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Healing Ogaa (Walleye *Sander vitreus*) Waters: Lessons and Future Directions for Inland Fisheries Rehabilitation

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ABSTRACT
Culturally, economically, and nutritionally valuable inland fisheries face many new challenges on top of chronic disturbances. In the upper midwestern United States, declines in cool- and coldwater fisheries have been observed, including ogaa/walleye *Sander vitreus*. In response to population declines, agencies have implemented rehabilitation efforts, and the frequency and intensity of efforts have increased recently given declines. Evaluating intervention outcomes is critical for institutional learning and to understand strategy effectiveness, but is difficult to do when multiple interventions are applied concurrently and in the absence of replication or controls. This review documents walleye rehabilitation efforts in the upper Midwest U.S., where a rehabilitation effort was defined as a coordinated effort with the stated intention to restore a self-sustaining population such that it required limited-to-no further intervention. We discuss: (1) strategies used; (2) similarities and differences in metrics of success; (3) factors leading to success; and (4) recommendations that may increase future successful rehabilitation. Strategies included harvest regulation changes, stocking, fish community manipulations, habitat enhancement, and partner discussions. Overall, evaluations of environmental, habitat, and fish community factors causing walleye population declines were not included in most rehabilitation plans before implementation. This review highlights an increased need for ecosystem-based fisheries management principles and cultivating ecological conditions that favor walleye as a potential path for future rehabilitation plans. Lessons drawn from rehabilitation plans are applicable to global inland fisheries to inform the conservation of declining fish populations.

KEYWORDS
Climate adaptation; adaptive management; ecosystem-based management

Introduction

Inland fisheries rehabilitation

Inland fisheries provide important ecosystem services to individuals, societies, and the environment (Lynch, Cooke, et al. 2016). For centuries, humans in North America have practiced stewardship of these fisheries through indigenous practices, such as allowing lakes to rest, and management approaches, such as stocking (Reid et al. 2021). Although human management of fisheries is not new, many fisheries face new challenges due to climate change, land use shifts, and non-native beings, resulting in declines in some fish populations (Lynch, Myers, et al. 2016; Reid et al. 2019). Management responses to fisheries decline typically focus on regulatory changes, stocking, and, sometimes, habitat modifications, although these reactive measures may not fully address underlying factors beyond direct managerial control, such as climate change and habitat loss (Feiner, Shultz, et al. 2022). Nonetheless, local management actions can influence system responses to global change drivers (Carpenter et al. 2017). Critical to improving future outcomes is the systematic documentation and evaluation of these management interventions (Hilborn and Walters 1992). Evaluation is even more important under conditions of rapid change, as the effectiveness of management actions in the past may not necessarily predict future effectiveness. Given anticipated challenges that could further negatively influence inland

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fisheries, there is a critical need to understand which management strategies are most effective and under which conditions.

Multiple factors contribute to the challenge of stopping or reversing declines in fish populations. Human behavior in response to changing environments and associated management responses is inherently unpredictable, leading to unexpected responses in effort and harvest to new regulations (Hunt et al. 2011; Allen et al. 2013; Cooke and Murchie 2015; Kaemingk et al. 2019). Fisheries data, when available, may fail to detect declines in harvested populations due to many factors, such as hyperstability in catch rates (Ward et al. 2013; Dassow et al. 2020). These dynamics make it difficult to protect fisheries and to allow fish populations to heal after trauma or changes in the ecosystem, despite some success stories (Logsdon et al. 2016; Jeanson et al. 2021; Cahill et al. 2022; Radomski 2022). There is a growing consensus on the need for coordinated, adaptive approaches to fishery rehabilitation (e.g., Cowx and Gerdeaux 2004; Paukert et al. 2016; Radinger et al. 2023). Rehabilitation plans encompass diverse strategies but share the common goal of achieving self-sustaining fish populations that no longer require intensive intervention (e.g., restoration of natural recruitment to no longer require stocking) and involve some evaluation of population response.

Ogaa/walleye in the upper midwestern United States

In the upper midwestern United States (U.M. U.S.; Michigan, Minnesota, Wisconsin), including ceded territories where tribal nations retain the right to hunt, gather, and fish on off-reservation lands and waterbodies (U.S. Department of Interior 1993, 2019), declines in coolwater and coldwater fisheries have been observed (Hansen et al. 2015; Embke et al. 2019; Renik et al. 2020; Shultz et al. 2022; Feiner, Shultz, et al. 2022). Ogaa/walleye *Sander vitreus* populations support culturally, economically, and recreationally important fisheries (U.S. Department of the Interior 1993). Over time, walleye natural recruitment, adult abundance, and productivity have declined in the U.M. U.S. (Hansen et al. 2015; Rypel et al. 2018). Factors implicated include climate change, habitat loss, shifts in fish community composition (including non-native species), production overharvest (overfishing), and angler behaviors (Mercado-Silva et al. 2007; Hansen et al. 2015; Sass et al. 2017; Embke et al. 2019; Sikora et al. 2021; Broda et al. 2022; Embke et al. 2022). Walleye fisheries are generally harvest-oriented; therefore, their decline represents a critical cultural and subsistence loss to tribal and recreational fishers in the region (Hansen et al. 2015; Mrnak et al. 2018). Indigenous communities harvest walleye in the spring for consumption, usually with spears and/or nets, and may fish throughout the year for consumptive and non-consumptive purposes, where harvested fish are shared with elders, family, and tribal members or part of ceremonial feasts (Nesper 2002; Shultz et al. 2022). Similarly, many recreational anglers target walleye for consumptive purposes and share their catch with family and friends (Embke et al. 2020). Effective management strategies are therefore crucial to support the cultural, economic, and nutritional values associated with walleye in this region amidst ongoing population declines.

Cultural significance of ogaa/walleye

Indigenous communities may view fisheries as natural gifts, and their interaction with these giigoonyag/fishes as a relationship between equals (Table 1; Reid et al. 2021; Shultz et al. 2022). Reconciling these worldviews adds complexity to co-managed systems, where decisions about fisheries gifts and how to share them among recreational anglers and citizens of sovereign tribal nations must integrate multiple perspectives. Given these complexities, it is valuable for

Table 1. List of beings included in this rehabilitation effort synthesis, with Ojibwe (singular and plural), English, and Latin names.

Ojibwe name (singular)	Ojibwe name (plural)	English name	Latin name
Agwadaashi	Agwadaashiwag	Sunfishes	*Centrarchidae* spp.
Agwadaashi	Agwadaashiwag	Bluegill	*Lepomis macrochirus*
Asaawens	Asaawensag	Yellow perch	*Perca flavescens*
Ashigan	Ashiganag	Largemouth bass	*Micropterus salmoides*
Awaazisii	Awaazisiig	Bullheads	*Ameiurus* spp.
Gidagagwadaashi	Gidagagwadaashiwag	Black crappie	*Pomoxis nigromaculatus*
Maashikinoozhe	Maashkinoozheg	Muskellunge	*Esox masquinongy*
Namebin	Namebinag	White sucker	*Catostomus commersonii*
Namegos	Namegosag	Lake trout	*Salvelinus namaycush*
Odoonibiins	Odoonibiinsag	Cisco/tullibee	*Coregonus artedi*
Ogaa	Ogaawag	Walleye	*Sander vitreus*

All beings are considered swimmers.

practitioners to develop approaches that consider socio-ecological dynamics to support these diverse user groups.

Ogaa/walleye are part of the cultural identity of Anishinaabe (Native Americans of the Great Lakes region also known as Ojibwe and Chippewa) tribes that maintain traditional fishing rights in the ceded territories of the U.M. U.S. (U.S. Department of Interior 1993, 2019). In tribal communities, care of fishes are communal decisions based on the principles of respect, reciprocity, and relationships (Tribal Adaptation Menu Team 2019). The collective care provided to ogaa/walleye involves resisting declines in abundance of their relatives, but also realizing tribal communities may need to adapt to changing environmental conditions (Tribal Adaptation Menu Team 2019; Shultz et al. 2022). Here, Anishinaabe words and phrases have been incorporated to recognize that indigenous knowledge systems contribute to understanding how the environment may be changing, an attempt at two-eyed seeing (i.e., viewing the world through both western and indigenous knowledges and perspectives; Table 1; Reid et al. 2021).

