



Adapting to climate change: guidance for the management of inland glacial lake fisheries

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ABSTRACT

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Climate change is altering glacial lake fisheries in the United States, presenting a complex challenge for fisheries managers. Here we provide a regional perspective to guide management of heterogeneous and yet interdependent fishery resources in glacial lakes of the upper Midwest. Our main objective was to promote the adaptation of inland glacial lakes fisheries management to climate change by outlining processes that support regional plans. Using examples from the glacial lakes region, we outline an approach for regional prioritization, specify strategies for moving from regional prioritization to on-the-ground action, and provide guidance on the implementation of management plans given resource limitations and potential stakeholder conflict. We find that integrating ecological, social, and economic data with climate change vulnerability assessments can be useful in generating “lake-priority levels” to help identify where to focus actions to support system resilience. Managers can use lake-priority levels and ecosystem-specific strategies to make decisions about where and when to apply fisheries management action ranging from traditional (i.e., stocking, harvest regulations) to nontraditional approaches (i.e., catchment land management). Although the implementation of several approaches may be beyond an agency’s financial and logistical capacity, funds can be secured through other sources ranging from grant programs to nontraditional partnerships identified by “thinking outside the lake.” Regional plans may be an important step toward successful climate adaptation for inland glacial lakes fisheries management, and the proactive efforts of managers may help facilitate their development and implementation.

KEYWORDS

Adaptation; climate change; fisheries management; glacial lakes; regional approach

In the upper Midwestern United States, climate change is anticipated to lead to warmer air temperatures, higher intensity precipitation, and prolonged drought (Pryor et al. 2014). These changes are likely to strongly influence inland glacial lakes fishes and the ecosystem services they support. For example, increases in temperature have already contributed to abundance declines and extirpations of native, coldwater cisco *Coregonus artedii* (Jacobson et al. 2008a, Honsey et al. 2016), and further projected habitat

loss will disrupt food webs and ecosystem function in many lakes (Fang et al. 2012, Herb et al. 2014). Increased temperature is also a plausible driver of declines in recruitment and production of walleye *Sander vitreus* in Wisconsin lakes (Hansen et al. 2015a, Rypel et al. 2018). Current projections indicate additional loss of self-sustaining walleye populations (>75%; Hansen et al. 2017), threatening the persistence of the most popular fishery among multiple user groups (USFIA 1991, McClanahan and Hansen 2005,

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Holsman et al. 2017). Widespread shifts toward species assemblages dominated by tolerant, warmwater fishes have also been observed and are likely to continue (Hansen et al. 2017, Jacobson et al. 2017), further disrupting a recreational fishing industry that generates billions of US dollars annually (USDOI 2011).

Although inland lake fisheries management has historically focused on priorities at local or small spatial scales, adapting to climate change may require a regional perspective (Lester et al. 2003, Midway et al. 2016, Paukert et al. 2016). For example, widespread changes in suitable habitat for species conservation may require a shift from the protection of existing populations to promoting the ecological resilience (i.e., the ability to absorb disturbance and maintain structure and function; Holling 1973) of only those lakes likely to remain suitable (Heller and Zavaleta 2009, Monzón et al. 2011). Adapting management to sustain the ecosystems services provided by recreational fisheries will be even more complex, as fisheries are nested within a social-ecological system connected by feedbacks among anglers, managers, and fisheries (Post 2013, Hunt et al. 2013). Managing for recreational fisheries resilience therefore requires the management of social and ecological components in ways that allow the system to sustain itself (Hansen et al. 2015b). This

may be challenging for managers in the upper Midwestern United States, as inland glacial lakes are codependent entities with anglers that shift effort with changing conditions and regulations (Beard et al. 2003, Carpenter and Brock 2004, Johnston et al. 2018). As a result, climate adaptation at a local scale may need to be nested in the context of regional fishing opportunities and the social dynamics of users.

The primary objective of this perspective is to promote the adaptation of inland glacial lakes fisheries management to climate change by outlining processes that support the development and operationalization of regional plans. We direct our discussion toward managers as well as decision makers and stakeholders, hereafter referred to as planners. We first describe a regional prioritization approach that accounts for the relative interdependency and heterogeneity of inland glacial lake fisheries, integrating concepts from existing climate adaptation tools. This approach consists of (1) defining a regional goal, (2) assessing climate vulnerability, and (3) prioritizing lakes (Figure 1). Second, we present ecosystem-specific strategies and approaches, that when paired with regional prioritizations, can be used to help plan on-the-ground action. We then consider how to operationalize regional plans by facilitating action and securing alternative funding, as well as managing

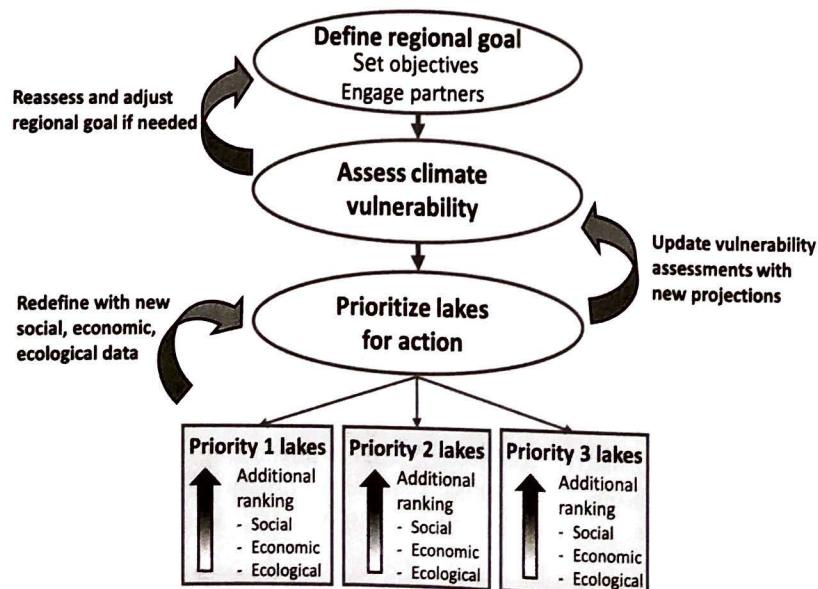


Figure 1. A conceptual approach for prioritizing inland glacial lakes for climate adaptation action.

stakeholder expectations. Finally, we close with a case study and a hypothetical example from the region that highlight the utility of the proposed processes. Although developed for inland glacial lakes, we aim to provide insight for adapting fisheries management to climate change in any system where heterogeneity and interdependency among fisheries creates a complex challenge for managers and decision makers.

