001). As seen in Fig. 2 of the main text, the population is centered around a few small towns. The residents of the NHLD are different from those of Wisconsin as a whole. They tend to be older, are more likely to be Native American, and usually have lower incomes than the general population. Currently, Native Americans make up about 9% of Vilas County, which is where the Chippewa Lac du Flambeau reservation is located (U.S. Bureau of the Census 2001). In 1990, the average per capita income of Native Americans was 40% of that of the overall population of the NHLD (U.S. Bureau of the Census 1992). The population of this region has been changing due to the emigration of young people and the much larger immigration of older people.

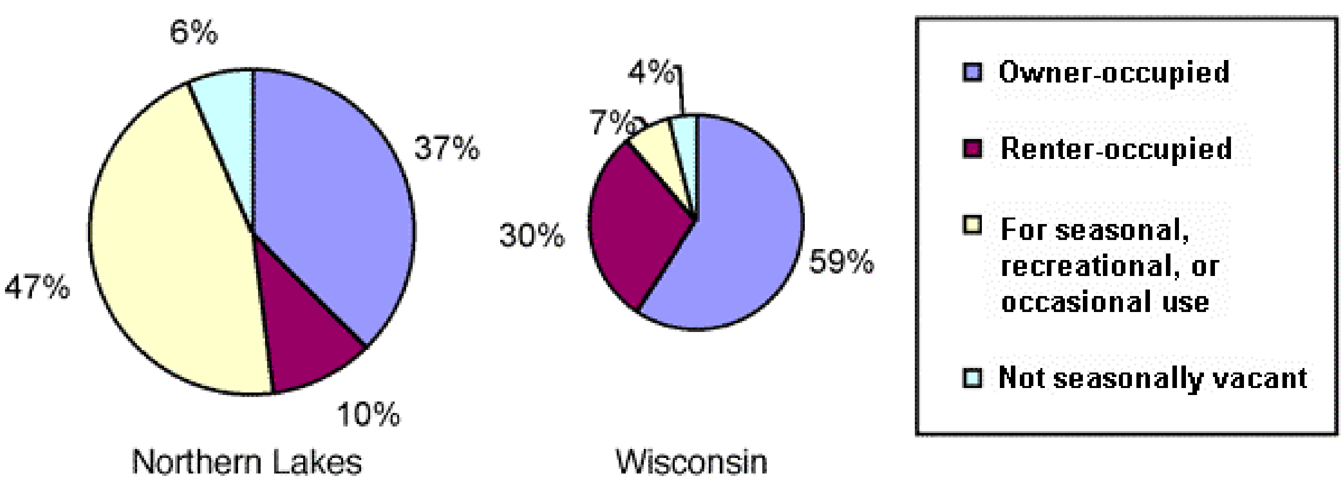
Tourism is very important to life in the NHLD. It is closely linked to lakes and the northern landscape. Major recreational activities include fishing and boating in summer, and hunting, snowmobiling, and ice fishing during the colder months. Many visitors also participate in hiking, bicycling, and bird-watching. In Oneida and Vilas counties, approximately $340 x 10^6 dollars or $6500/resident are spent per year on tourism activities (Wisconsin Deptartment of Tourism, *unpublished data*). There are many tourism-related facilities in the NHLD. There is an extensive network of trails, many public boat landings, campgrounds, and large amounts of public land. Private ventures that cater to outdoor recreational enthusiasts include numerous resorts, golf courses, fishing and hunting guides, and other recreation-related industries.

Fishing, one of the primary human uses of the northern lakes, occurs year round (Staggs et al. 1990). Peak fishing effort in this region occurs during the summer months, although the highest catch rates are in spring and early winter (Fayram 2000). Fishing pressure is unevenly distributed across the region (Staggs et al. 1990; T. D. Beard Jr. et al., *unpublished manuscript*). Fish densities can be good predictors of angling effort on particular lakes in this region, and anglers are attracted to the lakes that appear to offer them greater harvest opportunities (T. D. Beard Jr. et al., *unpublished manuscript*). Management policy also influences lake choice, with more effort directed at lakes with less stringent regulations (T. D. Beard Jr. et al., *unpublished manuscript*). The open-access fisheries of this region have led to lakes that have generally similar catch rates, fish densities, and fish catchability (Hansen et al. 2000).

