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ENHANCING WALLEYE (OGAA) RECRUITMENT:
EVALUATING ASSISTED REPRODUCTION AS A MITIGATION STRATEGY

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Abstract.- Over the past several decades, cold- and cool-water fish populations across the Upper Midwest, including Minnesota and Wisconsin, have shown troubling signs of decline. Among the most affected is the walleye/ooa (*Sander vitreus*), a species deeply embedded in the ecological balance, cultural identity, and economic vitality of the region, and central to the lifeways, treaty-reserved rights, and resource stewardship of Tribal Nations, including Ojibwe communities across the Upper Midwest. Despite ongoing stocking efforts and harvest regulations, many lake systems have experienced persistent declines in natural recruitment, prompting resource agencies to investigate the underlying causes. One such system is the Minocqua Chain of Lakes in northern Wisconsin. Historically regarded as a productive walleye fishery, the chain has witnessed a sharp and sustained drop in age-0 walleye abundance, suggesting the presence of ecological bottlenecks during early life stages. Recruitment failures in this region raise essential questions about the timing and drivers of mortality - whether these occur during egg incubation, larval emergence, or early juvenile development. First, this study draws on the existing literature to identify when recruitment bottlenecks are most likely to occur and to evaluate the biological and environmental conditions that may be contributing to the decline. Second, by employing assisted reproduction techniques, this research aims to improve understanding of egg survival, larval growth, exposure to predation, and key abiotic stressors. Findings will inform science-based management decisions for agencies such as the Wisconsin Department of Natural Resources and the Great Lakes Indian Fish and Wildlife Commission and contribute to the growing body of research on walleye recruitment challenges across North America.

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LITERATURE REVIEW:
FACTORS INFLUENCING WALLEYE REPRODUCTION, RECRUITMENT, AND SUSTAINABILITY

Douglass Keiser

This review summarizes recent research on age-0 walleye survival and early life-stage mortality in northern temperate lakes, drawing from a systematic search of peer-reviewed literature using defined keywords and selection criteria. Approximately 200 peer-reviewed articles, along with relevant historical and agency records, were evaluated. This review summarizes recent research on age-0 walleye survival and early life-stage mortality in northern temperate lakes. Studies examining predation, habitat complexity, and climate-driven thermal variability are included. Key sources addressing interactions among smallmouth bass, adult walleyes, and stocked juveniles are discussed. This review provides a more detailed synthesis of early recruitment dynamics and survival bottlenecks than what is presented within the thesis.

Walleye/Ogaa (*Sander vitreus*) are a significant cultural, economic, and ecological species across North America [1, 2, 3]. The walleye holds profound cultural importance across the Upper Midwest and northern regions of North America, symbolizing more than just a recreational species. Within Indigenous cultures, particularly among Ojibwe tribes in the Ceded Territories of the Upper Midwest, walleye holds profound cultural importance as a staple of both diet and tradition. Through treaty-protected harvesting practices such as spearing and netting, walleye serve as a living expression of sovereignty, self-reliance, and intergenerational knowledge. These practices are not only about sustenance but about maintaining a sacred relationship with the land and water [4, 5].

From an ecological perspective, walleyes are a keystone species in many northern freshwater ecosystems. As apex or near-apex predators, they play a critical role in shaping fish community structures by regulating populations of prey species such as yellow perch (*Perca flavescens*) and various forage fish [5, 6]. The presence and abundance of walleye can influence trophic dynamics, food web stability, and ecosystem resilience.

Indicators of environmental change

Walleye are also highly sensitive to changes in habitat quality, particularly during early life stages. Successful recruitment depends on specific environmental conditions such as clean, well-oxygenated gravel substrates for spawning, appropriate water temperatures, and adequate forage availability during larval development [7, 8]. Because of this sensitivity, walleye populations are often used as biological indicators of lake and river health in northern temperate systems. Over the past several decades, walleye populations have declined across the Upper Midwest due to declines in natural recruitment, habitat loss, warming water temperatures, changes in fish communities, and overharvest [9, 10, 11].

Additionally, declines in walleye recruitment can signal broader ecological degradation, such as eutrophication, impacts of invasive species, shoreline development, or altered hydrology [2, 12]. The combination of its ecological role and its responsiveness to environmental stressors throughout its lifecycle has made walleye a focus of fisheries management and conservation research, particularly in efforts to understand recruitment bottlenecks, the effectiveness of habitat restoration, and the impacts of climate change on cold-water fish communities.

Walleye lifecycle

In the cold or cool freshwater environments of Minnesota and Wisconsin, walleyes typically live between 10 and 15 years, though some individuals can exceed this range under ideal conditions. In rare cases, walleye may reach 20 years of age in cold, low-productivity northern lakes, where slower growth rates are offset by increased longevity [1, 13]. Multiple factors, including water temperature, prey availability, fishing pressure, and overall habitat quality, influence walleye growth and lifespan. In cooler waters, reduced metabolic rates can extend lifespan but may also delay sexual maturity and suppress annual growth increments [1]. Sexual maturity in male walleyes typically occurs at 2-4 years of age, while females mature 1-2 years later [1]. However, unpublished recent data from the Great Lakes Indian Fish and Wildlife Commission (GLIFWC) suggest that age at maturity may now be delayed, with individuals reaching maturity at 3–6 years [14]. Walleye occupy different habitat zones and face unique challenges throughout each of their five life stages–egg, larval, juvenile, subadult, and adult–as summarized in Table 1 [1].

The absence of nest guarding or egg tending in walleye further exacerbates these risks, making successful recruitment especially dependent on stable abiotic conditions and adequate habitat quality. Walleye exhibit notably high egg mortality rates, a consequence of multiple factors including incomplete fertilization, nonviable eggs, absence of parental care, and sensitivity to variable environmental conditions during incubation [15, 16]. Early estimates of survival were already low; according to Johnson [17], estimates of walleye egg survival to the pre-hatching (eyed-egg) stage in Lake Winnibigoshish, Minnesota, varied widely depending on substrate type, with survival as low as 0.6 percent on muck bottom (and as high as 35.7 percent on improved gravel–rubble substrate). More recent studies have confirmed similarly low hatch success under natural conditions, often below 5%, particularly when eggs are exposed to siltation, fungal infections, or suboptimal thermal regimes [18, 19]. Moreover, fluctuating water temperatures caused by climate variability can prolong incubation periods, increasing vulnerability to predation and microbial decay [1, 8].

Hatching occurs in 12 to 30 days, depending on temperature [13, 21]. Larval walleye, which hatch at around 6–10 mm in length, enter one of the most vulnerable stages of their life cycle immediately after emergence. Following successful hatching, newly emerged larvae drift with currents from spawning sites into shallow, warm nearshore zones [22]. During the first few days, they rely entirely on their yolk sac for nourishment while drifting passively from spawning sites into open water. As free-swimming larvae, they concentrate in the upper layers of the water column, where warmer temperatures and calm conditions promote development. Once the yolk sac is absorbed (typically within 3–5 days), larvae begin feeding externally, consuming small zooplankton [1, 8]. The success of larval walleye during this stage is highly dependent on environmental conditions, particularly the availability of zooplankton, water temperature, and turbidity. A mismatch between larval emergence and zooplankton bloom timing can result in starvation, while clear water and a lack of cover increase susceptibility to predation [1, 8].

In their larval stage, walleye are pelagic, feeding primarily in the water column on zooplankton and larval fish [22]. As larval fish grow, they gradually shift to larger zooplankton and early-stage insect larvae (Table 2). Larval walleye are the most vulnerable during the first four weeks when they occupy open water drift areas and have yet to move into the littoral zones and weedy bays. The success of larval walleye is highly dependent on environmental conditions, particularly the availability of zooplankton, water temperature, and turbidity [1, 8]. During this time, the larvae primarily consume small zooplankton, especially rotifers and small cladocerans ranging in size from ~0.2–0.6 mm [23]. The preferred food of post-larvae was crustacean zooplankton, which is about 1.2 mm in total length. Then, during the juvenile stage, the diet shifts from zooplankton to macroinvertebrates, including *Chaoborus* larvae and other benthic invertebrates [23].

Around mid to late June, these larvae undergo an ontogenetic shift, transitioning to the benthic or demersal stage. At this point, the young walleye are typically found in heavily vegetated habitats at depths of 2–5 m, where macrophyte cover offers both prey resources and protection [22]. As they become demersal, the larval walleye also shifts to piscivory, and their abundance becomes increasingly correlated with the presence of suitable prey fishes in these structured habitats. This habitat transition is a vulnerable phase in the recruitment process. The combination of habitat availability, prey density, and predation risk during the ontogenetic shift can result in failure even when earlier life stages are successful [24].

Juvenile walleye are defined as fish in their first year (age-0) through age-1. The young walleyes utilize different habitat types based on their developmental stage and environmental conditions specific to each lake [22]. As they grow, juvenile walleyes undergo a series of ontogenetic dietary shifts, with their diet closely linked to body size, mouth gape, and prey availability (Appendix A). These dietary changes occur rapidly during the first few months after hatching, reflecting their developmental needs and ecological conditions. Juveniles occupy shallow, nearshore habitats with abundant vegetation or turbid water, which offer protection from predators [1, 22].

Subadult walleyes are between the ages of 1-3 and have not yet reached sexual maturity and occupy habitats that serve as transitional zones between the shallow protective areas favored by juveniles and the deeper, more open-water environments preferred by adults [1]. The subadults are commonly found in moderate-depth zones, often ranging from 2.5 to 6 meters, which provide them with access to both structural cover and foraging opportunities for prey such as aquatic invertebrates and small forage fish. While subadults are more mobile than younger fish, their distribution is influenced by water temperature, turbidity, and food availability. They are reliant on habitat complexity to reduce predation risk from larger piscivores such as adult walleyes, northern pike (*Esox lucius*), and muskellunge (*Esox masquinongy*). As they grow and prepare to enter the adult population, subadult walleyes gradually shift to deeper waters and become more nocturnal in their feeding behavior. This stage is critical in determining future population structure, as survival rates during the subadult period are influenced by factors such as habitat quality, interspecific competition, and predation pressure [1].

Adult walleye habitat preferences vary seasonally in response to feeding and spawning needs. Typically, adult walleyes are found in deeper, cooler waters during daylight hours (between 5-12 m) and prefer water temperatures of 65–75°F (18–24°C), often avoiding warmer surface waters during the summer months. Key habitat features include substrates composed of gravel, sand, or rubble, as well as structural elements such as rock piles, submerged timber, weed edges, and drop-offs, which provide both cover and ambush opportunities for feeding. Walleyes are crepuscular feeders and have light-sensitive eyes, which afford them an advantage in low-light or turbid conditions [1]. Adults are opportunistic carnivores and primarily piscivorous, with their diets influenced by prey availability, water clarity, and season. Seasonally, adult walleyes migrate to shallow, rocky shorelines or tributaries to spawn in the spring, then move to deeper, cooler waters in the summer and fall. During winter, they typically remain near bottom structures in mid-depth to deep basins, continuing to feed sporadically under ice cover [1].

Walleye spawning and habitat preferences

Walleye spawning usually begins shortly after ice-out, from mid-April to early May, as water temperatures reach 38–44°F (3.3–6.7°C), with peak spawning between 42–50°F [1]. As broadcast spawners, walleye release their eggs and milt freely over suitable substrates without constructing nests or offering parental care [1]. Spawning usually occurs in shallow, near-shore habitats over coarse, rocky substrates, which provide optimal conditions for egg development [8]. Preferred spawning sites are generally located within 3 m of the shoreline and in water less than 0.3 m deep, with substrates primarily composed of gravel and cobble, occasional sand, and minimal silt [20]. A study of 28 lakes in Minnesota by Zetner [25] found that walleye eggs were commonly deposited within 2.2 m of shore, at depths averaging 0.3 m, on substrates made up of approximately 78% coarse rock/gravel and 21% sand. These loosely packed substrates support egg survival by promoting interstitial water flow for oxygenation, reducing the risk of displacement, and providing some protection from predators [20]. Earlier field research by Johnson [16] demonstrated that egg survival was highest on gravel-rubble beds, with nearly zero survival observed on soft, organic-rich bottoms. Laboratory experiments by Gatch et al. [26] further emphasized the sensitivity of walleye eggs to sedimentation, showing that a 2 mm layer of silt caused 71% mortality, while a 7 mm layer of sand caused 47% mortality.

During the spawning season, male and female walleyes exhibit distinct but coordinated behaviors that support external fertilization [1]. Males typically arrive at the spawning grounds earlier than females and remain there longer, often patrolling suitable substrate areas and competing for access to females. They do not establish strict territories but will follow and court females by nudging or swimming alongside them to stimulate egg release [1, 13]. Females arrive later, usually when water temperatures reach 42–50°F (5.5–10°C) and select a site. Once chosen, the female releases her eggs in bursts over the substrate, and one or more males simultaneously release milt into the water column, allowing for external fertilization. A single female may produce up to 500,000 eggs, depending on her size. After spawning, females typically leave the site, while males may remain to spawn with other females [1, 13]. In discussions around fertilized egg failure, recent research has examined the relationship between maternal size and egg survival in walleyes. The results indicate that large walleye produce eggs that survive better than or better than those from smaller fish and suggest that large female walleyes should be included in artificial spawning efforts to maximize spawning efficiencies [27].

Once deposited, the fertilized eggs settle into the interstitial spaces between rocks, where they incubate naturally over 12–30 days, depending on water temperature [1, 8, 20]. Settling into rock crevices provides protection from predation by benthic egg predators such as johnny darters (*Etheostoma nigrum*) and sculpins (*Cottus* spp.), while also stabilizing eggs during periods of wind-driven wave action [17, 28, 29, 30]. Fish eggs, including walleye, require sufficient oxygen flow to survive. When eggs become densely clustered, inner eggs may be deprived of oxygen, reducing survival and increasing susceptibility to fungal and bacterial infections [31, 32]. Infections are a significant threat to incubation success and often occur shortly after eggs are exposed to water. Low water temperatures (4–15°C), which align with the spawning season for walleye in Wisconsin, are particularly favorable for fungal development [33]. Fungal pathogens such as *Saprolegnia* are especially problematic because they typically colonize dead or unfertilized eggs first and can then spread rapidly to adjacent viable eggs, particularly when eggs are densely clustered [34]. This secondary spread can result in substantial localized egg mortality within spawning substrates. The risk of fungal infection is further exacerbated by reduced water circulation, low dissolved oxygen, or increased sedimentation, all of which can stress developing embryos and promote pathogen growth [26, 33, 35]. Consequently, even when spawning occurs in otherwise suitable habitats, biotic stressors such as fungal infections can significantly reduce hatching success and contribute to variability in recruitment outcomes [1, 8].

Moderate winds can enhance egg survival by increasing water circulation and oxygenation, and many walleye spawning areas are oriented to prevailing north or northwest winds during the spring. However, extreme wind and wave events can dislodge or bury eggs within the substrate, increasing the likelihood of mortality and predation. [1, 17, 26, 36, 37]. Studies have shown that wind and water level fluctuations contribute to unstable spawning conditions, particularly in shallow, nearshore habitats where walleye typically spawn [28]. In Lake Winnibigoshish in northern Minnesota, dead eggs were observed washed onto the shore after three days of moderate (6-7 to 11.1 m/s) easterly winds [17]. In the same study, heavy wave action carried eggs deeper, into less than suitable habitat, causing egg mortality [17]. Additionally, the researcher recorded a decrease in egg abundance (from 93 to 46 eggs per 0.09m following a night of "very strong winds" [17]. All three situations serve as an affirmation of the protection offered by suitable substrate habitat for spawning.

The availability of suitable spawning habitat is a critical component of walleye reproduction, and reductions in the quantity and quality of these habitats have been directly linked to decreased egg deposition, lower egg survival, diminished age-0 abundance, and ultimately reduced recruitment to the adult population [17]. Walleye are especially sensitive to habitat conditions during early life stages, relying on clean, well-oxygenated gravel substrates, appropriate thermal conditions, and sufficient prey availability to support successful development [7, 8]. The Walleye Habitat Suitability Index developed by McMahon et al. [19] identifies substrate quality and quantity as primary factors influencing reproductive success, with optimal materials ranging from 2.0 to 250.0 mm in diameter–classified as gravel, pebble, and cobble. These substrates allow fertilized eggs to settle into interstitial spaces where they are protected from large egg predators and benefit from oxygen-rich water flow [19]. When these habitats are degraded by sedimentation, eutrophication, or shoreline development, reproductive success can be significantly impaired [8, 11]. Consequently, habitat protection and restoration remain central strategies in recruitment-based management programs aimed at sustaining walleye populations [1].

Despite these well-documented substrate preferences, there remains a lack of comprehensive data on the quantity and condition of spawning habitat needed to support successful natural reproduction in smaller inland lakes. While walleye favor clean, coarse, rocky substrates in shallow nearshore zones [20, 25], not all visually suitable sites are used. For example, Raabe and Bozek [35] found that in Big Crooked Lake, Wisconsin, only 39% of shoreline areas containing coarse rock (gravel-sized or larger) were utilized for spawning. This finding suggests that walleyes exhibit a degree of habitat selectivity, choosing among available substrates based on additional, potentially unmeasured factors such as water flow dynamics, substrate packing, chemical cues, or proximity to suitable post-spawning habitat [35]. These complexities underscore the need for site-specific assessments and a better understanding of fine-scale habitat variables that may influence spawning-site selection and reproductive success in inland walleye populations.

Studies have indicated that walleye exhibit strong spawning-site fidelity and often return to the same locations to spawn each year. Research by Bade et al. [38] suggests that individual walleye may consistently return to specific reef sites to spawn. A similar study, focusing on spawning in Lake Michigan tributaries in Green Bay, confirmed walleye spawning-site fidelity [39]. Additionally, recent research on Mille Lacs Lake conducted by the Great Lakes Indian Fish and Wildlife Commission (GLIFWC) further supports this pattern, demonstrating that walleye exhibit a high preference for specific spawning reefs across years, reinforcing the importance of localized habitat conditions in reproductive success [40]. Given this reliance on specific spawning locations, deterioration of these habitats—through sedimentation, shoreline development, or loss of suitable substrate—may significantly reduce reproductive success by limiting access to preferred sites, decreasing egg survival, and ultimately contributing to declines in natural recruitment.

Spawning and water temperature

Water temperature plays a critical role in the reproductive success, larval survival, and early growth of walleye with spawning outcomes strongly influenced by both average thermal conditions and climate variability. Optimal incubation occurs at approximately 10°C (50°F), with successful hatching typically observed within a temperature range of 8.9°C to 10°C (48–50°F). Below 4.4°C (40°F), embryonic development slows considerably, extending the vulnerable incubation period and increasing susceptibility to infection, ultimately reducing hatch success [13, 21]. Furthermore, unseasonal or highly variable temperatures during incubation can disrupt developmental timelines and alter microbial dynamics on the egg surface, leading to poor survival [7, 29, 36, 41, 42]. In colder years, low water temperatures are frequently associated with poor hatching success and early life-stage survival. Sudden drops in water temperature can also signal walleye to cease spawning activity altogether, and in prolonged cold periods, entire spawning runs may be delayed or abandoned [1]. However, some studies have observed walleyes reinitiating spawning activity in response to renewed warming trends later in the spring season, suggesting a degree of behavioral flexibility in response to environmental conditions [43, 44].

Impact of climate change on spawning synchrony

Climate change is altering the phenology–or seasonal timing–of a wide range of organisms [45], with one of the most consistently documented patterns being the earlier onset of biological events associated with rising temperatures [46]. Among these changes is the advancement of spawning in spring-spawning fish species such as walleye, driven by warming water temperatures in early spring [47]. Ice-out serves as a cue for increases in lake primary productivity, initiating a cascade of biological events, including zooplankton production and other food resources for larval fish [48]. As a result, earlier or more variable ice-off phenology can disrupt lake food web dynamics, particularly by causing temporal mismatches between predator and prey peaks–ultimately reducing fish growth and survival [49, 50]. Specifically, earlier ice-out can disrupt the synchrony between walleye spawning and the peak availability of zooplankton, which are a critical food source for newly hatched larvae. If larval walleye hatch after the zooplankton bloom has already passed, they may face food limitations during a critical developmental window, increasing the risk of starvation and early mortality [16, 51]. This kind of phenological mismatch, driven by warming temperatures and shifts in thermal regimes, is increasingly recognized as a key driver of recruitment variability in northern temperate lakes.