Prioritization at a regional scale

Defining a regional goal

A successful regional goal is specific enough to provide a clear path forward for adapting inland glacial lakes management to climate change, but broad enough to allow flexibility in implementing actions at the local scale. To aid in goal development, planners can consider the underlying purpose of prioritization and planning and the geographic extent over which they aim to provide guidance (Swanson et al. 2016). Given that local action is required to achieve regional goals, engagement with local partners in a position to implement on-the-ground actions during this stage can be critical for success (Stein et al. 2014).

Defining a goal at a broad spatial scale can frame climate change adaptation in the context of an interconnected resource, shifting the discussion from local lake management to resilience of the larger system of lakes. Conservation targets are still characteristics of individual lakes, but goals and objectives address the broader resource. For example, a regional goal may be to protect coldwater fish from regional extirpation, with specific conservation targets being the retention of individual lake populations. Defining a regional goal with a narrow scope (e.g., a specific biotic response to climate change) can allow for explicit objectives and prevent plans from becoming overly complex, while still encompassing a broad spatial scale. It may also be important to consider that other species may benefit from actions implemented to support a regional goal, and identifying such co-benefits early in the planning process could allow planners to align adaptation plans with existing conservation efforts.

Assessing lake-specific vulnerability to climate change

Vulnerability assessments can be used to determine to what extent species or ecosystem processes may be affected by climate change and whether regional goals and objectives are feasible given future conditions (Joyce and Janowiak 2011). Vulnerability assessments have 3 components: sensitivity, exposure, and adaptive capacity. Sensitivity (i.e., how a resource is affected by climate change) and exposure (i.e., the magnitude of change to be experienced) together assess projected effects, while adaptive capacity is a measure of the ability to accommodate change (Glick et al. 2011). An emphasis on sensitivity and exposure may be most relevant to planners, as adaptive capacity could be assumed to be relatively low due to the limited dispersal abilities of inland glacial lake fishes (Lynch et al. 2016).

Multiple approaches exist to assess climate vulnerability (e.g., trait-based, mechanistic models; Pacifici et al. 2015), but correlative models may be most useful for developing lake-specific vulnerability assessments. Planners can develop correlative models by identifying relationships between current lake characteristics (physical and thermal) and species or ecosystem response on lakes with site-specific data, then pair these models with downscaled climate change projections to assess vulnerability. When extrapolated across lakes, such models can help visualize the heterogeneity and magnitude of change across a region and predict change at the local scale. An increase in the availability of regional datasets that include lake characteristics (e.g., Soranno et al. 2015) and thermal metrics (e.g., Winslow et al. 2017) makes the generation of correlative models increasingly feasible. If data are a limiting factor, existing lakes classifications (e.g., Schupp 1992, Rypel et al. 2019) could also be used to assess vulnerability, as they generalize lakes into types that may respond similarly to change and often include climate variables.

Any vulnerability assessment of glacial lakes to climate change will be uncertain due to uncertainty in future climates, as well as species or ecosystem responses. Documenting known sources of uncertainty is a critical component of

Table 1. Selected strategies, approaches and actions for inland glacial lake fisheries. Citations with asterisks indicate those that were modified from existing climate change adaptation tools, peer-reviewed literature or have been implemented in the inland glacial lakes region. Where appropriate, additional citations provide resources with further details on implementing suggested actions. Two asterisks indicate actions that authors concluded may have a high risk of unintended ecological consequences (see text for additional detail).