Box 1. *"Anwebimagad zaaga'igan (The lake is resting)"*—Anishinaabe worldview emphasizes healing fisheries through rest.

Anishinaabe people believe that to restore the health of a natural resource or an aquatic ecosystem, one must "*leave it alone and let the Manidoog (spirits) take care of it*." It is believed that the natural environment and its inhabitants are interconnected physically and metaphysically, thus there is a strong understanding of the metaphysical universe that is embedded in the stories, names, songs and traditions of Anishinaabe people. The Anishinaabe language is the foundation of their worldview. In the language are intricate understandings of how the ecosystem functions. Names and descriptors in the language denote how the world is understood through the lens of Anishinaabe philosophy.

Many Anishinaabe people have stated that "Anwebimagad zaaga'igan/The lake needs to rest." This understanding comes from the multi-generational experience of observing the negative influences of harvesting pressures on a particular resource like ogaa/walleye. Within the concept of "S/he is resting" is the notion that a particular non-human being needs to heal to replenish or revitalize himself/herself. Anishinaabe worldview recognizes the inherent ability of non-human beings to heal themselves, whether it be fish, plants, trees, or animal populations.

"Anwebi" is a verb in the Anishinaabe language that means "She or he is resting." This word pertains to animate or living beings. "Ogaa" is the animate noun for walleye, therefore an animate verb is required when referring to this species. Therefore, one would say, "Anwebi ogaa/The walleye is resting." The concept of allowing ecosystems and beings to heal has been part of Anishinaabe practices since time immemorial (Shultz et al. 2022).

Ogaa/walleye rehabilitation and healing

Walleye conservation efforts in response to declines have generally consisted of strategies aimed to maintain historical conditions (Dassow et al. 2022; Embke et al. 2022; Shultz et al. 2022; Feiner, Dugan, et al. 2022). Strategies have included some combination of fishery closure, conservative harvest regulations, stocking, habitat improvement, and fish community manipulations. Considering the co-managed nature of the joint fishery, management has also required compromise among indigenous, recreational angling, and partner groups; for example, through reduced harvest opportunities for all users (Sass et al. 2022; Elwer et al. 2023). These groups have developed coordinated walleye rehabilitation plans for declining populations across the region (Shultz et al. 2022), providing an opportunity to use these fisheries as a model social-ecological system to review rehabilitation efforts efficacy.

Walleye rehabilitation efforts have been a component of this beings' management throughout its history of exploitation (Box 1); however, the frequency and intensity of walleye rehabilitation efforts have increased over time given population declines. To date, the approaches used and their relative effectiveness among rehabilitation efforts have not been evaluated. This review documents case studies (i.e., peer-reviewed and gray literature) of walleye rehabilitation efforts in the U.M. U.S. to discuss: (1) strategies used to rehabilitate walleye populations given a predefined goal of reestablishing natural recruitment; (2) variability in metrics of success associated with walleye rehabilitation plans; (3) factors leading to successful walleye rehabilitation efforts; and (4) recommendations that may lead to successful walleye rehabilitation efforts in the future.

Selection of case studies

For this review, a rehabilitation effort was defined as a coordinated effort with the stated intention to restore a self-sustaining population such that it required limited-to-no further intervention. To identify relevant case studies, a literature search was performed to identify primary and gray literature sources of relevant walleye rehabilitation efforts. Regional fisheries managers at agencies including the Great Lakes Indian Fish and Wildlife Commission (GLIFWC), Minnesota Department of Natural Resources (MN DNR), and Wisconsin Department of Natural Resources (WI DNR) were consulted to identify additional case studies. Each of these institutions manages walleye populations using slightly different methods and goals. For example, MN DNR sometimes uses stocking to a greater extent than WI DNR or GLIFWC.

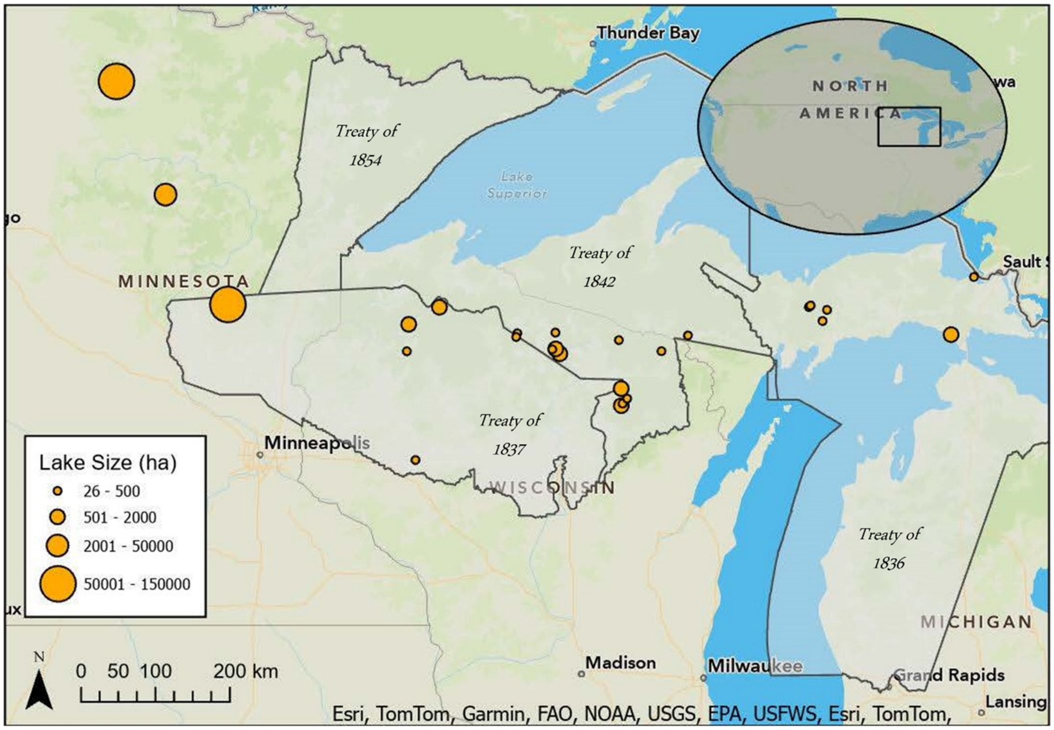

Figure 1. Map of ogaa/walleye (*Sander vitreus*) rehabilitation effort locations in Michigan, Minnesota, Wisconsin shown as orange points. Point size corresponds to lake size (hectares; ha). Indigenous ceded territory boundaries for the Upper Midwest are indicated by black outlines, with the treaty year identified.

This synthesis does not represent an exhaustive list of all possible rehabilitation efforts for walleye throughout their range (Figure 1; NatureServe 2013), nor is it necessarily representative of all individual management actions (e.g., harvest regulation, stocking). Rather, case studies were chosen to be informative of the range of actions taken by coalitions of local, state, tribal, and federal entities to respond to walleye declines in the U.M. U.S., broad evaluation of individual tools was not sought (e.g., stocking, Lawson et al. 2022; harvest management, Beard et al. 2003), but instead the use of these tools was evaluated in the context of larger rehabilitation efforts. The case studies highlighted in this review shared the following characteristics:

1. the ecosystem was a lake or reservoir in the U.M. U.S.
2. the ecosystem historically had a self-sustaining population of walleye that experienced declines in adult abundance and/or natural recruitment.
3. a committee (typically two or more organizations) was convened to review data on the ecosystem; and
4. the ultimate objective of the rehabilitation plan was to minimize/eliminate human intervention in the ecosystem once objectives of the plan were met.

To evaluate rehabilitation efforts, effort location, management actions used, duration, objectives for the walleye fishery, response of the walleye fishery, and whether the effort was considered successful were identified (Table 2). The intent of this review was to determine the traits of walleye rehabilitation plans that met their own benchmarks for successful population rehabilitation. Therefore, the efficacy of each rehabilitation plan was evaluated against the plan's stated rehabilitation goals (e.g., increasing adult walleye abundance above some threshold, restoration of natural recruitment; Table 2). In some cases, assigning success was challenging given unclear initial objectives of the respective rehabilitation plan, but case-specific goals were determined as best as possible.

