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Natural Resource Stewardship and Science

Using Climate Change Scenarios to Explore Management at Isle Royale National Park

January 2013 Workshop Report

Natural Resource Report NPS/NRSS/CCRP/NRR—2013/714

ON THE COVER

Middle Islands passage in autumn on Isle Royale; NPS photo.

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Contents

Executive Summary

Climate change in conjunction with other stressors is altering ecosystems and biota within National Parks and impacting park management and operations. The National Park Service (NPS) is actively developing climate change adaptation tools to support management options for a future characterized by both rapid directional change and great uncertainty. One tool to achieve this goal is participatory scenario planning, a technique that enables stakeholders to examine a range of plausible future conditions, identify key climate and ecosystem drivers, and explore management options that will be appropriate and effective across a range of potential futures. This report summarizes the Isle Royale climate change scenario planning workshop, convened in January 2013 to examine how climate change may affect the park's resources, with an emphasis on the island's forests and wolf and moose populations.

Workshop participants developed four divergent scenarios for the period 2013-2050, based on the range of projected climate change. The 'Least Change' scenario was the minimum level of expected change, while the other three scenarios incorporated greater climate change and additional associated disturbance events. The 'Summer Drought, Wind, and Fire' scenario included punctuated dry summer periods and an increased probability of wind storms. The 'Warmer than Duluth' scenario had temperature increases from the high end of projections (+6.5 °F) while the 'Isle Savanna' scenario included warm temperatures (+5 °F) and increasingly frequent drought events (i.e., strong precipitation variability). These descriptive narratives present potential futures based on the range of climate projections and scientific understanding of species interactions and ecosystem responses to climate change. Participants then explored several options for resource management within each of the scenarios.

The Isle Royale workshop identified outcomes common to all four scenarios, issues that remain uncertain, and areas for future research. All scenarios projected a loss of ecosystem resiliency and an inevitable shift in vegetation from cool-adapted boreal to warm-adapted temperate species. The rate of vegetation change depends on the magnitude of climate warming and on the occurrence of disturbance events, such as windstorms, wildland fire, and forest pathogens. Workshop participants noted that extreme events, including climatic (drought) and associated disturbances (wind and fire) would likely constitute trigger points, causing thresholds to be surpassed and an accelerated transition of ecosystem composition and structure. The rate of ecosystem change and formation of novel communities will challenge management decisions that focus on preserving natural processes and native species.

The response of Isle Royale's wolf and moose populations to these vegetation shifts is difficult to predict because although the system is a relatively simple food chain, trophic interactions are dynamic. Past trends may not adequately inform models of likely future change, especially given the rate and magnitude of climate change in this region. Moose are likely to both benefit and suffer from initial warming trends; increased warming will stress animals while less snow in the winter will reduce the likelihood of wolf predation. For wolves, the small population size and limited gene pool were seen as greater immediate threats to population persistence than direct impacts from climate change. Additionally, the island's geographic isolation, along with the inherent dynamics of island ecosystems, may reduce the resiliency of current populations to change and contribute to more rapid population swings.

Executive Summary (continued)

While the participatory approach described here is not designed to recommend specific management actions or report on the feasibility of success of any given actions, workshop participants had general agreement on the relevance of certain actions across all scenarios. Management strategies considered to be relevant under all scenarios include reducing non-climate stressors, such as nonnative species, as well as continued monitoring and expanded research on an array of ecosystem components. Restoration to pre-European settlement conditions (pre-1850) was deemed challenging under all scenarios, as climatic and ecosystem conditions shift beyond the historical range of variability observed on the island.

Projected changes in the coming years will also affect all aspects of park management, from facilities and visitor experience to natural and cultural resource management. Most of the land area of the park is federally designated wilderness, and climate induced changes will affect the character and quality of the wilderness. The shift away from historical vegetation (boreal forest) may be perceived negatively by visitors and the potential loss of moose and wolves could be a major impact to visitor expectations and experience. Thus, education and outreach will be needed to inform visitors of the changes occurring on the island. Trail and building maintenance backlogs may become exacerbated by fallen trees and increased storm damage. Most scenarios also identified an expanded visitor use season that begins earlier in spring and continues later into autumn, further pressuring the operating budget.

The future of Isle Royale will not be a replica of the past; some ecosystem components will remain while others will disappear as new elements arise. Resource stewardship must adhere to public policy and regulations, reflect the long-term public interest, and be informed by the best available science. For Isle Royale, this means acknowledging past ecosystem components and dynamics while simultaneously looking towards a future that harbors both expected changes and many uncertainties. The scenario planning workshop process and individual scenarios are intended to inform the development of robust climate change adaptation options. Conclusions from the workshop rely on peer-reviewed scientific literature and the expert opinion of participants and reviewers and are not meant to be a substitute for formal feasibility studies on future restoration of any species on the island.

Introduction

The National Park Service (NPS) is actively developing climate change adaptation decision-support options. Scenario planning is an important tool in the NPS strategy for managing parks into a future of climate uncertainty (NPS 2010). Climate change in conjunction with other stressors (for example, nonnative species, overabundant herbivores, disturbances, and insect outbreaks) is fundamentally altering ecosystem properties, processes, and composition. Thus, land managers are dealing with both rapid directional change and tremendous uncertainty. Management must be grounded in our understanding of past dynamics as well as the realization that future conditions may shift beyond the range of variability observed in historical data (Heller et al. 2009). With this backdrop, NPS applies scenario planning to explore the range of plausible future conditions and implications for resources and management.

For Isle Royale National Park, effective resource management, including that of the island's forests and wildlife populations, requires an understanding of past and present conditions as well as projected future trends. The climate of the region is changing, bringing warmer overall temperatures, extended summer seasons, changes to the precipitation regime, warmer water and reduced ice cover of Lake Superior, and many other shifts (Kunkel et al. 2013). Low wolf population numbers, as few as eight individuals in early 2013, and possible inbreeding depression have heightened concerns about the long-term persistence of wolves on the island (Vucetich and Peterson 2013). Moose populations in the region (outside of the park in northern Minnesota), have been declining for more than a decade (Lenarz et al. 2010, DelGuidice 2013). For many people these wildlife populations and their conservation are a central feature of Isle Royale's wilderness character. Some projected changes are relatively well understood but many are not. Given the uncertainty associated with climate change, the NPS held a workshop in January 2013 to explore the implications of plausible futures as climate and related ecosystem conditions change on Isle Royale. The NPS needs better understanding of the potential direction and magnitude of change on the island in the coming years and decades to inform appropriate and effective management of island resources and operations.

Isle Royale National Park History

Established in 1940, Isle Royale National Park is a densely forested archipelago located in the northwestern portion of Lake Superior, 15 miles off the coast of Minnesota and adjacent Ontario, Canada. The park includes the primary large island known as "Isle Royale" and more than 400 smaller islands. Ninety-nine percent of the land area is wilderness (132,018 acres) and park management largely focuses on backcountry-based recreation in concert with protection of natural and cultural resources. Although the park has no roads and is only accessible by boat or plane, roughly 16,000 visitors annually make the journey to the island. The park's wilderness area has one of the highest annual visitation rates in the National Park system.

The park's natural resources include boreal forest, temperate northern hardwood forest, and numerous wetlands, lakes, streams, and rocky outcrops (Kraft et al. 2010). Common boreal tree species are paper birch (B*etula papyrifera*), trembling aspen (*Populus tremuloides*), spruce (*Picea glauca and Picea mariana*), and balsam fir (*Abies balsamea*). Temperate northern hardwood forests occupy upland interior sites on the island and are dominated by sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) with white ash (*Fraxinus americana*), red oak (*Quercus rubra*), and white pine (*Pinus strobus*) on drier sites. Many existing forest stands were established after logging and fire events in the 1920's and 1930's, and there have been no large-scale stand replacing disturbances over the past 50+ years (Previant et al. 2012).

Mammal species on the island include moose (*Alces alces*), wolf (*Canis lupus*), beaver (*Castor canadensis*), snowshoe hare (*Lepus americanus*), and seven species of bats (Kraft et al. 2010). Moose arrived on the island in the early 1900s. Wolves reached the island via an ice bridge in the late 1940s and four wolves from the Detroit zoo were introduced in 1952, one or two of which may have persisted (Johnson and Shelton 1960). Present on the island prior to European settlement activities, woodland caribou (*Rangifer tarandus*) and lynx (*Lynx canadensis*) were eventually extirpated in the early 20th century due to hunting and trapping pressure and interspecific competition (Johnson and Shelton 1960).

Background and Setting: Climate, Vegetation, and Wildlife History, Trends, and Interactions

Vegetation, wildlife, and environmental variables, such as climate, have complex and dynamic relationships. Comprehensive, long-term studies of climate, forest dynamics, and the wolf-moose-vegetation system on Isle Royale provide a broader understanding of ecosystem change, trophic interactions, and how the importance of drivers can vary over time (Kraft et al. 2010). Past dynamics and the relative roles of various biotic and abiotic drivers inform our understanding of the plausible rates and direction of ecosystem change in the near future.

Isle Royale National Park wilderness; NPS photo.

Climate History and Projected Trends

Isle Royale's climate is influenced by both its regional location in the center of the continent as well as its local position in Lake Superior. The upper Midwest experiences wide extremes of temperature and precipitation due to influences of warm and humid air masses from the Gulf of Mexico and by cold and dry Arctic air masses from the north (Kunkel et al. 2013). Mean annual temperature on Isle Royale is 39.0 °F (3.9 °C) and annual precipitation, relatively well distributed across the four seasons, averages 28.9 inches (734 mm) (1971-2000 average, Daly et al. 2008). Lake Superior has many effects on the local climate of the island. The waters of the lake modify the air temperature, resulting in cooler summers and warmer winters than on nearby inland areas. The cool lake waters also suppress summer convective weather systems and thus limit the amount of summer precipitation on the island. Winter conditions on the island are influenced by regional and northern hemisphere climate variability, in particular the phase and strength of the Arctic Oscillation (AO) and its regional manifestation, the North Atlantic Oscillation (NAO) (Hurrell 1995, www.cpc.ncep.noaa.gov). On Isle Royale, cold winters and heavy snowfall characterize the NAO's negative phase, while the positive phase brings extended warm and dry periods during winter (Post and Stenseth 1998).

