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Review



# Integrating acoustic telemetry research into management: successes and challenges in the Laurentian Great Lakes

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## Abstract

In the Laurentian Great Lakes, the application of acoustic telemetry to track fish movements has evolved into an important part of multijurisdictional management. Nevertheless, barriers remain in translating telemetry research into management or conservation actions. Here, we synthesize acoustic telemetry literature within the Great Lakes basin to explore factors that have contributed to successes and failures of integrating research with the needs of decision-making processes. Collaboration between researchers and managers, facilitated by consistent opportunities for stakeholder engagement, stood out as one of the most effective means of integration. For example, 79% (95 of 127) of articles published (up to 2023) included co-authorship by both government and academic organizations. Case studies on lake sturgeon (*Acipenser fulvescens*), walleye (*Sander vitreus*), and sea lamprey (*Petromyzon marinus*) further highlight how telemetry has informed management through collaborative engagement among researchers, stakeholders, and managers, as well as ongoing challenges. By exploring facets of acoustic telemetry research and connections to conservation and fisheries concerns, we identify pathways to reduce knowledge–action gaps widely applicable within and outside of the Great Lakes.

**Key words:** biotelemetry, movement ecology, animal tracking, knowledge–action gap, knowledge transfer

## Introduction

Acoustic telemetry is a principal method of tracking fishes and other aquatic animals, producing information about habitat use, movement patterns, behaviour, survival, physiology, life history, and interactions with their environment (Lennox et al. 2017; Matley et al. 2022). Collaborations among individuals and groups, including the sharing of equipment, infrastructure, and data through organizations, such as the Ocean Tracking Network (OTN) and the Great Lakes Acoustic Telemetry Observation System (GLATOS), have further expanded the ability to track fishes across wide geographic areas and throughout distinct life stages (O'Dor and Stokesbury 2009; Krueger et al. 2018; Barnett et al. 2024; Lennox et al. 2024). Accordingly, acoustic telemetry has increasingly been used by academic and governmental organizations across the world to study fishes, often tying critical biological information relating to space use (e.g., spawning, migrations, and high-use areas) to management priorities (e.g., passage, protected areas, and fisheries; Crossin et al. 2017; Brooks et al. 2019*a*; Iverson et al. 2019; Lowerre-Barbieri et al. 2019; Alós et al. 2022; Matley et al. 2022).

A predominant challenge of integrating acoustic telemetry with species or ecosystem management is bridging the gap between applied knowledge and the needs of decision-making processes (Young et al. 2013; Cooke et al. 2016; Ogburn et al. 2017; Nguyen et al. 2018, 2021). To determine how well research aligned with management needs globally, Matley et al. (2022) evaluated the use of acoustic telemetry across Food and Agriculture Organization (FAO) fishing areas, associating broad management topics (e.g., protected areas, fisheries/aquaculture, climate change) to study objectives in peer-reviewed literature. One of the regions that stood out as diverse in its research-to-management application was the inland waters of North America, consisting, in large part, of research conducted in the Laurentian Great Lakes (hereafter referred to as the Great Lakes).

As the largest surface freshwater system on earth, the Great Lakes basin spans ~765 000 km$^2$ with more than 17 000 km of shoreline (IJC 2023*a*). The Great Lakes encompass a rich cultural heritage as well as intrinsic ecological and economic value in North America. However, historical and ongoing human development has led to detrimental ecological consequences, including wetland destruction, channelization of streams and rivers, species extirpations, pollution from industrial processes and agriculture, and the introduction of non-native species (Allan et al. 2013; Smith et al. 2015). Coordinating legislative and regulatory actions across jurisdictions that include the USA (eight states) and Canada (one province), as well as numerous Native American Tribes and Canadian First Nations, has further complicated management oversight (Hartig et al. 1998; Ronan 2017; IJC 2023*b*).

In recognition of historical and ongoing environmental degradation of aquatic ecosystems and fisheries, the first significant attempts to manage and rehabilitate the Great Lakes system began in the latter half of the 20th century (Hartig et al. 1998). The Convention on Great Lakes Fisheries, a treaty between Canadian and American federal governments, was signed in 1954 and created the Great Lakes Fishery Commission (GLFC) to control invasive sea lamprey *Petromyzon marinus*, advance fisheries science, and promote cooperation of binational agencies (GLFC 1955; Gaden et al. 2008; Gaden et al. 2021). The 1970s brought the creation of the International Joint Commission (IJC) and the Great Lakes Water Quality Agreement, the first basin-wide actions that were established to restore, maintain, and protect the lakes (IJC 2023*b*). However, it was not until 1981 and the signing of a Joint Strategic Plan for Management of Great Lakes Fisheries that agencies began coordinating fisheries management across borders (Gaden et al. 2008). Present-day fisheries management of the Great Lakes remains the responsibility of multiple national and subnational jurisdictions in Canada and the United States, facilitated under the auspices of the GLFC (GLFC 1981, 2007).

Concerted efforts by management agencies, aided by advancing technology and investments in infrastructure, has led to the Great Lakes becoming a globally significant area where acoustic telemetry is widely used. For example, 41% of published acoustic telemetry studies in the inland waters of North America (up to 2023) occurred within the Great Lakes basin (Matley et al. 2024). Research infrastructure within the Great Lakes is supported by GLATOS, which was created in 2012 to facilitate the growing use of acoustic telemetry in the Great Lakes through equipment and data sharing, project coordination, research collaboration, and the promotion of science transfer to managers (Krueger et al. 2018). Acoustic telemetry has since directly contributed to management and conservation initiatives in the Great Lakes (Brooks et al. 2017; Krueger et al. 2018; Nguyen et al. 2021); however, the disconnect between the scientific evidence provided by acoustic telemetry and its applied integration with management (often referred to as the knowledge–action or science-practice gap) is still a broad concern (Nguyen et al. 2021; Matley et al. 2022).