Strategy	Approach	Action
Protect or restore water quality		
	Prevent new sources of sediment, pollutant, and nutrient runoff	<ul style="list-style-type: none"> Establish private conservation easements in priority catchments (Jacobson et al. 2013*).^a Catchment land acquisition by federal, state, or local governments (Jacobson et al. 2013*, BTL 2015*). Promote or support new outreach programs or incentives for leaving natural areas on privately-owned shorelines undisturbed or by establishing conservation easements (BTL 2015*, Nohner et al. 2018).^a Engage local governments and associations to support the implementation of innovative local zoning regulations and stricter shoreland standards (BTL 2015*, Fuller et al. 2016, MNDNR 2019).^a
	Reduce sources of sediment, pollutant and nutrient runoff	<ul style="list-style-type: none"> Develop private forest stewardship planning programs and highlight tax incentives for landowners (BTL 2015*, Jacobson et al. 2013*). Restore riparian vegetative strips on public lands to buffer runoff and reduce wind action (BTL 2015*; Shannon et al. 2019*). Establish collaborations with forest managers to mitigate the effect of harvest and timber road development using existing Best Management Practices (BMPs; Shannon et al. 2019*, USFS 2012). Establish collaborations with forest managers to increase or restore soil infiltration capacity (BTL 2015*, Shannon et al. 2019*, USFS 2012). Engage local governments and associations to support the implementation of ordinances that reduce impact of existing disturbance (e.g., required vegetative buffers; BTL 2015*, Fuller et al. 2016, MNDNR 2019).^a Promote or support new landowner incentive programs for the voluntary implementation of stormwater or agricultural BMPs (EPA 2005, Sharpley et al. 2006, Palm-Forster et al. 2017). Engage landowners in agricultural catchments to promote the use of BMPs to reduce surplus soil P input and losses and enhance P retention in buffers (Sharpley et al. 2006, Jeppesen et al. 2009*, Carpenter et al. 2018*). Protect or restore streamflow to maintain baseflow during periods of prolonged drought or with likely changes in seasonal precipitation, mitigating intensity of P inputs (Jeppesen et al. 2009*). Encourage local governments and associations to require stricter regulations for minimizing discharge, reducing sources of pollutants to runoff, filtering surface water, and increasing water retention (BTL 2015*, EPA 2005, Fuller et al. 2016). Offer science-based support for the construction of water treatment wetlands and detention ponds (Magee et al. 2019*). Support the use of resilient or adaptive BMPs and the adjustment of total maximum daily load (TMDL) standards to account for projected increases in intense rainfall, droughts, and temperature (Sarkar et al. 2018*, Giese et al. 2019*, Schmidt et al. Forthcoming*).
	Implement dredging to eliminate sources of phosphorus from connected streams	(Magee et al. 2019*).
Implement engineering solutions to retain habitat during periods of stress		Install artificial aeration structures to prevent the loss of coldwater habitat (Magee et al. 2019*).
Protect or restore access to physical habitat		
	Restore or prevent the degradation of littoral habitat	<ul style="list-style-type: none"> Promote or support new outreach programs and incentives that encourage preservation of CWH, macrophytes, and natural shorelines (Amato et al. 2012, Amato et al. 2015, Nohner et al. 2018). Land acquisition by federal, state, or local governments along the shoreline (BTL 2015*). Revegetate shorelines, littoral, and transition zones using regionally successful species and proven practices (e.g., extended-use wave breaks; Vanderbosch and Galatowitsch 2010). Install artificial spawning habitat within lakes and rivers.
	Ensure access to physical habitat remains under more variable and extreme precipitation regimes	<ul style="list-style-type: none"> Addition of coarse woody habitat at greater depths in drought-vulnerable lakes (Gaeta et al. 2014*). Engage agricultural landowners to promote water conservation to limit drawdowns (Magee et al. 2019*). Protect CWH stranded above water so it is available when lake levels rise (Magee et al. 2019*).
Restore hydrologic connectivity among habitats		
	Install adequate drain structures, remove perched culverts, and alter stream crossings (Diebel et al. 2015).	
	Remove or modify dams and impoundments to allow fish movement	
Mitigate the threat of invasive species (approaches and actions taken or modified from Magee et al. 2019*)		
Reduce the chance of spread to un-impacted lakes		
	Continue effective outreach efforts for existing invasive species and establish new programs for emerging threats.	
	Expand youth education and develop simple and consistent messaging.	
	Advertise success of existing outreach programs.	
	Install fish passage barriers or chlorinated locks to prevent further spread in connected systems.	
	Support regulations or voluntary programs for vessel decontamination, ballast water treatment.	
Control invasive species effects once introduced		
	Incentivize invasive species harvest at edge of invasion.	
	Promote general health of lake to mitigate effects of invasive species.	
	Develop biological controls programs for common invasive species.	
Adjust management of current fisheries or populations to ecological change		
	Adjust regulations to anticipated population-level changes	
	Lower bag limits or restrict harvest on sportfish permanently or in vulnerable years (Kumar et al. 2013*, reviewed by Myers et al. 2017*).	
	Maintain age diversity to lower risk of year-class failures (Gwinn et al. 2015*, Hansen et al. 2015b*).	

(continued)

Table 1. Continued.

Strategy	Action
Approach	
Retain or promote genetic diversity	Eliminate bag limits or extend harvest seasons on non-native introduced or expanding competitors or predators (Pasko and Goldberg 2014*, Paukert et al. 2016*, reviewed by Myers et al. 2017*). Alter fishing season in response changing phenology (OMNRF 2013*, reviewed by Myers et al. 2017*).
Adjust management to emerging or anticipated ecological constraints	Establish fishing restrictions for lakes with increasingly unique stocks. Use source stocks that are genetically similar to existing populations. Eliminate supplemental stocking for naturally recruiting populations. Translocate populations of unique genetic strains into climate resilient lakes.**
Facilitate transitions in response to changing conditions	Implement stocking of species to retain recreational put and take fishery. Implement stocking for new gamefish.** Introduce alternative prey source for game species.** Improve or protect habitat for species anticipated to become dominant.
Eliminate ineffective or unsustainable management actions	Eliminate or reduce stocking to systems unlikely to support viable fisheries. Reduce current habitat management for species on lakes unlikely to continue to support populations.
Facilitate shifts in stakeholder or user preference to emerging or dominant fisheries	Develop outreach efforts highlighting recreational or consumptive value of expanding or alternate species. Change regulations to shift perception of appropriate conservation practices among anglers (Sass et al 2017).

*Actions are also likely to protect physical structure by reducing sediment loading and retaining current substrate composition.

vulnerability assessments and can be achieved using multiple sources of information (Pacifici et al. 2015). For example, Panci et al. (2018) used published literature, traditional ecological knowledge, and trait-based questions from NatureServe's climate change vulnerability index (Young et al. 2011) to bound uncertainty in sensitivity estimates for 60 species/beings important to Great Lakes Indian Fish and Wildlife Commission member tribes. For correlative models, uncertainty in sensitivity and exposure could be bound using multimodeling approaches and generating assessments under multiple possible future climates (i.e., low vs. high emission scenarios; Pacifici et al. 2015). If patterns in change are similar, average or median values may suffice for further prioritization. If not, planners may consider developing alternative prioritizations to depict multiple potential future scenarios, or integrating measures of confidence into priority rankings (see later description). Finally, identifying known sources of uncertainty can help identify where additional study can improve the vulnerability assessment, which can then be updated as new information becomes available.