The climate of the Great Lakes region and Isle Royale exhibited detectable changes over the past century and particularly over recent decades (Gonzalez 2012). The upper Midwest region showed some of the most rapid warming trends within the coterminous U.S. in recent years, +0.5 °F (+0.26 °C) per decade between 1979 and 2010 (Pryor and Barthelmie 2012). Warming trends have been strongest in winter and for overnight low temperatures (Kunkel et al. 2013). Annual precipitation across the region also increased over the past century, though this trend was weaker near Lake Superior (NCADAC 2013). Since 1980, the predominantly positive phase of the NAO has contributed to mild winter conditions on the island (Hurrell and Deser 2009).

Changes in Lake Superior water temperature and lake ice are also evident over the past several decades. Lake Superior summer water temperatures increased 4.5 °F (2.5 °C) from 1979 - 2006, faster than the rate of air temperature warming (Austin and Coleman 2007). Ice cover on the Great Lakes decreased 71% between 1973 and 2010 due to warmer winters and windier conditions (NCADAC 2013). The frequency of an ice bridge forming between the mainland and Isle Royale declined over the past 50 years, from occurring two out of every three years in the 1960s to only once during the first decade of the 21st century (Vucetich and Peterson 2012).

Climate projections for the 21st century indicate a continuation of recent trends, including projected temperature increases of 5.0 - 8.8 °F (2.8 - 4.9 °C) by the end of the century, depending on the CO_2 emissions scenario (Gonzalez et al. 2010, Kunkel et al. 2013). The rate of warming will likely be 4-7 times faster than that of the previous century (Gonzalez 2012). Warming is likely in all seasons, with the strongest trend in winter (Kunkel et al. 2013). Projections include a decrease of approximately 3 weeks in the number of days below 32 °F (0 °C) and a 3 week lengthening of the frost free-season by mid-century (2041-2070) (Kunkel et al. 2013). Concomitant with winter warming is a decrease of up to 50% in the number of snow days (Hayhoe et al. 2010). Lake Superior summer water temperatures will increase a projected 8.3-12.1 °F (4.6-6.7 °C) and ice formation and duration will decrease, with up to 40% of winters ice free by 2100 (Trumpickas et al. 2009, Lofgren et al. 2002). Annual precipitation is also projected to increase, +5% by mid-century and +10% by century's end, with the greatest increase occurring in winter and a slight decrease projected for summer (IPCC 2007, Kunkel et al. 2013). Confidence in the direction and magnitude of climate change is higher for temperature than precipitation trends for the region (Kunkel et al. 2013). The general circulation models (GCMs) used in the above projections do not model the effects of the Great Lakes on temperature and precipitation patterns and thus the climate at Isle Royale may exhibit differing trends than mainland areas. Similarly, the GCMs do not consistently simulate the NAO, though there is some evidence that the NAO will intensify its positive phase in the future with increasing atmospheric greenhouse gas concentrations. Climate has direct and indirect effects on all trophic levels within an ecosystem and recent and projected climate change will continue to alter interactions among wolves, moose, and vegetation.

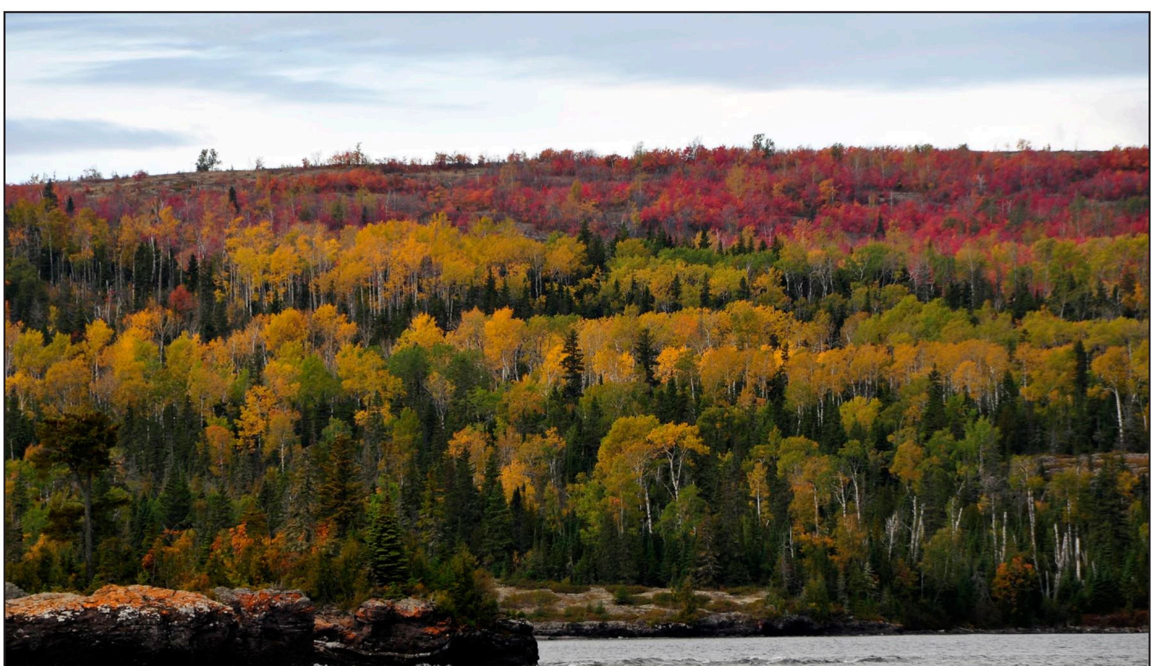
Vegetation Dynamics

The park lies within the Laurentian Mixed Forest Provence, also known as the temperate-boreal forest transition zone (Goldblum and Rigg 2010). Temperate tree species on Isle Royale are at or near their northern range limits and conversely, boreal trees are near their southern range margins, suggesting that small changes in climate may cause major shifts in vegetation (Parmesan et al. 2005). Indeed, paleoecological studies verify this concept and show that the vegetation on Isle Royale changed substantially over the past 11,000 years as the climate warmed and cooled, and shifted between dry and wet periods (Flakne 2003). After the retreat of the continental ice sheet, boreal species colonized the island, with dominance by spruce 8,000-11,000 YBP (years before the present). During the warm and dry period 4,000-6,000 YBP, pine and birch replaced spruce as the main species. A slight shift to cooler and wetter conditions over the past few thousand years permitted boreal species to once again increase on the island.

Ice along the shore of Isle Royale National Park. Rising temperatures are reducing the occurrence of an ice bridge between the island and mainland, thus decreasing the opportunities for species to migrate to the island. NPS photo.

In addition to these major shifts in vegetation over the past several thousand years, vegetation trends over the past 150 years illuminate the dynamic nature of the park's ecosystems over relatively narrow temporal scales (Kraft et al. 2010). Recent trends suggest the beginning of a shift from boreal to temperate vegetation. Drivers of vegetation dynamics include disturbances (natural and human-caused), climate, herbivory, and interspecific competition. The relatively short-lived boreal paper birch and aspen, which established widely on lands disturbed by European settlement activities, are reaching the end of their natural lifespans and rapid successional changes in favor of more shade-tolerant tree species are underway. In colder climates, boreal conifers (spruce and fir) typically replace aspen and paper birch, while under warmer conditions temperate species such as maple, oak, and white pine are more likely to form the future overstory. Successional trends on the island indicate that recent conditions favored temperate hardwood species, which expanded and replaced boreal trees. Between 1957 and 2008, the area covered by upland boreal forest declined from 72% to 53% of the island and northern hardwood forest area more than doubled, from < 10% to 23% (Kraft et al. 2010). The composition of standing dead trees, 94% boreal (56% paper birch, 19% aspen, 19% spruce/fir) and < 1% yellow birch and sugar maple, also reflects this trend (Previant et al. 2012). The decline in balsam fir is evident relative to original surveys of the island. In 1847, 44% of trees on the island were balsam fir, by 1978 this had decreased to < 10%, and is now at roughly 15% (Janke et al. 1978, Previant et al. 2012). Dramatic changes also occurred in the shrub layer, from dominance by yew (*Taxus canadensis*) in 1848 to thimbleberry (*Rubus parviflorus*) in 1974, likely due to moose browsing (Janke et al. 1978).

Vegetation trends at Isle Royale mirror other forests within the temperate-boreal transition zone where warmer temperatures appear to be mediating temperate tree expansion and boreal forest contraction (Beckage et al. 2008, Fisichelli et al. 2013a). These recent forest changes will likely continue, with the rate and direction depending on many interrelated drivers, including climate change, herbivory, nonnative species, the disturbance regime, and management actions (Fisichelli et al. 2013b, 2013c).



Middle Islands passage in autumn on Isle Royale. Temperate hardwood tree species (orange and red colored foliage) are found on the upper slopes while boreal trees (dark green conifers and yellow-green foliage of aspen and paper birch) dominate mid and lower slope positions. Warming temperatures are facilitating the expansion of temperate species into boreal forest across the Northeast and Great Lakes regions. NPS photo.

Moose and Wolf Dynamics

The Isle Royale wolf population was initially founded by three wolves in the late 1940's and over the past few decades has fluctuated from a high of 50 animals to a recent low of eight (Adams et al. 2011, Vucetich and Peterson 2013). The primary controls on the wolf population, including intraspecific interactions, prey availability, demographic stochasticity, disease, and possibly genetic deterioration, have shifted over time (Vucetich and Peterson 2004a, Räikkönen et al. 2009). Moose are the primary prey for wolves on Isle Royale and thus have been one of the main regulators of the wolf population (Peterson et al. 1998). The wolf population crashed from a very high density of 50 animals in 1980 to 14 individuals in 1982 due to malnutrition and intraspecific strife (Peterson and Page 1988). Canine parvovirus (CPV), a disease which can be fatal to wolf pups, was detected in the wolf population in 1988 and 1989 and again two decades later (Peterson et al. 1998, Vucetich et al. 2012); however, the relative role of CPV in influencing the wolf population density on the island remains uncertain (Mech 2013). Following the population crash of the early 1980's, the strength of the relationship between moose and wolves decreased dramatically (Vucetich and Peterson 2004b; see paragraph on moose below for further elaboration). Inbreeding and genetic deterioration, manifest in skeletal abnormalities, may also be reducing the fitness of the Isle Royale wolves (Räikkönen et al. 2009).