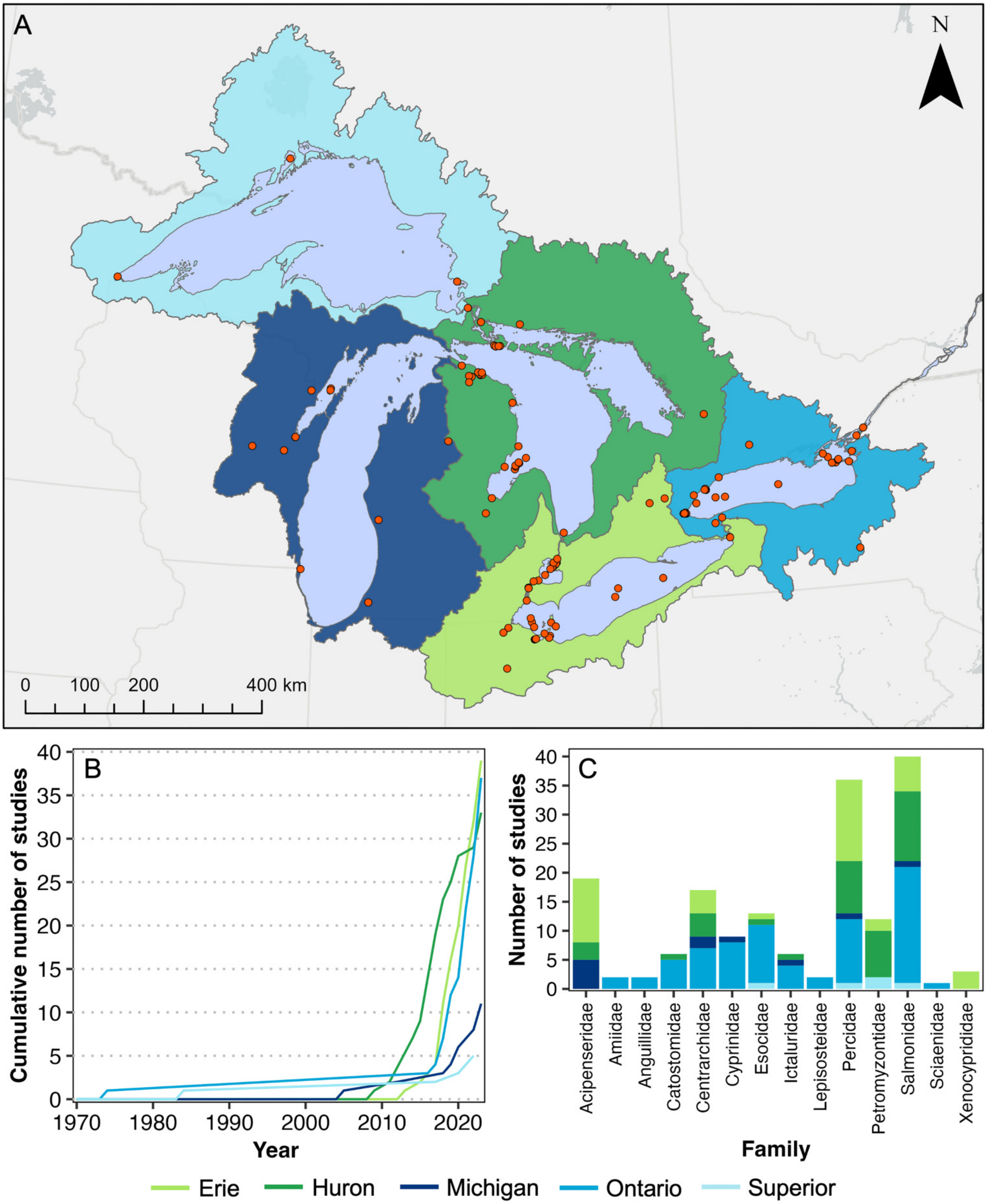
To explore the specific aspects of research in the Great Lakes that have been effective at translating findings into policy or management actions, in addition to those that have not, we conducted a comprehensive synthesis of acoustic telemetry research pertaining to research–management integration. Specifically, our objectives were to (1) identify spatiotemporal trends in research and management themes from all peer-reviewed acoustic telemetry literature within the Great Lakes, (2) quantify the contribution of academic and government organizations to research as a proxy for collaboration and integration, (3) identify the factors that have contributed to the successful adoption of telemetry-derived knowledge in fisheries management and conservation, and (4) evaluate shortcomings in management uptake and challenges that still exist. We also present case studies of three species (lake sturgeon *Acipenser fulvescens*, walleye *Sander vitreus*, and sea lamprey) in the Great Lakes, each characterized by different management needs, and incorporate perspectives from researchers and managers alike to examine the role of acoustic telemetry in management. By exploring factors that have both contributed to and limited the successful integration of acoustic telemetry research with management in the Great Lakes, we hope to provide advice and actionable steps that can be used in other locations around the world to bridge the persistent knowledge–action gap.

## Materials and methods

### Data collection

A literature review of all acoustic telemetry journal articles in the Great Lakes through 2023 was conducted through TrackdAT (www.trackdat.org), an open-source platform that compiles acoustic telemetry study metadata from primary journal articles (Matley et al. 2024). TrackdAT features a Great Lakes repository where published peer-reviewed research done in the Great Lakes is catalogued and can easily be retrieved. Great Lakes research is identified as any acoustic telemetry article with study coordinates located in the Great Lakes basin (Fig. 1). Information associated with articles retrieved from TrackdAT (Matley et al. 2024) included the type

**Fig. 1.** Distribution and occurrence of acoustic telemetry studies in the Laurentian Great Lakes basin. Lake basins Erie, Huron, Michigan, Ontario, and Superior are denoted by colour. (A) Distribution of studies that included a location ($n = 125$) where each orange circle represents a single study. Note that study locations do not encompass the entire study area but rather represent the approximate center of the study area (e.g., receiver array), and for studies with more than one unique location, the central or more focal point of the area is selected. The map was created using ArcGIS Pro with the "Light Gray Canvas" basemap from Esri and projected coordinate system NAD83/Great Lakes Albers. (B) Cumulative number of studies published through 2023 by lake basin ($n = 127$). (C) Total number of studies by family and lake basin. In instances where more than one species was part of a study, each species was recorded separately as an observation for a total of 168 occurrences.



of study (e.g., ecology, tagging effects, methodology/analysis, range testing, review), geographic and technical information (e.g., coordinates, lake basin, number of tagged individuals), biological data (e.g., species, life stage, length), and publication details (e.g., year). TrackdAT is currently confined to peer-reviewed primary journal articles only, and therefore, research and output produced through other means (e.g., agency-specific reports) are not evaluated. However, publication of research findings in primary journals is increasingly common among both academic and government agencies, and we believe, represents a large proportion of telemetry research being conducted.

## Research objectives of telemetry studies

We quantified how often acoustic telemetry research in the Great Lakes was associated with common research themes by assigning each "ecology" article to one or more predefined categories based on the scope of the article. Research objective categories were derived from those defined in Matley et al. (2022) with minor adaptations to suit the current study and reflect focal themes in research that often provide information relevant to present-day management goals (Supplementary Material Table S1). Categories included aquaculture, climate change, fisheries, general movement, invasive species, migration, passage/impediments/construction, population demographics, protected area/fishery closure, spawning/mating, stocking/restoration, tourism, and water quality/pollution/pathogens/disease. This study categorization provided insight into the type of research being conducted that is pertinent to management, and that was likely implemented due to existing management concerns; and while it does not reflect direct management integration, we considered it a valuable approach to reflect knowledge–action potential.

## Author affiliations of telemetry studies

We identified the composition of author affiliations for all publications to evaluate trends in collaboration across academic, government, and other organizations as a proxy for management uptake in the Great Lakes. Assessing the contribution of peer-reviewed journal articles to management is challenging—it is not always evident in what capacity, if any, specific research findings are adopted by managers. Similarly, science transfer to management is a complex process and readily occurs outside of primary literature (via meetings, face-to-face interactions, grey literature, etc.). Nevertheless, we deemed the extraction of author affiliations an effective preliminary approach, albeit cursory, to broadly evaluate management integration with research. The affiliations of each author were recorded, with different offices of the same overarching institution (e.g., physical locations of the U.S. Geological Survey) considered as the same affiliation. Each author's affiliation was then grouped into three broad categories: government, university, or other. In instances where authors listed more than one affiliation on a publication and affiliations included more than one category (<1% occurrence), the author's primary affiliation was used to assign the final category (i.e., government, university, or other). "Government" affiliations were considered any state, provincial, federal, or Indigenous governing bodies or organizations founded or funded by any level of the government. "University" affiliations were any post-secondary educational institution, and "other" affiliations were considered organizations not designated as either government or university, such as non-profits, not-for-profits, and industry. Although some government agencies have management authority or more direct links with decision-making than academic (or other organizations), several government agencies are research-based only and thus, a government affiliation does not necessarily equate to management action. Still, the research produced by government agencies is likely to be applied in nature since mandates are often to support management in some capacity. University research is also sometimes funded by management agencies, further complicating identifying management relevance of research. However, it is likely that articles published from these projects will include agency biologists, reflecting collaboration and management involvement.