Moreover, changes in ice-out timing can lead to broader trophic mismatches, in which peak prey abundances are no longer aligned with predator demand, further diminishing offspring survival rates [52]. Recent research in lakes within the Ceded Territories of Wisconsin supports this concern, showing that increased climate variability may be weakening the historical coupling between ice-off timing and walleye spawning, potentially contributing to more frequent failures in natural recruitment [49].

Spawning habitat improvements

Habitat improvement efforts, such as restoring gravel and cobble substrates or mitigating shoreline erosion, are being examined as strategies to support natural reproduction and sustain walleye populations. Although constructing artificial rock reefs is generally considered beneficial for enhancing walleye spawning habitat, comprehensive assessments of their effectiveness in improving walleye production remain limited. Some earlier studies have documented increases in adult walleye abundance, egg deposition, and egg survival on artificial reefs [17, 53, 54]. However, clear evidence demonstrating significant improvements in actual walleye recruitment following reef construction is scarce.

A review conducted by Neuswanger and Bozek [55] examined 20 artificial reef projects implemented in northern Wisconsin between 1968 and 2003 – 90% of which were constructed after 1992. The findings revealed that, in 19 of these cases, age-0 walleye survival either did not improve (17 instances) or was inconclusive (2 instances). In the only project where recruitment increased, an aeration system was also installed concurrently, making it difficult to attribute the improvement solely to reef construction [55].

Similarly, a survey conducted by the Ontario Ministry of Natural Resources evaluated 43 walleye habitat alteration projects, most of which were in river or estuary settings. Geiling et al. [56] reported that in 17% of cases aimed at enhancing self-sustaining populations, project leaders rated the outcomes as having low success. Notably, in situations where natural reproduction was already limited or absent, success ratings dropped to zero. Bozek et al. [1] further speculated that the limited effectiveness of artificial reef projects may stem from low hatching success or, in some cases, from spawning habitat not being the genuine limiting factor. This suggests that other ecological or biological constraints–such as predation, food availability, or environmental variability–may play a more critical role in influencing survival outcomes, regardless of habitat enhancement efforts.

Walleye recruitment bottlenecks

Walleye recruitment refers to the successful survival of individuals from the egg and larval stages through to a stage at which they are detectable in population assessments, typically as age-0 or age-1 juveniles [1, 16, 24]. This process represents a critical bottleneck in the walleye life cycle, as survival through early developmental stages is influenced by a complex interplay of biotic and abiotic factors. Recruitment in walleye populations is influenced by multiple ecological and environmental factors. Key determinants include successful spawning and fertilization, suitable incubation conditions, hatch success, adequate food availability, predation pressure, and stable environmental conditions such as water temperature and substrate quality [15, 20].

Results of a 2003 study suggest that walleye recruitment in northern Wisconsin lakes is regulated by multiple factors that include compensatory, density-dependent interactions between adult and age-0 walleyes, density-independent factors that operate across a broad regional scale and density-dependent interactions between yellow perch and age-0 walleyes [57]. Walleye recruitment showed high synchrony across northern Wisconsin, suggesting that overall climatic effects strongly influenced walleye reproductive success [57]. In the study, years with high recruitment of age-0 walleyes were characterized by relatively warm, stable water temperatures, followed by 2 years of relatively poor walleye reproduction, suggesting that broad-scale climatic patterns can strongly influence recruitment [57].

Fluctuations in the walleye population are frequently linked to environmental factors such as habitat quality, climate variability, and interspecific interactions [1, 58, 59]. In northern temperate systems, studies have attributed declines in walleye abundance to recruitment bottlenecks during the first year of life, when age-0 individuals are most vulnerable to environmental pressures [16, 60]. While the precise mechanisms underlying these recruitment declines remain complex and multifactorial [61, 62], evidence suggests that climate-induced changes in lake ecosystems, including altered thermal regimes, water clarity, and fish community composition, may play a significant role [60]. However, lake-specific physical and biological characteristics have long been shown to strongly influence walleye population success, with factors such as lake morphometry, productivity, and species assemblages predicting both occurrence and recruitment outcomes [60]. Additionally, recent work by Olaf P. Jensen and colleagues demonstrates that, across Midwestern freshwater systems, fishing pressure has historically exerted a stronger influence on fish population dynamics than warming in many cases [63].

As natural recruitment has declined in many Midwestern lakes, fishery managers have increasingly relied on stocking to sustain walleye populations [18, 60]. In Wisconsin, this trend has been particularly evident since the mid-1990s, with a growing number of walleye populations now supported either partially or entirely by stocking, as the number of lakes sustaining natural recruitment continues to decline [20].

To evaluate which fish community compositions are most favorable for walleye recruitment, Nate et al. [6] compared stocked and naturally reproducing walleye lakes. They found that lakes dominated by largemouth bass (*Micropterus salmoides*) and northern pike were more often associated with stocked walleye populations, while lakes supporting high densities of walleye and muskellunge were more likely to sustain natural recruitment [6]. Consistent with other work, these patterns highlight the importance of fish community structure and species interactions in shaping recruitment outcomes. Together, this suggests that walleye recruitment is strongly mediated by predator assemblages and interspecific dynamics, potentially creating feedbacks that reinforce conditions favorable to walleye persistence, rather than indicating that walleye themselves actively "cultivate" these ecosystem conditions [64].

Predation

Predation is a significant factor limiting walleye recruitment, particularly during the vulnerable egg, larval, and age-0 juvenile stages. Without parental care or nest guarding behavior, walleye eggs are highly vulnerable to predation by both fish and benthic invertebrates can substantially reduce hatching success [18, 65]. A long-term study on Lake Erie by Roseman et al. [30] found that fish species such as white perch (*Morone americana*), yellow perch, and others frequently consumed walleye eggs during the spawning season, underscoring the role of interspecific egg predation.

Benthic invertebrates such as rusty crayfish (*Orconectes rusticus*) may exert significant predation pressure on walleye eggs. Weisbord, Callaghan, and Pyle [66] demonstrated that male rusty crayfish can develop conditioned behavioral responses to walleye egg cues, indicating an ability to learn and associate these cues with a reliable food source. Collectively, these findings highlight the multifaceted threats to walleye egg survival during early developmental stages. Studies have indicated that fish egg survival rates are highest in areas where predatory invertebrates are scarce or where substrate conditions limit invertebrate access to egg clusters. In Lake Simcoe, Ontario, research suggests that the low survival of naturally spawned lake trout (*Salvelinus namaycush*) eggs may be partially due to high crayfish densities, which are known egg predators [67]. With a preference for rocky substrate, rusty crayfish are voracious and omnivorous, foraging opportunistically on aquatic plants, detritus, invertebrates, and fish eggs [66, 67]. Additional studies have indicated that rusty crayfish can negatively affect aquatic macrophytes, benthic macroinvertebrate abundance, particularly snails, and the survival of some fish in northern lakes [68]. While they are a major dietary item for some fish species, including smallmouth bass, their rapid growth can make them too large for certain predators. As a result, rusty crayfish have proven disruptive in littoral zones and aquatic food webs.

Age-0 walleyes utilize different habitat types depending on their developmental stage and the specific environmental conditions of each lake [22]. After hatching, larval and juvenile walleyes face intense predation pressure from gape-limited piscivores, especially centrarchids like largemouth and smallmouth bass (*Micropterus dolomieu*), which are increasingly abundant in many northern lakes due to warming temperatures [49, 51, 69].

Cannibalism is another important source of mortality that can influence walleye recruitment, particularly in systems with limited prey availability or high densities of older age classes. As opportunistic predators, larger juvenile or adult walleye may consume smaller conspecifics, especially during the early life stages when newly hatched larvae and age-0 individuals are most vulnerable [70, 71]. This behavior tends to be density-dependent and is often exacerbated under conditions of low food availability, where age-1 and older walleyes target the abundant but smaller age-0 cohort as an accessible energy source [69, 70, 72, 73].

Similarly, predation is one of the most commonly cited factors for the survival of stocked walleye, with peak predation mortality often occurring within 24-28 hours [74, 75]. Numerous studies have documented high predation-induced mortality of stocked age-0 walleyes in lakes with established piscivore populations, particularly centrarchids. These instances highlight the vulnerability of stocked walleye to size-structured predator-prey dynamics, where gape-limited predators can quickly decimate smaller, recently introduced individuals. In a recent study, Olivencia et al. [76] found that smallmouth bass and, to a lesser extent, adult walleyes were the primary predators of stocked age-0 walleyes, particularly during the fry and early fingerling stages. During the post-stocking period, age-0 walleyes accounted for up to 11.4% of smallmouth bass diets and 14.6% of adult walleye diets. Notably, most predation occurred within the first 14 days following stocking, with up to 14.7% of stocked individuals consumed in that short window [76]. These findings underscore the importance of accounting for resident predator populations when evaluating stocking success and recruitment potential. Predation pressure can be especially acute in systems where walleye recruitment is already compromised by environmental stressors or habitat degradation, compounding mortality risks and contributing to persistent recruitment failure [44, 77, 78].

Interspecies competition

Interspecies competition presents another challenge to successful walleye recruitment, particularly during the early life stages when resource needs overlap with other fish species. Native competitors such as yellow perch and northern pike often occupy similar habitats during spawning and nursery periods, leading to competition for food and space. Yellow perch can outcompete larval walleyes for zooplankton, especially when perch populations are abundant, reducing the availability of essential forage during a critical developmental window [79]. Northern pike may not only compete for habitat but also prey directly upon juvenile walleyes, contributing to both competitive and predatory pressures [80]. These interspecies interactions can significantly reduce the survival of young walleyes, especially in ecosystems where environmental change or anthropogenic pressures have already compromised habitat quality [77].

A similar downward trend in population has been observed for yellow perch, whose relative abundance has markedly decreased across both Minnesota and Wisconsin, signaling broader shifts in fish community structure and recruitment dynamics in northern lakes [81]. Walleye recruitment success is closely linked to the relative abundance of juvenile yellow perch, which serves as an important prey source during the early life stages of walleye [81]. Therefore, sustained declines in yellow perch populations may reduce prey availability for age-0 walleyes, potentially contributing to lower survival rates and diminished recruitment [79, 81].

Influence of centrarchidae on walleye recruitment

Recent work in fisheries management highlights that ecosystem shifts toward centrarchid-dominated communities can fundamentally alter walleye recruitment dynamics, often requiring intensive and sustained intervention to maintain walleye populations [82]. In Wisconsin, the populations of species belonging to the family Centrarchidae are predicted to continue to increase over time [16, 60, 77, 83, 84]. These increases have been linked to climate change [77], as well as to conservative recreational fishing regulations [84, 85] and to nearly exclusive voluntary catch-and-release [86, 87]. As a result, lakes in northern temperate regions like Wisconsin are becoming more suitable for centrarchid species because of warming average temperatures, increasing water clarity, and increasing vegetation [88].

Increasingly, walleye recruitment declines have coincided with increases in warmwater species, such as largemouth bass in Wisconsin [60, 89] and Ontario, Canada [90]. Numerous studies have identified the negative impacts of centrarchids on walleye, both through predation and competition [9, 16, 77, 89, 91, 92, 93]. In particular, black crappie (*Pomoxis nigromaculatus*) species have shown a strong inverse relationship with age-0 walleye relative abundance in northern Wisconsin lakes from 1991 to 2017. During this period, age-0 walleye catch-per-effort (CPE) declined significantly as black crappie CPE increased. A threshold effect was observed within lakes: when black crappie CPE was high, age-0 walleye CPE was consistently low. Among the tested abiotic and biotic variables, black crappie had the greatest adverse effect on walleye recruitment [24]. Potential mechanisms include direct predation on larval or juvenile walleye, competition for zooplankton, and a lack of spatial or dietary partitioning in shared habitats.

Studies have found that in Northern Wisconsin lakes, the relationship between age-0 walleye and black crappies showed a threshold effect, with age-0 walleye CPE always low when black crappie CPE was high, suggesting that black crappies may negatively influence walleye recruitment [88]. Both piscivorous species, walleye and black crappie, occupy similar habitats at different life-history stages [88]. During the age-0 walleye transition from pelagic to the littoral zone, there is the potential for the age-0 walleye and post-spawn black crappie to compete for zooplankton resources or for predation of age-0 walleye by black crappie to occur [88].

Largemouth bass have been identified as the primary species exhibiting strong interactions with walleye populations and have been implicated in suppressing walleye populations through indirect mechanisms, such as competition and behavioral interference [1, 69]. A 2005 study conducted by Fayram et al. [69] found: (1) in lakes with naturally reproducing walleye, population indices of largemouth bass and walleye were inversely related; (2) juvenile walleyes were present in the diet of largemouth bass; and (3) walleye growth rates were positively associated with largemouth bass abundance indices [69]. Furthermore, studies have found that largemouth bass are the primary source of predation mortality on stocked walleyes [65, 69]. Notably, largemouth bass abundance indices also rose in conjunction with increased walleye stocking intensity [69]. While studies have shown variable predation rates, bioenergetics modeling suggests that in Northern Wisconsin lakes, largemouth bass can exert considerable pressure on walleye, especially when densities are high [74]. Modeling suggests that a largemouth bass population could consume up to 82,500 juvenile walleyes per year in these lakes [69]. Moreover, warming temperatures linked to climate change may favor largemouth bass over walleye by increasing growing degree days, potentially shifting lake communities further toward warm water species dominance [64, 77, 83].

Similarly, smallmouth bass have expanded their range and abundance in many northern lakes, often becoming primary predators of age-0 walleye, especially in post-stocking scenarios [76]. In Lake Oahe, South Dakota, smallmouth bass consumed up to 14.7% of stocked walleye, with most predation occurring within the first two weeks. While their impact is context-dependent and sometimes minimal, their increasing prevalence creates opportunities for novel interactions and shifts in predator-prey dynamics that may not favor walleye [76].

In an effort to evaluate whether intensive management could counteract these trends, Embke et al. [82] experimentally removed approximately 285,000 centrarchids from a 33-ha lake over 4 years while monitoring the fish community's response. Although centrarchid abundance declined and yellow perch increased, no evidence of walleye recruitment was observed, suggesting that removal of competing species alone may be insufficient to restore natural recruitment in systems that have undergone broader ecological change [82].

Impact of shoreline development and human disturbance

Shoreline development and human recreational use significantly impact walleye recruitment by altering nearshore habitats essential for spawning and early development. The construction of docks, boathouses, and seawalls often leads to the removal of coarse woody debris and aquatic vegetation, which reduces available cover and disrupts the structural complexity required by larval and juvenile walleye [94, 95]. Additionally, increased boat traffic and wave action can disturb spawning substrates, resuspend sediments, and increase turbidity, thereby reducing egg survival through sedimentation and oxygen depletion [1, 22].

Residential development along lake shores has been linked to increased nutrient loading and shoreline erosion, which degrade spawning habitat quality by promoting siltation and algal blooms [96]. These cumulative impacts reduce habitat availability and suitability across critical early life stages and can contribute to recruitment failure, even in lakes with otherwise adequate fish community structure and water quality [94, 97]. As such, managing shoreline development and preserving natural littoral zones are increasingly recognized as essential components of fisheries conservation in northern lakes [94, 97].

Beyond direct habitat degradation, lakeshore residential development has been shown to alter littoral habitats and significantly influence fish community structure. The impact may not change total fish abundance but rather alter the structure through species-specific responses that support increases in centrarchids, such as bluegill (*Lepomis macrochirus*), and declines in walleye [98]. In addition, increased lakeshore residential development has been positively associated with the growth of juvenile largemouth bass, suggesting that developed lake systems may promote higher centrarchid abundance and productivity. Together, these findings indicate that lakeshore development can both reduce habitat suitability for walleye and shift fish community composition, potentially further disadvantaging walleye recruitment [99]. These patterns occur through both habitat-mediated and non-habitat-mediated mechanisms, indicating that lakeshore residential development can reshape fish communities in ways that may disadvantage walleye despite minimal changes in overall fish abundance [98, 99].

In addition to physical habitat degradation, chemical stressors associated with aquatic management practices may further influence fish populations. Fluridone, a commonly used herbicide for invasive plant control, does not cause direct mortality in fish at operational concentrations but can produce significant sublethal effects. Studies on fathead minnows (*Pimephales promelas*) demonstrate that prolonged exposure can lead to endocrine disruption, altered behavior, and reduced prey capture ability, potentially decreasing individual fitness and affecting population dynamics [100]. Similarly, the herbicide 2,4-D, widely used to control aquatic invasive species, can impact the survival of non-target fish, particularly during early life stages. Experimental results by Dehnert, White, and Karasov show that walleye are more sensitive to environmentally relevant concentrations of 2,4-D than northern pike, with toxicity strongly influenced by water chemistry, especially pH [101]. Together, these findings suggest that chemical management strategies, when combined with habitat degradation, may further constrain recruitment success in walleye populations.

Knowledge gaps

Collectively, the literature reveals that walleye recruitment is constrained by a complex interplay of biological, environmental, and anthropogenic factors [1]. Early life stages are particularly vulnerable to habitat degradation, food web shifts, and predation, with high mortality often observed during egg incubation, larval drift, and the juvenile transition to nearshore habitats [16, 18]. Despite decades of study, key uncertainties remain, especially regarding the survival of age-0 walleyes in structurally complex littoral zones and the cumulative effects of climate-induced thermal variability and shifts in predator abundance [35, 88].

While habitat restoration efforts and supplemental stocking are widely employed to bolster walleye populations, their outcomes have been inconsistent and often fail to address underlying ecological limitations such as predator density, substrate quality, or forage availability [26, 55]. These challenges highlight the need for site-specific, integrated research approaches that account for local habitat conditions, species interactions, and climate variability to develop adaptive management strategies that promote sustainable, naturally reproducing walleye populations [11, 77].

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TABLES

Table 1: Walleye Life Stages Summary

Stage	Duration	Key Habitat	Food Sources	Challenges
Egg	~12–30 days	Gravel/rocky shallows		Siltation, predation, water temperature
Larval	~1–4 weeks	Open water/drift	Zooplankton and insect larvae	Food shortage, predation
Juvenile	First summer–1 yr	Littoral zones/ weedy bays	Larger zooplankton, aquatic insects, amphipods, and small fish	Predation, food, habitat complexity
Subadult	Age 1–3	Deeper waters/ broader range	Small forage fish and aquatic invertebrates	Growth, competition, habitat change, fishing pressure
Adult	Age 3+	Feeding/spawning ground habitat; change seasonally	Forage fish and aquatic invertebrates	Fishing pressure, habitat quality

Table 2: Larvae and Juvenile Walleye Dietary Progression

Life Stage	Size Range	Primary Diet
Yolk-sac larvae	~6–10 mm	Yolk reserves (non-feeding stage)
Early free-swimming larvae	~10–15 mm	Zooplankton (e.g., Bosmina, Daphnia)
Late larval / early juvenile	~15–30 mm	Larger zooplankton, insect larvae, small aquatic invertebrates
Juvenile (age-0)	~30–100+ mm*	Aquatic insects, amphipods, small fish fry
Juvenile (age-1)	~100–200 mm*	Mostly small fish (e.g., minnows, perch age-0), crayfish

**According to GLIFWC fall surveys in Wisconsin, Minnesota and Michigan, age-0 walleyes are regularly caught measuring up to 178mm and age-1 are sometimes as large as 279mm.*

ENHANCING WALLEYE (OGAA) RECRUITMENT: EVALUATING ASSISTED REPRODUCTION AS A MITIGATION STRATEGY

Abstract - Over the past several decades, cold- and cool-water fish populations across the Upper Midwest, including Minnesota and Wisconsin, have shown troubling signs of decline. Among the most affected is the walleye/ooga (*Sander vitreus*), a species deeply embedded in the ecological balance, cultural identity, and economic vitality of the region, and central to the lifeways, treaty-reserved rights, and resource stewardship of Tribal Nations, including Ojibwe communities across the Upper Midwest. Despite ongoing stocking efforts and harvest regulations, many lake systems have experienced persistent declines in natural recruitment, prompting resource agencies to investigate the underlying causes. One such system is the Minocqua Chain of Lakes in northern Wisconsin. Historically regarded as a productive walleye fishery, the chain has witnessed a sharp and sustained drop in age-0 walleye abundance, suggesting the presence of ecological bottlenecks during early life stages. Recruitment failures in this region raise essential questions about the timing and drivers of mortality - whether these occur during egg incubation, larval emergence, or early juvenile development. First, this study draws on the existing literature to identify when recruitment bottlenecks are most likely to occur and to evaluate the biological and environmental conditions that may be contributing to the decline. Second, by employing assisted reproduction techniques, this research aims to improve understanding of egg survival, larval growth, predation exposure, and key abiotic stressors. Findings will inform science-based management decisions for agencies such as the Wisconsin Department of Natural Resources and the Great Lakes Indian Fish and Wildlife Commission and contribute to the growing body of research on walleye recruitment challenges across North America.