Climate on the island has a very weak direct influence on wolves and a much stronger indirect role through impacts on the moose population and predation success (Vucetich and Peterson 2004a). The small population size, demographic stochasticity, and possible inbreeding depression of the isolated Isle Royale wolves signal a potential for extirpation in the near future (Peterson and Kumenaker 1989, Peterson et al. 1998), though the population has rebounded from previous low densities.

The Isle Royale moose population size and growth rate are primarily controlled by wolf population density, intraspecific competition (density dependence), balsam fir, climate variables such as the North Atlantic Oscillation (NAO), and winter tick (*Dermacentor*

Wolf pack in winter on Isle Royale National Park. Indirect climate change impacts, such as reduced occurrence of ice bridges with the mainland, may adversely impact the island's wolf population. Photo by Rolf Peterson.

albipictus) outbreaks (Post and Stenseth 1998, Wilmers et al. 2006). Change in the strengths of these variables has shifted regulation of the moose population between top-down and bottom-up processes (Vucetich and Peterson 2004a, Wilmers et al. 2006). Wolf predation has been recognized as the main determinant of average moose abundance on the island (Peterson 1977, Vucetich and Peterson 2004a). Drivers of the moose population growth rate (interannual variability in population size) changed over the past few decades (Vucetich and Peterson 2004a). Prior to wolf population crash of 1980-1982, the top-down control of wolf density was a primary driver of the moose population growth rate (Wilmers et al. 2006). Since the population crash and later detection of CPV in the wolf population, the role of wolves in influencing the moose population declined sharply and the influence of climate has become a dominant driver (Wilmers et al. 2006).

Winter conditions (characterized by the phase of the NAO) and spring temperature explain five times more of the variance in the moose population than do wolves (Vucetich and Peterson 2004a). Long winters with heavy snow (negative phase of the NAO) lead to a scarcity of forage in early-spring, compounded by winter tick parasitism, can cause increased moose mortality (Stewart et al. 1976, DelGiudice et al. 1997). Short mild winters with less snowfall (positive phase of the NAO) favor moose survival, decreased wolf predation success, and positive moose population growth rates (Wilmers et al. 2006). However, warm springs can also result in increased survival of winter ticks and greater rates of parasitism on moose the following winter (DelGiudice et al. 1997). Growth of balsam fir, the main winter forage species, also explains twice as much of the variance in the moose population as wolves, indicating the importance of bottom-up processes (Vucetich and Peterson 2004a).

Similar to boreal tree species, moose on Isle Royale are near their southern range limits. Although mild winters can favor positive moose population growth rates, moose are also temperature sensitive and prone to heat stress in both summer and winter months (Renecker and Hudson 1986). Winter temperatures above -5 °C (23 °F) induce thermoregulatory behavior in moose and have been correlated with increased mortality later in the year (Lenarz et al. 2009), while summer temperatures above 14 °C (57 °F) cause increased respiratory rates (Renecker and Hudson 1990). Moose populations near southern range limits in northeastern and northwestern Minnesota declined rapidly in recent years (Murray et al. 2006, Lenarz 2012). The northwestern Minnesota population plummeted from over 4,000 individuals in the 1980's to < 100 in 2007 (Murray et al. 2006, Lenarz 2007).

Climate change in conjunction with malnutrition and pathogens carried by white-tailed deer (*Odocoileus virginianus)* were likely causes of the population decline (Murray et al. 2006). The northeastern Minnesota moose population, the closest mainland population to Isle Royale, has shown a declining density trend since the early 2000's, decreasing at a rate of approximately 15% per year (Lenarz et al. 2010, DelGuidice 2013). Over the past five years, the population declined from an estimate of 7,840 moose in 2009 to 2,760 in 2013 (DelGuidice 2013). However, population decline across the southern range limit is inconsistent. Moose expansions in North Dakota, southern Ontario, and New England indicate that climate may not be the only control of moose at southern range limits (Foster et al. 2002, Murray et al. 2012).

It remains unclear how sensitive moose on Isle Royale will be to the changing climate and if the lack of deer, which are hosts for pathogens lethal to moose (e.g., meningeal worm - *Parelaphostrongylus tenuis*), will promote longer persistence of moose on the island even under climate change. The island's moose population exhibited very high recruitment in the past year, the same time period over which the nearby northeastern Minnesota population declined by over 30% (Vucetich and Peterson 2013, DelGuidice 2013). As temperatures continue to warm, heat stress may eventually overwhelm the positive effects of mild winters and lack of deer and associated diseases on the island, though the potential timing and actual temperature at which chronic heat stress becomes a tipping point for the population are unknown.

Moose browsing on paper birch in Isle Royale National Park. The quality of food available to moose on the island is likely to change as vegetation on the island changes in response to shifts in the climate. NPS photo.

Methods

Scenario Planning General Overview

Scenario planning is a process designed for managing into futures characterized by rapid directional change and complex uncertainties (Peterson et al. 2003). Scenario planning is not a technique for predicting the most probable future and the step-by-step management actions to be taken; rather, the objective is to consider management options relative to a variety of plausible futures (Weeks et al. 2011). Doing this proactively, essentially rehearsing for multiple futures, strengthens an organization's ability to recognize, adapt to, and take advantage of changes over time (Global Business Network 2009). Scenario planning is an important tool in the National Park Service's strategy for managing parks under conditions of climate uncertainty (NPS 2010). Within the NPS, scenario planning is a participatory process that engages a broad range of collaborators, including land managers from neighboring lands, climate scientists, and researchers from academic institutions.

Guided by the needs and concerns of park managers, scenario planning synthesizes information and potential implications from climate change projections in a way that is relevant to the conservation of park resources and landscape values. Strengths of this approach include clarifying the numerous points of view on complex issues and grasping levels of uncertainty (Biggs et al. 2009). Scenario planning in the NPS integrates quantitative, model-driven data with qualitative narratives to explore plausible futures that incorporate climate change, ecological responses, cultural resource impacts, and varying socio-political conditions (Weeks et al. 2011). The resulting scenarios represent divergent ecological, physical, social, political, and/or economic factors that define the decision environment for a given issue. The NPS approach deliberately abstains from assigning probabilities during scenario creation because doing so counteracts the intent of an exploratory process. Emphasizing plausibility over probability helps to ensure adequate consideration of low-probability/high consequence events (Weeks et al. 2011). The scenarios are descriptive narratives that can provide highly useful communication tools to inform the public and underscore the level of complexity involved in managing towards an uncertain future (Bennett et al. 2003). Scenario planning facilitates robust decision making and may also identify important factors previously not recognized in management discussions.

The scenario planning process utilized by the NPS involves five stages, based on the Global Business Network (2009) model. The initial step characterizes the focal issue or management challenge defining the scope and spatial and temporal scales of the exploration. Identifying fundamental factors at play in the issue, such as climate change and environmental drivers is the next step. Third, small groups of decision-makers and subject matter experts build the 3 - 5 plausible and divergent scenarios, using critically important and critically uncertain drivers. The scenarios are descriptive narratives of events that transpire over the near future (typically 20 - 50 years), based on specified strengths or levels of drivers, such as magnitude of temperature change or sea level rise. Expert understanding of how the system under study reacts to shifts in the identified drivers supports descriptions of ecological responses and changes associated with the climate scenarios. The completed scenarios may inform management planning and decisions in numerous ways, including their use as a "wind tunnel test" to examine how a defined set of management options would perform under various future conditions. This step facilitates identification of 'robust' or 'no-regrets' management actions successful under all future scenarios as well as 'no-gainer' actions deemed ineffective in all futures (Peterson et al. 2003). Finally, monitoring of key attributes over time assesses the actual direction of the system and supports continued evolution of the scenarios to guide managers.

Scenario Planning Process Details for the Isle Royale Workshop

Preparing for this scenario workshop included multiple steps following the general approach described above. A core team, established after an initial interdisciplinary discussion in February 2012, framed principal management issues for exploration during the workshop. A fundamental goal was to explore potential effects of climate change on ecosystem dynamics and large mammals (including predator-prey relationships) and the range of potential management responses. Core team members identified key climate and environmental drivers as well as scientists and managers with expert knowledge in relevant arenas to invite to the workshop. Areas of emphasis for the management issues and workshop included historical and current wildlife species of Isle Royale, particularly large mammals, wolf-moose-vegetation trophic dynamics, ecology and dynamics of temperate and boreal forests, disturbance ecology, and the projected magnitude of climate change and associated vulnerability of biota on the island.

The selected management period of interest was 2013-2050, for which relevant climate data and projections were synthesized. The workshop used projected climate conditions through 2050 based on the A2 greenhouse gas emissions scenario (IPCC 2007). The current trajectory of global emissions is similar to the A2 scenario (Friedlingstein et al. 2010). Multiple sources supplied the relevant climate data, projections, and related research (Table A1). In-depth information on climate change at Isle Royale is available in Gonzalez (2012), including general temperature and precipitation projections for the end of the 21st century based on output from 18 GCMs. Because the GCMs do not specifically model the effect of Lake Superior on weather and climate, climatologists from NOAA's Great Lakes Integrated Sciences and Assessments (GLISA) center provided localized information for Isle Royale. The climate projections were synthesized to temporal and spatial scales relevant to workshop participants, specifically island level projections for 2050. When mid-century projections were not specifically available, climate variable values for 2050 were calculated as roughly 50% of the change forecast for 2100.

Prior to the workshop, organizers identified climate projections for the baseline scenario, named the 'Least Change' scenario, which provided the workshop starting point. Climate variable values for this scenario drew from the low end of projections for 2050 (Table 1) to represent the minimum amount of expected change. It is important to note that this did not represent the most likely scenario, but only defined the lower bounds of projected change. Participants then examined the ranges and variations in the climate projections and identified critical uncertainties to incorporate into subsequent scenarios. Specifically, the magnitude of warming, shifts in the precipitation regime, and occurrence of disturbances in conjunction with climate change provided crucial scenario drivers (Table 1).