Evaluating case studies

Walleye rehabilitation efforts spanned numerous approaches, and multiple management strategies were often used concurrently. In total, 26 walleye rehabilitation efforts were identified (Table 2, Figure 1). All case studies were in ceded territories; therefore, all efforts corresponded to shared fisheries. Mean duration of all efforts was 7.5 years, with several efforts still ongoing. All fully successful efforts (i.e., efforts that met their own criteria for success) were initiated

Table 2. Summary of ogaa/walleye (*Sander vitreus*) rehabilitation effort case studies highlighted in this review, where actions were implemented 1978–2023.

Lake	State	Lake size (ha)	Maximum depth (m)	Mean depth (m)	Implementation timeline(s)	Rehabilitation strategies	Ogaa/ walleye goal	Ogaa/walleye response	Successful?
Monocle	MI	60	17	n/a	1978–1991	ST, HAB	NR, AA	NR, AA	Yes
Fish	MI	66	17	n/a	1979–1998	ST, HAB	AA	No change	No
Brevoort	MI	1712	8	n/a	1984–1989	ST, HAB	NR, AA	NR, AA	Yes
Moccasin	MI	32	8	n/a	1990–2000	ST, HAB	NR, AA	NR	No
Thunder	MI	146	6	n/a	1993–1995	ST, HAB	NR	NR	Yes
Steuben	MI	55	19	n/a	1998	ST, HAB	NR, AA	NR, AA	Yes
Leech	MN	41,698	46	6	2005–2014	ST, HR, HAB, FCM, DIS	NR, AA, SS, AC, AH, CF	NR, AA, SS, AC, AH, CF	Yes
Mille Lacs	MN	51,901	13	6	2013–2023	ST, HR, DIS	AA	AA	Yes
Red	MN	114,995	11	n/a	1990s–2006	ST, HR, DIS	NR, AA	NR, AA	Yes
Kentuck	WI	405	12	4	1998–2006	ST, HR, HAB, DIS	NR, AA	NR, AA	Yes
Crane	WI	144	8	4	2012–2014, 2017	FCM, ST	NR, AA	NR, AA	Yes
Metonga	WI	825	24	8	2008–2017	FCM, ST	NR, AA	NR, AA	Yes
Patten	WI	103	16	5	2011, 2016	FCM, ST	NR, AA	NR, AA	Yes
Pickerel	WI	515	6	2	2012, 2014, 2017–2018	FCM, ST	NR, AA	NR, AA	Yes
Howell	WI	69	5	4	2020–2021	FCM, ST, DIS	NR, AA	No change	No
McDermott	WI	33	5	3	2018–2021	FCM, ST, DIS	NR, AA	No change	No
Jungle	WI	73	4	2	2013–2022	FCM, ST, DIS	NR, AA	AA	Partial
Patterson	WI	26	10	5	2009–2020	FCM, ST	NR, AA	NR, AA	Yes
Sparkling	WI	64	18	n/a	2002–2009, 2020–2023	FCM, ST, DIS	NR, AA	AA	Yes
Kawaguesaga	WI	283	13	6	2015–2023	ST, HR, HAB, DIS	NR, AA	AA	Partial
Minocqua	WI	542	18	7	2015–2023	ST, HR, HAB, DIS	NR, AA	AA,	Partial
Tomahawk	WI	1401	26	10	2015–2023	ST, HR, HAB, DIS	NR, AA	AA	Partial
Sand	WI	384	15	6	1996–2006	ST, HR, DIS	NR, AA	NR, AA	Yes
Chippewa	WI	386	9	3	2012–2022	ST, HR, HAB, DIS	NR, JA, AA	NR, JA, AA	Yes
Nelson	WI	1099	10	3	2005–2009	ST, HAB, DIS	AA, SS	No change	No
Namekagon	WI	1172	16	5	2018–2023	ST, HAB, DIS	AA, HAB	AA	Partial

Ogaa/walleye goals and responses included: restablish/increase natural recruitment (NR), increase adult abundance (AA), increase age-0 abundance (JA), increase size structure (SS), increase angler catch rate (AC), increase angler harvest rate (AH), increase condition factor (CF), increase habitat (HAB). Rehabilitation strategy codes included: fish community manipulation (FCM), stocking (ST), harvest regulations (HR), habitat evaluations (HAB), partner discussions (DIS).

before 2013, however, we acknowledge these data are right censored, and newer efforts may need additional time to respond to interventions (Figure 2).

Evaluating rehabilitation success

Forms of evaluating success of a given rehabilitation effort varied widely. Most often, success was determined based on biological metrics, although a few efforts focused on abiotic or social factors. For most rehabilitation efforts evaluated (80%, $n = 21$), success was partially (i.e., some, but not all, objectives were achieved) or completely met. Rehabilitation efforts failed to meet metrics of success for 20% of attempts, many of which were in small (<100 ha) lakes. For some rehabilitation efforts, it was challenging to evaluate effectiveness given unclear objectives set at the start, emphasizing the importance of establishing clear and specific measures of success in rehabilitation efforts.

Management strategies

Dominant management strategies used in rehabilitation efforts included stocking ($n = 26$; 100%) harvest regulation changes ($n = 9$; 35%), fish community manipulations ($n = 10$; 38%), habitat evaluations/modifications ($n = 14$; 54%), and partner discussions ($n = 15$; 58%) (Table 2, Figures 2 and 3). All case studies used a minimum of 2 strategies; most used ~3 strategies and one used all 5 strategies (Box 2, Table 2, Figure 2).

Stocking

The dominant strategy used in all evaluated rehabilitation efforts was the stocking of various lengths of age-0 (lengths of 2.5–20.3 cm) walleye (Sass et al. 2022; Elwer et al. 2023). Unlike put-and-take fisheries, stocking in rehabilitation efforts was meant to increase the number of walleye recruiting to the adult population and ultimately work to restore natural reproduction, despite limited evidence of stocking success broadly (Elwer et al. 2023). The efficacy of rehabilitation plans that used stocking commonly relied on biological metrics of success. Stocking was often used as a tool to supplement populations that have potentially been impacted by overharvest (Sass et al. 2021). Stocking also relied on the assumption that environmental conditions were sufficient to support a

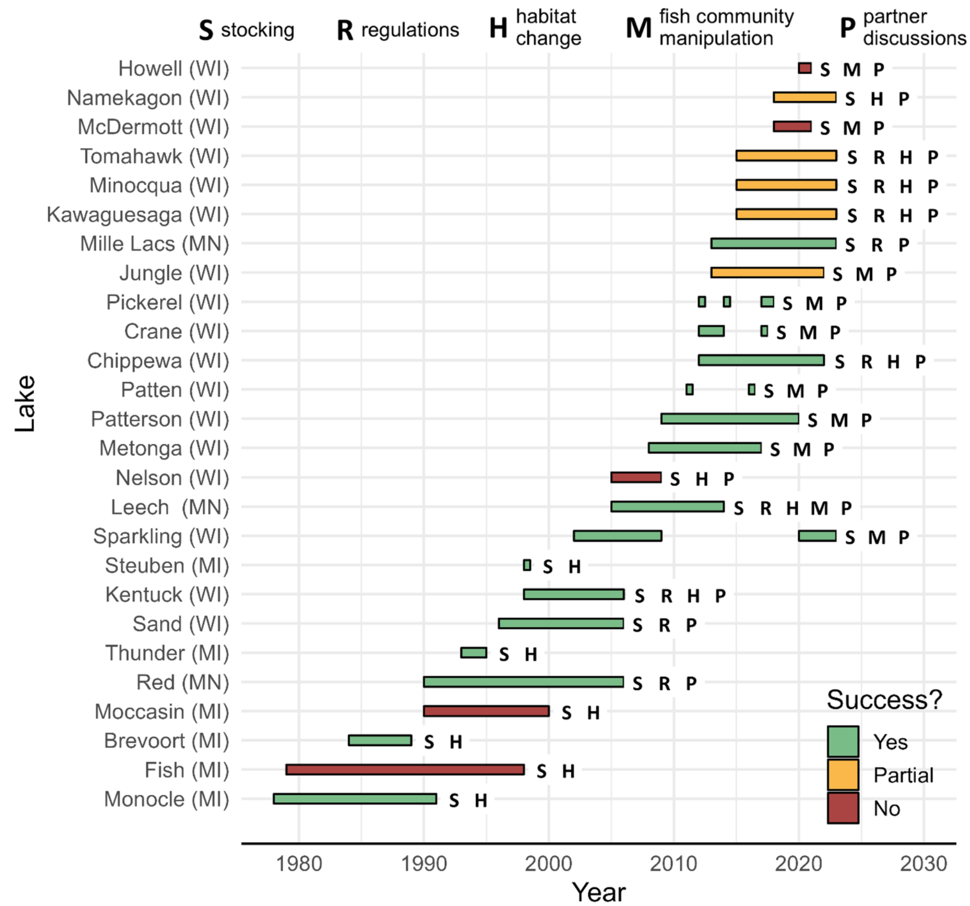

Figure 2. Lake name and plan duration (years) for walleye rehabilitation efforts evaluated in this study. Locations of lakes are shown in parentheses next to names. Effort duration is designated by bar length, with color indicating whether the plan was successful. Letters indicate management strategies used in each effort, including stocking, regulations, habitat change, fish community manipulation, and partner discussions as indicated by the top legend.