INTRODUCTION

Walleye/Ogaa (*Sander vitreus*) is an ecologically, economically, and culturally significant species across North America [102, 103]. In the Upper Midwest, walleye plays a central role in ecosystem function, regional economies, and cultural identity, and is deeply embedded in the lifeways, treaty-reserved rights, and resource stewardship of Tribal Nations. For Ojibwe tribes in the western Great Lakes region, walleye is particularly important within the Ceded Territories of the Upper Midwest, where tribes retain legally protected rights to hunt, fish, and gather. Beyond access to resources, these treaty rights carry an enduring responsibility to steward ecosystems and ensure the resources for future generations.

Within this context, declines in walleye populations represent a significant ecological and social concern. For Ojibwe tribes, these declines have far-reaching implications for cultural, subsistence, and management systems. As a central traditional food source, reduced walleye abundance disrupts subsistence practices and weakens cultural connections to fishing and stewardship. Although treaty-reserved rights remain legally protected, diminished populations limit their meaningful exercise and often necessitate harvest restrictions. At the same time, declining walleye populations affect recreational fisheries relied upon by nontribal anglers, reducing angling opportunities and contributing to broader economic and management pressures.

In the Upper Midwest, reductions in cool- and cold-water fisheries have been well documented [104], with walleye populations decreasing over recent decades due to a combination of reduced natural recruitment, habitat degradation, warming water temperatures, shifts in fish community structure, and overharvest [104, 105, 106]. These trends are especially pronounced in inland systems, where natural recruitment has declined markedly since the 1990s, particularly in Wisconsin and Minnesota [103, 107, 108, 109, 110, 111]. In northern Wisconsin, the proportion of lakes supporting self-sustaining walleye populations fell from 68% in 1993 to 37% by 2018, accompanied by substantial reductions in both age-0 and adult abundance [103, 104, 112].

In response, the Wisconsin Department of Natural Resources (DNR) and other agencies have increasingly relied on stocking and harvest regulations to stabilize walleye populations [111]. Although natural fluctuations in walleye populations are expected due to the species' broadcast spawning strategy and sensitivity to variable environmental conditions [110, 113, 114, 115, 116, 117], persistent recruitment failures in certain systems suggest underlying ecological constraints. The near absence of age-0 walleye in some lakes—despite evidence of spawning activity and supplemental stocking—indicates that early life-stage mortality, particularly during egg incubation and larval development, may represent a critical bottleneck [118].

Accordingly, management efforts have shifted toward identifying the ecological drivers of recruitment failure and population variability, recognizing that long-term fishery sustainability depends not only on harvest management but also on addressing broader ecosystem-level stressors. Likely contributing factors include degraded spawning habitat, elevated predation pressure, and altered abiotic conditions [119, 120]. The increasing frequency of recruitment failures underscores the need to identify and address bottlenecks during vulnerable early life stages. These failures also complicate co-management efforts and signal broader ecosystem imbalance, further challenging the long-term sustainability of fisheries.

These dynamics are observable within individual lake systems across the region. The Minocqua Chain of Lakes (Figure 1), in the Ceded Territories of Wisconsin, exemplifies the challenges facing walleye recruitment. Historically a productive walleye fishery, the lake has experienced a pronounced collapse in natural recruitment since the early 2000s, raising concerns among fisheries managers [111, 119, 121, 122, 123, 124]. An unpublished 1959 survey by the Wisconsin Conservation Department described Lake Minocqua as a “productive fishery,” with a one-mile electrofishing effort collecting 2,800 walleyes and documenting strong year-classes in 1958 and 1959, along with abundant yellow perch and minnows. By 1973, fyke netting and electrofishing continued to indicate a robust population with a broad size distribution, and biologists concluded that natural reproduction was sufficient to sustain the fishery, making stocking unnecessary [125]. Even so, Wisconsin DNR records show walleye stocking in the Minocqua Chain since the 1950s, with more than 750,000 walleyes stocked between 1956 and 1985, primarily as fingerlings. Stocking remained sporadic for decades, became more consistent after 2012 with biannual stocking of extended-growth fingerlings, and expanded substantially beginning in 2022 as natural recruitment continued to decline (Figure 2).

However, later comparisons by the Great Lakes Indian Fish and Wildlife Commission (GLIFWC) revealed declining abundance and variable recruitment. Fall electrofishing surveys conducted in 1986 and 1990 documented substantially lower total catches—299 and 532 walleyes, respectively—over a 19.1-mile effort, including 143 and 168 age-0 individuals, indicating fluctuating year-class strength and reduced overall abundance relative to earlier conditions [126; Appendix B]. Beginning in the early 2000s, regular assessments identified a significant decline in natural walleye reproduction in Lake Minocqua (Figure 3), with fall surveys from 1986–2017 documenting continued population declines and raising sustainability concerns (Figure 4).

By 2015, the adult walleye population had fallen to less than 1.5 fish per acre with little to no evidence of natural reproduction [127]. This led to the formation of a collaborative walleye rehabilitation initiative between the Wisconsin DNR, GLIFWC, Lac du Flambeau, and Walleyes for Tomorrow, with the overall goal of reestablishing natural reproduction and increasing the adult population to 3 walleye per acre. The strategies implemented included a full five-year harvest moratorium for tribal and recreational anglers and regular stocking of fry and fingerlings. Although adult densities rebounded to target levels (≥3 adults/acre), natural reproduction did not recover [127]. The 2019 spring survey conducted by GLIFWC found an age structure dominated by older fish (ages 3–10), suggesting limited recruitment of younger year classes and potential long-term decline. This result was confirmed by a fall 2023 survey that documented no evidence of natural recruitment [122; Appendix C] and found that, although walleye abundance had increased from 2015 lows, it remained below 2019 and 2021 levels and substantially lower than in 1992 and 1998.

Walleye early life stages are highly sensitive to both biotic and abiotic conditions, requiring specific habitat characteristics, stable environmental conditions, adequate prey availability, and low predation pressure; disruptions to any of these factors can create bottlenecks that significantly limit survival and recruitment. In response, management efforts have extended beyond harvest regulation to include habitat enhancement and targeted interventions to address recruitment bottlenecks. Beginning in 2018, the nonprofit Walleyes for Tomorrow installed gravel and rock to create artificial spawning reefs in Lake Minocqua, with three sites established near Crescent Island, Stack's Bay, and the southeastern shoreline [121, 123]. However, fall electrofishing surveys have not shown increased age-0 recruitment following reef installation, and spring netting indicates higher catches in natural spawning habitats [121]. In 2023, GLIFWC implemented an assisted reproduction effort, combining controlled spawning, targeted egg dispersal, and large-scale fry stocking. Despite these interventions, fall surveys detected only 2 age-0 walleye, indicating near-complete failure of early-life-stage survival [122, 127].

Together, these findings and prior research suggest that walleye recruitment may be constrained by critical bottlenecks arising from biotic and abiotic factors, including habitat degradation, shoreline development, human activity, sedimentation, spawning conditions, predation, and interspecific interactions with warm-water species [122]. Building on these patterns, this study evaluates the mechanisms limiting age-0 walleye survival in the Minocqua Chain of Lakes. Specifically, the objectives were to: (1) assess habitat quality and abiotic conditions associated with egg incubation and early larval development; (2) quantify egg and larval survival during assisted reproduction efforts; (3) evaluate the extent to which predation pressure and fish community structure may negatively impact early life stage survival; and (4) determine whether the use of incubation boxes to protect fertilized eggs from predation improves hatching success relative to unprotected conditions. By targeting the incubation and early larval stages, where recruitment bottlenecks are most likely to occur, this study intends to identify the timing and drivers of early mortality, including hatching success, growth, predation, and environmental stressors.

Results will inform stocking practices, harvest regulations, and habitat management strategies implemented by the Wisconsin DNR and GLIFWC, not only for Lake Minocqua but also for other lakes within the region experiencing, at varying stages, similar recruitment challenges. By clarifying key bottlenecks limiting early life-stage survival, this study will support more targeted and effective management actions, including habitat protection, habitat restoration, adaptive stocking strategies, and refined harvest decisions across species. In doing so, the findings will contribute to long-term stewardship efforts to sustain self-reproducing walleye populations and maintain resilient fisheries, while also advancing a greater understanding of recruitment limitations in inland walleye systems across the Upper Midwest.

METHODOLOGY

Study area

This study was conducted on Lake Minocqua, a 1,360-acre mesotrophic freshwater lake located in Oneida County, northern Wisconsin. The lake is part of the Minocqua Chain of Lakes and lies within the Ceded Territories of Wisconsin –an area where treaties affirm the off-reservation hunting, fishing, and gathering rights of Native American tribes. Lake Minocqua has a maximum depth of 18.29 m and is classified as a soft-water drainage lake, with light-brown water and moderate transparency. It receives inflow from the Minocqua and Tomahawk Thoroughfares and discharges into Kawaguesaga Lake. The lake is heavily developed along its 30.7 kilometers of shoreline, with approximately 375 private dwellings, 23 resorts, two parks, and a golf course [121, 128]. A complex two-story lake, Minocqua supports both cold-water and warm-water fish communities and has a diverse fish assemblage of at least 15 species. Predatory species include walleye, largemouth bass (*Micropterus nigricans*), smallmouth bass (*Micropterus dolomieu*), muskellunge (*Esox masquinongy*), northern pike (*Esox lucius*), yellow perch (*Perca flavescens*), black crappie (*Pomoxis nigromaculatus*), and bluegill (*Lepomis macrochirus*). Other species, such as bluntnose minnow (*Pimephales notatus*) , mimic shiner (*Notropis volucellus*), yellow bullhead (*Ameiurus natalis*), and various sucker (*Catostomus*) species, are also present [128; Appendix B].

The lake has long been revered as a premier walleye fishery in northern Wisconsin and supported robust naturally reproducing walleye populations throughout much of the 20th century [107, 113, 118, 119, 121, 128, 129, 130]. However, the lake has experienced a pronounced collapse in natural recruitment since the early 2000s [120, 121, 122, 123, 128]. Using the Walleye Recruitment Source Codes (Appendix D), Lake Minocqua was initially classified as Category NR (natural reproduction sustaining the population), later reclassified as C-NR in 1998 (natural reproduction sufficient, with supplemental stocking), and changed to C-ST in 2015, indicating adult populations are primarily sustained through stocking with limited natural recruitment. However, the 2024 recruitment survey [123] suggests the lake no longer sustains natural recruitment and will likely be reclassified as Category ST, meaning stocking is the sole source of recruitment.

Selection criteria

Lake Minocqua was selected for this study due to its extensive historical fisheries data and ongoing management and monitoring by the Wisconsin Department of Natural Resources (DNR) and Great Lakes Indian Fish and Wildlife Commission (GLIFWC). Following the reaffirmation of tribal treaty rights in 1985, these agencies established a regional walleye assessment and management program across the Ceded Territories of Wisconsin. The lake's inclusion in long-term fisheries assessments and stocking programs has made it one of the most well-documented lakes in the region, providing valuable longitudinal data on fish populations, recruitment trends, and management outcomes [121]. Its complex two-story structure supports a diverse fish community, including both cold- and warm-water species. However, a pronounced collapse in natural walleye recruitment since the early 2000s has made it a critical system for investigating recruitment bottlenecks [121]. High shoreline development, habitat degradation, and evidence of sedimentation and potential egg disturbance further position the lake as an ideal setting to examine environmental and biological stressors affecting early life stages. Additionally, the established absence of consistent natural recruitment [127] allows for evaluation of assisted reproduction efforts without confounding influences from ongoing natural reproduction, enabling a more precise assessment of artificial spawning interventions.

Site selection

Lake Minocqua's inclusion in long-term fisheries assessments and stocking programs has made it one of the most well-documented lakes in the region, offering valuable longitudinal data on fish populations, recruitment trends, and management outcomes. The lake's complex two-story structure supports a diverse fish community, including both cold- and warm-water species. However, a pronounced collapse in natural walleye recruitment since the early 2000s has made it a critical site for investigating recruitment bottlenecks.

Recent collaborative rehabilitation efforts including stocking, assisted reproduction, and habitat restoration have had limited success in restoring natural reproduction, highlighting the need for further research. Additionally, the lake's high shoreline development, habitat degradation, and evidence of sedimentation and potential egg disturbance make it an ideal site to examine environmental and biological stressors impacting the early life stages of age-0 walleye.

Experiment location

A comprehensive survey of potential spawning habitat on Lake Minocqua (Figure 5) was compiled by GLIFWC using a combination of sources, including qualitatively identified sites from assessments by GLIFWC and Wisconsin DNR personnel, agency netting catch rates, and spearing locations reported by Lac du Flambeau tribal members [121, 123].

Two primary spawning sites were selected for this study: Fisher's Island and Crescent Island**.** These locations have been historically known as key walleye spawning areas, providing rocky substrates that should be suitable for egg deposition and incubation. The state of Wisconsin owns both islands, which are "designated sensitive areas" with limited development, thereby reducing the potential influence of human activity, shoreline modifications, and associated environmental disturbances such as sedimentation and pollution. Additional peninsula spawning sites were considered, but there was limited time available before the spawn to secure the required permits and landowner consents.

Fisher's Island, the largest island on Minocqua Lake, is located in the central part of the east basin. This site offers a biological buffer zone where the establishment of existing vegetation on the southeast portion of the island reduces the likelihood of exotic invasion. Aquatic vegetation also stabilizes sediments, which reduces nutrient recycling and the possibility of algae blooms. The island also reduces the fetch across the lake, minimizing wave action and erosion potential. The substrate is primarily gravel and rubble on the northern portion of the island and sand and muck on the southeast portion.

Crescent Island is a small island east of Fisher's Island. This site offers a biological buffer zone where existing vegetation on the southeast portion of the island reduces the likelihood of exotic invasion. Aquatic vegetation also stabilizes sediments, which reduces nutrient recycling and the possibility of algae blooms. The island also reduces the fetch across the lake, minimizing wave action and erosion potential. The substrate is primarily sand and gravel.

Study design

The study design involved monitoring egg survival and age-0 recruitment using incubation enclosures placed on historical spawning sites in controlled and natural conditions using a combination of incubation enclosures, DNA analysis, and fall electrofishing surveys. Two spawning sites on Lake Minocqua were selected. At each site, three box configurations were deployed, all with permeable sides for unobstructed water flow and a layer of clean, ideally sized gravel for walleye spawning. Each enclosure configuration was designed to provide a varied level of protection from predation and habitat disturbance. Fertilized walleye eggs were also distributed on a substrate near the placement of the enclosures. The study period lasted for 44 days following the fertilization and deposition of eggs from April 15 to May 29, 2024.

Experimental incubation enclosures

Three box enclosure configurations were used to support walleye egg incubation while allowing evaluation of habitat suitability, predation pressure, and environmental disturbances. All enclosures featured permeable sides to permit natural water flow. In total, nineteen one-square-meter area "incubation boxes" were constructed of untreated lumber (Appendix E). There were three treatments for the boxes (six each): lidded with 1.27 cm diameter hardware cloth mesh inside a wooden frame or lidded with very fine mesh or no lid at all. The enclosures simulate natural environmental conditions and allow unobstructed water flow while providing varying levels of protection for eggs and larvae from predation, water disturbance, and sedimentation. The configurations allow for different levels of access to eggs and larvae - full access, limited access, and no access.

Enclosure placement

The enclosures were assembled on the shoreline and transported to the sites between April 8 and April 12, 2024. At each of the spawning sites (Site 1 – Fisher's Island and Site 2 – Crescent Island), three enclosures of each configuration were placed upon the spawning reef (Appendix F). The boxes were placed at an average depth of 54.5 cm. The westward-facing side of the islands was selected to support adequate water flow through the enclosures. Each enclosure contained a layer of clean, appropriately sized gravel to mimic suitable spawning conditions. To ensure consistency between natural and experimental settings, washed rock substrate sourced from a local quarry was used in each enclosure. A prefabricated metal enclosure with a lid was placed at each location, using the same gravel treatment, to monitor whether hatching had occurred. HOBO data loggers were attached to each box to monitor water temperature. A system using trail cameras and a staff gauge was installed to monitor water levels and wave action at 15-minute intervals. In order to protect the eggs from boats, each box was affixed with a red buoy marker, and signs were posted at each of the lake's three boat launch sites alerting boaters of the research project.

Walleye capture and sampling

Following the ice-out on Lake Minocqua, GLIFWC staff began monitoring the lake for signs of spawning activity. On April 8 and April 12, night electroshocking was used to capture ripe adult walleye from the lake to collect sperm and eggs for fertilization. The survey team used electrofishing to capture males for the population estimate, then placed them in holding pens until the experimental sites were prepared. The capture process spanned several days until the necessary number of males and females is obtained. Captured walleyes were held in a retainer enclosure submerged near the boat landing and tethered to the dock. During that time, the walleyes were measured and sexed. A total of 124 males and 22 females were captured and used to collect eggs and sperm.

Between April 15 and April 19, 2024, the ripe walleyes were removed from the holding pens, placed in aerated fish crates in the boats, and taken to the spawning sites. At each site, a female walleye was identified and placed in a separate bin, and then 4-5 males were placed into a second bin. The selected fish were transported in the bins to each spawning site. At each site, the selected male and female walleyes were measured for length. The adult fish measured between 12.1 and 27.9 inches (30.7–70.9 cm), with the females generally larger in size than the males (Figure 6).

The DNA sample was collected from each fish used, and standard procedures for fin clips were followed. A small piece of fin tissue from the caudal is collected using scissors and wiped clean between samples. The tissue size was approximately five sq. mm. Each fin sample was deposited into a preservative-filled (at least 95% ethanol) cryotube after placing the tissue sample in a cryotube filled with EtOH. The sample number and collection date were placed on each vial. The samples were shipped to the Molecular Conservation Genetics Lab at the Wisconsin Cooperative Fishery Research Unit, University of Wisconsin-Stevens Point, for DNA analysis.

Egg collection and fertilization procedures

Following a predetermined fertilization procedure prescribed by the University of Wisconsin-Stevens Point (Appendix G), the female was removed from the bin, and the fish's abdomen was dried to remove any water. Eggs were removed from gravid female walleyes by manual stripping, where the abdomen was gently squeezed, starting near the vent and moving toward the head. The eggs were expressed into a beaker, measured, and recorded. The exact process was followed to express sperm from 4-6 male walleye, with the milt placed in a graduated cylinder. Once the eggs and sperm are collected, the milt from the male fish is gently mixed with the eggs, and the mixture is stirred for a minute using a rubber utility brush to ensure fertilization. A small amount of lake water is added to the graduated cylinder to rinse any remaining sperm from the sides and transfer it to the eggs. The addition of water also activates the eggs, causing them to become adhesive and adhere to the substrate. The beaker is covered to avoid spillage, and the fertilized eggs are dispersed over the designated spawning area. In addition to placing the fertilized eggs in the incubation enclosures, fertilized eggs were placed directly onto the spawning site near the boxes without a treatment protocol. The process was repeated at each location and spawning enclosure. (Appendix H).