Prioritizing lakes

Certain lakes are likely more important to regional goals than others, and developing lakes prioritizations can help determine where to implement action. However, this may not be as simple as

promoting resilience on lakes most vulnerable to climate change, as some goals may require implementing a triage approach. Further, managers are tasked with meeting objectives in the context of the broader social-ecological system (Hunt and Grado 2010), and support from decision makers may be more likely if aspects of fisheries prioritized by agencies are addressed (i.e., recreational, economic, ecological; Carlson et al. 2019). Therefore, developing discrete "lake-priority levels" that integrate vulnerability assessments with social, ecological, or economic datasets (and potentially with continuous priority rankings within levels; Fig 1) can be useful for directing and implementing congruent actions in similar lakes.

Data integrated with climate change vulnerability assessments for prioritization will depend on the regional goal and data availability. For example, readily available fisheries effort datasets (e.g., creel data, reported harvest) can reflect the value of lakes from a fisheries perspective. Economic factors, such as contribution to the local economy, may also appeal to decision makers, but could conflict with actions that promote resilience and may need to be paired with ecological value-based data (Christensen et al. 1996, Honsey et al. 2016, Radomski and Carlson 2018). Finally, ecologic characteristics important to existing conservation issues (e.g., species of conservation interest) could also be used to encourage collaborative efforts. When multiple factors are included, weights could be assigned based on

the importance of individual lake characteristics to supporting a regional goal. Following the development of priority levels, planners can consider where gaps in understanding may limit prioritization, and can work toward generating these datasets in the future.

Moving from regional prioritization to action

Ecosystem-specific strategies and approaches

Following prioritization, planners still need to identify what actions may support a regional goal and on which lake-priority levels to implement them. When paired with an adaptation workflow, “menus” of management adaptation strategies (i.e., broad ecosystem-specific responses to change) and approaches (i.e., site- and goal-specific responses) have helped forest managers customize adaptation plans and develop unique actions (Janowiak et al. 2014, Shannon et al. 2019; www.adaptationworkbook.org). Here we present 5 strategies based on anticipated effects of climate change on inland glacial lakes (Table 1). Strategies exist along a continuum of adaptation response ranging from resisting change to adapting current management to inevitable change (Millar et al. 2007, Janowiak et al. 2014, Swanston et al. 2016). We note that our goal was to organize existing information on adaptation for inland glacial lakes fisheries management into a menu that could be easily paired with prioritizations to guide the development of regional plans. Therefore, strategies, approaches, and potential actions were compiled and modified from existing adaptation resources (reviews, workbooks, glacial lakes implementation plans) or developed based on glacial lakes fisheries management techniques (see Table 1 for additional details).

Strategy 1. Protect or restore water quality

Water quality is a critical component of fish habitat (Jacobson et al. 2016), and increased water temperature is likely to exacerbate effects of excessive nutrient and pollutant loading (e.g., seasonal habitat loss, harmful algal blooms, shifts in trophic state, pollutant-related fish mortality; Sokolova and Lannig 2008, Moss 2011, Jacobson et al. 2017, Till et al. 2019). In addition, more frequent and intense precipitation events may increase nutrient and pollutant

pulses (Carpenter et al. 2018), contribute to greater erosion and combined sewage overflow (Pryor et al. 2014), and lower baseflows during summer months (Jeppesen et al. 2009). Therefore, a critical strategy for adapting inland glacial lakes management to climate change may be protecting or restoring water quality to retain or promote ecosystem resilience. Approaches include preventing new sources of pollutants, sediments, and nutrient runoff, reducing sources in altered systems, and implementing engineering solutions to retain habitat.

Strategy 2. Protect or restore access to physical habitat

Physical structure (coarse woody habitat [CWH], macrophytes, and substrate; Jacobson et al. 2016) is a second critical component of fisheries habitat. Restoring or preventing the degradation of littoral and spawning habitat in prioritized lakes may be an important approach to retaining resilient systems (Magee et al. 2019). In addition, increased drought (Pryor et al. 2014) may lower lake water levels and limit available spawning, foraging, and refuge habitat (Hardie 2013, Gaeta et al. 2014). Ensuring that physical habitat remains available to fishes during and following drought conditions can increase ecological resiliency within vulnerable lakes. Finally, restoring hydrologic connectivity among lakes and fluvial habitat can allow fishes to move to more suitable connected habitat under extreme conditions (Jeppesen et al. 2010). In addition, populations of some potadromous fishes (e.g., walleye) may be more resilient to warming temperatures in lakes with hydrologic connectivity to naturally recruiting river populations (RW Tingley, Missouri Cooperative Fish and Wildlife Research Unit, Research Associate, Aug 2019, unpubl.).

Strategy 3. Mitigate the effects of invasive species

Climate change may result in increased habitat availability and range expansion, altered pathways of introduction, and changes in the effect of aquatic invasive species (AIS) on native ecosystems (reviewed by Rahel and Olden 2008). Reducing the chance of spread and controlling established AIS can mitigate the effects of invasive species and help retain the ecological resilience of lakes to climate change by limiting

additional stressors, while promoting system resilience by ensuring viable fisheries are retained (Staudt et al. 2013, Magee et al. 2019)

Strategy 4. Adjust management of current fisheries or populations to ecological change

Changes in fish populations may result in shifts in angler effort across the landscape, leaving individual populations and regional fisheries vulnerable to overharvest. In addition, declines in popular harvest species may result in anglers increasing pressure on alternative species with liberal harvest regulations (e.g., bluegill *Lepomis macrochirus*; Tingley et al. 2019). Other population-level changes (e.g., earlier spawning, greater interannual variability in recruitment success) may also increase the risk of overexploitation (Paukert et al. 2016). Proactively adjusting regulations may protect individual populations and promote overall system resilience. Adjusting stocking protocols to retain or promote genetic diversity as stocking efforts increase in response to change is another important approach, as stocking has the potential to degrade genetic variability (Araki and Schmid 2010) and harm naturally recruiting populations (Gilbert and Sass 2016).