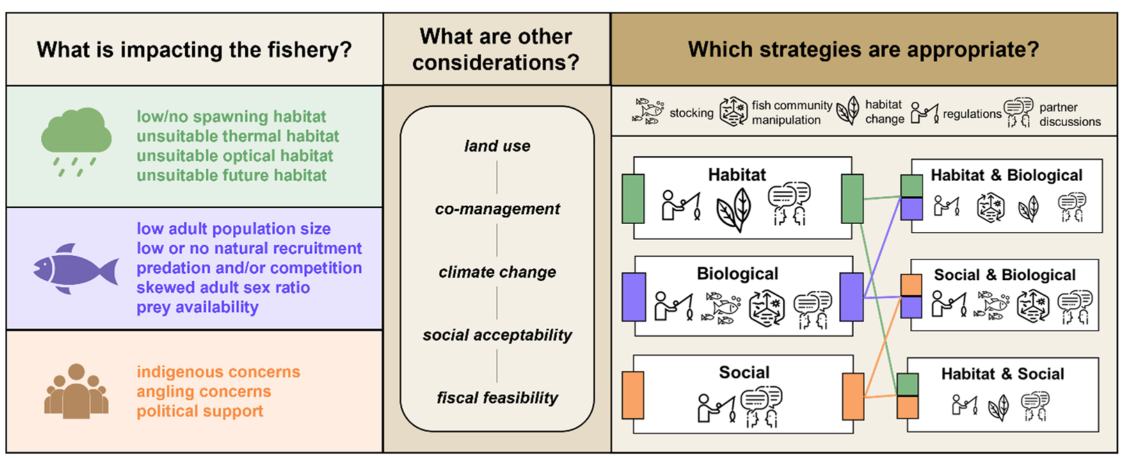

Figure 3. Diagram of approach to fisheries rehabilitation including assessing impacting factors, challenges to rehabilitation, and potential rehabilitation strategies. First need to assess which factors are impacting the fishery, then understand considerations influencing rehabilitation feasibility. Based on these considerations, a practitioner may determine which strategies from may be reasonable for rehabilitation.

self-sustaining population; however, these characteristics were not always identified before plan implementation (see *Identifying the Limits and Setting the Ecological Stage*).

Stocking strategies differed depending on the length of the stocked fish, timing, and frequency of stocking, and stocking density. In Red Lake, MN, he stocking of fry (7–10 mm) proved successful. As part of the

Box 2. A walleye rehabilitation effort case study of all strategies—Leech Lake, MN.

In this review, many rehabilitation efforts used a combination of two or three strategies; however, the rehabilitation of Leech Lake, MN applied all five strategies in conjunction (Pedersen 2020). In the mid-2000s, walleye abundance declined, and a rehabilitation effort was implemented during 2005–2014. Strategies involved a combination of harvest regulations aimed to protect large adults (protected slot length limit 46–66 cm, maximum daily bag limit of 4 fish), predator (double crested cormorant *Phalacrocorax auritus*) control, fry stocking, increased habitat protection, and partner discussions (Pedersen 2020). Prior to and throughout implementation, spawning and thermal habitat was evaluated and found to be suitable. To identify the efficacy of these actions, thresholds across biological, abiotic, and social dimensions were evaluated including adult abundance, female biomass, population size structure, natural recruitment abundance, angler catch rate, anger harvest, and condition factor. Continuous annual monitoring has been in place for Leech Lake, MN since the 1980s, thus allowing this rehabilitation action to be designed in an adaptive management framework. In 2016, thresholds were evaluated with 3-year moving averages, to incorporate temporal variability. In response to these actions, walleye abundance has increased and remained relatively stable since 2007, thus management targets are currently set to maintain conditions (Pedersen 2020). Stocking has not been implemented since 2014. The concurrent use of multiple rehabilitation approaches has proved successful for this walleye population and may provide guidance for additional rehabilitation efforts.

Red Lake rehabilitation plan, fry were stocked at varying levels every year to reach an overall density goal of 2471 fry per littoral ha (combination of wild and stocked fry; Radomski 2022). Initial fry stockings were conducted bi-annually during 1999–2003 at higher rates and then in 2004 and 2005 at lower rates as wild fry production increased (Radomski 2022). Notably, Red Lake exhibited recruitment overfishing and had plenty of suitable spawning habitat (Radomski 2022). These conditions may have made it favorable for successful rehabilitation through stocking and shifted harvest regulations.

As opposed to stocking fry walleye, almost all WI rehabilitation plans used extended growth walleye (stock in Sept–Oct at length of 12.7–20.3 cm) stocking, including the Minocqua Chain of Lakes (Table 2). Most of these rehabilitation plans stocked extended growth fish bi-annually to avoid density-dependent interactions between age-0 and age-1 walleye (Zebro et al. 2022). Small fingerlings in WI were generally stocked at a higher rate than extended growth walleye (i.e., ~86 fish/ha); however, the Kentuck Lake, WI rehabilitation stocked small fingerlings annually at an even higher rate of 124–185 fish/ha. Extensive small fingerling stockings in Kentuck Lake, WI, were part of a short-term successful rehabilitation effort as adult abundance increased and natural recruitment was reestablished (Table 2). In contrast, extended growth walleye stocking in the Minocqua Chain of Lakes has shown some returns to the adult population but these populations have not met natural recruitment rehabilitation goals (Shultz et al. 2022). This was not unexpected as natural mortality of extended growth walleye across northern WI has been found to be >90% for all stocking densities (Elwer et al. 2023), potentially acting as a factor leading to limited success. Overall, small fingerling stockings in Kentuck Lake likely led to some successful natural reproduction, whereas extended growth fingerlings may be underperforming.

Harvest regulations

Harvest regulations were changed or implemented in 35% of case studies in an attempt to reduce adult fishing mortality. These harvest regulations focused on protecting or enhancing the adult population and included minimum length limits, protected no-harvest or limited harvest slot length limits, more conservative daily bag limits, and limited-to-closed harvest periods (e.g., mandatory catch-and-release, gear restrictions). For the rehabilitation efforts that used harvest regulations as a strategy, metrics of success were primarily focused on biological factors (e.g., adult abundance, age-0 abundance); however, fisheries-dependent and social metrics (e.g., angler catch rate, tribal harvest access) were heavily emphasized in partner discussions. Harvest regulation changes were not used in any rehabilitation efforts for lakes <200 ha. Notably, these harvest regulations on case study lakes occurred against a backdrop of state level regulations that have in some cases also shifted to more restrictive measures, such as higher minimum length limits, protected no-harvest slot length limits, and restrictions on harvesting large fish.

In combination with other strategies, all efforts that implemented harvest regulations have been at least partially successful (i.e., at least one, but not all, objective was met; Table 2). For instance, Kentuck Lake, WI, used a highly conservative minimum length limit of 71 cm implemented in 2000, along with a voluntary suspension of tribal harvest during 1998–2004 and various stockings from 1999 to 2001 (Table 2; Kentuck Lake Subcommittee 2005). These efforts successfully increased adult walleye densities and natural recruitment, but further interventions were required after a decade, suggesting unresolved underlying issues.