Boating is a highly valued recreational activity in Wisconsin. Most boats are used for fishing, but other kinds of boats are becoming more common. The impacts of motorboats on lake ecology include reductions in water clarity and quality, increased shoreline erosion, damage to aquatic macrophytes, and interference with wildlife (Asplund 2000). Most studies of boating impacts have been short term. The physical effects of waves and turbulence appear to be more serious than pollution from motorboats. The most striking impacts have been found in shallow and near-shore waters, where increases in nutrients, turbidity, and shoreline erosion and decreases in aquatic plant biomass are associated with boat traffic (Asplund 2000). Reed-Anderson et al. (2000) found that the distribution of boats on lakes was related to lake area, distance from major roads and population centers, measures of public facilities on lakes (i.e., lots of boat ramps and campgrounds), and the perception of good fishing. In general, isolated lakes high in the landscape and lacking public facilities have fewer boats. Currently in Wisconsin, personal watercraft are required to operate at no-wake speeds within 200 m of shore, and other motorboats are required to operate at no-wake speeds within 100 m of the shore (Asplund 2000).

Many people visit the NHLD as tourists for part of the year. Some of these people stay in motels, cabins, or campgrounds, whereas others have second homes. Most of the houses in the NHLD are in Vilas and Oneida counties. Summer homes make up almost 60% of the housing units in Vilas County. Most of the ecological impacts of settlement are probably produced by nonresidents (Fig. A.1). For example, many people appear to manage their land for aesthetic rather than commercial values. An economic analysis of forest management decisions in northern Wisconsin estimated that people found the nontimber value of trees to be more than twice the potential timber revenue and that this value increased from the 1960s to the mid-1980s (Scarpa et al. 2000).

Figure A.1. Housing occupancy in northern Wisconsin vs. Wisconsin as a whole in 1990 (U.S. Bureau of the Census 1992).



Institutions

Because the population of northern Wisconsin is sparse, the state government plays a substantial role there. The use of natural resources is regulated primarily by the Wisconsin Department of Natural Resources (DNR). The state also owns the 14% of the NHLD that is inside the Northern Highland-American Legion State Forest.

Local government influences local land-use decisions and zoning. However, federal and state regulations provide a regulatory framework for issues such as land conversion, pollutant emission, the protection of endangered species, and fish and game management.

Another influence on ecological management in the NHLD was the reconfirmation of Ojibwe treaty rights in 1983. Following federal occupation of northern Wisconsin, various groups of Native Americans signed treaties with the U.S. government, surrendering their sovereignty in exchange for the right to hunt, gather, and fish on the lands ceded to the federal government (Loew 2001). As the result of a series of court decisions, fisheries in northern Wisconsin are now regulated by the Wisconsin DNR. The Great Lakes Indian Fish and Wildlife Commission is responsible for monitoring the off-reservation extraction of natural resources by tribal members. Spearfishing is a separate fishing activity that is conducted only by Native Americans. The resumption of Native American spearfishing was originally protested by non-native sportfishers and sportfishing business interests, and the issue is still a source of tension between Native Americans and other people in the NHLD.

The management of individual lakes is also influenced by lake associations. Lake associations are groups of people who own lakeshore property and work in partnership with the state government and the DNR to achieve mutually agreed upon goals for the lake. Lake associations are local organizations that can operate dams, maintain lake access, remove aquatic plants, purchase wetlands, improve fish habitat, and stock fish.