Strategy 5. Adjust management to emerging or anticipated ecological constraints

Climate-driven changes in habitat and fish communities may be inevitable for some lakes, and planners may need to consider eliminating ineffective or unsustainable management actions. Although appropriate, these approaches may be unpopular and may not align with deep-rooted stakeholder values. Societal values are adaptive and will change as conditions evolve, but forcing stakeholders to align with transitional approaches is unlikely to be successful (Manfredo et al. 2017). However, actions that facilitate shifts in stakeholder preferences have potential if not in direct conflict with current values. For example, outreach programs that highlight the consumptive value of emerging species have promise (Weis 2011, LDWF 2018) and could be used to redirect angler effort to expanding warmwater species as cool- and coldwater species decline. Further, changes in thermal guild preference may

already be occurring passively among recreational anglers in the United States (Hunt et al. 2016). This provides hope that outreach programs or the alteration of regulations to promote different conservation norms may be useful and successful during times of transition.

Finalizing regional plans

For some initiatives, simple assessments can allow planners to consider tradeoffs and determine actions that support regional goals. In others, uncertainty in climate projections, user response (e.g., changes in angler behavior), and other factors (e.g., effectiveness of actions) presents a challenge. Methods ranging from expert-based elucidation to structured decision making (SDM) have been suggested to help in climate adaptation decision making and to balance tradeoffs among actions (Stein et al. 2014). Scenario-based planning (SBP) may be particularly useful, as it allows planners to work within the confines of uncertainty by using “what-if” scenarios under multiple possible futures (Peterson et al. 2003, Stein et al. 2014). SBP could be used with regional prioritizations in instances where substantial uncertainty exists in the outcomes of climate change and planners aim to identify those actions that may promote resilience across diverse future conditions. Even in instances where uncertainty is relatively low, it is likely that many approaches and actions may at first seem suitable for meeting regional goals. Considering the risk and uncertainty associated with each potential action may help reduce the number included in a final regional plan, such as:

- Will the action have the desired ecological effect? Is there science to support its effectiveness? Application of ineffective actions is maladaptive (Barnett and O’Neill 2010) as it draws funds away from effective ones.
- Is the action socially feasible? Will it be accepted by stakeholders or decision makers? Are there complementary actions that increase the likelihood of acceptance (e.g., outreach)?
- Is the action financially feasible? Although the answer may be “no,” it may be valuable to retain costly, but effective, actions until all funding opportunities are considered.

- Is there potential for unintended ramifications? For example, biological manipulations, from prey species introduction (e.g., Fredrickson 2017) and sportfish stocking (e.g., Gauthier 2001) to range extension and bolstering of unique genetic stocks (e.g., Spurgeon et al. 2015, Parks and Rypel 2018), have all had unintended consequences.

As climate change may result in novel conditions, certainty in the effectiveness of actions in promoting resilience cannot be based fully on past management experiences (Hansen et al. 2015b). Monitoring and subsequent adjustments in on-the-ground action have proven effective in improving the results of regional conservation initiatives (e.g., Pierce et al. 2013), and planners may wish to integrate monitoring protocols into regional plans to ensure that actions have the intended effect. Adaptive management can also play a role in reducing uncertainty related to action effectiveness in a changing climate (Hansen et al 2015b). Successful implementation of adaptive management requires clear identification of objectives and uncertainties, as well as a long-term commitment from stakeholders and managers to conduct management experiments in support of learning (Walters 2007). Managers therefore may need to consider if they have a commitment from stakeholders before moving forward with this approach.

Operationalizing climate adaptation plans

Facilitating action and securing alternative funding

The allocation of funds targeted for climate change adaptation may be impractical or of low priority for decision makers, making implementation of regional plans challenging (Paukert et al. 2016, Carlson et al. 2019). In addition, management agencies may be unable to take direct action on privately owned lands, which can dominate many catchments. “Hourglass” approaches, where regional prioritization drives many local actions that together address regional goals, may be an important strategy when action is required but agencies have limited capacities (Pierce et al.

2013). Providing local lake managers with materials to engage landowners can be valuable, as can targeting nonprofit organizations and local governments to promote action (see Table 2 for examples). Planners can also aid conservation partners in securing federal- (e.g., Healthy Watersheds Program) and state-funded grants (e.g., Michigan Fisheries Habitat Grants; Table 2). Although individual actions may vary, ensuring local actions are linked directly to regional objectives set during planning may improve the chance of funding being secured.

Planners can also identify nontraditional funding opportunities by “thinking outside the lake.” For example, conservation actions for species in State Wildlife Action Plans can promote resilience if conducted in prioritized lakes or catchments. An additional \$1.4 billion annually from the State Wildlife Grant Program could become available through the Recovering America’s Wildlife Act (The Wildlife Society [TWS] 2019), making the identification of parallel conservation goals increasingly valuable for implementing regional plans. Further, engaging and partnering with state agencies with differing missions (e.g., fisheries; water quality) and external organizations focused on climate adaptation and outreach (e.g., Agricultural Experiment Stations; Carlson et al. 2019) may help increase the breadth and magnitude of actions implemented. Finally, planners can offer science-based support for the establishment of programs that accumulate funds for conservation, such as taxes on angling equipment (e.g., The Federal Aid in Sportfish and Wildlife Restoration Programs) and conservation stamps (e.g., NGPC 2011, Sass et al. 2017). Programs that explicitly support climate adaptation strategies may be invaluable to addressing large-scale change, as they can provide a consistent funding source, and adaptation plans can be used to justify their establishment.

Managing expectations

Climate change adaptation actions will often require investment and effort from many partners, the results of which are not guaranteed and, if achieved, may not be realized for many years. For instance, coldwater fishes may still be

Table 2. Example funding sources and partners to support inland glacial lakes climate adaptation action.