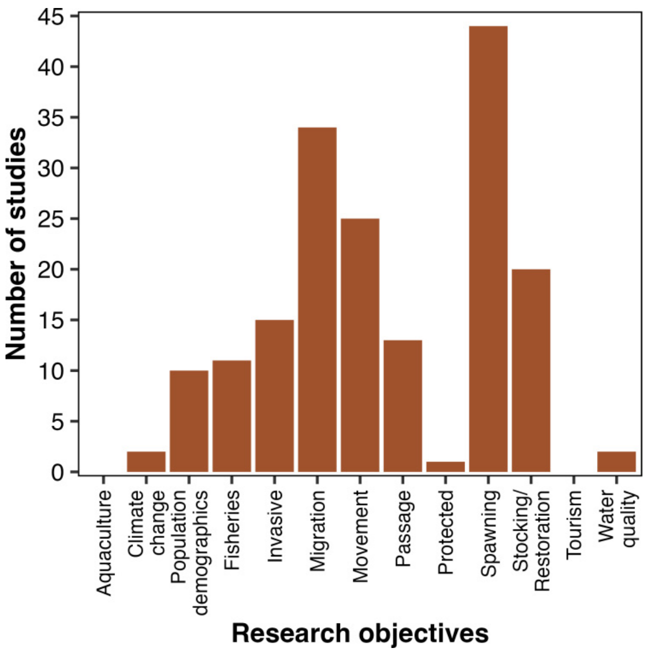
## Case studies

Three focal species (lake sturgeon, walleye, and sea lamprey) were selected for case studies based on being frequently studied with acoustic telemetry in the Great Lakes and demonstrating varied histories of management, management needs, and research themes. Case studies were presented to provide a detailed background of the species' history throughout the lakes and illustrate how, when, where, and why telemetry research was used to support management. Diverse perspectives from researchers and managers were incorporated to develop comprehensive case studies that capture the often-complex process of addressing knowledge–action gaps.

# Results

The acoustic telemetry primary literature dataset consisted of 127 articles published between 1974 and 2023 that featured research conducted in the Great Lakes basin. Types of studies included 101 ecology, 13 tagging effects, 7 range testing, 4 methodology/analysis, and 2 review papers. All articles except for two review papers ($n = 125$) had a location associated with the study. Studies were distributed widely throughout the Great Lakes basin, with the highest density occurring in the Huron–Erie Corridor, western Lake Erie, western Lake Huron, and the eastern and western ends of Lake Ontario (Fig. 1A). Although the first acoustic telemetry study in the Great Lakes occurred in 1974 (Kelso 1974), few studies were published in the decades following, and acoustic telemetry research did not gain steady traction throughout the basin until after 2010 (Fig. 1B). The basins of Lakes Erie, Ontario, and Huron featured the greatest number of studies with 39, 37, and 33 publications, respectively. The most studied families throughout the Great Lakes were Salmonidae ($n = 40$ studies; 24%), Percidae ($n = 36$ studies; 21%), Acipenseridae ($n = 19$ studies; 11%), Centrarchidae ($n = 17$ studies; 10%), Esocidae ($n = 13$ studies; 8%), and Petromyzontidae ($n = 12$ studies; 7%), with the greatest diversity of families studied in Lake Ontario (Fig. 1C). A total of 19 024 individuals were tagged across 34

**Fig. 2.** Research objectives associated with acoustic telemetry studies examining fish ecology in the Laurentian Great Lakes basin. The total number of studies is shown for each research objective category. All research objectives that applied to a study were counted as individual occurrences. See Supplementary Material Table S1 for descriptions of each research objective.




species. Species that were most frequently studied included walleye ($n = 30$ studies; 18%), lake trout (*Salvelinus namaycush*; $n = 20$ studies; 12%), lake sturgeon ($n = 19$ studies; 11%), and sea lamprey ($n = 12$ studies; 7%).

## Research objectives of telemetry studies

Nearly half (45%) of all "ecology" studies were assigned to more than one of the predefined research objective categories based on the scope of the article. Research objectives of ecological studies were most frequently related to spawning/mating ($n = 44$ studies; 35%), migration ($n = 34$ studies; 27%), general movement ($n = 25$ studies; 20%), and stocking/restoration ($n = 20$ studies; 16%; Fig. 2). Less common categories included invasive species ($n = 15$ studies; 12%), passage/impediments/construction ($n = 13$ studies; 10%), fisheries ($n = 11$ studies; 9%), population demographics ($n = 10$ studies; 8%), water quality/pollution/pathogens/disease ($n = 2$ studies; 2%), climate change ($n = 2$ studies; 2%), and protected area/fishery closure ($n = 1$ study; <1%). There were no instances of acoustic telemetry research with objectives linked to aquaculture or tourism in the Great Lakes basin.

## Author affiliations of telemetry studies

In total, 74 unique author affiliations were recorded across all 127 publications, which comprised 42 universities, 22 government institutions, and 10 other organizations. The number of authors on publications ranged from 1 to 15 with an average of 6. The majority of publications (91%) included authors from different affiliations, demonstrating a diverse network of collaboration (Fig. 3A; see Supplementary Material Table S2 for full list of affiliation acronyms and abbreviations), and 28% of publications were multinational (i.e., author affiliations included more than one country). Eighty-three percent of publications included authors from different affiliation types (i.e., more than one of "government", "university", or "other"; Fig. 3B). Government involvement was evident in most research, with 88% of publications including government-affiliated authors and 79% of publications including a collaboration between "government" and another affiliation type (i.e., "government + university" and "government + university + other"). For publications within the most common affiliation category of "government + university", authorship was split evenly with an average "government:university" authorship ratio of 1:1. As the yearly rate of publishing increased over time, reaching a peak of >10 new publications yearly since 2017 and >20 new publications in 2023, the application of acoustic telemetry by different types of institutions also increased. During the 5 year span of 2019 to 2023, several publications were led solely by authors with "government" affiliations and there was more inclusion of "other" affiliation types, such as conservation-focused non-profits, in collaboration with "university" and "government" bodies. For example, when "other" affiliations were included on publications, they comprised an average of 19% of listed author organizations.

# Case study 1: lake sturgeon

Lake sturgeon are large, long-lived, potadromous fish with one of the widest natural distributions of all freshwater fish in North America (Bruch et al. 2016). Lake sturgeon populations in the Great Lakes have faced significant declines, as much as 99% of historical values (Hay-Chmielewski and Whelan 1997), largely due to unregulated fishing and habitat degradation (Harkness and Dymond 1961; Bennion and Manny 2011). Characteristics of lake sturgeon life history, including slow growth, late maturity at 12–27 years depending on sex and system (Bruch et al. 2001), and intermittent spawning (4–9 years), make them particularly susceptible to overexploitation and further challenge the recovery potential of depressed populations (Peterson et al. 2007). In response to severe declines in annual harvest, restrictions or complete closures have been imposed by state and provincial agencies intermittently since the mid 1900s (Hay-Chmielewski and Whelan 1997; Auer 1999; Peterson et al. 2007; Haxton et al. 2014*a*). Current management of lake sturgeon follows a multifaceted approach that includes habitat restoration, stocking and fish transfers, construction of spawning grounds, re-establishment of river connectivity, and public education (Auer 1996; Peterson et al. 2007; Chalupnicki et al. 2011; Roseman et al. 2011). Heavy regulation and consistent monitoring have eliminated overfishing of lake sturgeon, leaving habitat degradation as the greatest remaining threat to populations (Haxton and Findlay 2009; Haxton et al. 2014*b*; Bruch et al. 2016; Sweka et al. 2018).