The institutional regulation of fishing, lake development, and other extraction activities is a necessary condition for the sustainability of these activities. However, the success of particular institutions depends on both human behavior and ecological dynamics. In the following sections we describe the ecological processes that influence fish populations and water quality.

Fish

The fish communities of the larger lakes in the region are dominated by walleye (*Stizostedion vitreum*), the primary piscivore (Becker 1983). These larger lakes are a focus of human use and fish management (Beard Jr. et al. 1997, Fayram 2000, Nate et al. 2000). In smaller lakes, fish communities are usually dominated by either mudminnow, *Umbra limi*, or bass (Tonn and Magnuson 1982). Mudminnow lakes commonly contain shiners and dace and generally lack specialized piscivores. These lakes are usually small and shallow. Bass lakes commonly contain bluegills (*Lepomis macrochirus*) and yellow perch (*Perca flavescens*). Bass lakes also tend to be small, but these lakes are deep and isolated with high oxygen levels in the winter. Panfish such as bluegill are the most popular fish in Wisconsin. Consequently, the small bluegill-dominated lakes are valuable for fish, whereas mudminnow lakes are not.

Walleye are the main sport fish and the subject of treaties with Native Americans. Consequently, walleye management has been contested and has become the focus of considerable management and research activity. Over the past several decades, walleye population densities have been stable (Fayram 2000), although there has been substantial year-to-year variation within individual lakes (Hansen et al. 1998). There is little information about the dynamics of other species, except in a few lakes used for long-term ecological research (see http://limnosun.limnology.wisc.edu/).

People have substantially influenced the fish communities of the NHLD. Within the fish communities of individual lakes, community structure is typically controlled by age- and size-dependent competition and predation (Colby et al. 1987, Kerfoot and Sih 1987). Fishing, fish management, the introduction of species, and habitat modification have all transformed the fish communities across the NHLD. Fishing and fish stocking can strongly influence fish populations (Carpenter et al. 1994). Fishing changes the age and size structure of fished species, and fish stocking changes the genetic mix of fish populations. Both these changes can in turn influence nonfished species that are also present in lakes. Case studies have shown that the response of a particular fish community is dependent on specific circumstances (Colby et al. 1987).

Indirectly, people have substantially altered aquatic ecosystems by introducing new species. In some lakes, rainbow smelt have driven the native planktivore cisco, *Coregonus artedii*, extinct and reduced the abundance of yellow perch (Hrabik et al. 1998). Hrabik and Magnuson (1999) modeled the spread of smelt based on current rates and predicted that lakes with less human access would provide important refuges for native fish communities. The invasion of the rusty crayfish has negatively affected macrophyte communities, fish, and other crayfish. Although invasions are difficult to predict (Lodge et al. 1985), further introductions of non-native species into the NHLD seem highly likely.

Many lake organisms require the habitat structure provided by coarse woody debris (CWD) and macrophyte beds for growth and survival. Physical structures protect young fish and macroinvertebrates from predators and provide food for young fish (Crowder and Cooper 1982). Some fish appear to grow more slowly when the amount of CWD is limited (Schindler et al. 2000). The distribution and abundance of CWD is influenced by climate, soils, stream flow rates, and topography as well as forest age, density, and composition. Humans have decreased the production of new CWD by removing trees from the edges of lakes and have even removed CWD from within the lakes themselves. Both the density and basal area of CWD have been observed to decline as the density of shoreline cabins increases (Christensen et al. 1996). Consequently, unless people stop removing CWD and riparian trees, the increasing settlement of lake shorelines will homogenize and simplify lake habitat.

Water quality

Most lakes in the district receive the majority of their water from direct precipitation; many are seepage lakes with no surface-water inputs or outputs and are connected only by groundwater flow. Consequently, they are highly sensitive to changes in the precipitation regime. Short-term dry and wet periods related to the El Niño Southern Oscillation have caused lake level fluctuations of up to a meter (Webster et al. 1996). Land use in catchments affects the delivery of water to catchments and lakes through its effects on infiltration and evapotranspiration rates (Stednick 1996).