Climate Driver	Scenario			
	Least Change	Summer Drought, Wind, and Fire	Warmer than Duluth	Isle Savanna
Mean annual temperature	**increase 3.4 °F**	same as Least Change	**increase 6.5 °F**	increase 5 °F
Cold days (< 32° F)	**15 fewer days**	same as Least Change	**up to 30 fewer days**	**up to 30 fewer days**
Hot days (> 95 °F)	increase of < 5 days	same as Least Change	increase of 5 days	same as Least Change
Growing season	**2 weeks longer**	same as Least Change	**4 weeks longer**	3 weeks longer
Annual precipitation	+5% (up Winter, down Summer)	same total as Least Change	same as Least Change	10-15% increase
Intense precipitation	20% increase in number of days with >1 inch precip	same as Least Change	same as Least Change	**summer: sporadic extreme events, 30% increase in > 1" events**
Snow	snow days -25%	same as Least Change	**snow days -50%**	**snow days -40%**
Wind	20th century conditions	**Increased probability of large wind events (derechos)**	same as Least Change	same as Least Change
Lake levels	20th century conditions	same as Least Change	same as Least Change	same as Least Change
Lake temperature	+3.6 °F in warm season temp, >50 °F water temp for 25 more days	same as Least Change	+8.3 °F in warm season temp, >50 °F water temp for 60 more days	+6.0 °F in warm season temp, >50 °F water temp for 45 more days
Lake ice cover	12 fewer days	same as Least Change	45 fewer days	30-40 fewer days
Climate variability	20th century conditions	**Punctuated dry summer periods**	**Greater variability in seasonal and annual temperature**	**Greater variability in seasonal and annual precipitation**
Arctic Oscillation	20th century conditions	same as Least Change	same as Least Change	**Predominance of positive phase (7 out of every 10 years)**

Table 1. Climate and related drivers for each Isle Royale scenario. Conditions in bold denoted as significant drivers causing divergent scenarios.

Using the completed climate analyses, the scenario planning workshop occurred over two days in mid-January 2013. A total of 22 participants with backgrounds in climate change science, wildlife biology, forest ecology, and natural resource and park management participated (Table A2). Four groups of 5-6 collaborators each developed scenarios using selected low- or high-end climate projections and associated details, such as disturbance events. Descriptive narratives of the responses of ecosystem components and processes to the identified drivers and disturbances over the period from 2013 to 2050 enabled workgroups to examine implications for natural and cultural resources, wilderness, facilities, and visitor experience. The scenarios and their implications provided a 'wind-tunnel test' to examine how four possible management approaches concerning wolves and restoration of historical conditions might perform under the conditions described in the scenarios. Participants then compared the scenarios and identified commonalities and differences among both the ecological responses to change as well as the efficacy of potential management approaches.

Isle Royale Scenario Planning Workshop participants discuss recent climate trends at the park. NPS photo.

Results

Isle Royale Scenario Descriptions and Impacts

Scenario planning workshop teams constructed four divergent scenarios (‘Least Change’, ‘Summer Drought, Wind, and Fire’, ‘Warmer than Duluth’, and ‘Isle Savanna’), using ‘Least Change’ as the base model and incorporating differing levels of the critical drivers into the other three scenarios (Table 1). The ‘Summer Drought, Wind, and Fire’ scenario included punctuated dry summer periods and an increased probability of wind storms. The ‘Warmer than Duluth’ scenario had temperature increases from the high end of projections (+6.5 °F) while the ‘Isle Savanna’ scenario included warm temperatures (+5 °F) and increasingly frequent drought events (i.e., strong precipitation variability). These descriptive narratives present potential futures based on the range of climate projections and scientific understanding of species interactions and ecosystem responses to climate change.

Descriptive Narrative Summaries of Each Scenario

Scenario 1: Least Change Scenario Narrative (2013-2050)

The ‘Least Change’ scenario uses the lower bounds of climate projections for 2050 (generally 1 standard deviation below the mean of model outputs; Table 1). Warming of the past several decades will continue, with mean annual temperature increasing by 3.4 °F over the first 50 years of the century. This results in 15 fewer days with temperatures below 32 °F in winter and a warmer growing season that is extended by two weeks. Annual precipitation shows a slight increase (5%), though seasonal changes result in increased winter precipitation and less summer rainfall compared to the recent past (1961-1990 average). Additionally more winter precipitation falls as rain, reducing the overall snowpack and accelerating snowmelt in early spring.

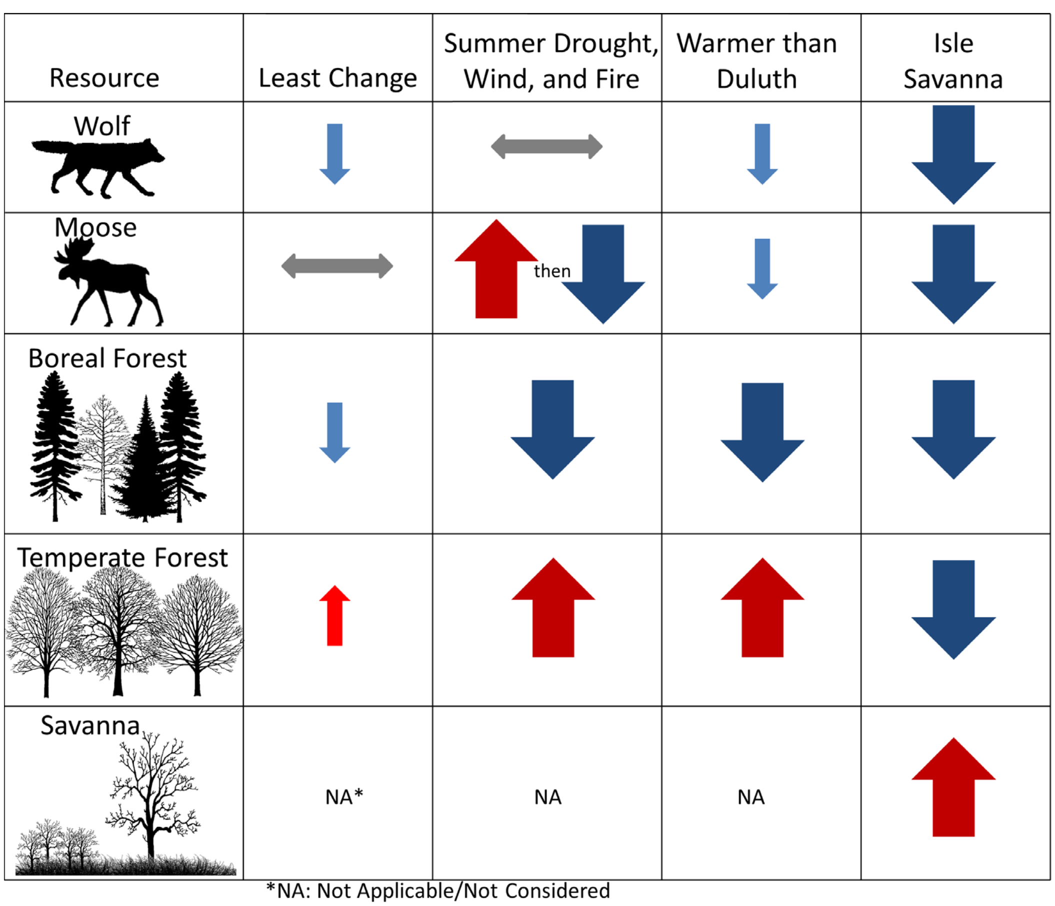


Figure 1. Changes to species population numbers and total area of ecosystem types over the course of each Isle Royale scenario. Arrow size denotes magnitude of change and arrow direction signifies increase, decrease, or no change from recent trends. Savanna was only examined in the ‘Isle Savanna’ scenario. Tree silhouettes from Natural Resources Canada, Canadian Forest Service.

The combined warmer temperatures, earlier onset of spring conditions, and less rainfall during summer months result in moderately drier soils. Additional changes include 12 fewer days per year of lake ice cover and a 3.6 °F warming of summer water temperatures in Lake Superior.

Ecosystem changes observed over the past few decades will continue, though at an accelerated rate, over the coming decades under the 'Least Change' scenario (Figure 1). The decline of the boreal forest will continue as temperate tree species expand into forest previously dominated by aspen, paper birch, fir, and spruce. Periodic droughts stress all species and push scattered patches of boreal forest trees beyond their physiological limits, causing mortality. Nonnative plant species and invasive European earthworms expand on the island and further alter natural plant community composition. Red maple is favored over sugar maple in earthworm invaded areas and thus expands across the island.

In the scenario, moose become stressed by the warmer conditions while the greatest risk to wolves continues to be extirpation due to low population numbers and low genetic diversity. Warm winters inhibit the formation of a stable ice bridge with the mainland and thus new wolves are less likely to naturally immigrate and diversify the genetic pool. In 'Least Change', demographic stochasticity causes the small wolf population to die out in the near-future. Moose numbers increase in the absence of a predator, resulting in heavier herbivory and limited recruitment of preferred-browse tree species (e.g., fir and maple). Additional cascading effects of wolf extirpation include a possible increase in the beaver population and subsequent greater pressure on aspen as a beaver food source.

Aquatic and wetland systems continue to warm and dry, causing extirpation of coldwater fishes from shallow lakes and plant succession towards upland species in previously shallow wetlands.

Isle Royale Scenario Planning Workshop team developing one of the plausible future scenarios. NPS photo.

'Least Change' Summary

Key Elements

1. Annual temperature increases 3.4 °F
2. Less severe winters (15 fewer days < 32 °F, 25% fewer snow days)
3. Growing season expands by 2 weeks
4. Warmer summer Lake Superior water temperatures (+3.6 °F)
5. Less ice cover and for shorter duration (12 fewer days
6. Existing stressors exacerbated

Impacts for Wilderness

1. Reduced water quality and availability
2. 'Boreal forest' wilderness character decreasing
3. Increased annual trail work due to fallen trees (dead boreal trees)

Impacts for Facilities

1. Increased inability to keep up with deferred maintenance, including historic resources

Impacts for Visitor Experience

1. Access may be limited due to downed trees
2. Fall foliage color improves with expansion of maple
3. Mismatch between visitor expectations and reality

Impacts for Natural and Cultural Resources

1. Vegetation
   a. Boreal forest thinning due to overstory mortality and decreased regeneration success
   b. Temperate trees expanding into boreal forest patches (increased regeneration success)
   c. Above results in greater proportion of mixed temperate-boreal forest on the island and fewer pure boreal forest stands
   d. Continued expansion of earthworm invasion simplifies the forest understory plant community
   e. Nonnative plant invasions expand due to boreal forest thinning and earthworms
2. Moose
   a. Shallower snowpack in winter increases access to forage and decreases wolf predation success
   b. Winter tick numbers increase
   c. Moose more stressed in summer and winter by warmer conditions
3. Wolves
   a. Immigration from mainland less likely due to lack of ice bridge
   b. Above results in greater inbreeding depression
   c. Extirpation very possible in the near-future
4. Aquatic
   a. Cold water fish species in decline
   b. Algal blooms increase
   c. Increased establishment of aquatic invasive plants along shorelines

Scenario 2: Summer Drought, Wind, and Fire Scenario Narrative (2013-2050)

Climatic conditions are very similar to the 'Least Change' scenario with the addition of large disturbance events and punctuated dry summer periods (Table 1), which further accelerate ecosystem changes (Figure 1). Warmer lake waters have diminished capacity to buffer the island from major convective thunderstorm systems. A powerful storm system, similar to that experienced in the 1999 'Big Blowdown' of the Boundary Waters Canoe Area Wilderness in neighboring Minnesota (which leveled a forest swath 3.5 times the size of Isle Royale's forest (Moser et al. 2007)), strikes the island in the near future. Winds of 60-100 mph topple overstory trees across the northeastern half of Isle Royale. Moose initially avoid the area due to difficulty travelling through the jackstraw of blown down trees and escaping predators. Moose density on the southwest end of the island rapidly increases due to this migration, causing heavy browse damage to boreal and upland northern hardwood forest stands. The blowdown area is inaccessible to back-country visitors and requires substantial trail work to reopen wilderness areas.