**Fig. 3.** Author affiliations for acoustic telemetry studies in the Laurentian Great Lakes basin. (A) Network of all affiliation connections in all acoustic telemetry studies, excluding publications with one author or all authors from the same organization (i.e., no collaboration with other organizations). All distinct pairings of affiliations within a publication are counted as one connection regardless of the number of authors from an affiliation. Lines that are the same colour as the affiliation node indicate publications where the affiliation was listed earlier in the author list than the connecting node, with incoming lines of different colours indicating a later position in the author list than the connecting node. See Supplementary Material Table S2 for full list of affiliation acronyms and abbreviations. (B) Yearly number of studies are divided by whether the affiliations of all authors on the paper were associated with government, university, other organizations, or a combination of the groups. The *x*-axis has been truncated to start at the year when publications were consistently released yearly, but prior publications include four articles in 1974, 1984, 2005, and 2009, which were in affiliation categories of government, government, government, and government + university, respectively.

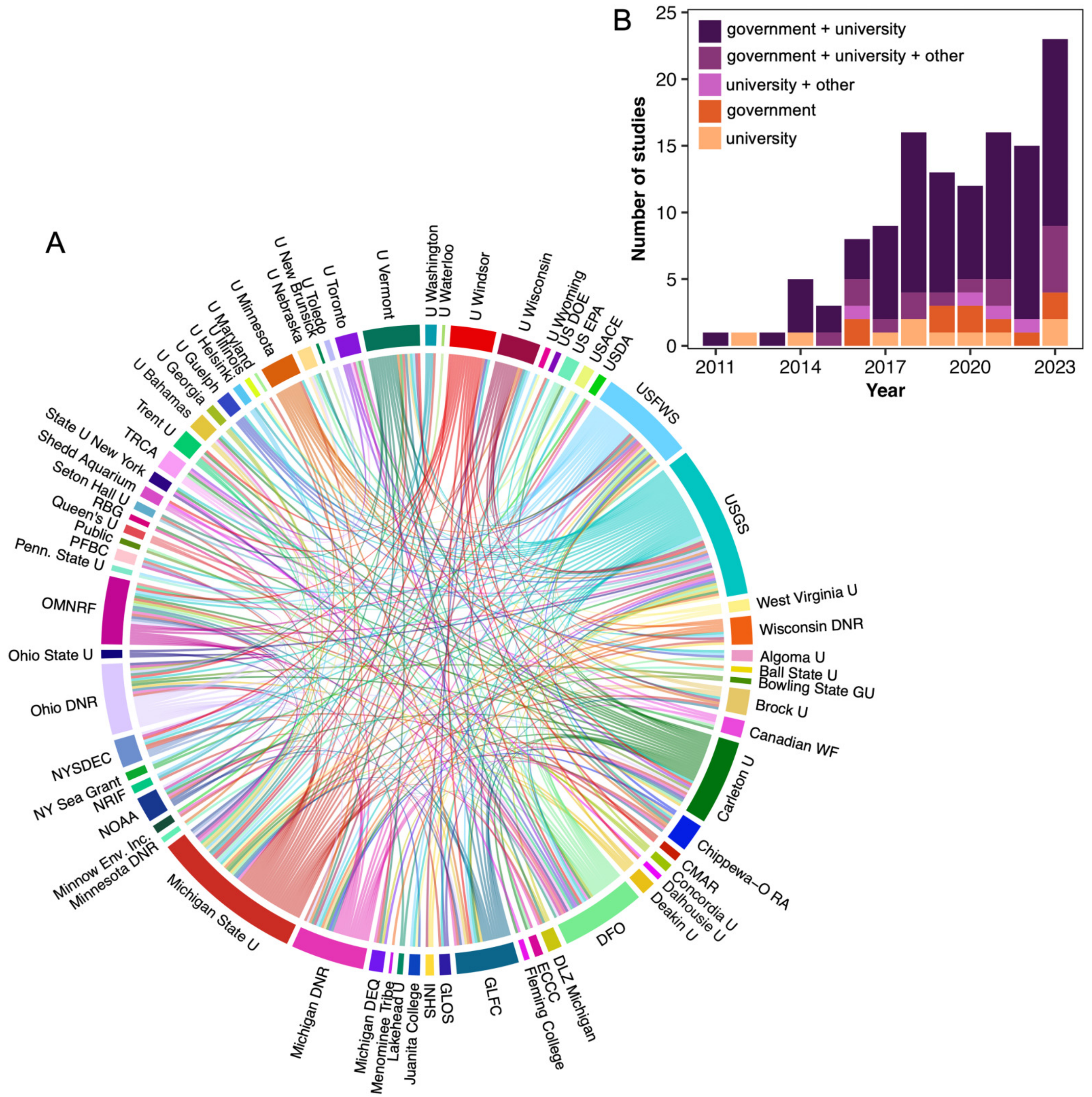


**Table 1.** Main findings from acoustic telemetry studies on lake sturgeon (*Acipenser fulvescens*) in the Great Lakes basin.

| Reference | Knowledge gap | Main study findings | Management relevance |
|---|---|---|---|
| Isermann et al. (2022) | Behaviour after trap and transfer around hydroelectric dams | • Most lake sturgeon (91%) remained upstream for one spawning opportunity regardless of sex or season of transfer<br>• Returned downstream after passage | • Potential to increase recruitment in Lake Michigan if transferred fish spawn and migrate |
| Withers et al. (2021) | Population abundance in eastern Lake Erie | • Addition of telemetry-derived parameters into mark–recapture model facilitated annual adult abundance estimates<br>• Models without telemetry data produced unreasonable results (e.g., >99% survival) | • Estimated population size exceeds management target (Holst and Zollweg-Horan 2018) |
| Colborne et al. (2021) | Annual adult survival in Huron–Erie Corridor | • High adult annual survival (95%–99%)<br>• Survival rates did not differ between tagging sites | • Survival rates consistent with recommended >89% for self-sustaining population<br>• Survival used to refine population abundance estimates (Chiotti et al. 2023) |
| Koenigs et al. (2019) | Success of trap and transfer around hydroelectric dams | • Spawning recorded at upstream location for first time in >100 years<br>• 72% spawning rate of gravid fish transferred <3 weeks to spawning<br>• Natural reproduction 2 years later | • Trap and transfer is cost- and biologically effective for spawning stock restoration |
| Crossman et al. (2009) | Effectiveness of hatchery programs | • >40% overwinter survival of stocked age-0 lake sturgeon<br>• No difference in survival between rearing environments or size at release | • Inform design and implementation of restoration programs<br>• Used in COSEWIC (2017) assessment |

**Note:** Knowledge gaps, main study findings, and management relevance are briefly summarized for five selected publications that produced novel results relevant to management, illustrating the value of acoustic telemetry in uncovering aspects of lake sturgeon ecology in the Great Lakes. Studies are listed in order of recent publication.