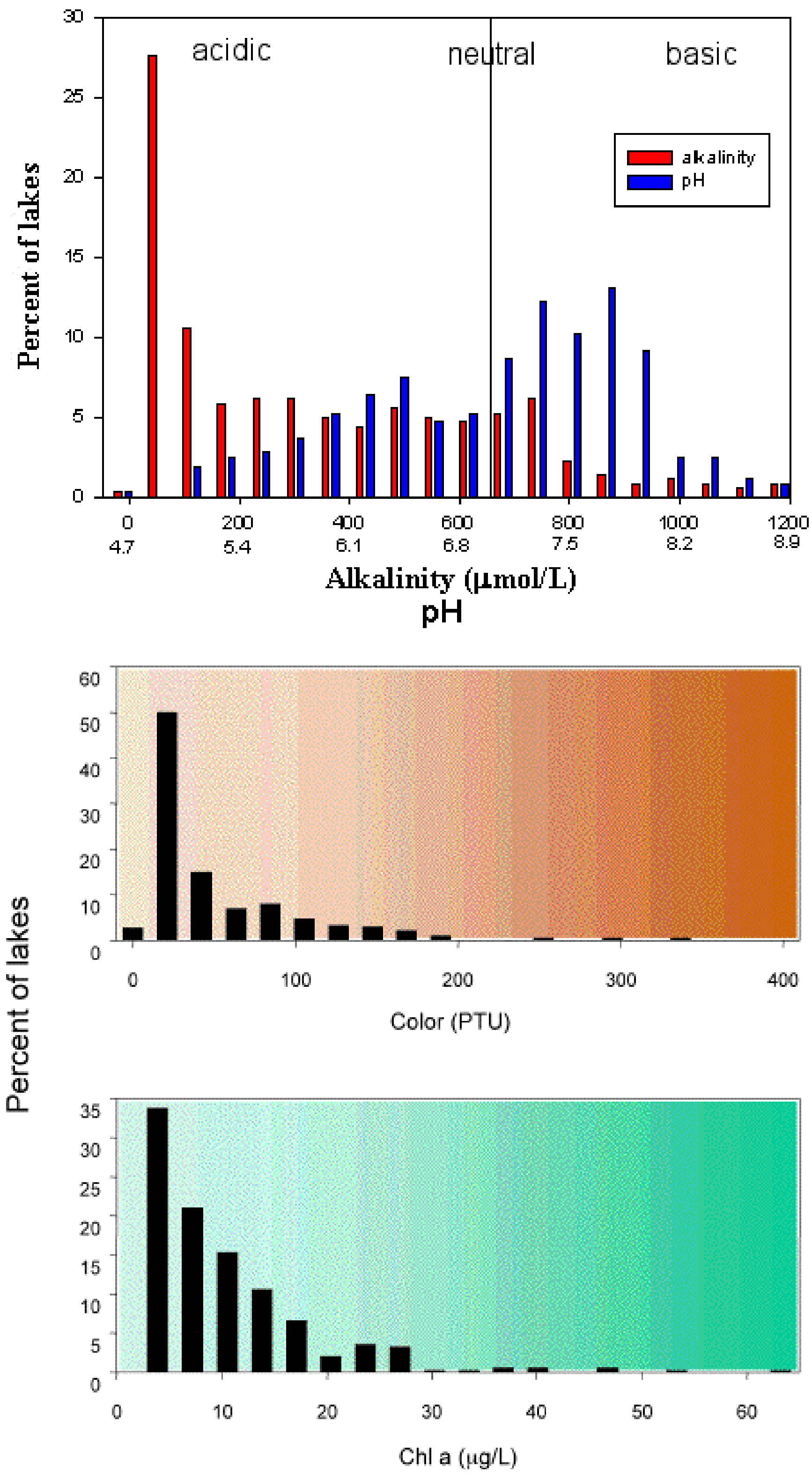
From an anthropocentric perspective, the quality of water depends on how it looks, i.e., whether people find it aesthetically pleasing; whether it is healthy, which depends on the presence of toxins and disease-causing organisms; and its ability to maintain healthy fish populations. The interrelated factors that determine water quality are water color, trophic status, the presence of toxins, and the presence of disease-causing organisms.