A few years after the blowdown in this scenario, the island experiences a relatively, though not unusual, warm and dry summer. A lightning strike from a passing thunderstorm ignites a fire within the blowdown area. Strong winds fan flames, which engulf the dried fuel loads of downed trees. The uncontrollable fire burns through most of the previously disturbed northeast end of the island, damaging or destroying several structures at Rock Harbor. Meanwhile, the very dense moose population on the southwest end of the island consumes most available browse. During the ensuing winter, heavy snowfall and increased predation success by wolves in addition to scarce forage causes the moose population to decline sharply.

Historic Barnum cabin in Isle Royale National Park. Stronger and more frequent storms (e.g., ice storms and wildfires) may adversely impact historic structures such as these. NPS photo.

In the first few years after the fire, several tree species colonize the burned area. Warm conditions favor red maple, yellow birch, and white pine, which disperse small windblown seeds long distances across the charred landscape. Vigorous growth of herbaceous and woody vegetation attracts moose back to the previously burned area. In this scenario, the moose population grows quickly and wolves are unable to keep the population in check, resulting in moose densities not seen since the early 1990s. This results in a boom and subsequent bust population cycle for moose as the availability of preferred vegetation diminishes due to overbrowsing and successional changes, and the number of moose consequently declines precipitously.

Browsing by moose can severely reduce the growth of palatable plant species, such as balsam fir. The additive stresses of browsing and climate change may accelerate the decline of cold-adapted plant species on the island, such as fir. NPS photo.

'Summer Drought, Wind, and Fire' Summary

Key Elements

1. Same climatic conditions as 'Least Change'
2. Catastrophic blowdown knocks down most overstory trees across the northeast half of the island
3. Moose pushed to the southwest end of island, causing heavy browse damage
4. Massive fuel loads and a subsequent dry period result in a large severe fire
5. Maple, pine, and birch establish in the burned area (shift to temperate forest)
6. Moose population sharply increases as forage on northeast end becomes available

Impacts for Wilderness

1. Fewer visitors (more untrammeled)
2. Short-term reduction in wilderness area accessible
3. Structures removed from wilderness by fire
4. Less opportunity for solitude (due to smaller area accessible and later open conditions after fire)
5. Naturalness declines with increase in invasive nonnative species

Impacts for Facilities

1. Loss of high-cost facilities (fiscal challenge to replace)
2. Short-term fewer visitor facilities, decision point to determine long-term impacts
3. Trails compromised by blowdown/fire
4. Increased number of social trails

Impacts for Visitor Experience

1. Overall, negatively affected because large portion of park not accessible to public; public enjoys Isle Royale because solitary nature of hiking experience; hiking accessibility would be concentrated.
2. Fewer facilities for visitors
3. Lose visitors wanting "no change"
4. Moose viewing opportunities increase
5. Shoreline recreation opportunities increase after the fire removes vegetation

Impacts for Natural and Cultural Resources

1. Vegetation
   a. Major forest community change after fire
      i. accelerated conversion from boreal to temperate forest
   b. Heavy browse damage in areas with very high density moose populations
2. Moose
   a. Moose initially stressed by reduction in area with available forage
   b. Quality and quantity of forage increase sharply after fire (effect lasts approximately 1-2 decades)
   c. Sharp fluctuations in moose numbers due to forage availability swings
3. Wolves
   a. Persist and track the moose population changes
   b. Extirpation highly probable, especially after moose population crash
4. Aquatic
   a. Less shade in burned areas causes greater warming of shallow streams and wetlands
   b. Sharply reduced brook trout spawning habitat in burned area
   c. Cold water fish species in decline
   d. Algal blooms increase
   e. Increased establishment of aquatic invasive plants along shorelines

Scenario 3: Warmer Than Duluth Scenario Narrative (2013-2050)

In the 'Warmer than Duluth' scenario, the climate changes at a rate near the upper end of projections (Table 1). By the middle of the century, temperatures warm 6.5 °F, adding an extra month to the growing season and 45 fewer days of ice on Lake Superior. There is also greater temperature variability within seasons and across years and more frequent thunderstorms.

Ecosystem changes progress at a faster rate than in the 'Least Change' scenario with a messy transition from boreal to temperate forest characterized by abundant dead and dying overstory trees and thick undergrowth across the island (Figure 1). In this scenario, boreal tree species present in the canopy, including spruce, fir, paper birch, and aspen, decline and fail to regenerate. Temperate tree species, such as red oak, red maple, and white pine, are adapted to the warm and dry growing season conditions and outcompete remaining boreal trees for resources. Warm spells during late winter cause many plant species to begin the onset of spring growth very early in the season, causing a decoupling of phenological events. In years with frost events after these early warm periods, vegetative and reproductive tissues are severely damaged, resulting in reduced ecosystem productivity and a scarcity of food sources for animals dependent on seeds and nuts. Nonnative invasive plant species establish widely during the messy forest transition. Disjunct populations of arctic plant species vanish and wetlands undergo major shifts in composition.

In the 'Warmer than Duluth' scenario, the moose population becomes increasingly stressed by the warm conditions and changes in habitat. Wolves persist at an extremely low density and continue to have a high likelihood of extirpation.

Boreal forest (primarily spruce, fir, paper birch, and aspen) in autumn on Isle Royale National Park. Warming temperatures will accelerate forest changes on the island and favor warm-adapted species such as maple, oak, and pine. NPS photo.

'Warmer than Duluth' Summary

Key Elements

1. Warmer than Least Change (+ 6.5 °F)
2. Greater temperature variability (within seasons and across years)
3. Dramatic lengthening of the growing season (4 more weeks)
4. Less ice cover, shorter duration of ice (45 fewer days)
5. Higher probability of wind/storm events (focus on microbursts)
   a. many patchy small blowdowns and occasional small fires

Impacts for Wilderness

1. Much greater trail work due to increased tree fall from mortality events
2. Increased annual visitation due to longer shoulder seasons
3. Water availability pressure from visitors

Impacts for Facilities

1. Increased maintenance costs due to hazard tree removal, ice-storm damage, freeze/thaw impacts
2. Expanded operational demands due to extended service time (concessions contracts, tour boats, support facilities, water treatment, sewage, etc...)

Impacts for Visitor Experience

1. Hotter conditions and fewer potable water sources in backcountry due to algal blooms
2. Possible trail closures due to blowdowns and/or fires

Impacts for Natural and Cultural Resources
Loss of resiliency to catastrophic events

1. Vegetation
   a. Increased tree vulnerability to pathogens
   b. Increased boreal conifer mortality (many patches of dead trees)
   c. Widespread temperate tree expansion
   d. Above results in patchy, young forest dominated by temperate species (yellow birch, maple, oak, pine)
   e. Increased potential for nonnative plant species to establish and expand
   f. Likely extirpation of disjunct arctic species
   g. Possible decoupling of phenological events
2. Moose
   a. Loss of thermal cover from declining boreal conifers
   b. Increased heat stress
   c. Likely sharp decline in population numbers
3. Wolves
   a. Lower numbers and greater chance of extirpation
4. Aquatic
   a. Warmer waters (especially in shallow lakes and streams)
   b. Continued and sharper decline of cold water fish
   c. Increase in algal blooms
   d. Shallow wetlands drying out
   e. Compositional shift towards upland species in dried out wetlands
   f. Increased survival of nonnative aquatic species

Scenario 4: Isle Savanna Scenario Narrative (2013-2050)

In the 'Isle Savanna' scenario, climate change is both more severe and more variable than in 'Least Change' (Table 1). Temperatures warm 5 °F by 2050 and although mean annual precipitation increases 10-15%, extreme variability in the timing and seasonality of precipitation events causes cycles of drought punctuated by heavy rain events. The frequency of summer droughts over six weeks in length increases steadily over the next few decades. The Arctic Oscillation shifts to strong positive phases 7 out of every 10 years bringing warmer and drier winters. More winter precipitation falls as rain in winter and quickly runs off the frozen ground, failing to fully recharge soil moisture.

In the near term in this scenario, increasing temperatures and isolated droughts stress vegetation and cause minor patches of forest dieback. Dying trees allow greater light to penetrate into the forest understory, encouraging the growth of shrubs and herbaceous species. Many of these plants are favored forage of moose and thus the moose population remains stable despite the increasing stress from rising temperatures.

Cascading events prove to be a major tipping point for the vegetation of the island in the 'Isle Savanna' scenario. A severe drought in conjunction with other stressors, such as native or introduced insects (e.g., emerald ash borer, balsam woolly adelgid, and Asian long-horned beetle) kills huge swaths of forest across the entire island. Wind-throw of dead and dying trees limits trail access and causes a large backlog of trail maintenance projects. Persistent warm and dry growing seasons prevent the establishment of new trees and the major upland vegetation type on the island shifts from forest to brushy savanna – a process termed savannification (Figure 1). The savannification process is not consistent across space or time, but rather occurs in fits and spurts driven by the size and severity of forest disturbances. Many native savanna species present on the nearby mainland are unable to disperse to the island, and a low diversity, novel ecosystem of native and nonnative species develops. Within the decade after savannification, moose die out due to the lack of suitable habitat. Wolves will be unable to survive on the island without their main prey, moose. Maintenance of a wolf population on the island would require a more savanna-appropriate prey species like white-tailed deer. Without wolves, the island would become more suitable to meso-carnivores such as bobcat (*Lynx rufus*) and coyote (*Canis latrans*).