## Acoustic telemetry research

Acoustic telemetry has been used in research on lake sturgeon in the Great Lakes since the late 2000s. Early research explored the overwinter survival of stocked age-0 lake sturgeon to aid in the development of management programs focused on population restoration through hatchery supplementation (Crossman et al. 2009). Research in subsequent years explored the impacts of tagging effects on various life stages of lake sturgeon (Hondorp et al. 2015; Hegna et al. 2019). The use of acoustic telemetry expanded around 2018 with studies published in Lakes Huron, Erie, and Michigan that used the technology to explore various aspects of ecology, including adult habitat use (Colborne et al. 2019), migration (Kessel et al. 2018; Whitaker et al. 2018), and spawning behaviour (Donofrio et al. 2018). More contemporary research themes have centered around management topics that range from improving abundance and survival estimates (Withers et al. 2019; Colborne et al. 2021) to evaluating the impacts of man-made physical barriers (Koenigs et al. 2019; Hegna et al. 2020; Isermann et al. 2022) and restoration strategies (Buchinger et al. 2023; McKenna 2023).

## Impact on management

Acoustic telemetry has filled a contemporary role in contributing to management through research that has largely explored behavioural aspects of lake sturgeon navigation, distribution, habitat use, spawning, and migration (Table 1). In the Menominee River, a tributary to Green Bay, Lake Michigan that supports one of the largest remaining populations of lake sturgeon in Lake Michigan, results from acoustic telemetry research on lake sturgeon passage, such as the numbers and season of passage, are used to inform passage strategies as part of a management program conducted by the Michigan Department of Natural Resources (FERC 2024). Acoustic telemetry research in the Menominee River has also shown that after transfer upstream above two dams to a location with high-quality spawning and early life habitat, adult lake sturgeon remained upstream for at least one spawning opportunity and had high survival and rates of downstream return to Green Bay resulting in no net loss to the overall Green Bay population and potential to increase recruitment (Isermann et al. 2022). These findings have led to a secondary stage of research, which has confirmed that lake sturgeon passing upstream are contributing offspring (Forsythe et al. 2025).

Research in the Huron–Erie Corridor revealed that while lake sturgeon tagged in the St. Clair and Detroit Rivers mixed in Lake St. Clair, the central lake connecting the two rivers, they rarely travelled further into the opposite river from where they were tagged (Kessel et al. 2018; Colborne et al. 2019). These findings supported the existing management strategy that involves the unique management of each river, with recreational harvest permitted in the St. Clair River but not the Detroit River, as opposed to uniform management across the entire system. Although no changes were made to management as a result of the study, it is equally important that findings provide evidence to advise against possible future changes to the management strategy. Acoustic telemetry research has revealed high residency and fidelity of lake sturgeon populations within the Huron–Erie Corridor indicating that natural repopulation of spawning tributaries is unlikely (J. Chiotti, U.S. Fish and Wildlife Service, written communication 9 October 2024). The lack of spawning capacity also prompted the use of stocking as a prominent tool in Lake Erie to re-establish populations. Data on residency, derived from acoustic telemetry, were also important in the St. Louis River and estuary, considering the ban on harvest in the river, estuary, and Minnesota waters of Lake Superior but allowance of restricted catch in the Wisconsin waters of the lake (Estep 2019). This research also encouraged a collaboration with the U.S. Environmental Protection Agency aimed at using complementary methods (e.g., stable isotopes) with telemetry to gain a more comprehensive understanding of lake sturgeon ecology (Gordon et al. 2020).

Acoustic telemetry has identified critical habitats for lake sturgeon throughout the Great Lakes basin, which can be used during environmental permit reviewing processes. For example, the Michigan Department of Natural Resources has used findings from acoustic telemetry on lake sturgeon to inform decision-making for dredging permits and conversations on bridge construction locations (C. Harris, Michigan DNR, written communication, 19 August 2024). Acoustic telemetry data have also been used to help develop information for the Lake Erie Priority Management Area through the Lake Erie Habitat Task Group (C. Harris, Michigan DNR, written communication, 19 August 2024). In general, a lot of acoustic telemetry research on lake sturgeon is also focused around obtaining more accurate estimates of abundance that are integral to population status assessment (e.g., Withers et al. 2019; Colborne et al. 2021). Continued telemetry research focused on refining abundance estimates may eventually compel managers to become comfortable with the cessation of stocking programs.

### Challenges and limitations

While valuable information on lake sturgeon ecology has been garnered using acoustic telemetry, research is still unable to answer some key management questions related to juvenile habitat use and adult spawning, although work on this front continues. Capture and tagging of small juveniles (<3 years old) is difficult and as a result, details of their movement and habitat use remain a mystery. Furthermore, juvenile sturgeon with low power tags can be difficult to detect following release, leading to questions about dispersal and survival. Adult sturgeon are often captured and tagged at some known spawning locations for easy capture, but the location of many spawning grounds remains unknown and is yet to be determined using acoustic telemetry. Acoustic telemetry has potential to contribute to several priorities for ongoing lake sturgeon research throughout the Great Lakes, including an improved understanding of the status of populations through estimates of abundance and determining habitat constraints throughout the life cycle, particularly for early life stages (Axelrod 2021).

## Case study 2: walleye

Walleye are a cool water piscivorous fish with native and stocked ranges in river and lake systems throughout Canada and the United States (Goeman 2002; Bozek et al. 2011). Walleye populations have been impacted by a variety of anthropogenic stressors such as fishing, pollution, habitat degradation, and the establishment of non-native fishes and mussels (Schneider and Leach 1977; Fielder et al. 2007; Kapuscinski et al. 2010; Zorn and Kramer 2022). Many declining populations stabilized in the 1970s through fisheries management efforts, including concomitant improvements to environmental conditions (Ludsin et al. 2001; Dembkowski et al. 2018; Vandergoot et al. 2019). As a result, stocks in Lake Erie, Lake Huron, and the Green Bay portion of Lake Michigan are now among the largest populations of walleye in the world and support important commercial and recreational fisheries (Roseman et al. 2010; Dembkowski et al. 2018; Fielder and Baker 2019; Vandergoot et al. 2019). Annual monitoring of walleye stocks (e.g., fisheries harvest and effort, population demographics, recruitment), facilitated by specific lake committees, helps inform lake-specific management to balance ecological, social, and economic priorities (Kayle et al. 2015).

### Acoustic telemetry research

Research on walleye in the Great Lakes using acoustic telemetry began in the early 2010s and sought to quantify migratory movements into Lake Erie via the Maumee River system (Pritt et al. 2013) and large-scale migration patterns in Lake Huron (Hayden et al. 2014). Migration has since remained a common theme in walleye studies, which often aim to identify space use patterns within (e.g., sex, age class) and between (e.g., fish stocks) populations (Raby et al. 2018; Hayden et al. 2019; Matley et al. 2020; Elliott et al. 2022, 2023; McKee et al. 2022; Izzo et al. 2023). Research has also looked at thermal ecology to determine the role of thermal preferences and environmental conditions in seasonal habitat use and contribute to the development of bioenergetics models (Peat et al. 2015; Madenjian et al. 2018; Raby et al. 2018; Matley et al. 2020; Brooks et al. 2022; McKee et al. 2022; Brownscombe et al. 2023). Other studies have used telemetry to understand fishery–walleye interactions, including investigations of how spawning behaviour influences vulnerability to harvest by recreational anglers (Bade et al. 2019) and the contribution of different stocks to recreational and commer-