Type	Funding source	Funding	Description
Federal-grant programs			
	State Wildlife Grant Program	State specific	Conserve species identified in State Wildlife Action Plans. Funds allocated to state agencies. Opportunities for multi-state grants through the competitive subprogram. ¹
	Healthy Watersheds Initiative	\$50,000–150,000	Accelerate and expand the strategic protection of healthy, freshwater ecosystems and their watersheds. Entities who are linked to collaborative partnership with other groups having similar healthy watersheds protection goals. ²
	Regional Fish Habitat Partnerships (Primary: Midwest Glacial Lakes Partnership)	Typically \$10,000–75,000	Conserve fish habitat through projects that align with a regional partnership's strategic plan. Applicants include land owners, public agencies, non-governmental organizations, and governments. ³
State-grant programs			
	Michigan Fisheries Habitat Grant Program	Minimum of \$25,000	Address causes of habitat degradation as opposed to symptoms, provide long-lasting benefits, address needs on the Fisheries Division priority habitat projects list, be cost-effective, use appropriate methods, monitor project outcomes, address health and human safety for dam management, and/or address research and assessment needs to inform future habitat conservation. State, local, federal and tribal governments, academic institutions, and nonprofit organizations are eligible. ⁴
	Clean Michigan Initiative: Nonpoint Source Pollution Grants	Minimum of \$25,000	Restore waters impaired by nonpoint source pollution and prevent high quality waters from degradation. County or local units of government and nonprofit agencies eligible. ⁵
	Michigan Invasive Species Grant Program	\$25,000–400,000	Prevent establishment and control invasive species. State, local, federal and tribal governments as well as universities and nonprofit organizations eligible. ⁴
	Wisconsin Wetland Conservation Trust	Variable	Restore wetlands. Applicants including individual land owners, public agencies, consultants, and Wisconsin Tribes. ⁶
	Wisconsin Surface Water Grants	Program dependent	Easement acquisition, restoration, lake management and invasive species control. Most government entities and nonprofit conservation organizations eligible. ⁷
	Minnesota Conservation Legacy Grant Program	Typically \$5000–400,000	Restore or enhance forests, wetlands, prairies and habitat for fish, game and wildlife in Minnesota. Nonprofit organizations and government entities eligible. ⁸
	Minnesota Clean Water Fund Implementation Program	Typically \$5000–400,000	Protect, enhance, and restore water quality in lakes, rivers, and streams and protect groundwater and drinking water. Local governments or joint power boards working under various state-approved water management plans eligible. ⁹
Stakeholder organizations and governmental units			
	Lake associations	Variable	Voluntary organizations dependent on membership dues and donations. Numerous in many glacial lakes states ^{10,11,12}
	Lake or conservation districts	Variable	Local government units; specific power dependent on state law and district type. In some cases, can implement taxes that may fund local lake conservation efforts. ^{10,12,13,14}
	Local or national conservation organizations	Variable	Examples include watershed organizations or councils, Sturgeon for Tomorrow, Walleyes for Tomorrow, Trout Unlimited, Muskies, Inc., Ducks Unlimited, and Delta Waterfowl.

¹<https://wildlife.org/policy/recovering-americas-wildlife-act/>.²<https://www.epa.gov/hwp>.³<http://midwestglaciallakes.org/grant/>.⁴https://www.michigan.gov/dnr/0,4570,7-350-79134_81684--00.html.⁵https://www.michigan.gov/egle/0,9429,7-135-3307_3515-314499--00.html.⁶<https://dnr.wi.gov/Aid/wwct.html>.⁷<https://dnr.wi.gov/aid/surfacewater.html>.⁸<https://www.dnr.state.mn.us/grants/habitat/cpl/index.html>.⁹https://bwsr.state.mn.us/cwf_programs.¹⁰<http://www.wisconsinlakes.org/lake-organizations-wisconsin/>.¹¹<http://www.mnlakesandrivers.org/lake-associations/lake-associations-list>.¹²<https://www.mymlsa.org/association-web-sites/>.¹³https://www.dnr.state.mn.us/waters/watermgmt_section/shoreland/lake-improvement-districts.html.¹⁴<http://macd.org/>.

extirpated from inland glacial lakes despite efforts to increase resilience because of non-climate change stressors (e.g., invasive species, habitat loss) or greater warming than projected. Outreach programs tailored to manage local stakeholder expectations may mitigate the chance

such challenges derail climate change adaptation initiatives (Hunt et al. 2016). For example, conveying uncertainty associated with management actions (i.e., population extirpation despite efforts) and climate models (i.e., all models are inherently wrong; Box 1976) can improve

understanding and acceptance of risk. Highlighting co-benefits to ecosystem and economic health beyond retaining resilience to climate change may also help retain support even if the climate adaptation outcomes are mixed (Sarkar et al. 2018).

Stocking sportfish is usually viewed positively by the public, as it is perceived to be a direct action to improve their angling experience (Arlinghaus 2005, Lorenzen 2014). However, habitat limitations can limit stocking effectiveness (Sass et al. 2017) and user groups may fail to accept the restrictions climate change may put upon a lake fishery (Hunt et al. 2016). Clear communication with local stakeholders before local actions are implemented about the limitations of stocking may be pivotal to managing this conflict.

Case studies and hypothetical examples of regional approaches to climate adaptation

Retaining ecological resilience through the Cisco Refuge Lake Initiative

The Minnesota Department of Natural Resources (MN DNR) Cisco Refuge Lake Initiative is a successful example of retaining ecological resilience through regional planning. The Cisco Initiative was established after researchers determined that a downward trend in cisco relative abundance was the result of seasonal habitat loss driven by increased water temperature and excess nutrient loading (Jacobson et al. 2008a, Jacobson et al. 2008b, Jacobson et al. 2010). A goal of protecting coldwater fish populations in Minnesota lakes was established, with a primary objective of protecting climate change-resilient habitats (Figure 2a). A statewide climate change vulnerability assessment revealed that declines in summer coldwater habitat were likely for the majority of cisco lakes due to a combination of warming climate and depleted dissolved oxygen levels resulting from nutrient loading (Fang et al. 2012, Jiang et al. 2012). Subsequently, the MN DNR identified lakes as climate refuge (Tier 1 and Tier 2) or nonrefuge (Tier 3), based on the combined effects of climate warming and nutrient loading, and took additional steps to identify priority lakes, which could be conceptualized as 4 priority levels (Figure 2a). Top priority (P1) lakes included refuge lakes where current catchment

land use disturbance fell below a threshold associated with elevated phosphorus concentrations, but where lands were not sufficiently protected to ensure that land use would remain undisturbed in the future. P1 lakes were further prioritized based on investment efficiency and projected population growth (Jacobson et al. 2013). A primary approach of preventing new sources of nutrients, sediments, and pollutants to protect water quality has since been focused on P1 lakes.