Fallen trees blocking a hiking trail on Isle Royale National Park. Declining forests and increased storm damage will exacerbate trail maintenance efforts. NPS photo.

'Isle Savanna' Summary

Key Elements

1. Warmer than Least Change (+5 °F)
2. Greater variability in seasonal and annual precipitation
3. Summer droughts become more common and last longer (6+ week droughts)
4. Arctic oscillation more often in positive phase, causing warm and dry winters (-40% precipitation)
5. Slow initial changes in vegetation followed by a catastrophic event (drought and pests/pathogens) causing a rapid shift in vegetation from forest to a novel brushy savanna

Impacts for Wilderness

1. Increased perception of a 'trammeled' wilderness due to increased management intervention in order to maintain a mix of vegetation and wildlife that are no longer suited to conditions on the island
2. Increase in solitude when the island visitor operations shut down as facilities become inaccessible or are destroyed by fire
3. Inability to determine what the condition of the Natural Quality is because the reference condition of undisturbed boreal forest is no longer maintainable.
4. The Undeveloped Quality is improved as structures in wilderness are burned over.

Impacts for Facilities

1. Short-term: potential infrastructure damage from tree fall
2. Short-term: sharp increase in trail maintenance costs due to fallen dead trees
3. Long-term: reduction in trail maintenance due to savanna conditions
4. Long-term: catastrophic events close visitor facilities

Impacts for Visitor Experience

1. Mismatch between visitor expectations and reality
2. Inability to provide visitor services in the near term after fire damage

Impacts for Natural and Cultural Resources
Loss of resiliency to catastrophic events

1. Vegetation
   a. Short-term: isolated forest mortality due to minor droughts and root freezing damage caused by low snow-pack
   b. Long-term: widespread tree mortality and vegetation change from closed canopy forest to open brushy savanna due to severe droughts and tree regeneration failure
   c. Nonnative invasive plant species spread rapidly as the forest overstory declines
   d. Increased potential for nonnative plant species to establish and expand
   e. Likely extirpation of disjunct arctic species
   f. Possible decoupling of phenological events
2. Moose
   a. Forest disturbances are initially beneficial to moose, due to increases in forage
   b. Higher temperatures and lack of thermal cover exacerbate stress from pests and pathogens
   c. Population crashes soon after the shift to savanna species and is extirpated within 10 years of savanna shift
   d. New vegetation community not suitable for moose restoration
3. Wolves
   a. Wolves follow moose population to extirpation, if suitable prey to replace moose are not present on the island
4. Aquatic
   a. Hydrologic regime becomes 'flashy' in wetlands due to sporadic heavy rains
   b. Perennial streams become ephemeral
   c. Warmer waters (especially in shallow lakes and streams)
   d. Continued and sharper decline of cold water fish
   e. Increase in algal blooms
   f. Shallow wetlands dry out
   g. Compositional shift towards upland species in dried out wetlands
   h. Increased survival of nonnative aquatic species

Wind-tunneling Management Options

Following creation of the scenarios, a 'wind-tunneling' exercise examined four potential management approaches under each scenario. Three approaches dealt specifically with wolves: 1) no wolf management intervention ('no intervention'), 2) augment the wolf population now, before extirpation occurs ('augment now'), and 3) augment the wolf population in the future, likely as a restoration effort after extirpation ('augment later'). The final approach focused on restoration of past ecosystem features: 4) restore conditions and species present prior to European settlement, such as lynx and caribou.

In the 'Least Change' scenario, wolves die out in the near future. Thus, under the 'no intervention' management approach, participants identified vegetation damage from expanded moose herbivory as a major effect. Under the 'augment now' approach, wolves would persist and a larger wolf population would have the potential to further reduce moose herbivory pressure. Lower herbivory rates would also facilitate accelerated expansion of temperate species. Workshop participants concluded that 'augment later' could be a possible future modification of the 'no intervention' approach, whereas restoration of presettlement conditions would be problematic due to the changing climate, and (for caribou) the long-term transition to temperate hardwood forest and role of wolves on the island.

Under the 'Summer Drought, Wind, and Fire' scenario, the 'no intervention' approach would result in very low wolf numbers. This combined with increased forage after the fire would support a rapidly increasing moose population. The high moose density and associated intense browsing might lead to increased pressure for alternative methods to control the moose population. When wolves die out, research emphasis would shift to examining the island system in the absence of a top predator and to other understudied natural resources, fostering an enhanced understanding of the effects of island biogeography (isolation) in an era of climate change. The 'augment now' approach was seen as likely allowing wolves to persist for several decades and potentially reducing the amplitude of fluctuations in the moose population, thus minimizing moose impacts to vegetation. Emphasis on maintaining wolves would limit the ability of managers to assess responses of other species to the changing climate. Implications of 'augment later' are similar to the 'no intervention' approach, including the ability for researchers to study the process of extirpation. Restoring a new population of wolves would include additional difficulties and be more expensive than the 'augment now' approach since more animals may be needed. Restoring other extirpated species such as woodland caribou would be difficult, especially with moose and wolves present on the island. Caribou and moose together may be problematic; disturbances favor moose while old forests favor caribou.

The ‘Warmer than Duluth’ scenario identified similar impacts from the management approaches as the above two scenarios. For example, an unsustainably high moose population resulting from the ‘no intervention’ approach would require a policy decision on when and how to control the population. Wolf augmentation approaches would need to determine how many animals to introduce and whether it should be based on a number sufficient for genetic rescue, to boost the population to its long-term average, or to a number based on the prey population of moose on the island. The release of new wolves on the island would require increased research and monitoring, as would both the ‘augment now’ and ‘augment later’ approaches. Regarding restoration of extirpated species, workshop participants concluded that climate impacts and limitations would be stronger for lynx and caribou than for wolves and moose.

Within the ‘Isle Savanna’ scenario, projected results under the ‘no intervention’ and two wolf augmentation approaches were similar to the first three scenarios. The magnitude of change in this scenario (from forest to savanna) precluded the possibility of restoration to historical conditions that existed prior to European settlement. Workshop participants determined that instead of restoration to a past state, facilitation of the transition to a functioning savanna would be a more effective management strategy. This would include keeping out nonnative invasive plants and possibly assisting the migration of savanna plants and animals from the mainland.

Wolf on the move; NPS photo.

Discussion

A fundamental goal of scenario planning is to facilitate open exploration of plausible future conditions in order to provide an improved understanding of the potential magnitude of change in coming years and decades. The Isle Royale workshop identified robust conclusions common to all four scenarios, issues that retained high uncertainty, and areas for future research. Projected changes in the coming years will affect all aspects of park management, from facilities and visitor experience to natural and cultural resource management.

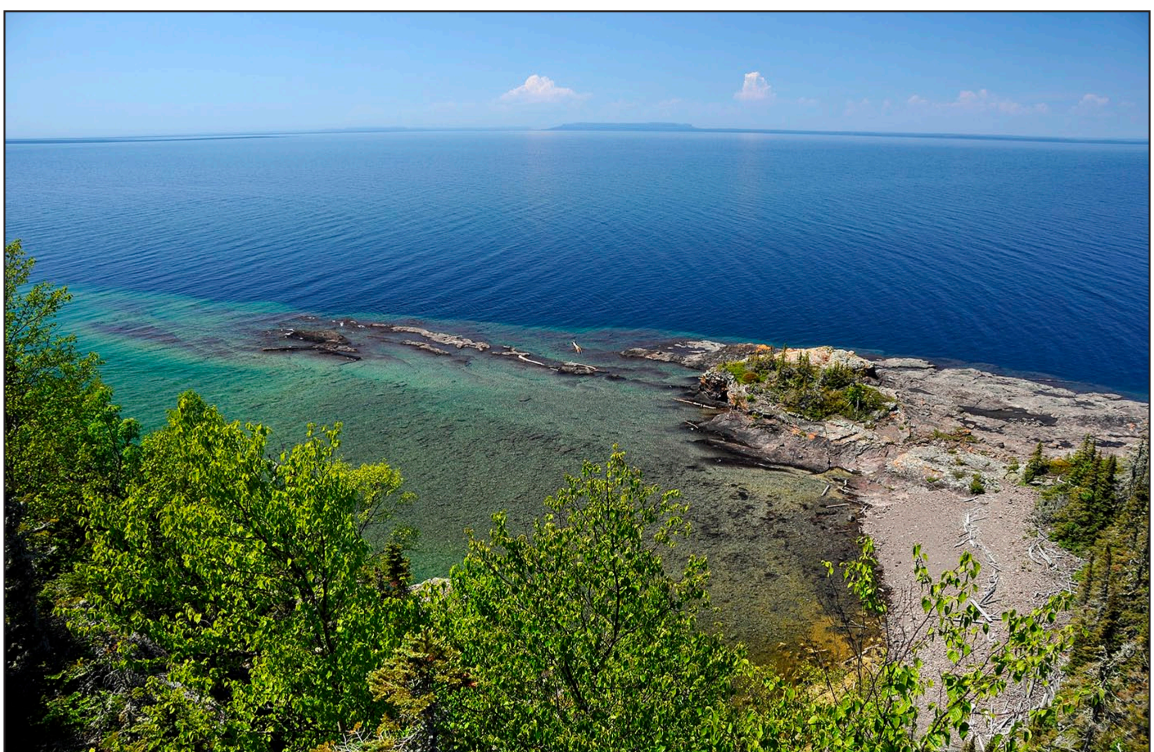
All scenarios projected a loss of ecosystem resiliency and an inevitable shift in vegetation from cool-adapted boreal to warm-adapted temperate species. The rate of climate change and occurrence of extreme climatic events and disturbances influenced the rate of vegetation change. In particular, warmer growing seasons (mean temperature shifts) coupled with greater drought stress (extreme climate events) were major drivers (Allen et al. 2010). Workshop participants noted that extreme events, including climatic (drought) and associated disturbances (wind and fire) would likely constitute trigger points, causing thresholds to be surpassed and an accelerated transition of ecosystem composition and structure (Diez et al. 2012). Thus, punctuated events and abrupt changes in ecosystems would be overlain on gradual changes in response to shifts in mean climatic conditions (Jackson et al. 2009). The rate of ecosystem change and formation of novel communities will challenge management decisions that focus on preserving natural processes and native species (Williams and Jackson 2007; Hobbs et al. 2009; Carey et al. 2012).