A total of 4180 mL of eggs were placed with the volume dispersed, averaging 190 mL at each location (with a range from 50 mL to 410 mL). Using the Wisconsin DNR's estimate for the number of eggs per mL (125 eggs per mL) – based on Malison and Held [131] and hatchery data, approximately 522,500 fertilized eggs were placed (4/14-19). In addition to the placement of fertilized eggs for research purposes, Walleyes for Tomorrow utilized its mobile fish hatchery to raise and release 3.9 million walleye fry (5/06-09; avg. length - 2.54 cm) into Lake Minocqua during the same period.

Experimental enclosure monitoring

During the 30 days following fertilization and egg placement, the experimental enclosures were regularly checked to monitor egg and hatching survival and address any issues with the enclosures or equipment. The interior and exterior of the incubation boxes were visually inspected for walleye larvae and fry (Appendix A). Following these inspections, the experimental boxes and monitoring equipment were removed after May 29, 2024.

In addition to regular visual inspections, HOBO data loggers were attached to each box to record temperature data, and a trail camera system was set up to capture wind speed. Water level fluctuations were measured at two field sites using time-lapse trail cameras positioned to capture a fixed ruler mounted vertically on a post. At the start of each deployment, the initial water level relative to the ruler was recorded as a baseline. Cameras were programmed to capture images at 10-minute intervals throughout the sampling period. For each image, the change in water level was calculated as the difference between the initial and observed values and standardized by dividing by the total depth of the wind gauge at each site (62.23 cm at Site 1; 76.2 cm at Site 2). This produced a normalized "wind level value" expressed as a fraction of total depth, allowing comparisons between sites with differing depths.

$$\text{Wind Level Value} = \frac{\text{Change in Water Level}}{\text{Total Depth}}$$

This standardization allowed water-level changes to be expressed relative to site-specific depths, facilitating comparisons between sites.

Fall sampling

On October 1 and October 29, 2024, Wisconsin DNR and GLIFWC staff conducted the annual electrofishing population survey on Lake Minocqua. These coordinated electroshocking surveys targeted gamefish populations–particularly juvenile walleye–in shallow, nearshore areas ranging from 0.30 to 1.22 m in depth. Standard electrofishing boats were used, each equipped with two booms, each fitted with three flexible, corrosion-resistant steel-tube dropper electrodes. Crews consisted of two netters and one operator, with the operator maintaining a boat speed of 2.25–2.57 kilometers per hour to minimize shoreline resampling. Routes for each boat crew were predetermined and used on both dates. According to the standard lake map, Lake Minocqua has 30.7 kilometers of shoreline. The lake was surveyed twice: on October 1, 19.8 kilometers were surveyed for all gamefish over 5.9 hours; on October 29, the total survey mileage was 30.7 kilometers, again targeting all gamefish. Water temperatures were 19.4°C on October 1 and 13.3°C on October 29. Size and species data were recorded for all captured fish, and DNA samples were collected only from age-0 walleyes during fall sampling. Collection protocols were consistent with those used for adult walleyes during the April spawning period.

DNA analysis

DNA samples were collected from adult walleye used for spawning in April, along with age-0 walleyes captured in October, and were shipped to the Molecular Conservation Genetics Lab with the Wisconsin Cooperative Fishery Research Unit at the University of Wisconsin-Stevens Point for DNA analysis. The DNA analysis was used to determine paternal lineage using reference samples from the adult walleyes involved in the spawning procedure.

RESULTS

Despite extensive stocking and assisted reproduction efforts, only three age-0 walleyes (*Sander vitreus*) were detected during the fall 2024 recruitment survey, indicating a near-total recruitment failure. Genetic analysis conducted by the Wisconsin Cooperative Fishery Research Unit at the University of Wisconsin-Stevens Point for DNA determined that none of the captured individuals originated from the stocked egg cohorts. Additionally, the extremely low number of juveniles, despite Walleyes for Tomorrow's fry stocking, further suggests that natural reproduction is virtually non-existent and that these assisted efforts may not be effectively contributing to recruitment.

Treatment effects on egg retention and survival

There were minimal to no observable differences between treatment groups (lidded vs. unlidded boxes), with both treatments exhibiting similarly low hatching success and widespread egg mortality. Visual inspections indicated that egg loss and mortality occurred across all boxes regardless of treatment. At the conclusion of the study period, unhatched eggs remained present within several incubation boxes, further indicating incomplete development and failed hatching.

The number of eggs dispersed from the incubation boxes could not be directly quantified. However, the absence of fry and egg remains during repeated inspections suggests that any eggs dislodged from the boxes were either transported out of the immediate study area or experienced mortality outside the enclosures.

Visual inspections of the boxes revealed widespread egg mortality at the incubation stage. Environmental data collected during the spawning and incubation periods identified several potential stressors present during the study, including fluctuating water temperatures, limited water circulation within the enclosures, and potential microbial activity (e.g., fungal or bacterial presence).

Temperature patterns during incubation

Following egg placement (April 15–19), mean water temperatures were 6.42°C at Site 1 (Fisher's Island) and 6.93°C at Site 2 (Crescent Island). Water temperatures increased over time and approached the optimal incubation range by approximately May 4. However, a cold period from April 20 to April 22 maintained average temperatures near 6°C across sites. Temperature also varied among box locations, including one location where temperatures reached approximately 8°C shortly after egg placement, then declined to less than 6°C during the cold period (Figure 7). Later in the study, from May 8 to May 29, water temperatures exceeded the upper range of optimal incubation conditions. Patterns in water temperature corresponded with trends in daily air temperature (high and low), with the April 20–22 cold period and subsequent warming reflected in both air and water temperature trajectories (Figure 8).

Incubation outcomes and biotic interactions

Box inspections were conducted three times per week throughout the incubation period. No dead fry were observed in or immediately surrounding the incubation boxes during any sampling event. The absence of fry remains suggests that either hatching success was minimal or that, upon hatching, fry did not remain within the vicinity of the boxes. These observations indicate that if hatching did occur, fry were likely capable of dispersing away from the incubation structures shortly after emergence.

Mudpuppies (*Necturus maculosus*) were observed occupying nesting sites beneath two incubation boxes, including one lidded and one unlidded treatment. No direct evidence of egg predation within the boxes was observed during routine inspections. However, the presence of mudpuppies in close proximity to the incubation structures suggests the potential for opportunistic predation on eggs that may have drifted beyond the confines of the boxes.

Wind exposure at incubation sites

Wind-driven water movement was quantified using time-lapse trail cameras positioned at each site, which captured images of a fixed ruler at 10-minute intervals. Initial water depth was recorded at the start of each deployment, and subsequent images were used to measure changes in water level relative to this baseline. Due to missing or incomplete image records, the dataset was filtered to include only valid observations, and analyses were restricted to time points with synchronous measurements at both sites. Mean wind level values differed between sites, with Site 1 averaging 0.097 and Site 2 averaging 0.033, indicating greater relative water displacement at Site 1 (Figure 9). Variability in water level was also higher at Site 1 across the observation period.

Age-0 walleye recruitment survey results

Recruitment surveys were conducted on two dates: October 1 and October 29. The initial survey on October 1 covered 30.7 kilometers of Lake Minocqua shoreline and resulted in the capture of two age-0 walleyes. Survey efforts were hindered by dense vegetation and numerous shoreline structures (e.g., docks and boat lifts), which limited nearshore access. The second survey, conducted jointly by Great Lakes Indian Fish and Wildlife Commission (GLIFWC) and the Wisconsin Department of Natural Resources (DNR) on October 29, covered 30.7 kilometers and netted one age-0 walleye. In total, 96 walleye, as well as several gamefish, were caught during the October 29 survey (Table 3; see Appendix I for the full survey record).

DISCUSSION

While the results were inconclusive in fully supporting the study's research questions, the findings provide important insights into the ongoing recruitment challenges facing walleye (*Sander vitreus*) in Lake Minocqua. The extremely low number of age-0 walleyes detected during the fall recruitment survey indicates that recruitment failure occurred. Results showed no genetic matches, reinforcing observations that post-spawning environmental conditions and biological pressures are likely limiting successful recruitment in Lake Minocqua, even when fertilized eggs are placed in high-quality habitats.

Hatching appeared to have failed within the incubation boxes and may have resulted from multiple factors, including poor fertilization success, suboptimal water temperature or flow, or external stressors such as bacterial or fungal infections. While there may have been hatching failures in the experimental boxes, 3.9 million walleye fry were released by Walleyes for Tomorrow during the same period. The extremely small number of walleye age-0 found in the fall recruitment survey reflects a failure across the recruitment cycle with an emphasis on reproduction as well as the larval and juvenile life stages.

Limitations in water flow and oxygen conditions

While this study aimed to evaluate key factors influencing age-0 walleye survival, the incubation box design, intended to simulate natural substrate and provide protection, may have inadvertently restricted water circulation, creating low-oxygen conditions unfavorable for egg development. Although wave action occurred over the boxes, the structure and mesh covering likely reduced water flow and agitation. Given that walleye eggs are highly sensitive to stagnant or low-oxygen conditions during early incubation, reduced circulation may increase susceptibility to microbial growth.

In natural spawning environments, eggs deposited on gravel or rocky substrates benefit from continuous exposure to oxygen-rich, flowing water. In contrast, eggs within the incubation boxes may have experienced limited dispersion and clumping, further restricting circulation and oxygen availability. On May 6, 2024, a substance visually consistent with *Saprolegnia* spp. (Oomycetes) was observed in two incubation boxes (Appendix J); however, identification was based on visual observation and was not laboratory-confirmed. This observation preceded the increase in water temperatures recorded by HOBO loggers beginning May 8, suggesting that reduced water flow—rather than temperature—may have contributed to fungal development. These findings raise concerns regarding water flow dynamics within the incubation boxes and the effectiveness of their design.

Fluctuations in water and air temperature

As noted in the literature review, spawning success is also strongly influenced by water temperature and climate variability, with unseasonal temperature fluctuations potentially disrupting development. Thermal conditions observed during the incubation period likely played a critical role in limiting hatch success. Optimal incubation for walleye typically occurs near 10°C, yet temperatures following egg placement remained below this range and were further disrupted by a short-term cold snap before later exceeding optimal levels. This pattern of early cold exposure followed by rapid warming reflects the type of phenological variability described by Barta et al. [131], who found that delayed spawning cues and increasing temperature extremes can negatively affect walleye recruitment in north-temperate lakes.

Exposure to prolonged suboptimal temperatures early in development may have slowed embryonic growth, extended the incubation period and increasing vulnerability to environmental stressors such as fungal infection. Subsequent increases in temperature later in the incubation period may have further compounded stress during critical developmental stages. Together, these fluctuating thermal conditions suggest that both the timing and variability of temperature are important drivers of incubation success. In this context, temperature instability may have contributed to the low hatching success observed in this study.

Bias in wind-driven water movement estimates

The interpretation of wind-driven water movement in this study is constrained by several methodological limitations that introduce bias into the estimates. Most notably, the cameras and associated gauges were deployed at different depths between sites (62.23 cm/24.5 in at Site 1 vs. 76.2 cm/30 in at Site 2). Because wave formation is depth-dependent, shallower water requires less energy to produce a given change in surface elevation, meaning that depth directly influences the energy required to generate observable wave motion. As a result, a 2.5 cm change in water level at the shallower site likely reflects less wind energy than the same change at the deeper site. This introduces inherent bias into the standardized "wind level value," as the greater magnitude and variability of water-level change observed at Site 1 may be driven in part by increased sensitivity to wind forcing under shallower conditions rather than true differences in wind exposure alone. Consequently, the shallower location (Site 1) would be expected to exhibit greater apparent variability in wave action even under similar wind conditions. In contrast, if comparable or greater variability is observed at the deeper location (Site 2), it can be more confidently inferred that stronger wind forcing occurred at that site. Additional limitations include reliance on visual interpretation of ruler measurements from images, potential measurement error due to image resolution or angle, and the exclusion of non-synchronous observations, which reduced the dataset and may limit representativeness. Together, these factors suggest that the results should be interpreted cautiously, with particular attention to the confounding influence of depth on inferred wind-driven processes.

Environmental monitoring limitations

Limitations in environmental monitoring also affected data collection. As noted, the monitoring system used to collect data on wind, water level, and water motion was inconsistent and sporadic, relying on daylight-only visual observations (via field camera). The inconsistency of the water-level measurement system did not provide reliable data to assess the impact on the assisted reproduction effort. In retrospect, wind gauges and water level gauges (HOBO) should have been placed in each location. Third, the egg disbursement may not have been adequate, and some clumping was observed in each box. Alternative methods for effectively depositing eggs onto the substrate to mimic natural deposition by females should be further investigated.

Observational limitations further restricted the ability to assess outcomes within the incubation boxes. Regular visual inspections could not reliably determine whether hatching had occurred or whether predation was taking place. Ideally, the visual inspection should have been augmented using time-lapse video. The absence of a direct predator exclusion assessment limited the study's ability to evaluate biotic pressures on early life stages. While predation was hypothesized as a potential factor in poor survival rates, no specific measures were implemented to test this directly. Taken together, these methodological challenges highlight the need for future studies to improve monitoring in incubation environments, investigate alternative enclosure designs that more accurately mimic natural flow conditions, and develop additional methods to track age-0 walleye survival. Enhancing environmental data collection and increasing replication would further strengthen statistical power and improve the reliability of interpretations.

Genetic analysis constraints and recruitment failure

While genetic analysis was intended to trace juvenile walleye collected during fall recruitment surveys back to the adults used in fertilization, the extremely limited number of age-0 walleye recovered (n = 3) severely constrained the effectiveness of this approach. This low sample size is consistent with fall survey data indicating near-complete recruitment failure in the system, reflecting both the lack of natural reproduction and the limited success of experimental interventions. As a result, the small number of individuals precluded meaningful genetic attribution and prevented evaluation of relative success across treatments.

Post-hatch juvenile habitat

Concurrently with the ongoing evaluation of walleye recruitment, Great Lakes Indian Fish and Wildlife Commission (GLIFWC) initiated a complementary study focused on age-0 walleye habitat in Lake Minocqua. Investigating this early post-hatch stage provides critical insight into how habitat availability and broader ecosystem conditions influence recruitment outcomes and help pinpoint where recruitment failure is occurring. As highlighted by Gostiaux et al. [118], recruitment bottlenecks in declining walleye populations consistently emerge after hatching but prior to mid-July. From June to August 2024, GLIFWC conducted a comprehensive assessment of juvenile fish habitat across Minocqua Lake to better understand the impacts of ecosystem changes on early life-stage walleye. Snorkeling and electrofishing surveys were used to locate, map, and characterize juvenile habitat, defined as areas used for spawning/hatching, feeding, and nursery by age-0 and age-1 fish across all observable species (Appendix K). In the study, juvenile fish were documented along approximately 12.87 km (48.1%) of the shoreline, and preliminary data indicated a strong presence of age-0 species in key nursery habitats. These included both piscivorous age-0 fish and their prey. The survey results are aligned with the fall recruitment survey results, which noted a significant lack of age-0 walleye. Of note, walleye abundance was notably lower than that of largemouth bass, smallmouth bass, and northern pike, prompting consideration of failure during the hatching, larval, or early demersal stages.

Presence of centrarchidae

The 2024 GLIFWC juvenile habitat survey indicated a high presence of centrarchidae species, including bluegill, black crappie, largemouth bass, and smallmouth bass, which aligns with a previous population assessment survey conducted by the Wisconsin Department of Natural Resources (DNR) and GLIFWC in 2015, which demonstrates that a shift in the population dynamics has been occurring over time. These findings align with broader trends in fish community restructuring, where climate change, shoreline development, and recreational fishing regulations have led to the increasing abundance of centrarchids in northern Wisconsin lakes [132, 133, 134]. This shift presents a challenge for fisheries management aimed at maintaining or restoring walleye populations. Reciprocal dynamics - where increasing black crappie, largemouth bass or smallmouth bass abundance coincides with declining walleye recruitment - underscores the management challenges for systems with multiple species [108, 115, 134].

IMPLICATIONS

The results of this study underscore the persistent, multifactorial nature of walleye recruitment failure in heavily developed lake systems such as Lake Minocqua. Despite implementing assisted reproduction techniques, including the controlled deposition of fertilized eggs and protective enclosures (and stocking of 3.9 million walleye fry by Walleyes for Tomorrow), the near-total absence of age-0 walleyes in fall surveys suggests that early life-stage bottlenecks remain a critical constraint on population recovery. The lack of results presents several key implications for fisheries science and management.

Limitations of assisted reproduction alone

The failure of assisted reproduction to produce measurable fall recruitment survey results highlights the ineffectiveness of both the stocking and fertilization efforts. The failure suggests that without concurrent improvements to environmental conditions–particularly substrate quality, water circulation, and protection from sedimentation–such interventions may yield limited returns. Habitat degradation, mainly due to shoreline development and sedimentation, continues to act as a significant barrier to natural reproduction.

Critical window: egg to early larval survival

Walleye recruitment bottlenecks likely occur before mid-July, during the first few months of the life cycle, as evidenced by the absence of age-0 individuals in mid-summer samples. This pattern suggests that recruitment limitations arise during early life stages [118]. Our study's results highlight that egg mortality and poor larval survival throughout the first few months are clearly a primary concern. Despite successful fertilization and targeted egg placement in suitable habitats, the near-complete absence of juvenile walleyes in fall surveys indicates substantial mortality during both incubation and the early post-hatch period. This position aligns with previous research identifying the transition from egg development to the ontogenetic habitat shift in early summer as a critical bottleneck for recruitment. This period must be a focal point for future investigation and adaptive management.

Expanding on the work of Gostiaux et al. [118], future studies could focus on the critical phase when larval walleye drift through open water feeding on zooplankton. Deeper offshore feeding areas for larval walleye are frequently subjected to recreational and wake boat activity, which may disrupt zooplankton communities and reduce prey availability. Monitoring this stage would help determine hatching success and assess the availability of early life energy sources. To accomplish this, researchers could employ ichthyoplankton nets, light traps, or other non-invasive sampling techniques specifically designed to collect larval fish without causing harm. Such approaches have already been effectively used in studies investigating recruitment bottlenecks for age-0 walleye in northern Wisconsin lakes.

Moreover, the absence of age-0 walleye also raises concerns about the survival of stocked fry. With nearly four million fry deposited into Lake Minocqua in April, the lack of age-0 representation in fall sampling suggests high post-stocking mortality. Prior studies have demonstrated that largemouth and smallmouth bass can exert intense predation pressure on stocked age-0 walleyes, often consuming a significant proportion within days of release. These results reinforce the importance of considering predator densities, timing of stocking, and refuge availability when designing stocking programs, particularly in systems with high warm-water predator abundance.

Temperature and ice-out phenology as recruitment drivers

One of the most consequential environmental stressors identified in this study is the effect of water temperature variability and early ice-out on recruitment dynamics. Earlier ice-out, a trend consistent with climate change, is known to disrupt the synchrony between spawning and the availability of zooplankton–a key food source for newly hatched walleye. If larvae hatch after the zooplankton bloom has peaked, they may experience food limitation during a critical window of development, contributing to starvation and reduced survival [108, 134, 135]. Moreover, fluctuating water temperatures during incubation can impair egg development, increase the risk of fungal infections, and delay or fail hatching. Future management should incorporate fine-scale monitoring of thermal regimes and consider timing-based strategies to align spawning, hatching, and food web productivity under changing climatic conditions.

Impacts of climate and biotic pressures

Warming temperatures, extended growing seasons, and expanding populations of warm-water predators, such as largemouth and smallmouth bass, are increasingly favoring species better suited to shifting thermal regimes. These changes, driven in part by climate change, are reshaping fish community structures across northern lakes. In systems like Lake Minocqua, where conditions are trending away from historical norms, this may place cold-water species like walleye at a distinct disadvantage. Compounding this trend is the widespread angler preference for catch-and-release practices targeting largemouth and smallmouth bass, which enables the continued growth and survival of mature individuals and contributes to sustained or increasing predator densities. Together, these forces underscore the urgency of reassessing the long-term viability of walleye in transitional or marginal systems and defining ecological thresholds beyond which natural recovery may not be feasible without substantial, ongoing human intervention.

Need for holistic habitat restoration

The study confirms the importance of high-quality spawning habitat but also reveals that even locations presumed to be suitable (e.g., Crescent and Fisher's Islands) may not offer the necessary microhabitat conditions for successful egg development and hatching. Restoration efforts must move beyond the installation of artificial reefs and toward more comprehensive shoreline management practices, including buffer zones, erosion control, and substrate rehabilitation tailored to site-specific hydrodynamics.