The Tullibee Lake Watershed Forest Stewardship Project was formed to provide funding to establish conservation easements and update stewardship plans in P1 catchments. By treating coldwater habitat as a regional resource tied to water quality, planners were able to use Minnesota's Clean Water and Outdoor Heritage funds. The MN DNR works with the Board of Water and Soil Resources to target local water and soil conservation districts that establish conservation partnerships with interested landowners (O'Brien 2016). Growing awareness of the Cisco Initiative and the Stewardship Project has also resulted in local stakeholders spearheading adaptation efforts (O'Brien 2016). To date, more than 60 P1 refuge lakes have benefited from conservation actions.

"Thinking outside the lake" has led to another unique funding opportunity; the protection of P1 lakes through the *Deepwater Horizon* oil spill post-disaster settlement. Minnesota conservationists identified common loon (*Gavia immer*) as a migratory species negatively influenced by the oil spill, and the MN DNR received funds to study migratory patterns and contaminant effects on the species (Henderson 2017). Ongoing research by MN DNR Fisheries and US Geological Survey researchers documented aggregates of common loons foraging on cisco in the fall before their migration to the Gulf of Mexico. As a result, the purchase of easements and shoreline management restoration to improve habitat and water quality in cisco refuge lakes were among primary tasks in a settlement plan that may result in about \$39 million for common loon conservation in Minnesota lakes (Baker and Henderson 2017).

A hypothetical approach to retaining resilient walleye fisheries

Walleye are culturally and economically valuable in the glacial lakes region, and widespread

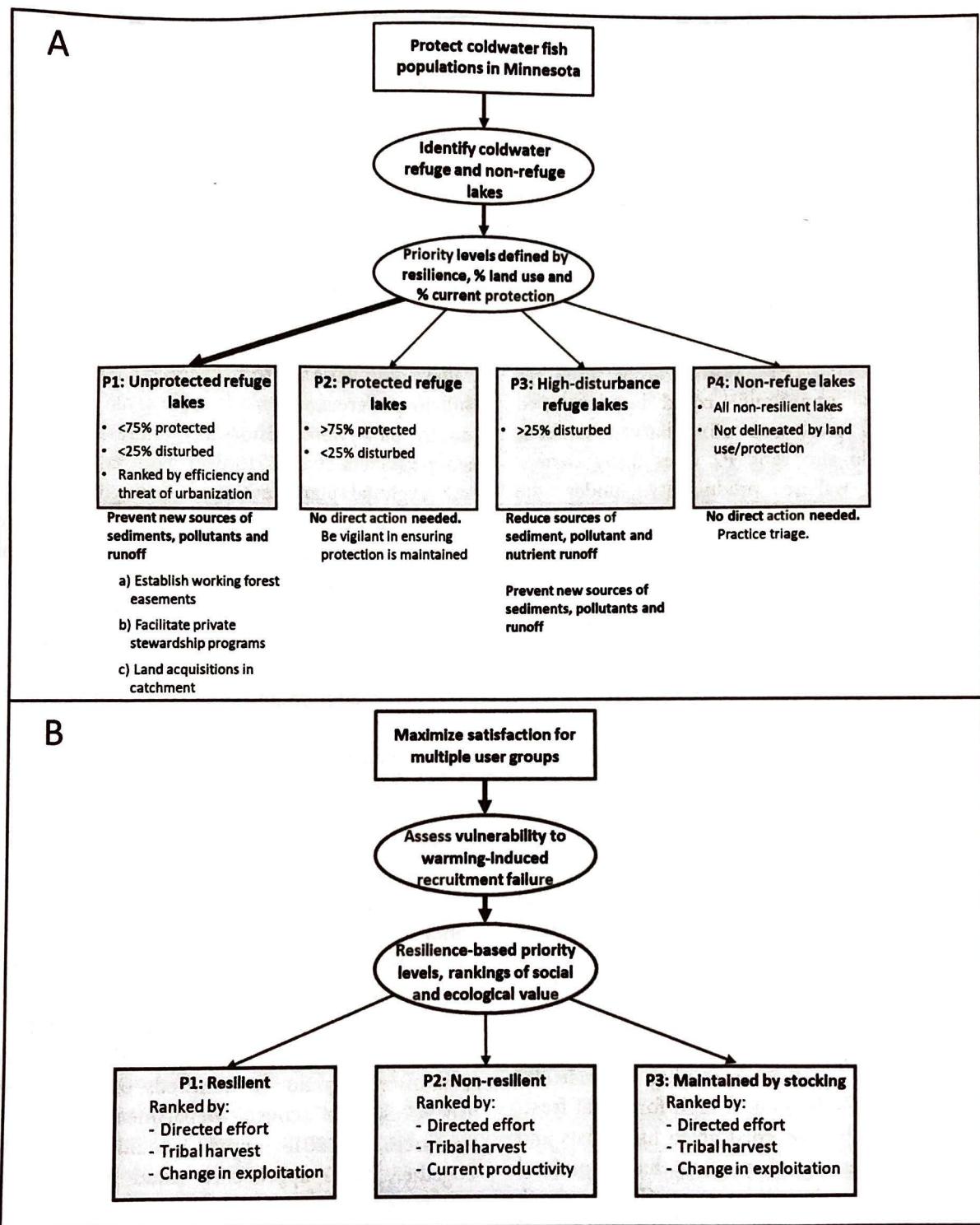


Figure 2. Application of the prioritization approach to inland glacial lakes for (a) the Minnesota Cisco Refuge Lake Initiative (approaches and actions for priority levels are shown) and (b) a hypothetical example of promoting recreational fisheries resilience for inland glacial lakes walleye fisheries.