Northern highlands lakes show a wide range of water color, mainly because of variations in dissolved organic carbon (DOC) concentrations (Fig. A.2). Lakes with high concentrations of DOC appear brown or "stained," and lakes with low DOC concentrations appear blue or "clear." Most DOC is derived from the soils or wetlands in the surrounding catchment (Hope et al. 1996, Gergel et al. 1999). The amount of DOC entering a lake from the catchment may be altered by drought, fire, or long-term weather patterns (Schindler et al. 1992, Schindler et al. 1997*b*). Inputs of DOC to lakes could also change with residential development as wetlands are drained or filled in.

DOC influences many properties of lake ecosystems (Jackson and Hecky 1980, Jones 1992, Williamson et al. 1999). High DOC levels reduce the penetration of solar radiation, which can in turn reduce primary production, decrease mixing depth, and change vertical distributions of organisms. DOC also alters the availability of nutrients and the toxicity of contaminants in complex ways and provides a substrate for microbial metabolism.

Phosphorus, nitrogen, and other nutrients are supplied to lakes from the surrounding catchment, from precipitation, and, in the case of nitrogen, by the process of nitrogen fixation. Inputs of P have received the most attention, because P limits the growth of algae and thus is a primary controller of eutrophication (Schindler 1977). P concentrations in a lake are a function of direct P inputs, lake depth, flushing rate, and rate of sedimentation. Accumulation of P in lake sediments can lead to high rates of recycling of P from lake sediments back into the water column, exacerbating problems of eutrophication (Carpenter et al. 1999). Sources of P inputs from the watershed include weathering of geologic materials and nonpoint (diffuse) pollution (Bennett et al. 1999).