**Table 2.** Main findings from acoustic telemetry studies on walleye (*Sander vitreus*) in the Great Lakes basin.

| Reference | Knowledge gap | Main study findings | Management relevance |
|---|---|---|---|
| Izzo et al. (2023) | Spawning locations and potential for stock mixing | • 21%–26% of walleye used open-water spawning locations, others used tributaries<br>• Differential movement between northern and southern stocks | • Open-water spawning occurs contrary to conceptual model used for monitoring and management<br>• Fishing regulations may not capture range of spawning locations<br>• Northern stocks move beyond spatial boundaries of regulations for sport fishery designed for their protection |
| Bopp et al. (2023) | Potential effects of invasive species barrier on native species | • Walleye departed river for spawning ∼50 days before grass carp arrived to spawn<br>• Barrier deployment could have high selectivity for excluding grass carp spawning with little effect on walleye spawning | • Support for proposed invasive species exclusion barrier (GLFC 2023) |
| Hayden et al. (2019) | Interlake exchange of two populations | • <0.5% of individuals exchanged lakes<br>• Seasonal mixing in Huron–Erie Corridor could result in population-specific exploitation | • Fishery-independent results that support current management strategies assuming negligible exchange |
| Brooks et al. (2019*b*) | Spatial ecology of reintroduced individuals in an urban harbour | • Stocked fish resident within Hamilton Harbour for most of the year (mean 357 days)<br>• Most walleye (80%) stayed in harbour for entire spawning period | • Support for ongoing stocking since 2012<br>• Potential for natural recruitment, enabling self-sustaining population<br>• Tagged walleye grew and moved into Lake Ontario, suggesting potential support for fisheries opportunities (Larocque et al. 2024*a*) |
| Hayden et al. (2014) | Timing and scale of migration of fisheries stock | • Most walleye (95%) migrated downstream to Saginaw Bay, 37% of those emigrated to Lake Huron<br>• Sex-specific timing of post-spawn movements<br>• 64% of walleye return to river for spawning following year | • Development of stock-specific management practices (e.g., harvest)<br>• Findings led to better informed stock assessment estimates (Fielder et al. 2020)<br>• Used in multispecies examination by management to develop new stocking windows (Fielder et al. 2023) |

**Note:** Knowledge gaps, main study findings, and management relevance are briefly summarized for five selected publications that produced novel results relevant to management, illustrating the value of acoustic telemetry in uncovering aspects of walleye ecology in the Great Lakes. Studies are listed in order of recent publication.

cial fisheries (Faust et al. 2019; Izzo et al. 2023). Lakes Huron and Erie are the focus of most studies due to the large populations of walleye in each lake and the importance of walleye management to jurisdictions around both lakes, but recent studies have expanded throughout the Great Lakes (e.g., Elliott et al. 2022; McKee et al. 2022; Izzo et al. 2023). Overall, research on walleye in the Great Lakes using acoustic telemetry has continually gained momentum with nearly half of all peer-reviewed articles published within the last few years.

## Impact on management

Management of walleye in the Great Lakes has primarily been focused on sustainable exploitation given the recreational and commercial fisheries value of the species. Within this context, acoustic telemetry has largely reinforced existing understanding of how walleye movement may impact management decisions and the tools that inform those decisions (Table 2). Early knowledge of walleye movement in Lakes Erie and Huron came from decades of conventional tagging studies (e.g., Wolfert 1963; Ferguson and Derksen 1971; Todd and Haas 1993; Vandergoot and Brenden 2014). Statistical catch-at-age (SCAA) models were predicated on knowledge of walleye movement based on these studies (Fielder and Bence 2014; Kayle et al. 2015), but acoustic telemetry has since built upon this knowledge and provided greater insight into the extent and timing of specific movement behaviours. For example, findings that nearly 40% of walleye in Saginaw Bay make predictable migrations to the main basin in Lake Huron, and are exploited by main basin fisheries, have been incorporated into SCAA models, providing more robust stock assessment estimates and better-informed fishery regulations than in the past (Fielder et al. 2020). Timing of these migrations has also been used to contrast with timing of salmonid stocking events in Lake Huron to inform managers of when to release hatchery fish for maximum survival and avoidance of predation by walleye (Fielder et al. 2023).

In Green Bay, Lake Michigan, acoustic telemetry studies similarly expanded on knowledge of movement from conventional tagging methods, showing increased migration of walleye following dreissenid colonization (Zorn and Schneeberger 2011; Whitinger et al. 2022). Acoustic telemetry revealed greater extent of migrations than previously known, with many individuals moving outside of the spatial boundaries of fishing regulations intended to protect larger walleyes in the stock and providing an important basis to alter spatial boundaries of sport fishing regulations to achieve their desired effect (Izzo et al. 2023). Initial confirmation of open-water spawning of walleye in Green Bay using acoustic telemetry also led to the allocation of additional funding to further explore spawning locations and behaviours in the context of the walleye fishery (D. Isermann, U.S. Geological Survey, verbal communication, 7 October 2024). Identification of potentially important spawning areas, such as Sturgeon Bay, resulted in a concerted effort to acoustically tag walleye as part of an ongoing study to evaluate exploitation rates by the Wisconsin Department of Natural Resources (Izzo et al. 2023).

Effective measures to control invasive species with minimal impacts on native species, such as walleye, have also recently been integrated into management based on acoustic telemetry. As part of an adaptive management approach in response to grass carp (*Ctenopharyngodon idella*) led by the GLFC's Lake Erie Committee (Herbst et al. 2021), tracking the use of the Sandusky River by grass carp and walleye revealed a ∼45 day gap between walleye departing the river and grass carp arriving (both in relation to spawning), providing a functional time window to potentially implement a non-physical barrier in the largest known source of wild grass carp recruitment in Lake Erie (Bopp et al. 2023). In Hamilton Harbour, Lake Ontario, acoustic telemetry has helped to identify potential spawning areas of stocked walleye and confirmed shoal spawning rather than river spawning (Brooks et al. 2019*b*). This information led to the development of targeted egg mat and larval trawl sampling protocols to look for evidence of recruitment, with a lack of walleye larvae during sampling revealing a likely recruitment bottleneck. Combined knowledge obtained from both acoustic telemetry and targeted conventional sampling resulted in the continuation of stocking in alternating years to maintain current walleye numbers in the system.

The Lake Erie walleye detection summary tool is a prime example of providing managers with the tools they requested to understand acoustic telemetry results that contain information that traditional fishery surveys are unable to provide. The detection summary tool was created as an output from a GLFC Science Transfer Program project and combines data from individual acoustic telemetry projects into a dynamic interactive web tool to address high-level information needs for managers (Hartman et al. 2023; GLFC 2024*a*). Information offered by the tool includes individual diagnostic plots and capture histories for tagged walleye, metrics summarizing animal and detection data, maps to visualize detection locations and frequencies in various formats (e.g., heatmap, bubble map), and the ability to separate data based on designations relevant to management, such as spawning basin and season. Outputs of the tool can be easily exported to facilitate use by managers in decision-making processes and while communicating with stakeholders.

### Challenges and limitations

Barriers to the integration of walleye acoustic telemetry research with fisheries management include the mismatch in scale between management and ecology. Management of walleye is generally implemented on a scale that reflects political distinctions or units of convenience, but telemetry studies have revealed that walleye range much further and in greater numbers than previously considered and constitute a shared stock amongst jurisdictions. Although knowledge of approximate stock delineation has been incorporated into management in Lake Erie (i.e., western basin vs. eastern basin; Kayle et al. 2015), other regions of the Great Lakes do not fully account for this information. For example, in Saginaw Bay, stock assessment models are designed to reflect the full range of walleye movement, but recreational management is tailored to the physical confines of the bay (Fielder and Bence 2014). Another challenge is a lack of accurate and efficient procedures for estimating parameters of interest using acoustic telemetry data. Estimation of natural mortality rates that could inform SCAA model inputs has been a common goal of walleye movement research in Lake Erie since 2011 (Peterson 2023). For example, the SCAA model in Lake Erie still uses a natural mortality estimate derived from an incomplete analysis of jaw tagging data from the mid-1990s despite acoustic telemetry data since 2011 that could provide more recent information. Models fit to acoustic telemetry data have produced total mortality estimates that were consistent with assessment model estimates (Peterson et al. 2021), but telemetry-based models that provide unbiased estimates of natural mortality remain elusive despite being a high priority for fishery managers.