A key issue affecting climate change adaptation at Isle Royale is geographic isolation. Island ecosystems are inherently unstable and climate change is likely to alter some of these characteristics, including colonization and extirpation rates and major population density swings. Distance to the mainland is a formidable bottleneck to species movement and will impede immigration of species and genes that may be better adapted to future conditions. Although the mainland population of wolves has increased over the past few decades and a wolf crossed over to Isle Royale as recently as 1997 (Erb and Don Carlos 2009, Adams 2011), fewer occurrences of an ice bridge forming in winter will further limit the migration of wolves and other terrestrial vertebrates to the island. The lower levels of biodiversity on the island compared with the mainland will likely reduce resiliency to climate change and may cause a more rapid shift to an alternate state (Chapin et al. 1997; Bengtsson et al. 2003). Similarly, some climate change adaptation strategies, such as expanding reserve networks and increasing habitat connectivity (Lawler 2009), are not feasible or relevant for this island park.

Based on commonalities among scenarios, workshop participants identified several 'no-regrets' and 'no-gainer' strategies. Relevant management strategies under all scenarios included reducing non-climate stressors, such as nonnative species, as well as continued monitoring and expanded research to include a broader array of ecosystem components. Participants concluded that restoration or management toward pre-European settlement conditions was highly unlikely to succeed. Conditions and ecosystem composition are in constant flux, from both natural and anthropogenic drivers, and historical conditions and specific species assemblages may no longer provide viable restoration and management goals (Swetnam et al. 1999; Heller et al. 2009; Lawler 2009). Furthermore, accelerating changes and novel conditions mean that the past cannot serve as a prescriptive guide for the future (Harris et al. 2006). Recent and projected changes in forest composition suggest that conditions at the time of European settlement, such as forest dominated by balsam fir, will not be attainable in the future.

Workshop participants concluded that for all scenarios, restoring caribou, which were present in the 1800's, would be difficult given the projected climate and habitat of Isle Royale in 2050. Anthropogenic disturbances and hunting pressure extirpated caribou from Isle Royale and nearby mainland areas in the early 1900's, pushing the southern boundary of their contiguous range north by several hundred kilometers (Vors et al. 2007). Successful caribou restorations on other Lake Superior islands in the 20th century occurred only where wolves were absent (Bergerud et al. 2007). The combination of moose and caribou, without wolves, could cause severe browse damage to vegetation on the island. There was insufficient information and expertise on lynx issues within workshop groups to fully assess the efficacy of a lynx restoration to an island ecosystem shifting beyond its historical range of variability.

The scenario planning workshop also identified uncertainties common to multiple scenarios. The future of moose and wolves on the island will depend on numerous factors with shifting strengths. Although Isle Royale's wolf-moose-vegetation system is a relatively simple food chain, the dynamic nature of trophic interactions and changes in the strength of drivers over time indicate that past trends may not adequately inform models of likely future change, especially given climate projections. Moose may both benefit and suffer from changing climatic conditions, though precise thresholds are unknown. Increased heat stress and parasitism by winter ticks will be detrimental while less snow in the winter will reduce the likelihood of wolf predation. The transition from boreal conifers to temperate broadleaf tree species will reduce thermal cover for moose. In one scenario, moose died out due to climate-mediated habitat changes. In the other scenarios, moose populations fluctuate as impacts from climate and wolves change over time. The scenarios did not address potential climate-mediated changes in moose summer forage, which is comprised mainly of terrestrial and aquatic forbs. Changes in summer forage could accelerate moose population decline if the quality and quantity of preferred forage decreases in response to climate change.

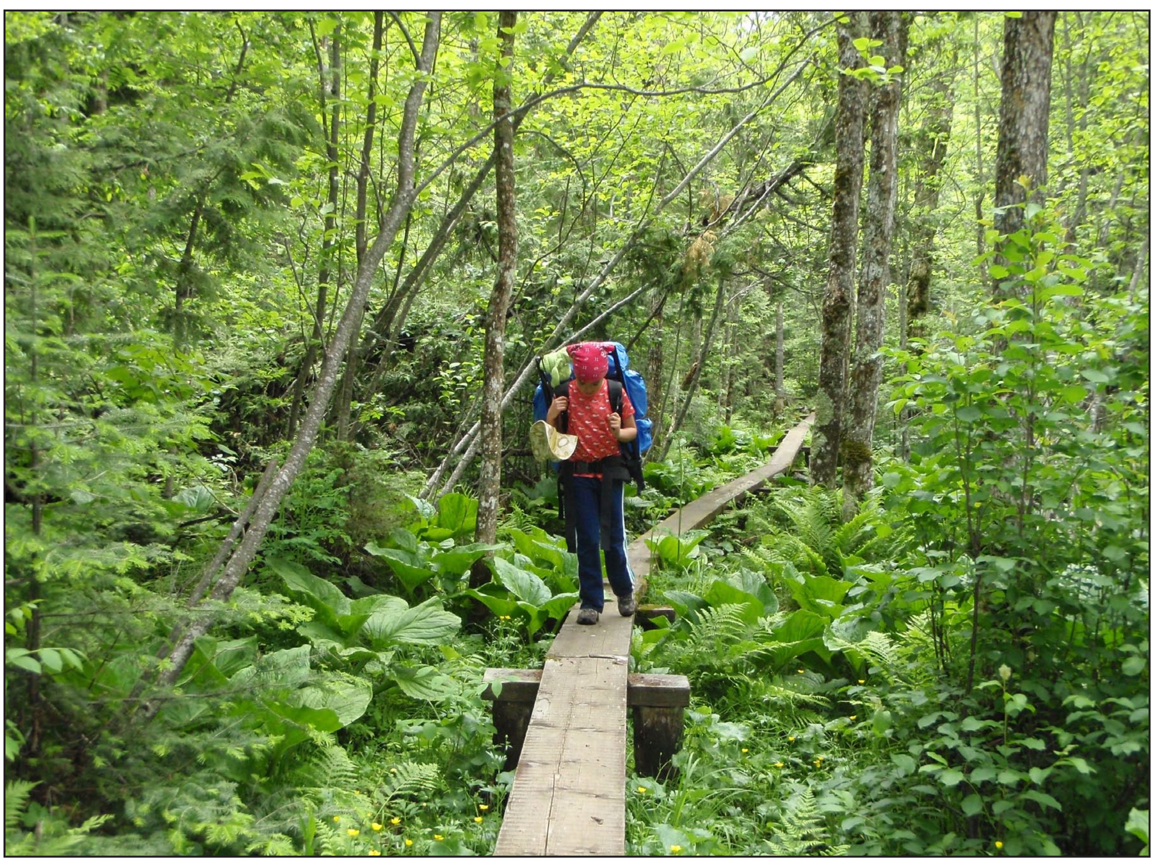


View of the mainland from above Deadhead Beach on Isle Royale National Park. The roughly 15 mile distance from the island to the mainland has limited the number of species able to colonize the island. This dispersal barrier will also impact the ability of the island's ecosystems and species to adapt to climate change, by limiting the flow of genes and species better adapted to the changing climate. Photo by Paul Brown, NPS.

For wolves, workshop participants observed that the small population size and limited gene pool are likely greater immediate threats to population persistence than direct impacts from climate change, noting that without management intervention, the likelihood of extirpation in the coming years could be high. Disappearance of wolves in the near term may facilitate an increase in the moose population, though recent studies indicate that the role of wolves in regulating the moose population is currently very minor (Vucetich and Peterson 2004a). Nevertheless, if the moose population does increase, this would cause heavier browse pressure and alter vegetation changes. Increased browse pressure on tree seedlings in winter months could accelerate shifts towards more open, shrub and herb dominated ecosystems (Zarnetske et al. 2012). If wolves persist longer, the moose population is less likely to irrupt due to combined predator, climate, and habitat constraints. This would lessen browse pressure on fir growth but may also encourage temperate tree expansion (Sell 2007; Fisichelli et al. 2012). Other species likely to be impacted by changes in wolf population density include beaver and red fox (*Vulpes vulpes*).

The majority of the park (99%) is federally designated wilderness and climate and associated ecological changes will impact the character and qualities of wilderness, including being natural, untrammeled, undeveloped, and an opportunity for solitude. Managing for natural quality will become more challenging as a changing climate affects vegetation, wildlife, and ecosystem processes. This will force managers to contemplate the naturalness of climate change and how that affects the ecology of wilderness. Fidelity to historical authenticity will, under a condition of continuous change, be a target in transition as managers struggle to identify which plants and animals are natural, or ecologically appropriate in the new climate reality. The island may experience increased trammeling in the short run, as managers strive to understand how or when to allow ecological processes and changes to persist. Catastrophic events like forest blow-down and wildfire may damage or eliminate structures in and around wilderness, thereby improving the undeveloped quality. Opportunity for solitude, based on the number and proximity of people to each other, could increase as visitation on the island becomes more difficult because of forest disturbances (wind and fire). The scientific and educational values of wilderness will increase through the ability to observe climate driven changes on the ecological landscape. Viewscapes, especially near-field scenery, will be subject to the influence of changing vegetation communities and tree mortality events.

Climate change will have additional direct and indirect effects on park operations and visitor experience. If the rate of environmental change outpaces shifts in visitor expectations, visitor experience will be strongly affected. For example, abundant dead and dying trees and the shift away from historical vegetation (boreal forest) may be perceived negatively by visitors and the potential loss of moose and wolves could be a major impact to visitor expectations and associated experience. Thus, education and outreach concerning the projected and realized changes on the island will be important to inform visitor expectations. Fallen trees and increased storm damage will exacerbate trail and building maintenance backlogs. Additionally, the buildup of woody fuels in the backcountry due to forest decline may prompt fire management actions to prevent cascading incidents that lead to catastrophic events. Lastly, most scenarios identified an expanded visitor use season that begins earlier in spring and continues later into autumn, further pressuring the park's operating budget.



Young backpacker hiking along a boardwalk in Isle Royale National Park. Climate change will alter recreation conditions on the island, including the types of ecosystems encountered, quality of wilderness, availability of potable water, and timing of the visitor use season. NPS photo.