Length-based regulations may also aim to protect vulnerable populations. Declining walleye populations often shift from male-dominated to female-dominated adult sex ratios (e.g., WI: Kentuck Lake, Minocqua Chain, Sparkling Lake, MN: Mille Lacs; Venturelli et al. 2014; Shultz et al. 2022). Skewed sex ratios toward females is a symptom of long-term recruitment failures without intervention (e.g. stocking) because female walleye longevity is greater than males (Shultz et al. 2022). Increasing minimum length limits may help protect males in these populations, although walleye life history (e.g., broadcast spawner with limited parental care) and spring tribal spearfishing primarily targeting males may limit the effectiveness (Mrnak et al. 2018). Current rehabilitation plans have not prioritized sex ratio rebalancing, though this is being considered for some ongoing efforts including the Minocqua Chain of Lakes, WI (Table 2; Shultz et al. 2022; Minocqua Chain Rehabilitation Working Group, *pers. comm.*). Other length-based regulations (e.g., no more than one fish >71.1 cm in some MN lakes; Wszola et al. 2022), can conserve reproductively important segments of the population where larger females are protected, which may positively influence recruitment through factors like fecundity and egg quality (Serns 1982; Moodie et al. 1989; Henderson et al. 2003; Shaw et al. 2018). Mille Lacs, MN has used a moving harvest slot length limit of 45.7–50.8 cm to protect males and immature females to keep harvest within quotas.

Reducing the daily bag limit for walleye was a common strategy in rehabilitation plans in an attempt to reduce harvest rates. For instance, the daily bag limit was reduced to one walleye in certain Wisconsin lakes (e.g., Kentuck Lake, WI). In Mille Lacs, MN, the daily bag limit has changed from six walleye per day pre-2001 to the current regulation of one walleye per day, occasionally including restricted or closed harvest periods. Although reducing the daily bag limit aims to decrease fishing mortality, it does not directly control total harvest since angler effort is unregulated in open access fisheries. Increased angler effort or catchability can negate the effects of these daily bag limits (see Feiner et al. 2020). Therefore, to effectively reduce harvest and boost adult densities, regulations may need to be highly restrictive, considering the interactions between angler effort, catch rate, and harvest at lower adult densities.

In some cases, rehabilitation efforts involved closing fisheries completely to harvest. This can relieve populations from exploitation pressure provided there is little-to-no illegal harvest and post-release mortality is at a minimum (Sullivan 2002). Red Lake, MN provided an example of such an approach, as it included a suspension of the commercial and recreational walleye fisheries in 1997 and 1998, respectively (Logsdon et al. 2016; Radomski 2022). The suspension of the walleye fishery on Red Lake, MN in conjunction with additional rehabilitation efforts (i.e., stocking) was considered a success as adult abundance and natural recruitment increased (Table 2). The walleye population was declared fully recovered in 2009 and the commercial and recreational fisheries were reopened (Radomski 2022). To date, Red Lake, MN remains one of the largest successful walleye rehabilitation efforts in the region. A similar effort focused on harvest restrictions and stocking in Sand Lake, WI beginning in the 1990s also led to restored natural reproduction and increased adult abundances (Wolter 2023). It is of note that the Red Lake and Sand Lake rehabilitation efforts occurred primarily in the 1990s when environmental conditions were likely different than present given changes in land use and climate change over time.

Another rehabilitation effort on the Minocqua Chain of Lakes, WI suspended recreational harvest for an initial period of five years (2015–2020), and in conjunction with stocking efforts, resulted in increased adult abundances (Table 2; Shultz et al. 2022). However, this closure was extended through 2025 because natural reproduction had not met rehabilitation goals (Shultz et al. 2022). In many walleye rehabilitation efforts that have included lakes with joint tribal and recreational fisheries, tribal fishers have voluntarily suspended or reduced harvest even in the absence of a moratorium on the recreational fishery (e.g., Kentuck Lake, WI). These efforts allowed for alleviation of harvest mortality from one primary user group while the recreational fishery remained open, albeit managed more conservatively after regulation changes.

The Mille Lacs, MN rehabilitation plan was based on four principles prioritizing reduced mortality: (1) no harvest of juvenile fish; (2) allow fish to reproduce at least once before harvest; (3) protect older and larger females; and (4) maintain adult biomass above lowest observed levels (Myers and Mertz 1998; Froese 2004). Various regulations have been used over the years to manage harvest in Mille Lacs, MN, including reduced annual angler and Tribal harvest quotas and closed seasons. Since 2016, the recreational fishery has sometimes been closed to harvest during part of the open water season and to all walleye fishing (including catch-and-release) for part of the year to minimize mortality. The MN DNR has also implemented length restrictions, night angling bans, and bait restrictions to reduce fishing mortality. Bait restrictions, though uncommon in walleye rehabilitation efforts, have proven effective in lowering angler mortality rates by reducing catch rates and hooking mortality and directed walleye angler effort when using artificial bait (Payer et al. 1989; Bailey et al.

2019). These regulations have allowed the co-managed fishery to adapt as needed. Annual regulation changes are aimed at ensuring mortality stays below agreed upon safe harvest levels, with in-season adjustments as necessary, but some anglers and lodge owners initially resisted annual and in-season adjustments in regulations (Page and Radomski 2006). Conservative management following walleye biomass declines in 2014 has relieved harvest pressures, leading to increased adult abundances. The rehabilitation effort was considered successful based on identified metrics (Table 2), although environmental changes suggest the walleye population cannot sustain previous harvest levels (Hansen et al. 2019).

Fish community manipulation

High-effort rehabilitation strategies included targeted removal of potential competitive or predatory fishes. In some WI lakes, native warmwater species (e.g., awaazisiig/bullheads [*Ameiurus* spp.], agwadaashiwag/sunfishes, crappies, black basses [Centrarchidae, *Lepomis* spp., *Pomoxis* spp., *Micropterus* spp.]) were removed, while in others, invasive coldwater species like rainbow smelt *Osmerus mordax* were targeted, where all manipulated lakes supported some level of natural recruitment (Gaeta et al. 2015; Sikora et al. 2021; Embke et al. 2022; Mrnak et al. 2023). Success was measured with biological indicators, for example increases in age-0 relative abundance (index of recruitment) and adult abundance, though results varied (Sikora et al. 2021; Embke et al. 2022).

In five northern WI lakes, bullhead removals led to improved walleye recruitment and stocked walleye survival in four lakes, taking 2–9 years of effort (Sikora et al. 2021). Reduced bullhead abundances in combination with concurrent walleye stocking may have allowed walleye to take over vacated resources or escape bullhead predation or competition (Sikora et al.0.2021). In Jungle Lake, WI, bluegill and largemouth bass removals increased walleye abundance but did not restore natural recruitment (G. Matzke WI DNR, *unpublished data*). In McDermott Lake, WI, despite removing 285,000 sunfishes, no increase in adult or recruiting walleye was observed (Embke et al. 2022). Non-native removals of rainbow smelt were used in Sparkling Lake, WI, along with walleye stocking and reintroducing native odoonibiins/cisco *Coregonus artedi*, led to increased adult walleye abundances and cisco persistence (Krueger and Hrabik 2005; Gaeta et al. 2015; Mrnak et al. 2023).

In Patterson Lake, WI, a complex strategy involved removing namebin/white sucker *Catostomus commersonii* and bluegill while stocking multiple namegos/trout (i.e., maazhamegoons/brook trout *Salvelinus fontinalis*, namegos/brown trout *Salmo trutta*, rainbow trout *Oncorhynchus mykiss*) (note: brown and rainbow trout are not native to WI) annually and walleye for four years leading to increased adult walleye abundances and natural recruitment (CNNF Fisheries USDA 2020). Food web dynamics may have shifted in direct and indirect ways to result in increased walleye. Directly, trout may have provided an important prey base for walleye. Indirectly, decreased abundances of white sucker and bluegill may have reduced competitive pressure on walleye. Replacing prey that compete and/or eat walleye eggs or juveniles (e.g., white suckers and bluegill) with prey that may have fewer adverse interactions (e.g., trout) may present novel rehabilitation options in the future (Walters and Kitchell 2001). It is important to note that habitat may have played a role in the efficacy of this rehabilitation strategy as the lake was relatively deep (10.5 m) and provided sufficient oxythermal habitat to support warmwater and coldwater fisheries (Rypel et al. 2019).