## Case study 3: sea lamprey

The sea lamprey is a primitive, parasitic fish that was inadvertently introduced to the upper Great Lakes following the opening of the Welland Canal between Lakes Ontario and Erie in 1829 (Lawrie 1970; Eshenroder 2014; Marsden and Siefkes 2019). By 1947, sea lamprey had become established throughout the Great Lakes and inflicted devastating ecological changes and fishery collapses through parasitism (Applegate 1950; Robinson et al. 2021); sea lamprey have since been found in ∼10% of tributaries in the Great Lakes basin (Morman et al. 1980; Marsden and Siefkes 2019). The invasion of sea lamprey and their widespread ecological and economic impacts on native fish populations was a catalyst for the formation of binational organizations responsible for managing Great Lakes fisheries. Since its creation in 1955, the GLFC has acted as a coordinating body tasked with eradicating or minimizing sea lamprey populations (GLFC 1955). Successful suppression of sea lamprey relies heavily on lampricides, but integrated management programs also use physical (e.g., barriers, traps) and biological (e.g., sterile-male releases, pheromones, and chemical cues) control methods (Christie and Goddard 2003; Marsden and Siefkes 2019). These control programs have reduced adult sea lamprey abundance by 78%–95% from pre-control levels, but funding limits the extent and frequency that lampricide treatments or other methods are carried out in affected areas (Smith and Tibbles 1980; Marsden and Siefkes 2019; Robinson et al. 2021; GLFC 2024*b*).

### Acoustic telemetry research

Acoustic telemetry was first used with sea lamprey in the Great Lakes in the early 2010s to explore whether pheromones could be used to manage this invasive species (Vrieze et al. 2011). Further research aimed at studying the stream-finding behaviour of migratory adult sea lamprey in Lake Huron was driven by the need to establish management strategies that would limit proliferation throughout the Great Lakes (Meckley et al. 2014; Meckley et al. 2017). In the late 2010s, studies were conducted almost exclusively in Lake Huron and aimed to build on existing knowledge that would be applicable to control measures by understanding the complexity of movement during spawning migration within tributaries (Holbrook et al. 2014, 2015, 2016*b*), upstream passage at lock and dam complexes (Holbrook et al. 2014, 2016*a*), and the success of adult trapping (Holbrook et al. 2016*a*; Rous et al. 2017). Finally, research published in the early 2020s sought to understand the outmigration behaviour and survival of juvenile sea lamprey by making use of technological advances in the miniaturization of tags (Haas et al. 2023, 2024).

### Impact on management

Management of sea lamprey in the Great Lakes has been exclusively associated with controlling populations given the detrimental impact of this invasive species on native fishes. Acoustic telemetry has proven to be a powerful tool to inform management through research that has focused on spawning stream selection and navigation ability, effectiveness of control tools (e.g., trapping), and rates of survival during migrations (Table 3). Acoustic telemetry has been particularly helpful at providing useful information relevant to the control program. For example, results from Holbrook et al. (2016*a*) were used to help inform the discontinuation of sterile male releases in the St. Mary's River in favour of more effective lampricide efforts. Acoustic telemetry revealed adult sea lamprey populations that were larger than initially thought from traditional mark–recapture methods, meaning the ratio of sterile to non-sterile males was lower than estimated, calling into question the efficacy of sterile male releases. Since tripling the area treated with lampricide in the river each year, larval sea lamprey abundance is estimated to be approximately half of what it was during the time of sterile male releases (Criger et al. 2021).

Numerous acoustic telemetry studies also indicated that trapping was an ineffective strategy of control and led to an important change in philosophy about how adult sea lamprey control tactics are viewed (Holbrook et al. 2014, 2015, 2016*a*; Rous et al. 2017). As a result, the Supplemental Sea Lamprey Control Initiative (SupCon; Lewandoski et al. 2021; Siefkes et al. 2021) was developed, which states that additional control tactics (e.g., trapping) should supplement, but not replace, primary tactics, such as lampricides and barriers. SupCon successfully prevented production of new sea lamprey larvae or blocked access of adult sea lamprey in four experimental streams and is being applied on an additional 13 streams in a second phase of the study. If success continues, SupCon may be incorporated more broadly into sea lamprey control in the future. Combined management efforts to control or eradicate sea lamprey across the Great Lakes, which have been informed and guided by results from acoustic telemetry studies, have led to a significant decrease in sea lamprey populations (Mattes and Kitsen 2021).

### Challenges and limitations

Limitations of acoustic telemetry research on sea lamprey include the technological restrictions of small tags (i.e., detection range and battery life) and adequate receiver coverage to detect them. Sea lamprey control aims to achieve a better understanding of the ecology of outmigrating juveniles, but very few receivers are deployed that are compatible with higher frequencies associated with the smallest tags available. The life cycle of sea lamprey also presents challenges as sea lamprey inhabit large expanses of tributaries throughout the Great Lakes that are difficult to monitor, even with improved receiver coverage, due to the vast spatial scale.

## Discussion

Our literature review identified a broad assemblage of species with relevance to management being studied based on the specific roles they have within ecosystems and relationships with humans. For example, species with fisheries (e.g., walleye and lake trout) and conservation (e.g., lake sturgeon) priorities, as well as those that disrupt ecosystem services (e.g., sea lamprey), were highly targeted study species. The geographic distribution of studies, particularly in Lakes Huron, Erie, and Ontario, included locations where important spawning grounds (e.g., Marsden et al. 2016; Binder et al. 2018; Gatch et al. 2023), valuable recreational or commercial fisheries (e.g., Faust et al. 2019; Hayden et al. 2019; Hessenauer et al. 2021), migration corridors (e.g., Kessel et al. 2018; Hayden et al. 2019), urbanized or degraded habitats (e.g., Peat et al. 2016; Rous et al. 2017; Brownscombe et al. 2023), and stocking practices (e.g., Hegna et al. 2020; Klinard et al. 2020; Gatch et al. 2022) were studied. Focus on species and locations that support sustainability values aligns with the GLFC Strategic Visions (GLFC 2011, 2021*a*), which formalize three major commitments involving conservation and rehabilitation of healthy ecosystems that sustain fisheries, integrated sea lamprey control, and strategic alliances and partnerships to promote a healthy Great Lakes ecosystem. Research has also reflected GLFC's Fish Community Objec-

**Table 3.** Main findings from acoustic telemetry studies on sea lamprey (*Petromyzon marinus*) in the Great Lakes basin.