Conclusions

Scientific research over the past 50+ years, on Isle Royale and across the globe, demonstrates the significant and inextricable role of human activities in driving ecological processes and properties, even on protected lands such as National Parks. For example, human settlement activities (logging and associated wildfires) that occurred a century ago heavily influenced current forest structure and composition on Isle Royale. A canine virus accidentally introduced to the island by a domestic dog is carried by the island's wolves. Warming air temperatures across the region and signs of boreal decline and temperate tree expansion within forests on Isle Royale are unmistakable (NCADAC 2013, Kraft et al. 2010). Moreover, these direct and indirect effects of human activities on Isle Royale occur within the context of the inherently unstable characteristics of island ecosystems, for which colonization, extirpation, and large swings in population densities are common traits (MacArthur and Wilson 1967).

The interrelationships and interactions between natural and anthropogenic processes pose immense challenges for land managers tasked with resource stewardship. The future of Isle Royale will not be a replica of the past; some ecosystem components will remain while others will disappear as new elements arise. Resource stewardship on Isle Royale and across all National Parks must adhere to public policy and regulation, reflect the long-term public interest, and be based on the best available science (Colwell et al. 2012). For Isle Royale, this means acknowledging past ecosystem components and dynamics while simultaneously looking towards a future that harbors both expected changes and many uncertainties. Together with other sources, information from the climate projections and scenarios developed in this workshop will serve to inform adaptation strategies for Isle Royale.

Red Fox at Isle Royale National Park. NPS photo.

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Appendix

Supplementary Material

Table A1. Isle Royale and Great Lakes region historical trends and climate projections for 2050 and 2100. Data quality statement: There are no continuous time series data for Isle Royale. Of the data that do exist for Isle Royale, they consist mostly of observations from the warm-season and few observations exist for the cold-season. Since data at Isle Royale are not reliable it is necessary to use records from nearby regions that are of higher quality. We recommend using reliable observational records from areas to the west and north (MN and Canada), as opposed to records from the mainland to the south (Michigan's Upper Peninsula), because the distance from shore is minimal and those stations, similar to Isle Royale, are not in the heavy lake-effect zones. Minnesota's weather station at Grand Marais, MN (National Climatic Data Center, www.ncdc.noaa.gov) was used for some of the historical trends in the table below.

Climate or Physical Variable	Trend	Historical (20th Century) Climate Change	Projected Change 2050	Projected Change 2100	Confidence in Scientific Understanding (HML)
Temperature	↑	Warming temperatures occurred in the Great Lakes region, +1.3 ± 0.5°F/century (1901-2002). Some parts of the northwest Gt Lakes warmed the most, but Isle Royale has likely[1] warmed less quickly than surrounding mainland areas due to the modifying effects of Lake Superior.[2,3] The most warming was during the cold season.	+3.42 to 6.48°F (1.9 to 3.6°C) (warmer emission scenario)[4,5] (mean-1std dev to mean+2 std dev)	+6.84 to 12.78°F (3.8 to 7.1°C)/century (warmer emission scenario)[5] (mean-1std dev to mean+2 std dev)	**High** confidence in the direction of global and regional change (increasing);[6] **Low** confidence in the magnitude of change, particularly for local ISRO micro-climate.
Precipitation	↑	Precipitation has generally increased over the Midwest.[1] However, precipitation over Lake Superior (including Isle Royale) during the warm-season is generally less than the mainland.[7]	5% to 15% increase over the Midwest[4]	9% to 31% increase over the Midwest	**Medium** confidence that precipitation will increase;[8] **Low** confidence of the magnitude of change.
Snowfall	↓ Likely	Regionally, snowfall has decreased, but there are not enough records on Isle Royale to draw any local conclusions.[7,9] Spring snow melt is occurring earlier.	snow days reduced by 25% for MI[4]	snow days reduced in half for MI	**Low**

Table A1. (Continued)

Climate or Physical Variable	Trend	Historical (20th Century) Climate Change	Projected Change 2050	Projected Change 2100	Confidence in Scientific Understanding (HML)
Frost-Free Growing Season Length	↑	The growing season across the Midwest is increasing days on both sides of the warm-season. Isle Royale's growing season may be extended further into Autumn as water temperatures remain warm for a longer period of time.[10]	Last spring freeze 1 week earlier +20-25 frost-free days in growing season	Last spring freeze 2 weeks earlier +29 frost-free days in growing season	**High** confidence that there will be more warm days; **Low** confidence that those warm days will occur consecutively in the growing season.
Extreme Temperature Events	↑ ↔	Anomalous Midwest warm events in the 1930s cause the trend to appear as if no change has occurred, but there is a positive warming trend for the past 30 years. There is not as much change in extreme heat during the warm-season, rather, there are fewer cold events during the cold-season.	days with temperatures ≥95°F will increase by less than 5 days heat waves are not expected to increase in the northern Midwest days with temperatures ≤32°F will decrease (about 15 less days)	heat waves will increase across the Midwest (up to 25 heat waves by end-of-century) days with temperatures ≤32°F will decrease (about 30 less days)	**High** confidence that there will be less cold days.
Wind	↑ Likely	Winds over Lake Superior have generally increased. Extreme wind events in November have historically caused strong wind storms that impact shipping on Lake Superior as well as ice formation in general. Strong winds can break up ice or prevent ice from forming.	likely no change in extreme wind events	wind events more extreme than the historical envelope will likely not develop until the end of the century	**Low**
Extreme Precipitation Events	↑	The intensity of extreme precipitation events has increased. Severe drought is less common in northeast MN, near Isle Royale, than other parts of MN. November is historically when the most extreme snow events have occurred over Lake Superior.	up to +30% increase in number of days with greater than 1 inch precipitation for parts of the northern Midwest region	20% increase in days where precip > 2.5cm; decrease of 4 to 6 days where precip < 3mm	**Medium**[11]
Lake Levels	↓ ↔	There has been a shift to an earlier spring maximum, but historically, lake levels have fluctuated.	-0.6m to 0.4m change[4]	-0.6m to 0.9m change	**Low–Medium**

Table A1. (Continued)

Climate or Physical Variable	Trend	Historical (20th Century) Climate Change	Projected Change 2050	Projected Change 2100	Confidence in Scientific Understanding (HML)
Lake Temperatures	↑	Warming lake temperatures, especially in the fall, cause a delay in ice formation. Greater ice-free periods will allow more moisture flux to the atmosphere that may impact precipitation/snowfall.[12]	+3.6°F (2°C) in warm-season water temperatures. Water temperatures will reach 50°F (10°C) in the spring 10-12 days earlier. Water temperatures will cool to 50°F (10°C) in the fall 15-17 days later.	+8.28°F to 12.06°F (+4.6°C to 6.7°C) increase in warm-season water temperature. Water temperatures will reach 50°F (10°C) in the spring 26-39 days earlier. Water temperatures will cool to 50°F (10°C) in the fall 36-52 days later.	**High**[13]
Lake Ice Cover	↓	Ice cover has dramatically decreased. Ice cover is greatest during late winter/early spring, but the existence of a solid ice bridge between Isle Royale and the mainland has become more rare.[14]	Days with ice are expected to decrease by 12 to 47 days (1950-1995 ranged from 77 to 115 days of ice cover)	Days with ice are expected to decrease by 37 to 81 days (1950-1995 ranged from 77 to 115 days of ice cover)	**High**[15]
Arctic Oscillation	↔	It is difficult to predict the mode of the Arctic Oscillation (AO), and one extreme negative mode can be followed by an extreme positive mode. The modes determine the type of weather that is experienced: warmer and dryer air, soil is dry (+ phase); or colder and wetter conditions, wet soil (- phase). The AO is primarily a wintertime variable (DJFM)[16]			**Low**

Table A1. (Continued)

Climate or Physical Variable	Trend	Historical (20th Century) Climate Change	Projected Change 2050	Projected Change 2100	Confidence in Scientific Under-standing (HML)
Weather "Blocking" Patterns	⟷	Warming air temperatures in the Arctic may impact the direction storms travel and how quickly they pass a region. Severe weather (conditions for flood, drought, hot, or cold spells) may persist for longer periods of time.			**Medium**
ENSO	⟷	Although El Niño events and strong La Niña events are associated with lower ice cover on the Great Lakes, interferences between ENSO and NAO can complicate the overall outcome of ice cover.			**Low**

1. Isle Royale does not have a continuous record of observations, and very few cold-season observations, so we can not have high confidence in the historical trends.

2. Island temperatures are generally cooler (warmer) than the mainland in summer (winter) because they are insolated by the relatively cold (warm) waters of Lake Superior

3. GCMs do not simulate the Great Lakes, so they will not capture the important lake-induced influences on local air temperatures for Isle Royale.

4. a. b. c. d. mid century projections were determined by taking 1/2 of the end-of-century change. For mid-century change the choice of emission scenario has little impact on the outcome, and the after mid-century rates of change are expected to increase)

5. a. b. these values are based on gridded downscaled CMIP3 projections that do not include any local information for Isle Royale or Lake Superior in general.

6. a. b. c. confidence is for global and regional projections. Because of the micro climate at Isle Royale, confidence for local change is lower

7. a. b. GCMs do not simulate precipitation processes well, especially warm-season convective precipitation and lake-effect precipitation (including snowfall).

8. Confidence is for global and regional projections. Because of the micro climate at Isle Royale, confidence for local change is lower.

9. The weather stations nearest Isle Royale do not pass quality control tests or they are located within the lake-effect zone that is not characteristic of Isle Royale.

10. GCMs have difficulty simulating precipitation mechanisms at the warm-season/cold-season transitions (too dry in September and too wet in May)

11. Most increases have been observed in lake-effect precipitation, which is not as prevelant at Isle Royale.

12. The lakes are not simulated in GCMs so future lake temperature information will likely need to come from regional or hydrologic models.

13. Water temperatures will be influenced by the rate of warming air temperatures.

14. The lakes are not simulated in GCMs so future lake ice information will likely need to come from regional or hydrologic models.

15. Loss of ice cover will be related to warming air temperatures.

16. GCMs do not simulate the AO consistently, which produces different outcomes for regional weather predictions. There is evidence to suggest that the NAO will intensify its positive phase with increasing greenhouse gas concentrations.

Table A2. Isle Royale National Park Scenario Planning Workshop Participant List

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