Management implications

For the Great Lakes Indian Fish and Wildlife Commission (GLIFWC) and the Wisconsin Department of Natural Resources (DNR), the study emphasizes the importance of integrating habitat assessment, biotic community monitoring, and environmental trend analysis into stocking and harvest strategies. The reliance on stockings to maintain adult walleye populations may be hiding deeper ecological issues.

Restoring sustainable walleye populations in northern Wisconsin's inland lakes will require more than supplemental stocking or isolated habitat enhancements. Successful management requires a comprehensive, systems-based approach that addresses the interconnected influences of habitat quality, predation, climatic variability, and human lake use. While this study may not have yielded new solutions to the challenges presented by age-0 walleye survival, it has contributed insights into the use of protective incubation enclosures. It reaffirmed the vulnerability of age-0 walleye during critical early life stages and underscores the low viability of natural egg hatching under current environmental conditions in Lake Minocqua.

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TABLES

Table 3: Gamefish caught during Fall recruitment surveys

	October 1	October 29
Walleye age-0	2	1
Walleye age-1	93	64
Walleye other (over 13.0”)	50	31
Largemouth Bass	87	111
Smallmouth Bass	8	22
Muskellunge	1	4
Northern Pike	9	40
Other species observed: black crappie, bluegill, pumpkinseed, rock bass, yellow perch, and minnows		

FIGURES

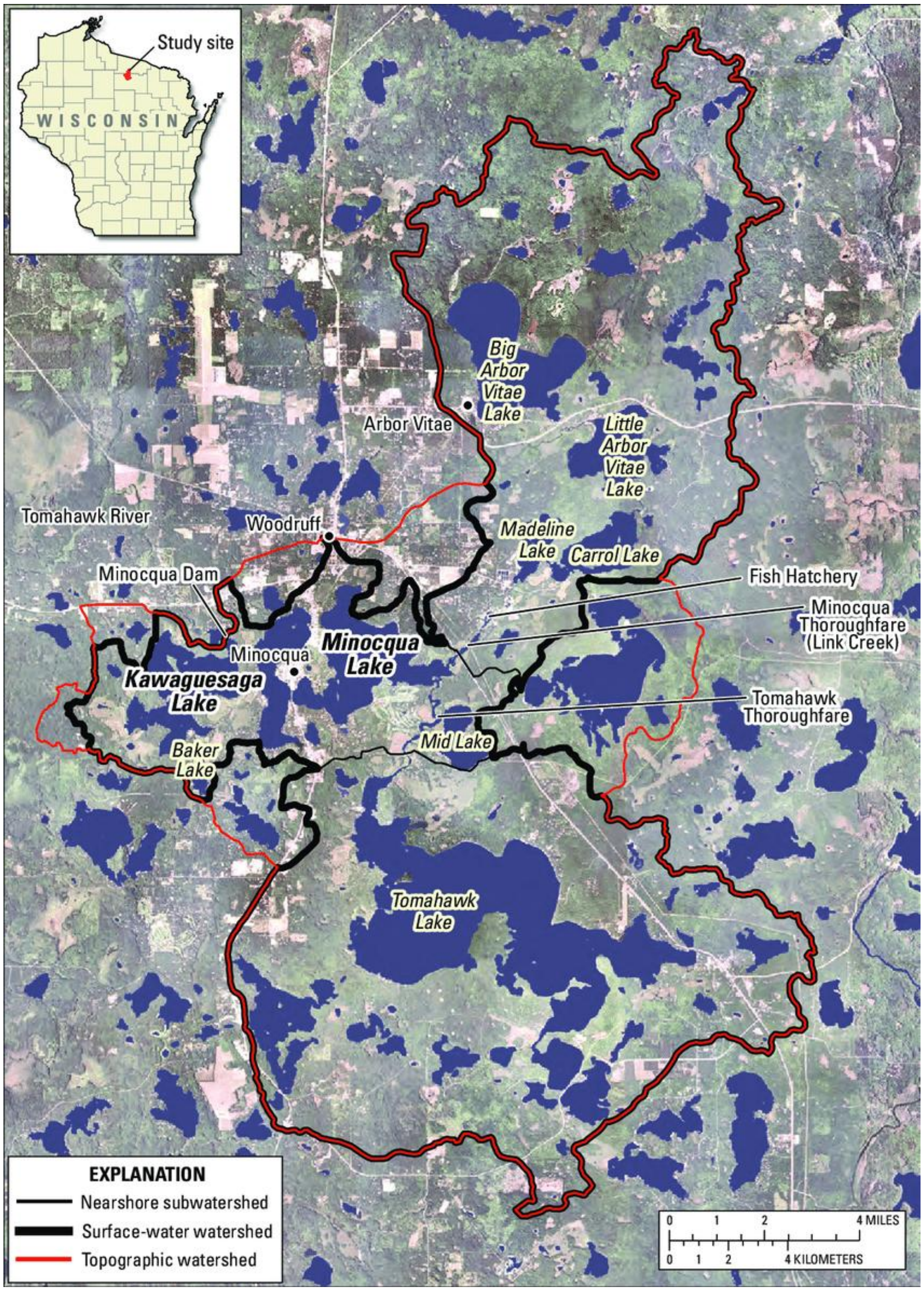


Figure 1 Satellite imagery of the Minocqua Chain of Lakes watershed, showing Minocqua Lake, Kawaguesaga Lake, Tomahawk Lake, and connected waterbodies. The map delineates nearshore subwatersheds (black outline), surface-water watersheds (gray outline), and the broader topographic watershed (red outline). (From Garn, H. S., Robertson, D. M., Rose, W. J., & Saad, D. A. (2010). *Hydrology, water quality, and response to changes in phosphorus loading of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, with special emphasis on effects of urbanization* (Scientific Investigations Report 2010–5196). U.S. Geological Survey.

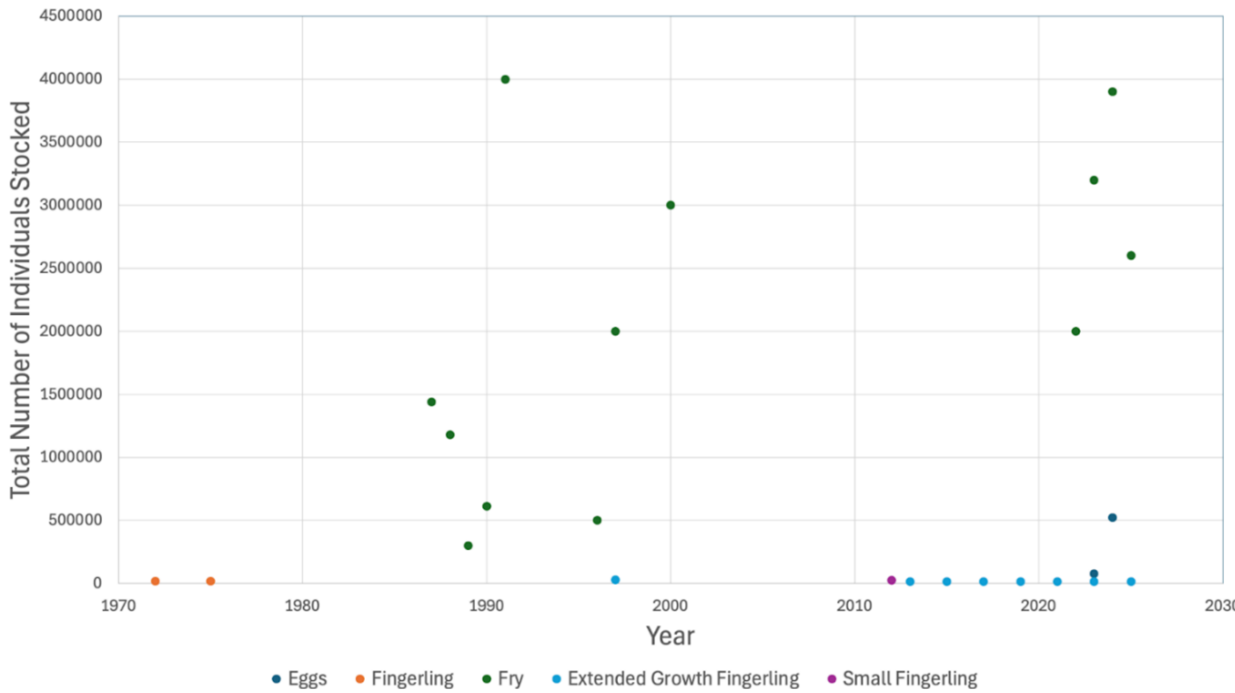


Figure 2. Annual walleye stocking numbers for Lake Minocqua between 2007-2024, based on Wisconsin DNR data

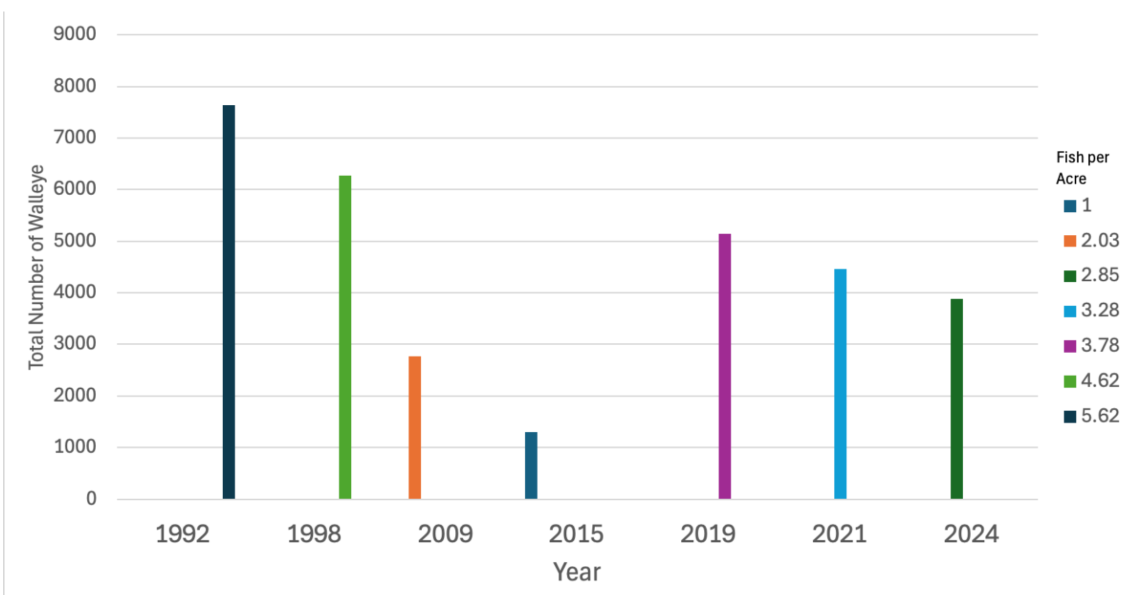


Figure 3. Estimated adult walleye population in Lake Minocqua across selected years (1992–2024), showing a long-term decline followed by partial recovery in recent surveys (Wisconsin DNR/GLIFWC records)

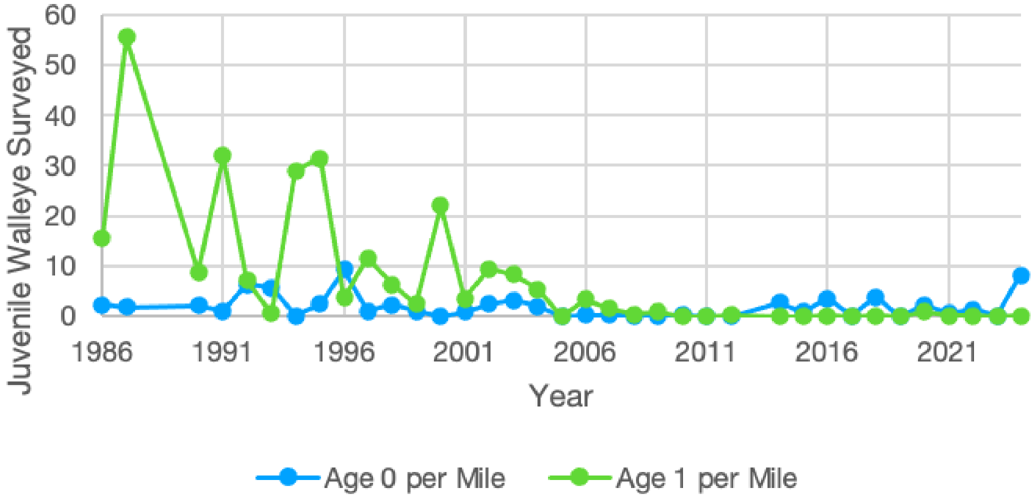


Figure 4. Annual estimates of total walleyes, age-0 and age-1 from Fall assessments (1986 to 2024). Fluctuations in age-0 abundance highlight variable recruitment success, while age-1 and total walleye numbers reflect survival and broader population trends over time. (GLIFWC and Wisconsin Department of Natural Resources records)

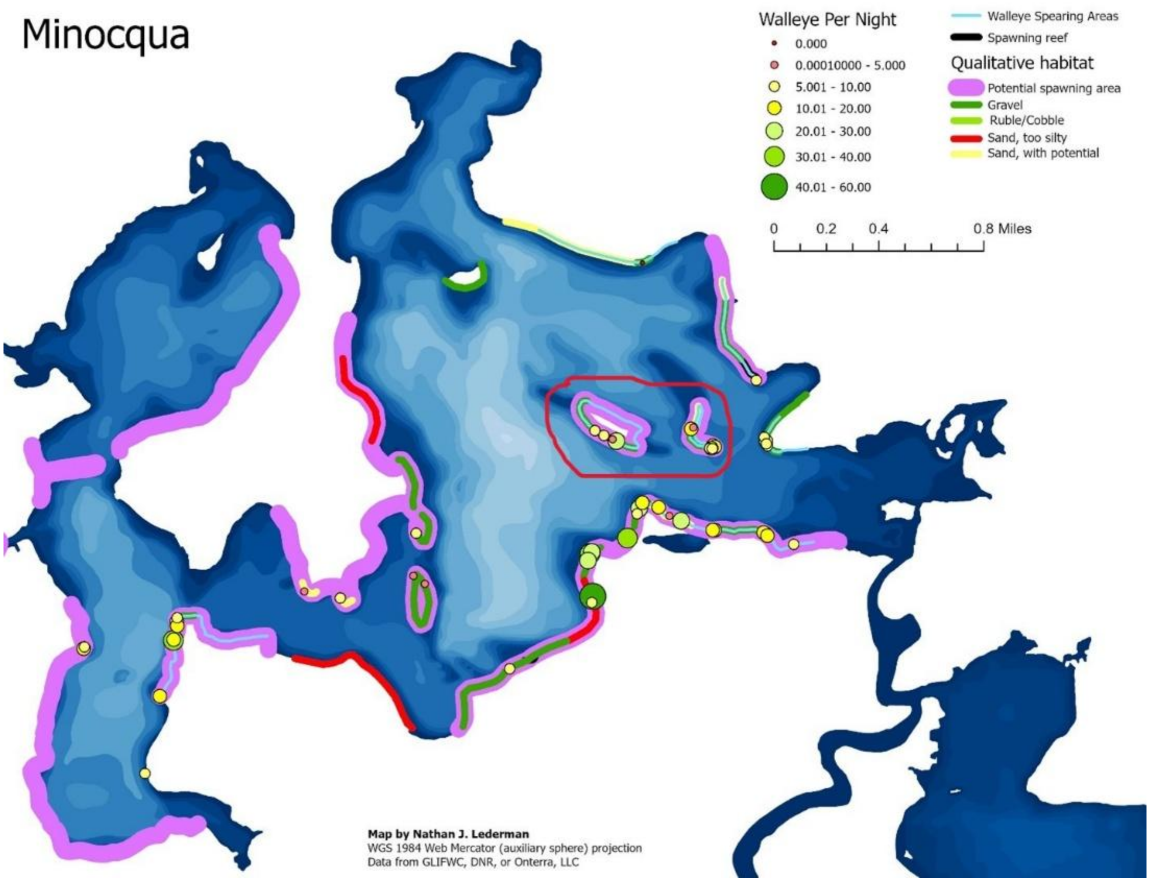


Figure 5. Map illustrating walleye spawning habitat on Lake Minocqua. The primary spawning sites selected for the study – Fisher's Island and Crescent Island are circled in red (source GLIFWC)

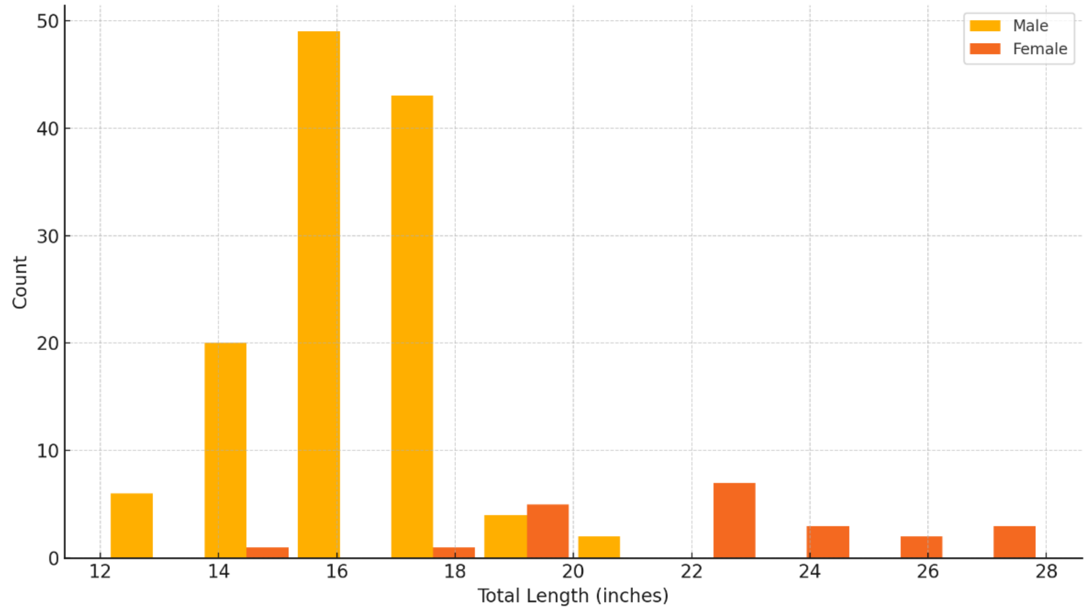


Figure 6. The size distribution of male and female walleyes used to fertilize the eggs used in the study.