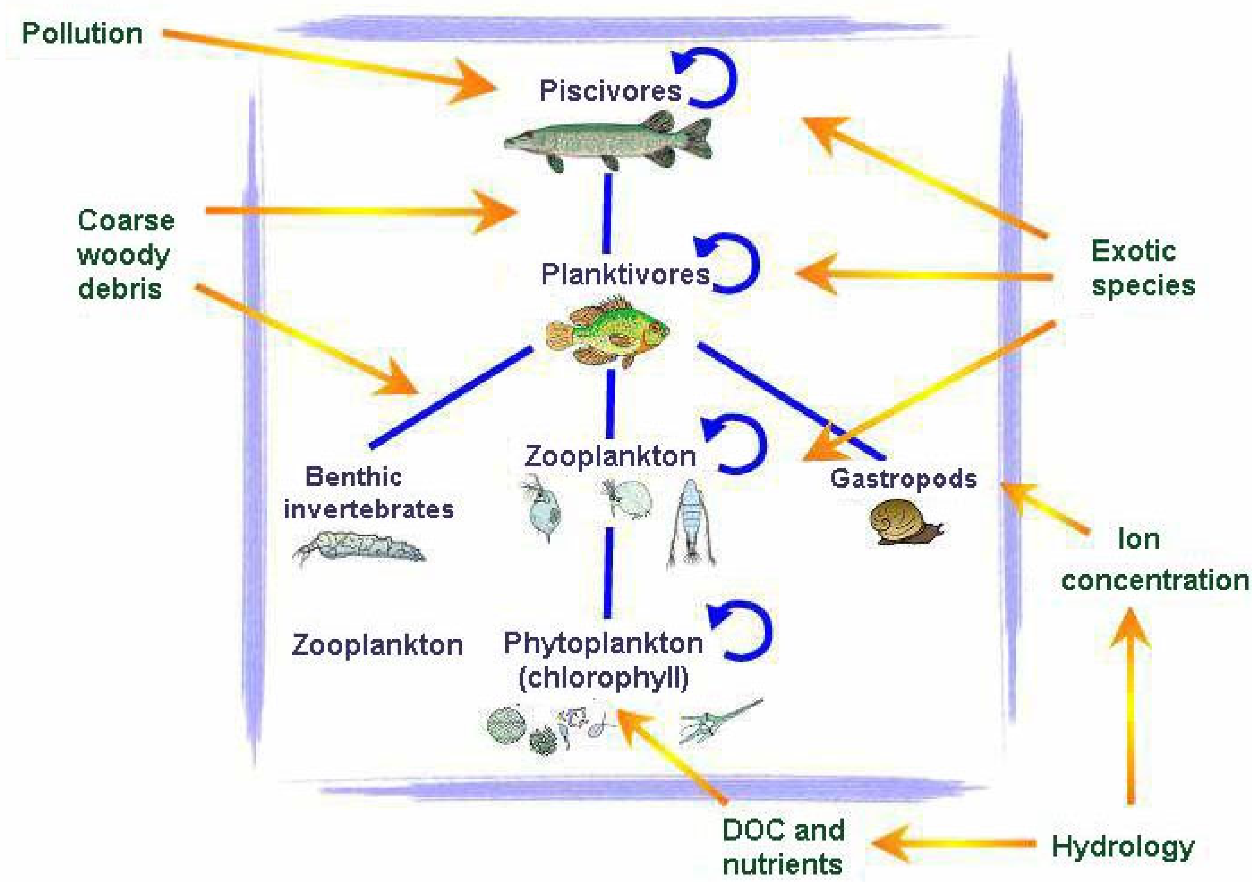
Figure A.2. Lake attributes in northern Wisconsin. Most lakes are relatively clear and somewhat basic. a) Lake acidity, b) lake color (platinum units), c) lake algal biomass (Chl-a).



Residential development has been associated with increased lake P concentrations (Dillon and Rigler 1975, Dillon et al. 1994). Inputs from fertilizers or septic systems can increase nutrient loading. In 1990, there were more than 50,595 septic tanks in the Northern Lakes region, most of which (72%) were in Vilas and Oneida counties (U.S. Bureau of the Census 1992).

Algal growth is affected not only by nutrient availability but also by predation and the presence of macrophytes and grazers. In shallow lakes, macrophytes also influence overall algal biomass and water clarity by competing for light and nutrients with phytoplankton (Scheffer et al. 1993). Large-bodied daphnids are the most effective predators of algae. They are able to significantly reduce algal biomass and thus improve water quality. The size structure of the zooplankton community is, in turn, a function of cascading effects generated by changes in fish communities (Carpenter and Kitchell 1993). Feeding by planktivorous fish can cause a shift from large- to small-bodied daphnid assemblages with no changes in the total biomass of zooplankton (Carpenter et al. 1985). Piscivorous fish can suppress populations of planktivorous fish (Carpenter and Kitchell 1993, Schindler et al. 1997*a*). As shown in Fig. A.3, because of the vastly different generation times of the components of pelagic food webs, responses in the plankton to changes in the balance between piscivores and planktivores are rapid (Carpenter and Kitchell 1993).

Figure A.3. Factors influencing food web structure in lakes. There are internal factors such as competition and predation between members of a single trophic level and predation activities involving adjacent trophic levels. Many external factors also influence the structure of the food web as discussed in the text, and these relationships are outlined outside of the food web box in this figure.