Habitat modification

Various forms of habitat evaluation, modification, and enhancement were part of walleye rehabilitation efforts including adding physical structure or changing water levels (Tingley et al. 2019; Feiner, Shultz, et al. 2022). The most common case of direct habitat enhancement was the addition of artificial reef structures to increase spawning habitat and natural recruitment. The Minocqua Chain of Lakes, WI rehabilitation added rock to a known spawning reef, in combination with other non-habitat approaches (harvest restrictions, stocking). Walleye were observed using the enhanced reef during the spawning season, but little to no improvement has been documented in natural recruitment (i.e., relative abundance of age-0 walleye in fall; Shultz et al. 2022). Similarly, spawning reefs were added to six lakes in the Hiawatha National Forest, MI (Brevoort, Fish, Moccasin, Monocle, Steuben, Thunder) to increase walleye spawning habitat and recruitment (U.S. Forest Service, *pers. comm.*). Before the reef addition, these lakes were thought to have little-to-no natural walleye recruitment. Based on post-habitat-addition surveys, managers deemed four of the six lake rehabilitation projects successful, with one or more strong year classes within 5 years of reef construction. The two unsuccessful rehabilitation projects may have been limited in efficacy due to a low number of adult individuals in each lake. Implementers of artificial reef rehabilitation efforts emphasized that long-term effectiveness of reefs (e.g., restoration of natural recruitment and increased adult walleye abundance) was influenced by lake level and the relative abundance of competitor or predator beings (U.S. Forest Service, *pers. comm.*).

Other efforts aimed to rehabilitate walleye by improving ecosystem habitat, including riparian habitat and in-lake coarse woody habitat. The restoration plan for Namekagon Lake, WI emphasized the importance of habitat restoration by explicitly stating increased fish habitat and protected water quality as an objective, which has led to increased adult abundances (Table 2; M. Luehring GLIFWC, *pers. comm.*). An alternative approach to bolstering habitat was used in the Chippewa Flowage, WI and Nelson Lake, WI with contrasting outcomes. As water levels in these systems are regulated, practitioners used targeted water level fluctuations to reintroduce seasonal variability to water levels to mimic natural patterns more closely. Practitioners hypothesized that reinstating winter drawdowns could lead to multiple benefits for walleye recruitment including aeration of spawning substrates, de-vegetation of shallow habitat used for walleye spawning and competitor habitat, and creation of unfavorable winter habitat for competitors (e.g., largemouth bass). Both waterbodies were also stocked with extended growth fingerlings biannually or annually, respectively. In the Chippewa Flowage, WI altered water levels over 10 years led to a successful restoration where years with a restored drawdown produced walleye year classes that were twice as large, on average, as years without a fluctuation (Table 2; M. Wolter WDNR, *unpublished data*). No change in the walleye population was observed in a shorter-term (5 years) effort in Nelson Lake, WI (Table 2; Pratt and Neuswanger 2004).

Partner discussions

In co-managed and very popular fisheries, incorporating multiple perspectives can be beneficial to ensuring rehabilitation efforts meet the needs of diverse user groups, however, partnership efficacy can depend on several factors, such as governance structures, cultural compatibility, and the political environment (Bamzai-Dodson et al. 2021). Most rehabilitation efforts that used partner discussions were at least partially successful (Table 2). Partners included local communities (e.g., homeowners on a given waterbody), tribal nations, intertribal agencies (e.g., GLIFWC), state agencies, non-governmental organizations (e.g., Walleyes for Tomorrow), and federal agencies (e.g., U.S. Fish and Wildlife Service). For some of the strategies, including stocking policies or harvest regulations, partner discussions were commonly formalized through workshops and structured processes. Even with other strategies, such as fish community manipulations or habitat evaluation where partnerships may have been less formal, continuous discussions were critical to garner public support, interest, and feasibility of an intervention effort. Inland fisheries are social-ecological systems, therefore partnerships between communities of use and practitioners can be valuable to determine palatable, effective, and feasible rehabilitation approaches. Exploring structured decision-making tenets and decision support tools in future walleye rehabilitation efforts may be a productive framework for incorporating diverse user groups and partner engagement to increase the probability of rehabilitation success (Dassow et al. 2022; Lynch et al. 2022).

Discussion

This review undertook a wide-ranging survey of cooperative walleye rehabilitation efforts across the U.M. U.S. with the goal of identifying commonalities in successful plans. Most walleye rehabilitation efforts have hinged on a strategy of increased walleye stocking, while fewer have approached reduced walleye harvest, or fish community manipulations, or habitat modifications. All efforts involved varying degrees of partner discussions to inform intervention strategies. The results of these efforts, particularly for plans implemented in the 1990s and early 2000s, were often at least partially successful (80% of plans were considered successful by their own metrics), and a few commonalities of successful plans were apparent. Below, this review synthesizes this information into discrete lessons to inform future walleye management in the face of widespread population declines, identifies barriers to the development and implementation of successful walleye rehabilitation efforts, and identifies a potential path forward founded on the principles of ecosystem-based fisheries management.

Management strategies used in rehabilitation

All case studies used stocking in combination with one or more other strategies including harvest regulations, habitat modifications, food web manipulations, and partner discussions. Stocking was the most pervasive response to declining or failing walleye natural recruitment. In most cases, the goal of stocking was to reestablish natural recruitment by increasing the abundance of adult fish in the population. Overall, stocking had mixed results in rehabilitation efforts. Stocking was effective when combined with other rehabilitation strategies (e.g., fishery closures, fish community manipulations; Table 2), but when used in isolation had limited success. Stocking efforts before 2013 in larger (>100 ha) lakes, along with harvest reductions or ecosystem alterations (e.g., food web manipulation, habitat enhancement), increased the likelihood of successfully rehabilitating walleye. Since 2013, stocking has increased adult abundance, but natural recruitment has not been reestablished in many recent efforts. Thus, suitable conditions for all life stages may be a prerequisite for stocking effectiveness to meet rehabilitation objectives where changing environmental conditions (e.g., warming waters, altered fish communities, shoreline development) may limit the effectiveness of stocking as a rehabilitative tool for walleye in this region. Further, stocking success itself has been declining over time (Lawson et al. 2022). Although stocking may be effective in conjunction with other rehabilitation strategies, it comes with many important tradeoffs for consideration, such as cost, negative influences on ecosystems, and skewed sex ratios (Bootsma et al. 2021; Grausgruber and Weber 2021a, 2021b; Sass et al. 2022; Elwer et al. 2023).

Harvest regulations were often included with other strategies, such as stocking, habitat enhancement, and partner discussions, leading to at least partial success (Table 2). Conservative harvest regulations for walleye included increased minimum length limits, protected (no harvest) length limits, reduced daily harvest limits, fishery closures, quotas, or compromises in joint fisheries (e.g., catch-and-release only in angling fishery, harvests reductions or abstaining in tribal fisheries). Acknowledging that harvest regulations were only implemented in larger lakes (>200 ha), which tended to have generally higher rates of success, all rehabilitation efforts that included harvest reductions except one were at least partially successful, indicating that reduced harvest through regulations may be effective to increase adult abundance for waterbodies with suitable habitat (Table 2). Conservative harvest regulations may have failed in walleye rehabilitation efforts for at least three reasons (or any combination): (1) adult abundance was not the limiting factor causing natural recruitment declines; (2) angler effort responses failed to limit harvest in open access fisheries; and (3) changes in fish community composition prevented or delayed reestablishing natural recruitment (i.e., depensation; Walters and Kitchell 2001; Sass et al. 2021; Dassow et al. 2023).

Changing harvest regulations is no small decision given social and political implications. Walleye hold a significant cultural and economic importance for the region, therefore reduced or varied harvest opportunities can cause public concern and infringe on tribal harvest rights. In some cases, maintaining previous harvest levels was not realistic for the population (e.g., Red Lake, MN; Radomski 2022). Less conservative measures including increased minimum length limits, protected no harvest slot length limits, and reduced daily bag limits were sometimes successful when used in conjunction with other rehabilitation strategies (e.g., stocking). More conservative efforts involving full fishery closures, even for a limited time, were most effective in meeting rehabilitation plan metrics of success. Full fishery closures are socially and politically challenging, thus may be seen as a strategy of "last resort" to jumpstart population recovery. Although some efforts limiting harvest opportunities were considered successful for practitioners, it is unclear how "success" may be defined by user groups (e.g., anglers and tribes). Ideally, population changes are identified before major and long-term declines and management can proactively use regulation changes to minimize overfishing and avoid complete closure of the fishery.