natural recruitment failure projected under warmer conditions may threaten many fisheries (Hansen et al. 2017). Although other stressors

have likely contributed to observed recruitment declines (Rypel et al. 2019, Embke et al. forthcoming), developing a regional plan could

provide guidance on what steps to take now, or in the future, to adapt fisheries management to these changes. In this scenario, a regional goal of maximizing satisfaction for multiple user groups could be established, with retaining high-value walleye fisheries and protecting resilient populations the underlying objectives (Figure 2b). A vulnerability assessment using modeled current and projected natural recruitment success combined with existing stocking records could be used to generate 3 lake-priority levels: resilient (P1), nonresilient (P2), and populations maintained by stocking (P3). Within levels, rankings of recreational importance could be developed using existing creel and tribal harvest datasets. Planners would also rank P2 lakes using current estimates of walleye productivity, under the assumption that highly productive lakes are more likely to retain quality fisheries when stocking is the primary recruitment source. A metric of risk of increased exploitation could be developed for P1 and P3 lakes based on nearby recruitment failures (e.g., total area of lost walleye fisheries within 30 miles of a lake). Planners may recognize the limitations of this simplistic approach to assessing increased exploitation, and the generation of a site-choice model to assess how shifts in effort may occur with changing conditions (e.g., Ahn et al. 2000, Parsons et al. 2009, Melstrom et al. 2015) could be identified as a future research need.

Following prioritization, planners would still need to identify appropriate actions to support a regional goal and address aspects of uncertainty. A reduced set of actions for each priority level could be established by first eliminating those with higher risk or uncertainty. For example, the construction of artificial spawning reefs in P2 lakes would likely be ranked high for social feasibility, but may be discarded given high costs and evidence suggesting they may have minimal impacts on recruitment success (Bozek et al. 2011). Remaining actions could then be classified as those that could be implemented now and as change is realized. For instance, the protection of littoral habitat in high-value P1 lakes through partnerships with local governments could be implemented in the near future, while the adjustment of harvest regulations could be identified as an important approach if surrounding natural

recruiting populations are lost. Finally, uncertainty in the underlying mechanism resulting in change could be addressed by bounding potential futures based on alternative hypotheses. It appears that largemouth bass *Micropterus salmoides* populations will likely expand in the coming decades regardless of the underlying mechanism driving declines in walleye recruitment (Hansen et al. 2015a, Hansen et al. 2017). Therefore, outreach efforts that highlight largemouth bass as a desirable harvest species could improve user satisfaction and protect resilient walleye populations from overexploitation, and a shift in preference seems feasible given that largemouth bass were historically more valued for harvest (Gaeta et al. 2013, Isermann et al. 2013).

A regional plan developed through the steps outlined in the preceding could provide guidance on where and what actions support the regional goal, but planners may recognize that adjustments to priority levels and rankings may be needed as actual change is realized. They could determine that clear communication about uncertainty may help mitigate conflict, and begin to develop mechanisms for conveying this information to managers, decision makers, and the public. Additionally, planners could determine that any transitional actions selected, such as not implementing stocking in P2 lakes as loss is realized, would be widely unpopular. To address this issue, they could identify ways to convey the limitations of working against emerging ecological constraints to local stakeholders. For example, demonstrating that stocked lakes are unlikely to retain catch and harvest rates close to natural recruiting systems (Nate et al. 2000) or that costs-to-creel could be hundreds of dollars per fish (G. Sass, Wisconsin Department of Natural Resources, Jan 2018, unpubl.) could be valuable. Together, these approaches could help prevent the regional plan from being abandoned as change is realized.

Conclusions

A regional perspective on adapting inland glacial lakes fisheries management to climate change begins with the definition of a clear regional goal and an assessment of vulnerability, which frames

adaptation in an achievable context and can stimulate discussion on needed action with partners. Prioritization of lakes can then provide a template for identifying actions that range over a spectrum of adaptation options from resisting to responding to change when it is inevitable (Millar et al. 2007). Such an approach has already been implemented to promote the resilience of Minnesota cisco lakes, and the Cisco Initiative demonstrates that having regional plans readily available can help secure alternative funding and take advantage of unanticipated opportunities. When applied to questions of recreational fisheries management that may require a range of actions over many years, regional planning can set the stage for progress toward adapting management to climate change despite known and unknown uncertainties.

We acknowledge that regional planning could require collaboration across political boundaries and may be challenging. However, the processes described here are meant to provide guidance at the regional scale and we anticipate that actions would be tailored to local needs and existing political structures. Such an approach could be perceived as unlikely to result in action due to lack of enforcement or regulatory strength, but we note the success of a similarly structured multistate conservation plan, the Southeast Conservation Adaptation Strategy, which has informed more than \$21 million in conservation funding to date (<http://secassoutheast.org>). However, there are ways to strengthen partnerships across political boundaries under appropriate circumstances (i.e., in support of adaptive management plans), such as formalizing communication through deliverables or cooperative agreements (Midway et al. 2016).

We also acknowledge that regional projects and adaptive management approaches are more likely to fail without strong leadership from single individuals (Walters 2007, Midway et al. 2016). As adaptation plans may occur over several decades, it will be unlikely for single individuals to lead efforts through to fruition. However, we note that the Cisco Initiative has been successful because a dedicated set of individuals from multiple agencies has continued to prioritize the regional plan. Identifying and nurturing these extraordinary individuals is identified as the

most important step to successful adaptive management (Walters 2007), and adapting inland glacial lakes fisheries management to climate change is likely no different. However, finding ways to generate momentum for adaptation efforts so they gain traction and are integrated into management systems, for example, through the advertisement of short-term success, may be the best opportunity to ensure continued implementation.

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