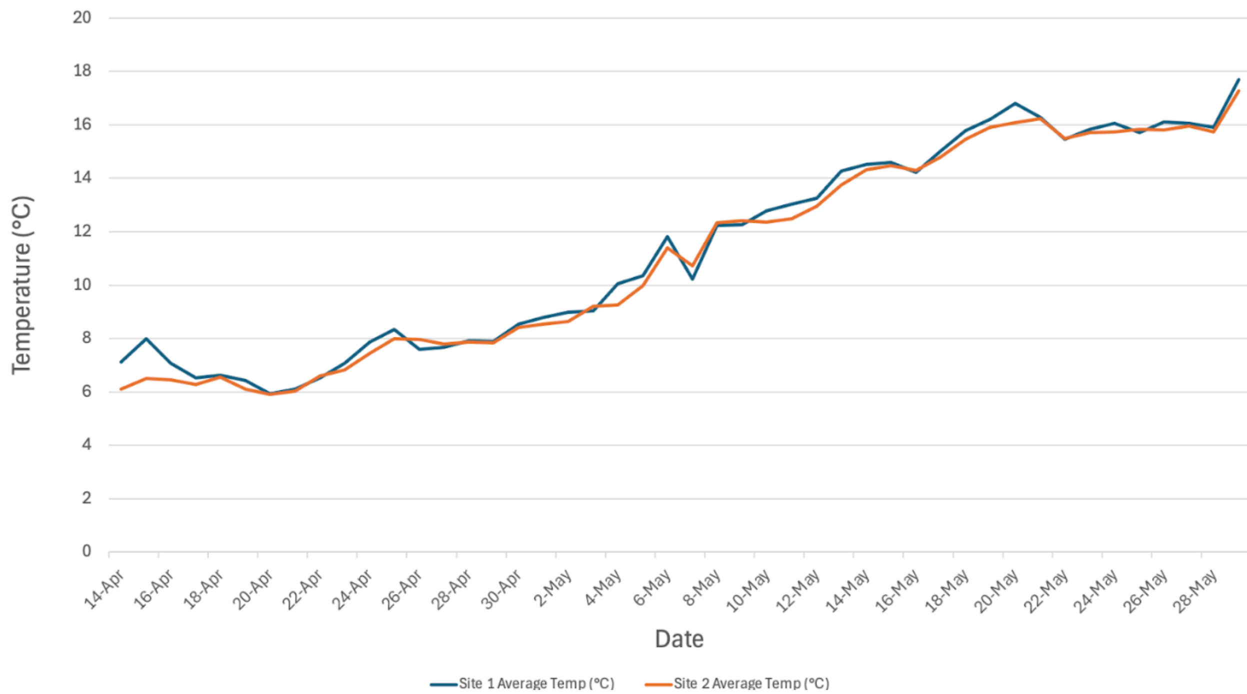


Figure 7. Chart tracking the average water temperatures within each spawning site based on temperatures taken in individual incubation box at each site from April 14-May 29, 2024

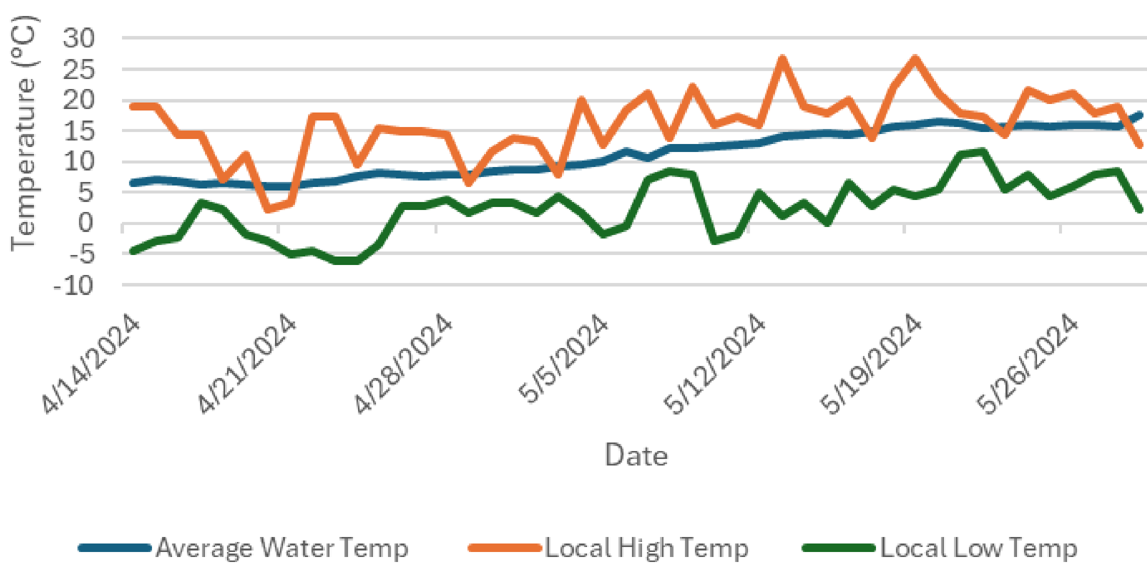


Figure 8. Comparison of the daily air temperature (high and low) and average water temperature at incubation sites from mid-April through late May (April 14 – May 29, 2024) (source: ExtremeWeatherWatch.com and HOBO data from the study).

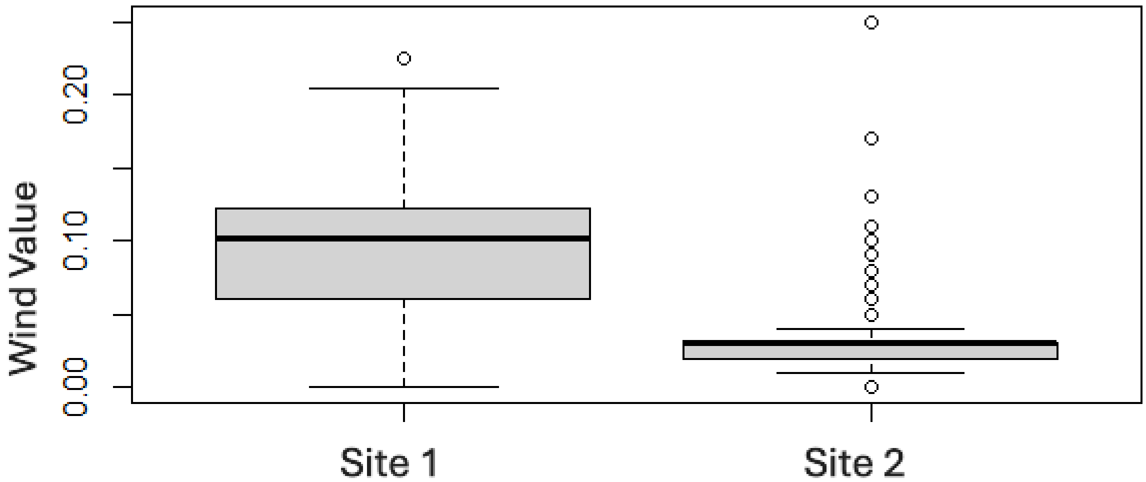
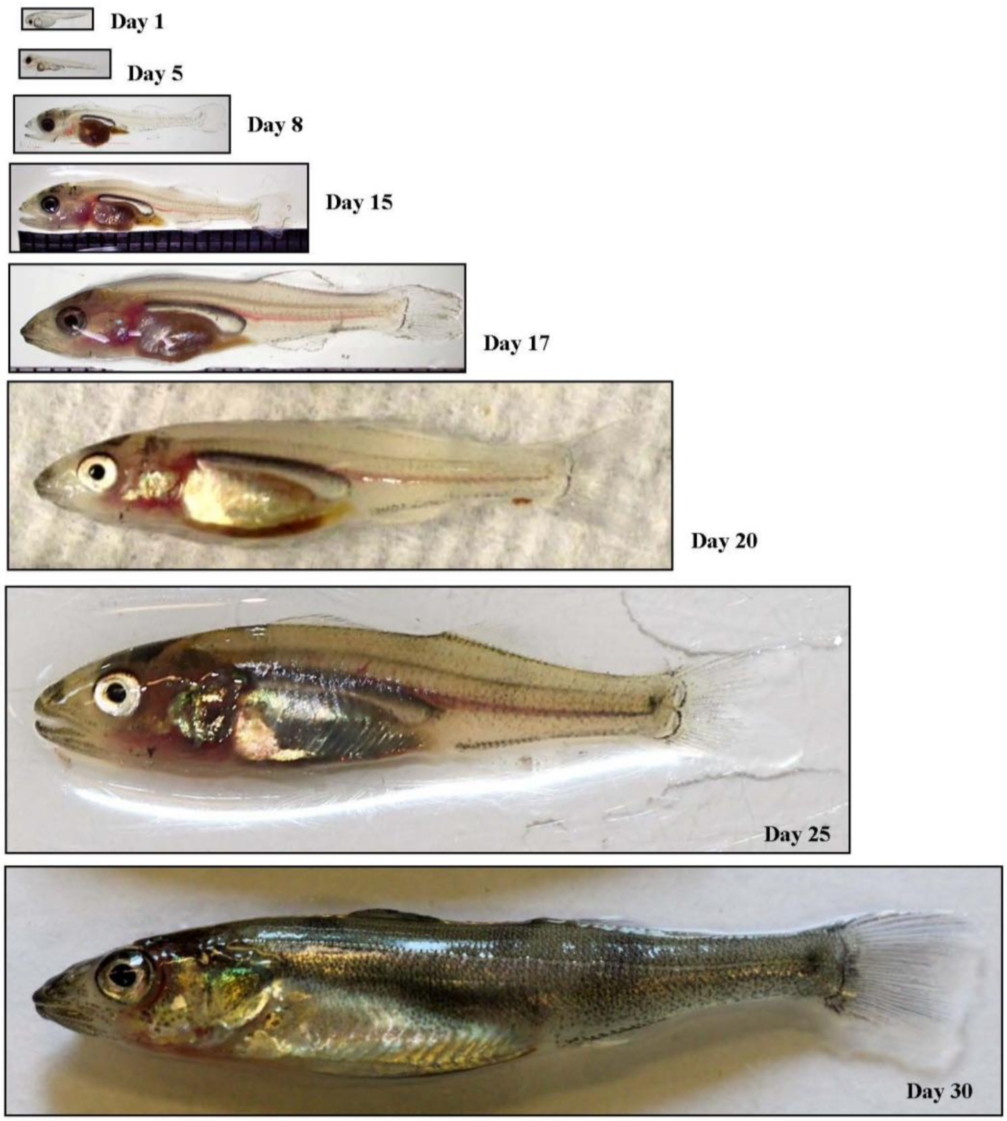


Figure 9. Boxplot comparison of standardized wind-driven water displacement between spawning sites. Values represent relative changes in water level over time, adjusted for gauge depth. Site 1 showed higher variability and median displacement than Site 2, with potential bias due to depth differences.

APPENDICES

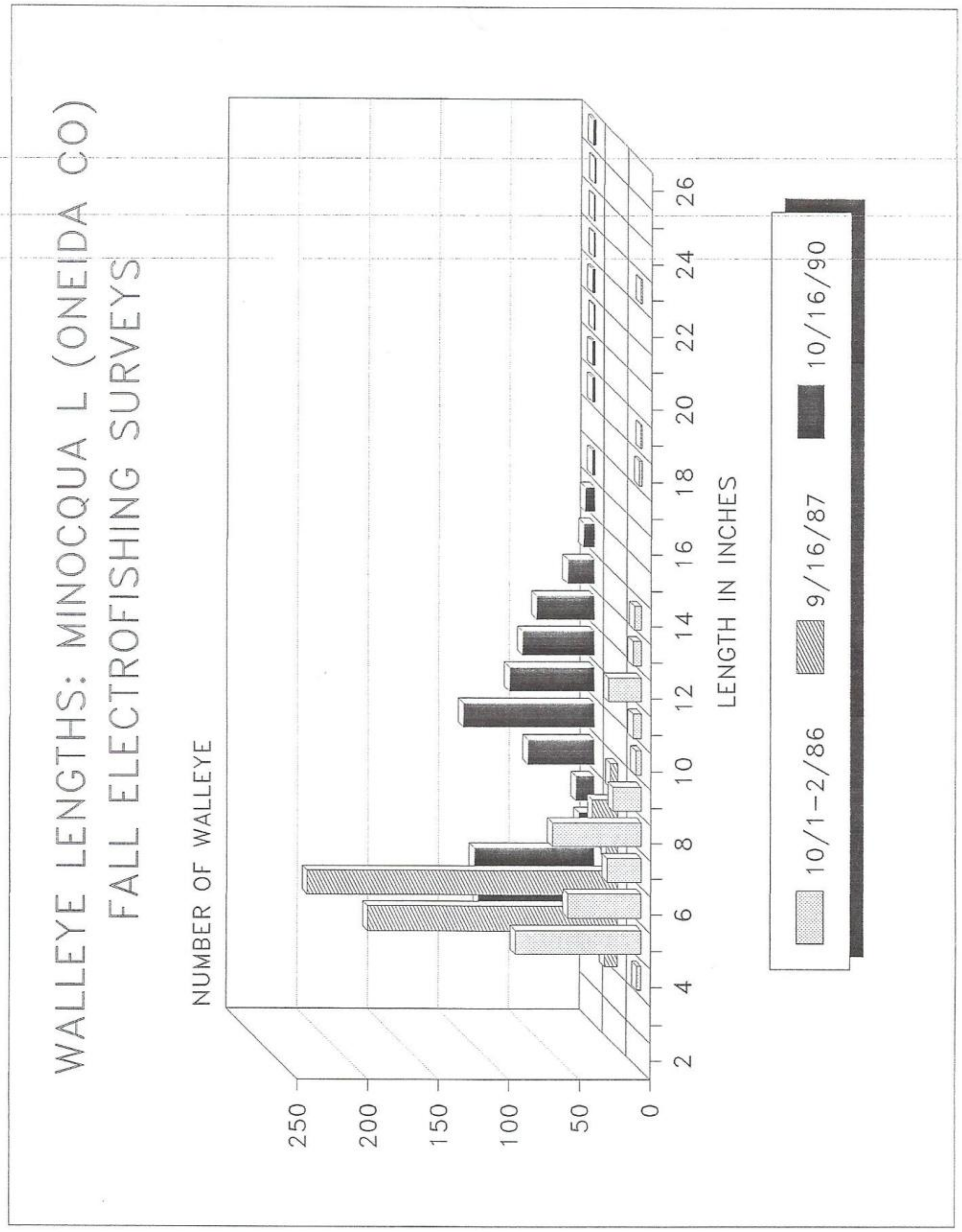
APPENDIX A
Visual Representation of Walleye Growth and Physical Characteristics

Visual representation of walleye growth and physical characteristics from 1 day post hatch at 7mm long (top) to 30 days post hatch at 40mm in length (bottom) when raised in the UWSP NADF larval rearing system. Photos show the physical change in characteristics and size is not to scale.



Source: Walleye Culture Guide (2023). University of Wisconsin–Stevens Point, Northern Aquaculture Demonstration Facility.

APPENDIX B
GLIFWC 1986, 1987, and 1990 Fall Electroshocking Survey Results



LAKE: MINOCQUA	COUNTY: ONEIDA
PERIOD FISHED: OCTOBER 1-2, 1986	OBJECTIVE: ASSESS YEAR CLASS STRENGTH OF AGE 0 WALLEYE.

GEAR

ELECTROFISHING	HOURS: 5.84	MILES SURVEYED: 9.2	RELIABILITY: HIGH
	WATER TEMP: 17.0 C	SHORE MILES: 19.1	
FYKE NET	NUMBER:	MESH:	
SEINE	AREA SAMPLED:	MESH:	
GILL NET	NUMBER:	MESH:	
	MATERIALS:	NET DIMENSIONS:	

SUMMARY

SPECIES	NUMBER	INCHES	CATCH/EFFORT
WALLEYE: TOTAL	299	4.6 - 23.2	32.5 / MILE
AGE 0	143	4.6 - 6.6	15.5 / MILE
AGE 1	108	6.9 - 9.6	11.7 / MILE
MUSKELLUNGE	19	6.9 - 33.5	2.1 / MILE
NORTHERN PIKE	3	24.6 - 25.4	0.3 / MILE
LARGEMOUTH BASS	21	2.1 - 19.1	2.3 / MILE
SMALLMOUTH BASS	5	2.2 - 16.9	0.5 / MILE
BLACK CRAPPIE	2	9.8 - 10.6	
GRASS PICKEREL	21	2.2 - 13.0	

COMMENTS:

LAKE: MINOCQUA	COUNTY: ONEIDA
PERIOD FISHED: OCTOBER 16, 1990	OBJECTIVE: ASSESS YEAR CLASS STRENGTH OF AGE 0 AND AGE 1 WALLEYE.

GEAR

ELECTROFISHING	HOURS: FULL TIME NOT RECORDED	MILES SURVEYED: 19.1	RELIABILITY: MODERATE
	WATER TEMP: 52 F	SHORE MILES: 19.1	
FYKE NET	NUMBER:	MESH:	
SEINE	AREA SAMPLED:	MESH:	

SUMMARY

SPECIES	NUMBER	INCHES	CATCH/EFFORT
WALLEYE: TOTAL	532	4.9 - 26.9	27.9 / MILE
AGE 0	168	4.9 - 6.8	8.8 / MILE
AGE 1	41	7.1 - 9.8	2.1 / MILE
MUSKELLUNGE	13	10.5 - 41.09	0.7 / MILE
NORTHERN PIKE	6	12.0 - 25.9	0.3 / MILE
LARGEMOUTH BASS	24	6.5 - 17.4	1.3 / MILE
SMALLMOUTH BASS	3	9.0 - 16.9	0.2 / MILE
BLACK CRAPPIE	48	5.8 - 12.4	
YELLOW PERCH	34	2.5 - 8.8	
BLUEGILL	27	2.6 - 6.9	
PUMPKINSEED	3	4.9 - 5.9	
ROCKBASS	2	6.3 - 6.6	
BOWFIN	1	6.0	
GRASS PICKEREL	16	6.0 - 10.9	

COMMENTS: Weeds, downed trees, and docks made sampling difficult.

CATCH PER EFFORT (NUMBER PER MILE OF SHORELINE SURVEYED) FOR AGE 0 (FINGERLING) AND AGE 1 (YEARLING) WALLEYE CAPTURED IN MINOCQUA L (ONEIDA CO) DURING FALL ELECTROFISHING SURVEYS.

YEAR CLASS		YEAR OF SURVEY 1990	1989	1988	1987	1986	1985	1984	1983	1982	1981
	DATE(S)	10/16			9/16	10/1-10/2					
	TEMP (F)	52.0			65.0	62.6					
	MILES	19.1			14.6	9.2					
	SHORE %	100%			76%	48%					
	AGENCY	GL/US			WDNR	GLIFWC					
1990		8.8									
1989		2.1									
1988											
1987					57.1						
1986					1.8	15.5					
1985						11.7					
1984											
1983											
1982											
1981											
1980											

YEAR CLASS		YEAR OF SURVEY 1980	1979	1978	1977	1976	1975	1974	1973	1972	1971
	DATE								9/6		
	TEMP (F)								N/A		
	MILES								2.2		
	SHORE %								12%		
	AGENCY								WDNR		
1980											
1979											
1978											
1977											
1976											
1975											
1974											
1973									37.7		
1972									0.9		
1971											
1970											

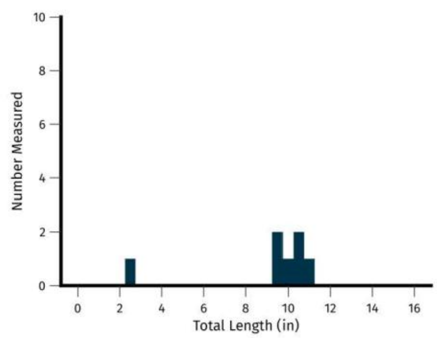
APPENDIX C
Wisconsin DNR Fisheries Information Sheet for Lake Minocqua

WISCONSIN DEPARTMENT OF NATURAL RESOURCES
Fisheries Information Sheet

LAKE: Minocqua **COUNTY:** Oneida **YEAR:** 2024

Introduction

The Wisconsin Department of Natural Resources (DNR), Great Lakes Indian Fish and Wildlife Commission and Walleyes for Tomorrow collaboratively assessed the fishery of Minocqua Lake during the spring of 2024. Minocqua is a 1,360-acre drainage lake with 375 dwellings, 23 resorts, two restaurants, two parks and one golf course along the 19.1 miles of shoreline. Gamefish were collected over three electrofishing transects covering 4.5 miles of the shoreline. All species were collected during three half mile transects covering one and a half miles of shoreline. Walleye were sampled with fyke nets checked daily over nine nights and three nights of electrofishing.



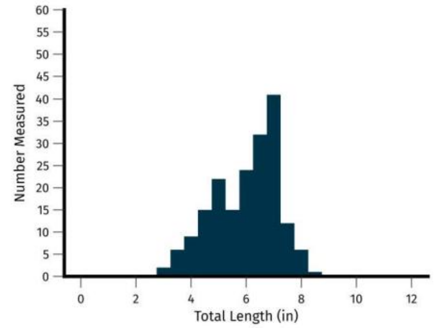
BLACK CRAPPIE

Seven black crappies were captured while electrofishing Minocqua. Counts of black crappies captured were not recorded during netting. Black crappie relative abundance was in the 34th percentile statewide and around the 25th percentile among other Oneida County lakes (i.e., 25% of Oneida County lakes have lower relative abundance of black crappie). The lengths of measured black crappies varied between 2.5 inches and 11.2 inches, with a mean length of 9.1 inches. Caution should be applied when interpreting black crappie findings as panfish data were not recorded during netting and the small sample size.