Fish community manipulations have been successful for restoring walleye natural recruitment in some cases ($n = 8$ at least partially successful), but not all. Most successful cases took place in larger (>100 ha), deeper (>5 m maximum depth) lakes (Figure 2). Rehabilitation efforts that were conducted in lakes with more deep, cool- and coldwater habitat were more successful (e.g., Leech Lake, MN, Patterson Lake, WI). As documented throughout various rehabilitation approaches, understanding the habitat availability before implementing a rehabilitation strategy was critical to increasing the probability of success.

It is important to consider the timescale in which manipulations were conducted and the monitoring longevity following a manipulation. All successful fish community manipulations were conducted over longer durations (>5 years), while manipulations that were unsuccessful may have been unresponsive due to restricted timescales. Food web changes can take extended periods of time (>5 years) to manifest, therefore appropriate temporal monitoring scales are key to determine manipulation effectiveness (Sass et al. 2019). Additionally, stocking in conjunction with fish removals was important to supplement populations and potentially fill newly available resources left void by fish removals (Mrnak et al. 2023). Although fish community manipulations may be effective in some cases, there are many logistical challenges associated with this rehabilitation strategy. Effort, expense, and social acceptability may be limiting, and the long-term viability and effectiveness are unclear.

Habitat is widely known to influence the potential for fish abundance, growth, and resilience as these conditions set the foundation for available resources for a given population (Sass et al. 2017). Of the 14 case studies that used some level of habitat modification, ~80% were at least partially successful, and fully successful efforts took place in deeper lakes (>5 m) potentially indicating sufficient oxythermal habitat to support warmwater and coldwater fisheries (Figure 2). When the importance of habitat was emphasized over long time periods (i.e., using targeted water level fluctuations for 10 years in Chippewa Flowage, WI), restoration efforts proved successful. In combination with food web manipulations (see above), these results demonstrate that habitat considerations may not be restricted to structural and spawning habitat needs but also to fish community characteristics, forage considerations, and physio-chemical properties of waterbodies (Sass et al. 2017; Raabe et al. 2020). For example, increased water clarity in Mille Lacs, MN, resulted in lower safe harvest limits than would be possible under previous environmental conditions (Hansen et al. 2019). In a changing climate, abiotic conditions are shifting broadly but these factors may be beyond the control of local managers (Carpenter et al. 2017). Understanding which systems may have limited habitat for walleye, especially given climate change, represents a foundation for determining the feasibility of rehabilitation strategies. This review suggests that proactive research to identify factors limiting different walleye life stages may lead to more informed rehabilitation plans with a greater probability of successfully restoring natural recruitment. In association with this proactive research, the probability of walleye rehabilitation success may also be improved by "setting the ecological stage" before management intervention.

Evaluation of rehabilitation

Regardless of the strategy used in each rehabilitation effort, approaches that incorporated adaptive management and/or structured evaluations were generally more successful. Predetermined evaluation measures allowed practitioners to shift strategies, thus supporting the fishery more effectively. The success of rehabilitation plans was evaluated using their own reported metrics of success; however, evaluation was challenging when evaluation criteria were not established before implementation. Metrics of success varied among plans with an emphasis on biological factors, such as increases in adult abundance or natural recruitment (Table 2). Two successful cases incorporated habitat or social satisfaction objectives (Leech Lake, MN, Namekagon Lake, WI), potentially indicating the wider considerations for the effort leading to success (Table 2).

For most efforts relying on biological objectives, they assumed an increase in population metrics (e.g., adult density) would satisfy social needs (e.g., availability of a harvestable population to support tribal rights and angler desires). The timeframe and rehabilitation approach may greatly affect whether ecological success leads to social success. Moreover, fisher dynamics like hyperstable relationships between walleye abundance and angler and tribal harvest rates may lead to decoupled perceptions of walleye recovery between fisheries-independent samples and walleye fisher experience, dampening the social value of walleye rehabilitations (Mrnak et al. 2018). Lastly, few plans plainly stated fisher-oriented objectives, such as targeted catch per unit effort or harvest in recreational fisheries (but see Leech Lake, MN; Box 2). Although it was implied that the goal was a sustainable, naturally recruiting fishery that could withstand some level of angling and harvest pressure, the lack of these explicit goals made it difficult to assess how many rehabilitation attempts provided desired outcomes for fishers. Incorporating goals for success that consider the long-term social desires of people interested in accessing recovered fisheries could improve expectations for rehabilitation outcomes among rightsholders/stakeholders while ensuring that managers are taking steps toward providing desired, long-term sustainable fisheries.

Comprehensive evaluation of rehabilitation efficacy often requires a complex of factors, including quantifiable metrics of success, replications, reference systems, and continued monitoring (Hansen et al. 2015). Very few rehabilitation efforts had comprehensive evaluations established, therefore it was challenging to discern whether efforts were effective. Management agencies may not be well positioned to learn whether and why actions work given the frequency of regulation changes, lack of clear objectives, lack of monitoring and evaluation, lack of reference systems and replication, high levels of process and measurement error, and the rapid pace of environmental change

(Hilborn and Walters 1992). Adaptive management offers a framework to learn while implementing rehabilitation actions (Williams 2011).

Lessons learned

Identifying the limits and setting the ecological stage

Restoring walleye populations is complex and depends on the mix of strategies and the specific dynamics of each population. Key to a successful rehabilitation plan was identifying the limiting factors for walleye recruitment, which can be abiotic (e.g., unsuitable thermal or spawning habitats), biotic (e.g., predation, competition, prey availability), or social (e.g., recreational or indigenous fishing concerns). For example, in Red Lake, MN, the cause of walleye decline was linked to recruitment overfishing, and therefore removing fishing mortality through harvest closures led to success (Radomski 2022). Often, multiple interacting factors were involved, such as in Leech Lake, MN, where habitat, harvest, and bird predation were addressed with multiple strategies (Box 1).

Identifying limiting factors is crucial for effective rehabilitation plans. A recurring issue was the lack of comprehensive habitat, fish community, and fishery evaluations before implementing management actions (but see Sikora et al. 2021; Embke et al. 2022). Identifying limiting factors and providing timely rehabilitation interventions presents a challenging balance for managers. This challenge is further complicated without established evaluation criteria (e.g., monitoring, reference systems; see more *Evaluation*). In many cases for walleye, natural recruitment was no longer occurring, making it difficult for managers to determine which life stage was limiting and the cause of such change. Timely intervention is critical: if a manager takes extended periods of time (>5 years) to determine a limiting mechanism, the abundance of adult fish may decline such that future rehabilitation efforts are no longer effective. Consistent evaluation and urgency need to be balanced to support the most effective rehabilitation efforts in the long-term. Structured processes, such as adaptive management and the resist-accept-direct framework in combination with early warning signals may allow for increased time to make and evaluate decisions (see more in *Evaluation;* Lynch et al. 2021; Dassow et al. 2022).

Proactive research on stocking considerations, risks, and goals preceding the initiation of stocking may lead to more successful outcomes. If stocking is deemed necessary, it may be conducted using the best available science (hatchery product, genetic management) and with consideration of other potential limiting and confounding factors (Figure 3). Stocking and harvest regulations can serve as triage to larger biotic or abiotic limitations on walleye populations, with their seeming (and at times mostly hypothetical; Lawson et al. 2022) short-term benefits becoming self-reinforcing through information feedbacks in these social-ecological systems (van Poorten et al. 2011; Arlinghaus et al. 2022; Radinger et al. 2023). This in turn can perpetuate unintended effects of common rehabilitation techniques (e.g., stocking) in fisheries and lead to the persistence of high fisher, partner, and management agency support despite underwhelming outcomes (Arlinghaus et al. 2022; Radinger et al. 2023).