Pollutants such as metals and hydrocarbons also affect the water quality of lakes. Mercury, a neurotoxin, is the pollutant of greatest concern in the NHLD. Fish with mercury levels high enough to warrant health warnings (> 0.5 ppm) have been found in one-third of the lakes tested in Wisconsin (Wisconsin Environmental Decade Institute 2000), and many of these are in the NHLD. The combustion of fossil fuels is the primary source of above-background atmospheric mercury. From the atmosphere, mercury enters lake water in precipitation and is methylated by microbial processes. The methylation process is enhanced by low pH, high levels of organic matter, and anoxic conditions (Driscoll et al. 1994, Rudd 1995). Fish absorb mercury directly, through their gills, and from prey; it accumulates over time in their body tissues, and consequently the highest mercury levels are found in fish that are older, larger, and piscivorous. The concentration of methylmercury in piscivorous fish can be 1–10 x 10^6 times higher than in the surrounding water (Wisconsin Department of Natural Resources 1996). Mercury is also likely to affect wildlife, particularly species such as loons that feed intensively on fish (Meyer et al. 1998).

The Wisconsin DNR generally assumes that most lakes in Wisconsin are contaminated with mercury. Therefore, it advises people not to eat many fish from inland waters. It recommends that children under 15 and women who could become pregnant should not eat more than one meal of panfish a week and one meal of gamefish a month. People who cannot become pregnant are advised to eat no more than one meal of gamefish per week.

Motorized watercraft are another source of pollution in the NHLD. Two-stroke engines such as those used by jet skis are particularly inefficient, emitting about 25% of their fuel unburned directly into the environment (see http://www.earthisland.org). Wisconsin now requires four-stroke boat engines.

In general, studies have shown minimal short-term effects of boat pollution on aquatic organisms, although, in some cases, polyaromatic hydrocarbons and fuel additives have been detected that could be a concern for drinking water supplies (Asplund 2000). The long-term effects of these fuel emissions on human health have not been studied.

Whereas lake water quality is threatened by development and toxins, most drinking water comes from groundwater in the NHLD. In 1990, only 20% of houses were connected to public water systems. Although groundwater can be affected by contamination in surface water, filtering through soil generally removes many contaminants. A more direct threat to groundwater quality is abandoned wells. If not filled with impermeable material, wells can channel contaminated surface or soil water directly into the groundwater.

Over the past century, Wisconsin's climate has remained largely unchanged. It is expected that during the 21st century the average temperature will increase by several degrees Celsius, especially during fall, winter, and spring. Precipitation is expected to increase 15–20% in summer, fall, and winter (Environmental Protection Agency 1999). These changes would have a variety of effects on the functioning of the ecosystems in the NHLD, but their cumulative consequences are uncertain. Expected impacts of climate change on aquatic systems include declines in cool-water fish such as trout and increases in warm-water species such as rainbow smelt and yellow perch (King et al. 1999), an overall decrease in fish habitat (Magnuson et al. 1997, Meyer et al. 1999), declines in the stability of invertebrate food webs (Beisner et al. 1997), the elimination of winterkill events (Fang and Stefan 2000), altered mixing regimes, and changes in the magnitude and seasonality of runoff patterns (Meyer et al. 1999). Although change is to be expected, the magnitude and type of ecological change produced by climate change is highly uncertain.

Invasive species

During the past several centuries, more than 100 species of plants, animals, and invertebrates have been introduced into the Great Lakes region, and a number of them have also become established in the NHLD. Some of these introductions were intentional and include managed populations of species such as brown trout (*Salmo trutta*) and carp (*Cyprinus carpio*). Other invasive species were introduced unintentionally as passengers in or on boats, in bait buckets that were indiscriminately emptied, or as escaped aquarium species (Rahel 2000). Among the more detrimental introductions for aquatic systems in the NHLD are Eurasian watermilfoil (*Myriophyllum* *spicatum*), purple loosestrife (*Lythrum salicaria*), rainbow smelt (*Osmerus mordax*), and rusty crayfish (*Orconectes rusticus*). These species have changed both the composition and functioning of many aquatic ecosystems.

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