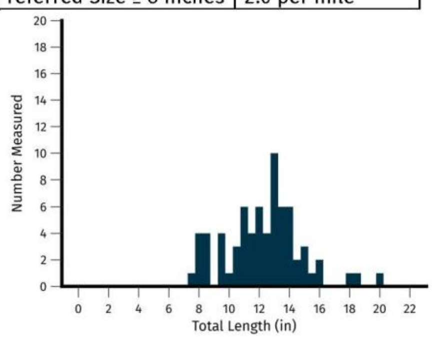
4.7 black crappie per mile	
Quality Size ≥ 8 inches	4.0 per mile
Preferred Size ≥ 10 inches	2.7 per mile

BLUEGILL

A total of 185 bluegills were captured while electrofishing Minocqua. Counts of bluegills captured were not recorded during netting. Bluegill relative abundance was around the 75th percentile for complex-two story lakes and 50th percentile among other Oneida County lakes. Lengths of measured bluegills varied between 2.9 inches and 8.4 inches, with a mean length of 6.0 inches. Caution should be applied when interpreting bluegills findings as panfish data were not recorded during netting.



123.3 bluegill per mile	
Quality Size ≥ 6 inches	73.3 per mile
Preferred Size ≥ 8 inches	2.0 per mile

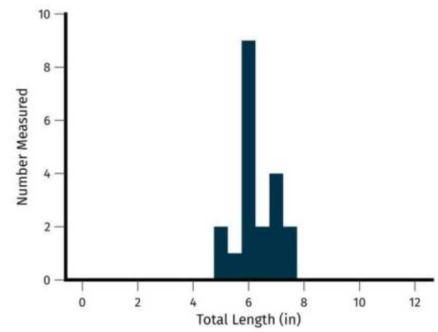


LARGEMOUTH BASS

A total of 70 largemouth bass were captured while electrofishing Minocqua. Counts of largemouth bass captured were not recorded during netting. Largemouth bass relative abundance was slightly below the 60th percentile for complex-two story and below the 50th percentile among other Oneida County lakes. The lengths of measured largemouth bass varied between 7.3 inches and 20.1 inches, with a mean length of 12.3 inches. Too few individuals were captured to calculate a population estimate.

6.6 largemouth bass per mile

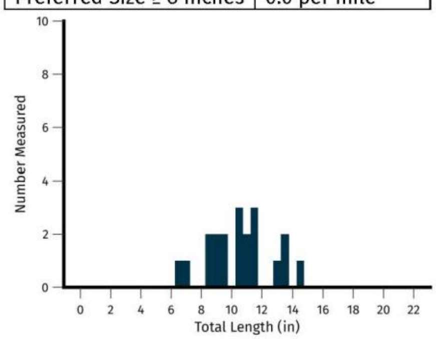
Quality size ≥ 12 inches	4.1 per mile
Preferred size ≥ 15 inches	0.8 per mile



PUMPKINSEED

Twenty pumpkinseeds were captured while electrofishing Minocqua. Counts of pumpkinseeds captured were not recorded during netting. Pumpkinseed relative abundance was around the 75th percentile for complex-two story lakes and above the 50th percentile among other Oneida County lakes. Lengths of measured pumpkinseeds varied between 5.0 inches and 7.5 inches, with a mean length of 6.3 inches. Caution should be applied when interpreting pumpkinseed findings as panfish data were not recorded during netting.

13.3 pumpkinseed per mile	
Quality Size ≥ 6 inches	8.7 per mile
Preferred Size ≥ 8 inches	0.0 per mile

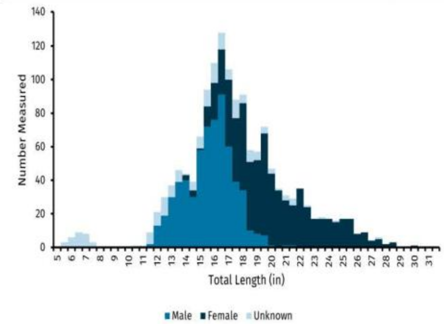


SMALLMOUTH BASS

Twenty smallmouth bass were captured while electrofishing Minocqua Lake. Counts of smallmouth bass captured were not recorded during netting. Smallmouth bass relative abundance was around the 50th percentile for complex-two story lakes and 25th percentile among other Oneida County lakes. The lengths of measured smallmouth bass varied between 6.5 inches and 14.2 inches, with a mean length of 10.5 inches. Too few individuals were captured to calculate a population estimate and data should be interpreted carefully.

1.9 smallmouth bass per mile	
Quality size ≥ 11 inches	0.8 per mile

Preferred size ≥ 14 inches	0.1 per net night



WALLEYE

A total of 1,464 walleye were captured while surveying Minocqua. The lengths of individuals varied between 5.7 inches and 30.0 inches. The walleye population was estimated to be around 3,880 adults. Walleye density was below the average density of 3.5 per acre for lakes in Oneida County and below the 3.0 per acre goal established in the walleye recovery plan.

Estimated 2.85 adult walleye per acre	
12 – 14.9 inches	0.29 per acre
15 – 19.9 inches	1.65 per acre
20 inches and greater	0.92 per acre

OTHER SPECIES

Other species encountered in Minocqua Lake included bluntnose minnow (eight), mimic shiner (two), northern pike (two), rock bass (25) and yellow perch (seven).

Summary

Minocqua Lake is a complex-two story lake possessing cold-water and warm-water fish species that can be accessed from one of the four public ramps or through the connection from Kawaguesaga Lake. A collaborative walleye rehabilitation project has been ongoing on the Minocqua Chain of lakes since 2015. Walleyes have increased in abundance since the low of 1.0 per acre observed in 2015 but decreased from the 3.8 per acre observed in 2019 and the 3.3 observed in 2021. Walleyes less than 8 inches were observed in the spring of 2024 likely indicating success from the 2023 stocking. Fall surveys have captured few age-0 walleye within Minocqua in recent years. Largemouth bass and smallmouth bass appear to be responding to the no minimum length limit implemented in 2012 as relative abundance has decreased since the 2014 survey. Panfish display a sharp decline in relative abundance when they reach harvestable size which may indicate angler harvest impacts or some density dependance influence.

Table 1. General fishing regulations for Minocqua Lake, in Oneida Wisconsin in 2024. While the regulatory information provided was current at the time of surveying, it should not be used as a substitute for the current fishing regulation pamphlet. You may obtain a copy of the current fishing regulations by downloading a copy from the DNR Fishing Regulations page.

SPECIES	SEASON DATES	DAILY BAG LIMIT	SIZE LIMIT
*Largemouth bass (harvest season)	May to March	5	No minimum length
Muskellunge	End May to Dec 31	1	50" minimum length
Northen pike	May to March	5	No minimum length
Panfish	Open all year	25	No minimum length
*Smallmouth bass (harvest season)	Mid-June to March	Catch and release only	Catch and release only
Walleye	May to March	1	18" minimum, 22" to 28" protected slot

* Catch and release fishing is allowed year-round for largemouth bass and smallmouth bass.

Acknowledgements

For answers to questions about fisheries management activities on Minocqua Lake, contact:

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nathaniel.lederman@wisconsin.gov

APPENDIX D
Walleye Recruitment Code Descriptions

Recruitment Code1	Recruitment Model2	Description
blank	None	unknown
NONE/ O	None	No walleye are present
REM	Remnant	Stocking provides the only source of recruitment but was discontinued. The stock is expected to disappear at some time in the future.
0-ST	Remnant	Stocking provides the only source of recruitment but was initiated only recently and has not yet resulted in a harvestable population of adults.
ST	Stocked	Stocking provides the only source of recruitment and is consistent enough to result in a multi-year class adult population.
C-ST	Stocked	Stocking provides the primary source of recruitment but some natural reproduction occurs and may augment the adult population.
C-	Natural	Natural reproduction and stocking provide more or less equal recruitment to the adult population.
C-NR	Natural	Natural reproduction is adequate to sustain the population even though the lake is being stocked.
NR	Natural	Natural reproduction only; consistent enough to result in multi-year class adult populations.
NR-2	Remnant	Natural reproduction only; inconsistent, results in missing year classes.

1 - Recruitment Code = Designation of the *primary* recruitment source and done by a technical working group.
2 - Recruitment Model is used for data analysis and groups various recruitment codes into one of three categories.

Primary source of walleye recruitment; U.S. Department of the Interior, 1991

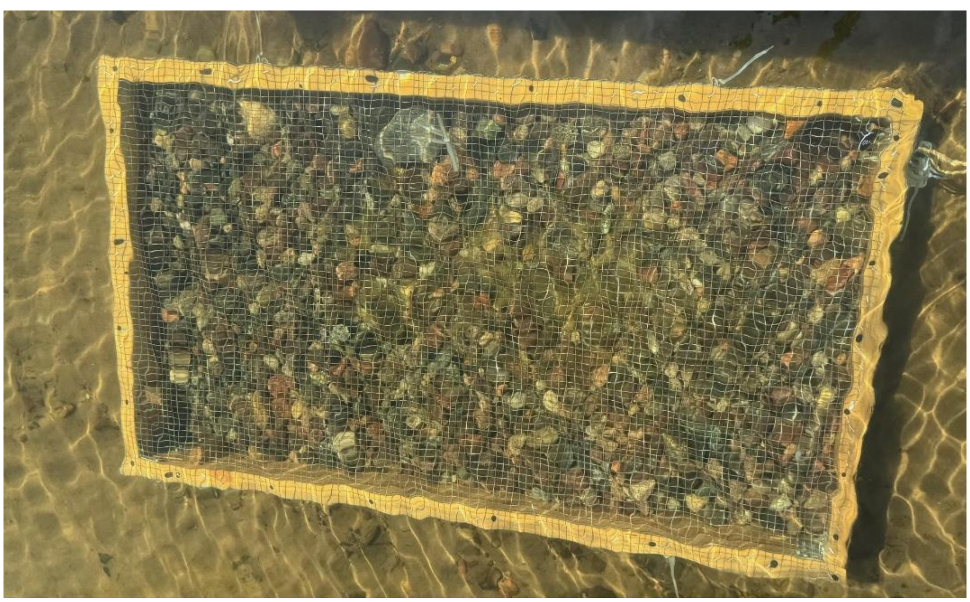
APPENDIX E
Photos of Enclosure Design and Construction

Photo of the incubation box taken during construction (Photo Credit Douglass Keiser)

Photo of the incubation boxes prior to installation (Photo Credit Douglass Keiser)

APPENDIX F
Photos of Enclosure Installation and Placement

Incubation box positioned in a spawning area, filled with substrates and prepared for fertilized egg deposition (Photo Credit Douglass Keiser)


Photograph of an enclosure with the mesh cover to protect the eggs from predation during incubation. (Photo Credit: Douglass Keiser)


A prefabricated box with lid was placed at each site to monitor if hatching had occurred (Photo Credit Douglass Keiser)


Placement of incubation boxes accompanied by a red buoy to notify boaters of the active research area (Photo Credit: Bay Paulsen, GLIFWC)


Aerial photo of the placement of the incubation boxes on the spawning shift along the westward side of Crescent Island – Site 2. (Photo Credit Douglass Keiser)


Aerial photo of the placement of the incubation boxes on the spawning shift along the westward side of Fisher's Island – Site 1. (Photo Credit Douglass Keiser)

APPENDIX G
Egg Collection, Fertilization and Disinfection Process

STEPS:

> ***Why is Dry Spawning Important?***
>
> *Timing Counts! Water activates both milt and opens micropyle of the egg. Sperm are only active for about 10-15 seconds after exposed to water. If the sperm are not combined with eggs during this time, fertilization will not occur. Therefore, fertilization is most successful if eggs and milt are kept dry until they are pooled together, then water can be added.*

1. For optimum fertilization success, dry spawning is recommended. Be careful that no water is present during the following process until step 7.

2. Check to ensure female walleye is ripe and ready to spawn. Vent should appear to be fully dropped and ventral region should appear plump.

3. Completely dry ripe female walleye with towel.

4. Hand strip female into a dry container by applying gentle pressure to the abdominal area. Eggs should flow easily from the vent into the container. If eggs are clumping or sticky do not collect.

5. It is important to strip all the eggs out of the female. Leftover eggs may cause blockage, which can lead to internal infections or problems with spawning the following year. Spawned out females should be placed back into a separate rearing tank and provided feed for continued holding.

6. Dry off several ripe male walleye and hand strip sperm (referred to as milt) into a shallow container. Pour the pooled milt over the eggs, making sure no water is present.

7. Pour tempered fresh water over the eggs and milt to activate fertilization.

8. Use a small paint brush or soft feather to gently mix the eggs, milt, and water together for several minutes.

9. Pour pre- mixed bentonite clay slurry over the fertilized eggs and stir for a few more minutes. The clay coats the eggs keeping them from clumping or sticking together.

10. Rinse and drain the eggs with tempered fresh water several times and set aside in container for about an hour to water harden, adding fresh water about every 10-15minutes.

Fig. 8. Both female (left) and male (right) fish are fully dried with a towel before eggs or milt are stripped into dry containers

11. After fertilized eggs are water hardened, it is recommended that they are iodophor-disinfected at 100ppm for 15 minutes (Fig. 9).

12. After iodophor treatment, rinse eggs with fresh clean water several times to ensure iodophor is washed out. Eggs can now be shipped in water to hatchery or facility for incubation. Eggs should be transferred in a covered container with aeration and kept cool.

Fig. 9. Eggs are disinfected with 100mg/L iodophor for 15 minutes.

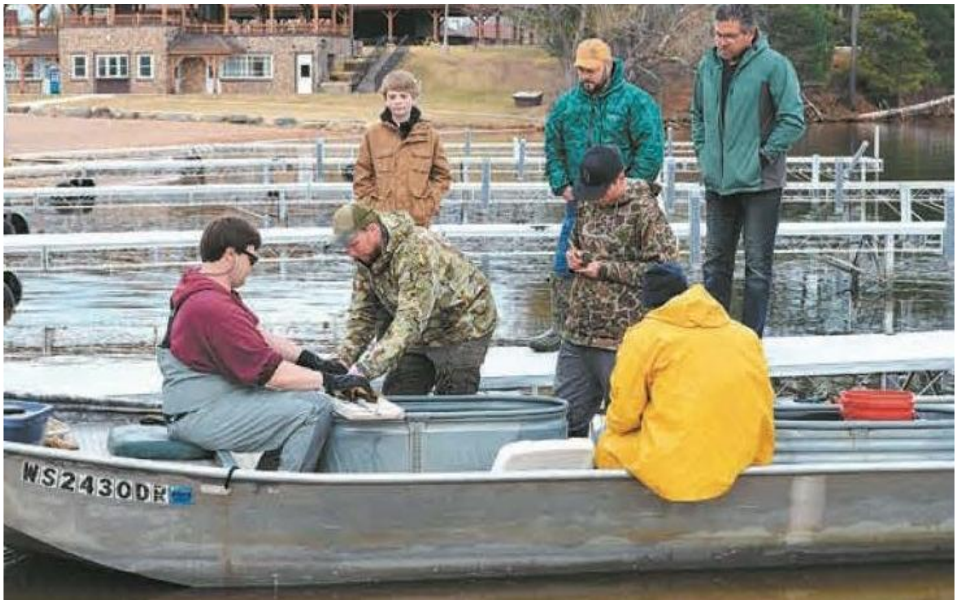
Fig. 10. Total volume of eggs is being determined by displacement.

10. Eggs can now be quantified using volumetric displacement.

- **For total volume**, pour eggs into a strainer. Funnel strained eggs into a known volume of water in a graduated cylinder. The change in volume after eggs are added equals the total volume of eggs (Fig. 10).
- **To determine egg numbers**, take a small random sample of eggs. Fill a small, graduated cylinder (10ml) to a known volume of water. Add dry eggs a few at a time until 1ml of water is displaced. Pour out water and eggs from the graduated cylinder onto a petri dish and count the number of eggs it took to displace 1ml. Repeat three times and take average. Take the average eggs/ml and multiply by total volume of eggs in ml. This will equal the total number of eggs you have. For example, if your average number of eggs that displaced 1ml was 220 eggs, and the total volume that all the eggs displaced was 2 liters (2000ml) than your total egg number would be 440,000 eggs = (220eggs/ml x 2,000ml).

Source: Walleye Culture Guide. (2023)
University of Wisconsin–Stevens Point, Northern Aquaculture Demonstration Facility

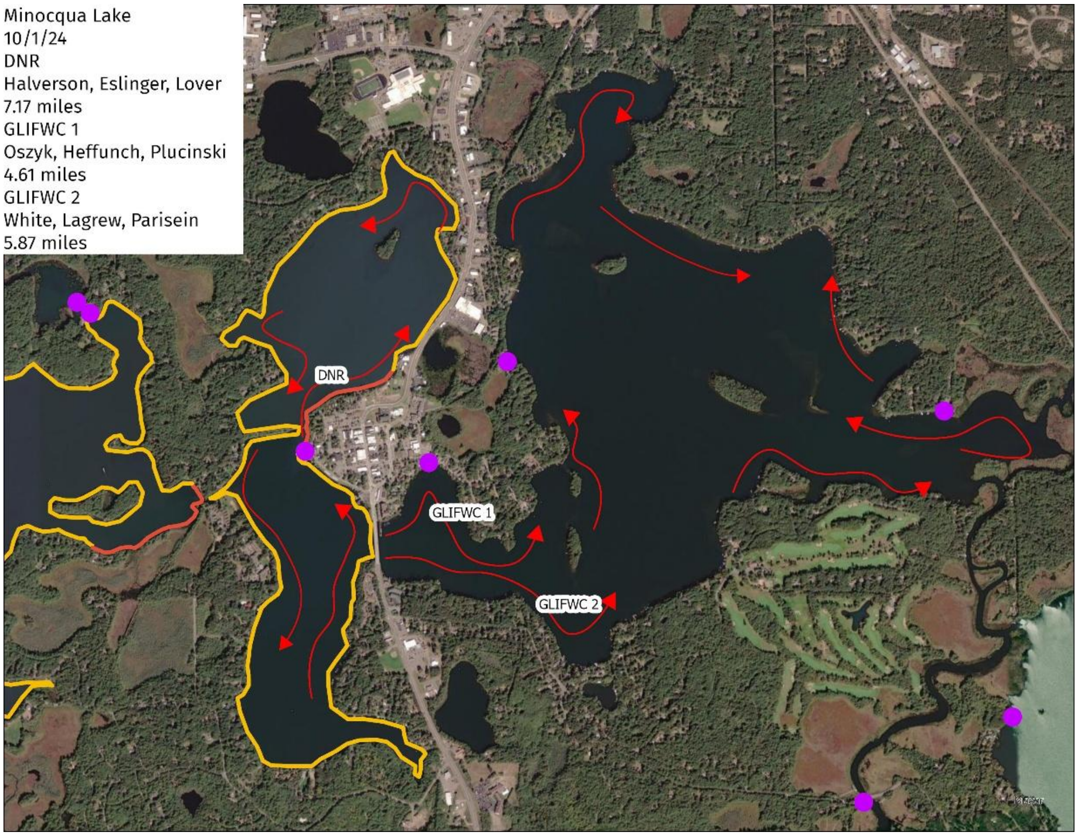
APPENDIX H
Egg Collection, Fertilization and Disinfection Process



Walleyes were sexed and measured upon capture, then temporarily placed in holding pens prior to sperm and egg collection (Photo Credit: Bay Paulsen, GLIFWC)

Eggs were gently expressed from female walleyes, then collected in a beaker for measurement and documentation (Photo Credit: Bay Paulsen, GLIFWC)

APPENDIX I
2024 Fall Walleye Recruitment Reporting Lake Minocqua
(October 1 and October 29)



Lake Minocqua map illustrating the Fall recruitment survey routes and distances (Source Wisconsin DNR)

SUMMARY FISHING RECORD
Form 3600-63

Department of Natural Resources

County: Oneida	Waters: Minocqua MWBC: 1542400
Sampling Objective: Walleye Recruitment Survey	Number and Locations of Stations (Habitat)
Period Fished (Dates): 10/01/24	Miles Actually Shocked = 19.1 (Source: LM) Acres = 1360 (LM) Total Miles of Shoreline = 19.1 (LM) Total Miles of Shockable Shoreline = 19.1 (LM)

GEAR

Boomshocker (Hours): 8.8		Time: √ Night		Day
Visual Hours	Time of Day	Haul Seine (Length)	Mesh Size	Area Covered
Angling (Hours)	Time of Day	Trap Net (No. of Net Lifts)	Mesh Size	Depth
Minnow Seine (No. of Hauls)	Area Covered	Gill Net (No. of Feet x No. of Lifts)	Mesh Size	Depth

Other (Hours or Lifts): Boomshocker(s): 3; Dip Netter(s): 6; Mini-boomshocker(s): ; Dip Netter(s):

Characteristics: Walleye Recruitment Code: C-ST

FISHING RESULTS

Species	No.	Modal Size(s)	Size Range	Catch/Unit	
Walleye (Age 0+)	2		6.3 - 6.5	0.23 / hour	0.10 / mile
Walleye (Age 1+)	93	9.2	7.7 - 10.3	10.57 / hour	4.87 / mile
Walleye (Other)	50	15.2, 18.7	10.4 - 26.4	5.68 / hour	2.62 / mile
Smallmouth Bass	8	8.7	3.5 - 18.9	1.36 / hour	0.65 / mile
Largemouth Bass	87	6.2, 8.2, 11.7, 14.7	3.0 - 18.9	14.75 / hour	7.07 / mile
Muskellunge	1		27.5 - 27.9	0.17 / hour	0.08 / mile
Northern Pike	9		14.0 - 26.4	1.53 / hour	0.73 / mile

OBSERVATIONS ≤3"

Other Species	Abundance	Size Range	Other Species	Abundance	Size Range
Black Crappie					
Bluegill					
Pumpkinseed					
Rock Bass					
Yellow Perch					
Minnows					

1) Tank Mortality: None   2) Weather: Cool, PCL, Light Wind   3) Reliability: High

4) Stocking: 2024 - est. 522,500 walleye eggs (4/14-19) and 3.9 mil. fry (5/06-09; avg. length - 1.0"); 2023 - 13,376 lg. fing. walleye, 3.2 mil. fry, and 76K+ eggs; 334 lg. fing. musky.