Walleye rehabilitation efforts were generally prompted by long-term declines in natural recruitment and persistent recruitment failures in previously self-sustaining populations. Successful rehabilitation hinges on developing hypotheses for these failures and identifying manageable factors to mitigate current limitations to "set the ecological stage." This may involve determining if reestablishing natural recruitment is achievable under current and future conditions, whether limitations can be managed effectively, and assessing factors limiting recruitment. For example, in Red Lake, MN, intense fisher participation, harvest compromises, and stocking led to a resurgence in natural recruitment by addressing overharvesting (Radomski 2022). In Patten Lake, WI, removing overabundant bullheads in conjunction with walleye stocking addressed potential competition and predation issues (Sikora et al. 2021). However, limitations may not be singular. In Leech Lake, MN, multiple limiting factors and thus rehabilitation strategies were identified. In each of these cases, limiting factors were within managerial control and allowed for successful population rehabilitation. Historically, rehabilitation plans seldom incorporated comprehensive assessments of habitat, food web effects, and multi-species fisheries with competing management goals. Common techniques like stocking alone often fail to restore long-term recruitment, indicating they do not address the root causes limiting natural recruitment. Given the labor-intensive and costly nature of walleye rehabilitation, investing additional time and effort to set the ecological stage is warranted. This includes establishing early warning signal benchmarks for recruitment issues and conducting directed research to understand and address limiting factors, such as habitat availability. Integrating these insights with common techniques, such as harvest regulations, may increase rehabilitation success.

Considerations for rehabilitation

Time for expected outcomes

Because walleye are long-lived beings (~20 years) and recruitment is unpredictable and often influenced by variable environmental and habitat conditions, immediate responses to intervention are unlikely. Long-term and persistent outcomes may be more favorable by first setting the ecological stage for success by identifying limiting factors and considering alternative restoration approaches, rather than immediate, reactive use of stocking and harvest regulations alone. A strong natural recruitment event every 4–5 years is relatively common in naturally recruiting walleye populations that are harvested (Hansen et al. 1998); however, populations are increasingly taking 1–2 years longer to regenerate given myriad factors (Embke et al. 2019). Clearly acknowledging the long timeline it may take to experience rehabilitation results (10+ years in some cases, Table 2) may assist in setting expectations for rightsholders/stakeholders as well as prioritize management effort.

Shifting baselines in the efficacy of old methods

Shifting environmental conditions are not favoring the persistence of walleye in some lakes, and the ability to resist those changes may become increasingly challenging (Feiner, Shultz, et al. 2022). Many walleye rehabilitation plans were recently initiated, highlighting a greater frequency of responses to declining walleye populations over time (Table 2, Figure 2). Non-stationary temporal dynamics in walleye habitat and population dynamics could be decreasing the viability of commonly used rehabilitation strategies for future use. Indeed, the increasing number of recent, ongoing walleye rehabilitation efforts may support this hypothesis. Lake temperatures are continuing to warm, and warming lakes are projected to experience reduced recruitment success (Hansen et al. 2017). In addition to declining coolwater habitats, earlier spring ice off may lead to earlier walleye spawning (Schneider et al. 2010), which can increase trophic mismatches between juvenile walleye and their prey, reducing survival (Feiner, Dugan, et al. 2022; Barta et al. 2024). The interactions between environmental and trophic stressors appears to have led to declining productivity in walleye populations (Rypel et al. 2018), reducing their ability to withstand historical harvest pressure (Embke et al. 2019). Actions taken during past successful rehabilitations may be less effective in the face of this new suite of walleye population stresses. In Wisconsin, survival of stocked fish has declined over time along with declines in natural recruitment (Lawson et al. 2022). These dynamics challenge biologists to set expectations when implementing traditional management approaches while calling for new strategies, or combinations of strategies, to meet emerging limiting factors for walleye recruitment.

Alternative paths forward—moving toward ecosystem-based fisheries management

As found here, rehabilitation plans that considered habitat, food web, or social dimensions were more successful. Walleye rehabilitation plans may better support struggling populations under current and future conditions when using ecosystem-based fisheries management (EBFM), which considers recreational, subsistence, and cultural fisheries as interconnected systems (Pikitch et al. 2004). EBFM focuses on ecological processes, habitat, and interactions to maintain healthy ecosystems and provide services, unlike single-species management which targets individual stressors and species-specific outcomes (Radinger et al. 2023). For example, common conservative minimum length limits and bag limits for maashikinoozhe/muskellunge (*Esox masquinongy*), increasingly conservative bag limits for bluegill and black crappie, and social norms for nearly exclusive catch-and-release by anglers for other beings (e.g., black bass, muskellunge) may lead to unfavorable conditions for walleye (Hansen et al. 2015; Hessenauer et al. 2018). EBFM addresses these issues by considering habitat, interactions, and food webs to create favorable conditions for walleye rehabilitation.

EBFM also encourages managers to look beyond individual lakes to watershed-scale management and identify "bright spot" walleye fisheries for conservation (Tingley et al. 2019; Jeanson et al. 2021). This is vital in regions like the U.M. U.S., where certain fisheries can be specifically managed for walleye, whereas others may provide different opportunities through habitat more favorable to non-walleye fish assemblages (Rypel et al. 2019; Dassow et al. 2022; Feiner, Shultz, et al. 2022). Climate change and other global factors may reduce the suitability of some lakes for walleye, requiring a broader approach (Carpenter et al. 2017). For instance, Minnesota's cisco conservation efforts use conservation easements and watershed land use restrictions to maintain thermal habitats (Jacobson et al. 2013). Similar approaches can identify resilient walleye populations for targeted conservation, though this may increase fishing pressure on these populations. Therefore, watershed-scale and "bright spot" management may require more conservative angler and subsistence compromises to maintain their resilience to disturbance.

Proactive management through partnerships was key to rehabilitation success, contrasting with past reactive efforts that required continuous intervention. Proactive measures include fisheries-independent monitoring, precautionary benchmarks, and suitable habitat conservation. Nimble, reactive management actions can support proactive efforts, ensuring timely changes to rehabilitation plans. Including social aspects in proactive approaches can improve acceptance of reactive measures, maintaining favorable conditions for walleye and enhancing rehabilitation success.

Finally, it is key to recognize that drivers outside managerial control may result in the loss of some walleye fisheries from the landscape (Embke et al. 2022). This review highlights the need to prepare fishers for this reality and the limited ability of management agencies to sustain unviable walleye populations. Fishers may need to transition to other species, focus on non-walleye catch utilities, or seek alternative walleye fisheries. This transition can be challenging, especially for cultural or subsistence fishers reliant on walleye, although Ojibwe teachings, such as "accept the gift that was given" has led to more harvest of other giigoonh (fish) by tribal members (Shultz et al. 2022). Sustaining fisheries of immense tribal subsistence and cultural importance may also be considered as a priority over considerations of recreational fishery opportunities given geographically-defined boundaries that do not allow indigenous communities to follow shifts in beings that may occur (Stults et al. 2016). When a former walleye fishery is unable to provide subsistence or recreational opportunities, joint decisions may be made to accept what the current habitat can support now and, in the future, moving away from a single species focus on walleye.

Conclusions and management implications

This review highlighted key themes for future fisheries conservation and rehabilitation efforts. Traditional walleye rehabilitation methods used in isolation—such as reactive stocking and conservative harvest regulations—yielded mixed success. These efforts may have failed due to a lack of identification of the limiting factors behind recruitment declines, compounded by legacy effects, social norms, and single-species management in multi-species fisheries. Efforts that considered habitat or fish community dynamics were more successful, especially in recent years when efficacy has been challenged by global change.

Ecosystem-based fisheries management (EBFM) offers a promising alternative, despite being less understood and facing financial and logistical challenges. Recent examples (Mrnak et al. 2023; Radinger et al. 2023) showed the benefits of EBFM for meaningful change and successful rehabilitation, where abiotic limitations and social values were considered.

For future rehabilitation plans, we highlight the benefit of:

1. Identifying system-specific limitations (e.g., lake productivity) before strategy implementation.
2. Setting the ecological stage by creating favorable conditions for walleye, such as establishing early warning signals to determine when intervention thresholds are met.
3. Including clear biological, abiotic, and socially relevant objectives to assess plan efficacy.
4. Incorporating EBFM principles in rehabilitation plans.

Proactive and flexible management designs could be developed among management, tribal, and public partners to recognize early signs of trouble such that rehabilitation efforts are avoided. After all, the best fisheries rehabilitation plan is to prevent the need for one.

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