5) Comments: Revised report to correct other gamefish (SMB, LMB, MUE, NP) CPUEs as 1 boat didn't dip all gamefish entire survey; used approximated mileage of 12.3 miles and 5.9 hours for effort values to calculate "other gamefish" catch rates; Left Walleye effort totals as is from original. Additionally, duplicated LMB catch data was removed from original report.

Joint survey. Run 1. Targeted all size gamefish w/emphasis on juveniles. Scales interpreted. DNR ran AC (volts, amps reported), GLIFWC ran pulsed DC. Each crew completed a 0.5 mi. index station (catch not reported here). Later FE Run 2 conducted - WAE CRs were lower.

Rev. 10-70   Signed (Compiler): Lawrence Eslinger   Date: 01/28/25

LAKE ELECTROFISHING DATA COLLECTION SHEET (FALL) Department of Natural Resources
Form 3600A-191 8-95

Lake: Minocqua MWB Code: 1542400 Date: 10/01/24 County: Oneida Collector(s): Halverson boat, Mieloszyk boat, White boat

Target Fish: Juvenile Walleye Survey Type: CPE Mark Given: None Water Temperature: 67°F Station: Entire Shoreline

Adverse Conditions: Docks, Vegetation Gear Type: Boomshocker Distance Shocked: 19.1 miles

Volts: 118 Amps: 2.8 Current Type: [X]AC [ ]DC [X]Pulsed DC Pulse Rate: 120 Duty Cycle: NA

Shocking Start Time: 1910 Shocking End Time: 2239 Generator Start Hour: 0.0 Generator End Hour: 8.8

Number of Dippers: [ ]1 [X]2 Entire Shoreline Shocked: [X]Y [ ]N [ ]I Dipnet Mesh Size: 3/8 inch bar H20 Clarity: Clear

Walleye < 12.0"			
Inches	Number	Inches	Number
<3.0		7.5	
3.0		7.6	
3.1		7.7	2
3.2		7.8	2
3.3		7.9	
3.4		8.0	2
3.5		8.1	2
3.6		8.2	2
3.7		8.3	4
3.8		8.4	7
3.9		8.5	6
4.0		8.6	4
4.1		8.7	6
4.2		8.8	5
4.3		8.9	3
4.4		9.0	7
4.5		9.1	4
4.6		9.2	9
4.7		9.3	6
4.8		9.4	5
4.9		9.5	4
5.0		9.6	3
5.1		9.7	2
5.2		9.8	5
5.3		9.9	1
5.4		10.0	1
5.5		10.1	
5.6		10.2	
5.7		10.3	1
5.8		10.4	1
5.9		10.5	1
6.0		10.6	
6.1		10.7	1
6.2		10.8	
6.3	1	10.9	
6.4		11.0	1
6.5	1	11.1	
6.6		11.2	
6.7		11.3	
6.8		11.4	
6.9		11.5	
7.0		11.6	1
7.1		11.7	
7.2		11.8	
7.3		11.9	
7.4		Total:	100

Inches	Walleye	Northern Pike	Muskellunge	Largemouth Bass	Smallmouth Bass	Inches	Walleye	Northern Pike	Muskellunge
<1.5						24.5-24.9	1	1	
1.5-1.9						25.0-25.4			
2.0-2.4						25.5-25.9			
2.5-2.9						26.0-26.4	1	1	
3.0-3.4				1		26.5-26.9			
3.5-3.9				1	1	27.0-27.4			
4.0-4.4						27.5-27.9			1
4.5-4.9						28.0-28.4			
5.0-5.4						28.5-28.9			
5.5-5.9				1		29.0-29.4			
6.0-6.4				5		29.5-29.9			
6.5-6.9				3		30.0-30.4			
7.0-7.4				1	1	30.5-30.9			
7.5-7.9				2		31.0-31.4			
8.0-8.4				5		31.5-31.9			
8.5-8.9				1	2	32.0-32.4			
9.0-9.4				3		32.5-32.9			
9.5-9.9				1	1	33.0-33.4			
10.0-10.4				1		33.5-33.9			
10.5-10.9				4	1	34.0-34.4			
11.0-11.4				5		34.5-34.9			
11.5-11.9				9		35.0-35.4			
12.0-12.4				7		35.5-35.9			
12.5-12.9	2			8		36.0-36.4			
13.0-13.4	2			5		36.5-36.9			
13.5-13.9	1			6		37.0-37.4			
14.0-14.4	4	1		2		37.5-37.9			
14.5-14.9	3			5		38.0-38.4			
15.0-15.4	6			4	1	38.5-38.9			
15.5-15.9	4			2		39.0-39.4			
16.0-16.4	2			2		39.5-39.9			
16.5-16.9	1					40.0-40.4			
17.0-17.4	2			2		40.5-40.9			
17.5-17.9	3					41.0-41.4			
18.0-18.4	1	1				41.5-41.9			
18.5-18.9	5	1		1	1	42.0-42.4			
19.0-19.4	3					42.5-42.9			
19.5-19.9	1					43.0-43.4			
20.0-20.4						43.5-43.9			
20.5-20.9						44.0-44.4			
21.0-21.4						44.5-44.9			
21.5-21.9						45.0-45.4			
22.0-22.4	1	2				45.5-45.9			
22.5-22.9						46.0-46.9			
23.0-23.4	1					47.0-47.9			
23.5-23.9	1	2				48.0-48.9			
24.0-24.4						49.0-49.9			
Totals:	45	9	1	87	8	50.0+			

SUMMARY FISHING RECORD
Form 3600-63

Department of Natural Resources

County: Oneida	Waters: Minocqua MWBC: 1542400
Sampling Objective: Walleye Recruitment Survey	Number and Locations of Stations (Habitat): Miles Actually Shocked = 19.1 (Source: LM); Acres = 1360 (LM); Total Miles of Shoreline = 19.1 (LM); Total Miles of Shockable Shoreline = 19.1 (LM)
Period Fished (Dates): 10/29/24	

GEAR

Boomshocker (Hours): 7.3		Time: √ Night Day		
Visual Hours	Time of Day	Haul Seine (Length)	Mesh Size	Area Covered
Angling (Hours)	Time of Day	Trap Net (No. of Net Lifts)	Mesh Size	Depth
Minnow Seine (No. of Hauls)	Area Covered	Gill Net (No. of Feet x No. of Lifts)	Mesh Size	Depth
Other (Hours or Lifts): Boomshocker(s): 3; Dip Netter(s): 6	Mini-boomshocker(s): ; Dip Netter(s):		Characteristics: Walleye Recruitment Code: C-ST	

FISHING RESULTS

Species	No.	Modal Size(s)	Size Range	Catch/Unit	
Walleye (Age 0+)	1		6.7	0.14 / hour	0.05 / mile
Walleye (Age 1+)	64	9.0	7.5 - 11.0	8.77 / hour	3.35 / mile
Walleye (Other)	31	14.2, 15.2, 20.7	13.0 - 24.9	4.25 / hour	1.62 / mile
Smallmouth Bass	22	8.2	4.5 - 16.9	3.01 / hour	1.15 / mile
Largemouth Bass	111	10.2, 12.7, 14.7	4.5 - 20.4	15.21 / hour	5.81 / mile
Muskellunge	4		8.0 - 35.4	0.55 / hour	0.21 / mile
Northern Pike	40	14.2, 19.0, 21.7	10.0 - 26.4	5.48 / hour	2.09 / mile

OBSERVATIONS ≤ 3"

Other Species	Abundance	Size Range	Other Species	Abundance	Size Range
Black Crappie					
Bluegill					
Pumpkinseed					
Rock Bass					
Yellow Perch					
Minnows					

1) Tank Mortality: None 2) Weather: Warm, S Wind 5-10 3) Reliability: Medium

4) Stocking: 2024 - est. 522,500 walleye eggs (4/14-19) and 3.9 mil. fry (5/06-09; avg. length - 1.0"); 2023 - 13,376 lg. fing. walleye, 3.2 mil. Fry, and 76K+ eggs; 334 lg. fing. musky.

5) Comments: Joint survey. Run 2 examining WAE catch rates w/Run 1 (colder H2O, fewer docks). Targeted all size gamefish w/emphasis on juveniles. Scales interpreted & used LF to assign age-1/age-2 break. DNR ranAC (volts, amps reported), GLIFWC ran pulsed DC. Run 1 CRs higher.

Rev. 10-70 Signed (Compiler): Lawrence Eslinger Date: 12/12/24

LAKE ELECTROFISHING DATA COLLECTION SHEET (FALL) Department of Natural Resources
Form 3600A-191 8-95

Lake: Minocqua MWB Code: 1542400 Date: 10/29/24 County: Oneida Collector(s): Halverson boat, DGK GLIFWC boat 1, GLIFWC boat 2

Target Fish: Juvenile Walleye Survey Type: CPE Mark Given: None Water Temperature: 56°F Station: Entire Shoreline

Adverse Conditions: Docks Gear Type: Boomshocker Distance Shocked: 19.1 miles

Volts: 110 Amps: 2.2 Current Type: [X]AC [ ]DC [X]Pulsed DC Pulse Rate: 60 Duty Cycle: 25

Shocking Start Time: 1820 Shocking End Time: 2106 Generator Start Hour: 0.0 Generator End Hour: 7.3

Number of Dippers: [ ]1 [X]2 Entire Shoreline Shocked: [X]Y [ ]N [ ]I Dipnet Mesh Size: 3/8 inch bar H20 Clarity: Clear

Walleye < 12.0"			
Inches	Number	Inches	Number
<3.0		7.5	1
3.0		7.6	
3.1		7.7	
3.2		7.8	1
3.3		7.9	1
3.4		8.0	
3.5		8.1	1
3.6		8.2	
3.7		8.3	1
3.8		8.4	4
3.9		8.5	4
4.0		8.6	4
4.1		8.7	1
4.2		8.8	4
4.3		8.9	2
4.4		9.0	6
4.5		9.1	4
4.6		9.2	3
4.7		9.3	2
4.8		9.4	1
4.9		9.5	5
5.0		9.6	3
5.1		9.7	
5.2		9.8	3
5.3		9.9	1
5.4		10.0	3
5.5		10.1	3
5.6		10.2	
5.7		10.3	1
5.8		10.4	
5.9		10.5	1
6.0		10.6	1
6.1		10.7	1
6.2		10.8	
6.3		10.9	
6.4		11.0	2
6.5		11.1	
6.6		11.2	
6.7	1	11.3	
6.8		11.4	
6.9		11.5	
7.0		11.6	
7.1		11.7	
7.2		11.8	
7.3		11.9	
7.4		Total:	65

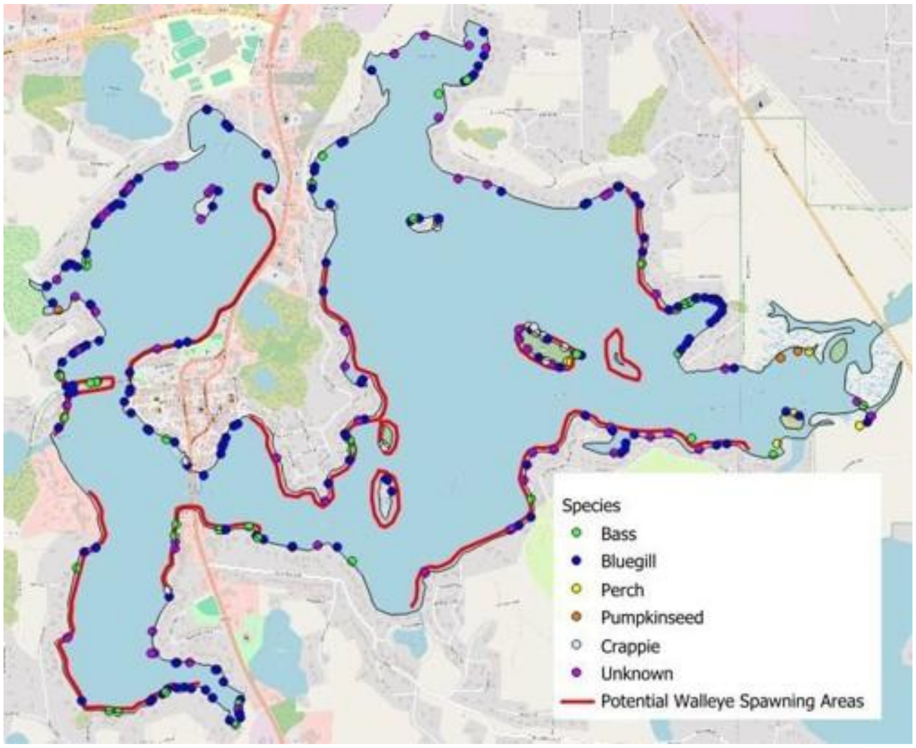
Inches	Walleye	Northern Pike	Muskellunge	Largemouth Bass	Smallmouth Bass	Inches	Walleye	Northern Pike	Muskellunge
<1.5						24.5-24.9	1		
1.5-1.9						25.0-25.4			
2.0-2.4						25.5-25.9			
2.5-2.9						26.0-26.4		1	
3.0-3.4						26.5-26.9			
3.5-3.9						27.0-27.4			
4.0-4.4						27.5-27.9			
4.5-4.9				1	1	28.0-28.4			
5.0-5.4						28.5-28.9			
5.5-5.9					1	29.0-29.4			
6.0-6.4				1		29.5-29.9			
6.5-6.9						30.0-30.4			
7.0-7.4				1	1	30.5-30.9			
7.5-7.9				3	2	31.0-31.4			
8.0-8.4			1	3	3	31.5-31.9			
8.5-8.9				3	2	32.0-32.4			
9.0-9.4				4	1	32.5-32.9			
9.5-9.9				7	1	33.0-33.4			
10.0-10.4		1		8	2	33.5-33.9			
10.5-10.9		1		3		34.0-34.4			
11.0-11.4				4	2	34.5-34.9			
11.5-11.9		1		7		35.0-35.4			1
12.0-12.4		1	1	9	1	35.5-35.9			
12.5-12.9				10	2	36.0-36.4			
13.0-13.4	2	1		9		36.5-36.9			
13.5-13.9	2			3		37.0-37.4			
14.0-14.4	3	3		5		37.5-37.9			
14.5-14.9	1	1		8	2	38.0-38.4			
15.0-15.4	3			7		38.5-38.9			
15.5-15.9	1	2		5		39.0-39.4			
16.0-16.4	2	1		4		39.5-39.9			
16.5-16.9	2	1		1	1	40.0-40.4			
17.0-17.4		1		1		40.5-40.9			
17.5-17.9	1	3	1			41.0-41.4			
18.0-18.4	2	1		2		41.5-41.9			
18.5-18.9	2	3		1		42.0-42.4			
19.0-19.4	1	3				42.5-42.9			
19.5-19.9	1	2				43.0-43.4			
20.0-20.4		2		1		43.5-43.9			
20.5-20.9	3	1				44.0-44.4			
21.0-21.4		3				44.5-44.9			
21.5-21.9		3				45.0-45.4			
22.0-22.4	1	3				45.5-45.9			
22.5-22.9	1					46.0-46.9			
23.0-23.4	1					47.0-47.9			
23.5-23.9		1				48.0-48.9			
24.0-24.4	1					49.0-49.9			
Totals:	31	40	4	111	22	50.0+			

APPENDIX J
Photos of fungi observed within enclosures

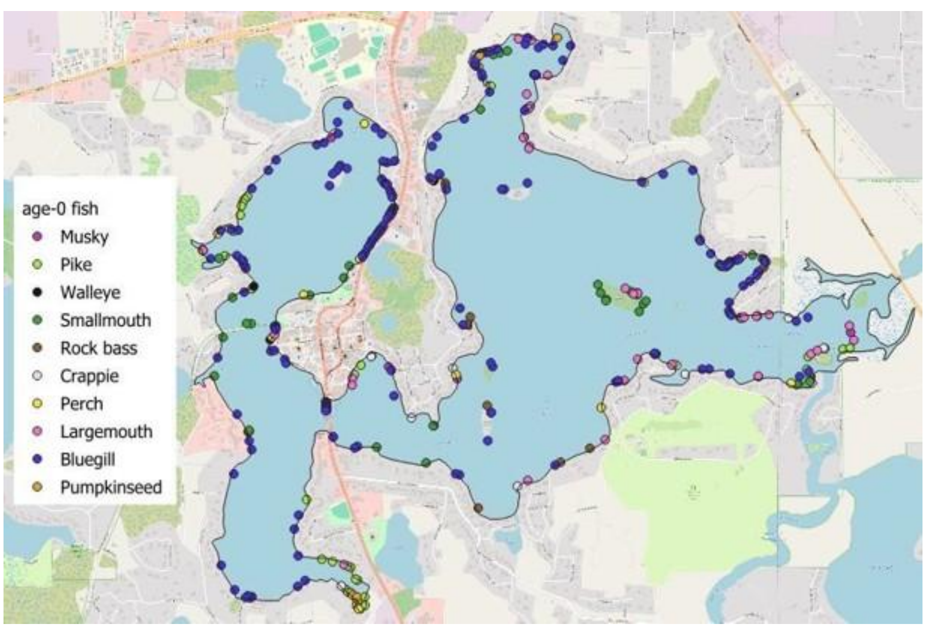
Photograph of fertilized walleye eggs taken on May 6, displaying an unidentified substance. Photo credit: Douglass Keiser)

Fertilized eggs photographed on May 6 with an unknown material present among the clutch. (Photo credit: Douglass Keiser)

APPENDIX K
Map illustrating results of GLIFWC juvenile habitat survey



Locations of spawning habitat in Minocqua Lake and Kawaguesaga Lake. Spawning locations were identified visually by the presence of the fish, presence of a nest, and/or the presence of eggs or egg masses. (Source: Lenz/GLIFWC, 2025)



Observed species-specific nursery habitats on Lake Minocqua (Source: Lenz/GLIFWC, 2025)