| Reference | Knowledge gap | Main study findings | Management relevance |
|---|---|---|---|
| Rous et al. (2017) | Cause of low trap encounter | • 73% of sea lamprey reached face of generating station<br>• Sea lamprey occurred near bottom of face and away from traps at surface<br>• Increased discharge did not change movement to increase trap encounter rates | • Improve trapping success<br>• Support for planned trap improvement projects (GLFC 2021*b*)<br>• Development of SupCon control initiative (GLFC 2024*c*) |
| Meckley et al. (2017) | Navigation behaviour during migration | • 81% of sea lamprey arrived at nearest coast by moving towards shallow water, potentially following gradient in hydrostatic pressure<br>• Tortuous movements near bottom associated with orientation, and faster linear movement for directed search | • New knowledge of stream-finding migrations to locate spawning streams |
| Holbrook et al. (2016*a*) | Performance of traps in two rivers | • Trap performance limited by number of migrating sea lamprey reaching traps and proportion of those captured<br>• Local trap efficiency in each river ranged from 13% to 18% and 0% to 17%, lower than estimates from mark–recapture methods | • Traps not effective enough in absence of lampricides, require improvements to existing traps, installation of new traps, or changes to improve retention (Siefkes et al. 2021) |
| Holbrook et al. (2016*b*) | Migrating through a major connecting channel | • 81% of sea lamprey moved upstream to St. Clair River, 41% of which moved back to Lake St. Clair, and 59% ceased migration in river<br>• 37% last observed moving downstream, but unsure if before or after spawning | • Spawning and rearing in St. Clair River could be significant contributor to Lake Erie<br>• More assessment needed in large rivers lacking migration barriers |
| Meckley et al. (2014) | Effects of partial pheromone on movements of migrants | • Vertical casting behaviour to find river plumes, circling in plume, and coastal rebounding to find spawning streams<br>• Partial pheromones caused migrants to search plumes for 57% more time, but no change in likelihood of river entry | • Proposed management using pheromones as a lure may require full blend of pheromone components<br>• Details of spawning migration behaviour |

**Note:** Knowledge gaps, main study findings, and management relevance are briefly summarized for five selected publications that produced novel results relevant to management, illustrating the value of acoustic telemetry in uncovering aspects of sea lamprey ecology in the Great Lakes. Studies are listed in order of recent publication.



tives within each of its Lake Committees, which outline, among other things, concerns and targets regarding important species and habitats within each lake (GLFC 2024*d*).

The literature review in this study also showed a diverse range of study types with growing application to different research themes across the Great Lakes. Ten or more "ecology" studies were each related to spawning/mating, migration, stocking/restoration, invasive species, passage/impediments/construction, fisheries, and population demographics. The evenness of focus across research objectives within the Great Lakes ranks as one of the highest in the world when compared with other FAO fishing areas (Matley et al. 2022). Furthermore, the common research objectives in studies, such as spawning/mating, migration, and restoration/stocking, often reflected major research and management themes outlined by the GLFC over the last decade (GLFC 2017). While this does not necessarily translate to management integration, it demonstrates that researchers are adept at responding to the different concerns that have management relevance within the Great Lakes. Further evidence of a productive relationship between research publications and management is the prevalence (79%), diversity, and consistency of multi-affiliation research articles with individuals from academic and government (and other) organizations. Collaborations of these types have been credited as one of the main factors that has led to the successful adoption of research by management (Brooks et al. 2019*a*; Brownscombe et al. 2019; Nguyen et al. 2018, 2019*a*).

In addition to quantifying collaborative and management-focused trends in acoustic telemetry research (as outlined above), our review identified how studies have directly contributed to management decisions (e.g., see Case Studies). Building on these findings, below, we outline main topics that have or continue to play a part in the growth and integration of research with management, including strengths and limitations.

## Governance in the Great Lakes

Management agencies throughout the Great Lakes basin have worked in a collaborative manner for decades, largely through coordination by the GLFC (Gaden et al. 2008, 2012). Lake Committees and Lake Technical Committees were created through the Joint Strategic Plan, with Lake Committees consisted of high-ranking managers with decision-making authority from each lake's fishery agencies and Lake Technical Committees consisting of fishery researchers, assessment biologists, and individuals with relevant expertise from universities and government agencies (Nguyen et al. 2021). Early establishment of adaptive multijurisdictional management strategies within the Great Lakes likely expedited the development of GLATOS and helped to facilitate the uptake and integration of acoustic telemetry research. Fish do not adhere to geopolitical boundaries, so well-established and ongoing collaboration among agencies and nations has been critical to fully realizing the movement capacity of many species and incorporating acoustic telemetry-derived knowledge into decision-making.

## Pathways to integration

The capacity of acoustic telemetry research to translate into effective policy and management action depends on its integration with and uptake in fisheries management. Ensuring telemetry-derived knowledge contributes to management requires facilitating and maintaining avenues through which information can be exchanged (Nguyen et al. 2021). Active collaboration between researchers and practitioners has been a primary factor in cases of successful integration of acoustic telemetry findings in decision-making (Brooks et al. 2019*a*; Brownscombe et al. 2019; Nguyen et al. 2018, 2019*a*; Piczak et al. 2022). Several acoustic telemetry projects throughout the Great Lakes basin have been carried out in collaboration with management agencies, such as the multispecies monitoring project in Hamilton Harbour with Fisheries and Oceans Canada, Carleton University, and the Ontario Ministry of Natural Resources (Brooks et al. 2017; Larocque et al. 2024*a*), and the development of the Lake Erie walleye detection summary tool in conjunction with managers through the GLFC's Science Transfer Program (Hinderer et al. 2021; Hartman et al. 2023). Data-sharing and collaborative platforms like GLATOS (Krueger et al. 2018) and TrackdAT (Matley et al. 2024) also aim to build accessibility to fish tracking data to support knowledge co-production. Lake Committee Meetings, task forces (e.g., sea lamprey task force), conferences (e.g., International Association for Great Lakes Research), and other forms of in-person communication among scientists and managers (e.g., annual GLATOS coordination meeting) have also played a large role in maximizing collaboration, application, and transfer of acoustic telemetry research (e.g., Brownscombe et al. 2019; Brooks et al. 2019*a*; Piczak et al. 2022), and have additionally contributed to the overall positive perception of acoustic telemetry in the Great Lakes. Furthermore, partnerships with anglers and commercial fishers have helped form opportunities for integrated research (e.g., Hessenauer et al. 2021; Slagle and Faust 2023; Kraus et al. 2024), while also supporting active engagement to address questions or concerns from stakeholders about telemetry technology, methods, and application of findings. Knowledge dissemination through primary literature, reports, and other forms of grey literature, although not fully captured in this review, has also been crucial to support management decisions. Importantly, acoustic telemetry research often provides information that may not directly contribute to management needs, but it advances fundamental ecological knowledge in ways that increase the credibility of researchers to stakeholders and facilitate future research with more direct management applications (Matley et al. 2022).

## Acoustic telemetry networks

The establishment of GLATOS has been one of the main reasons that acoustic telemetry has been impactful in the Great Lakes (Krueger et al. 2018). The ability to share tracking infrastructure and access detection data throughout different study areas has set a precedent for data-sharing and collaboration. Many receivers throughout the Great Lakes are routinely deployed and serviced by GLATOS users, reducing project costs (e.g., receiver purchase, deployment, and download) for researchers. For example, three of the five Great Lakes (i.e., Lakes Huron, Erie, and Ontario) are, at present, entirely covered by gridded arrays of hundreds of receivers, in addition to extensive arrays deployed in key regions within Lakes Michigan and Superior (GLATOS 2024). This expansive receiver coverage broadens the scope of research questions that can be addressed by enabling near-continuous monitoring of highly mobile species as they move throughout or between different lakes and connecting water. Overall, 61% of acoustic telemetry publications in the Great Lakes basin identified affiliation with GLATOS, typically through equipment loans or data management services (Matley et al. 2024). Globally, GLATOS has the 3rd highest number of affiliated acoustic telemetry publications after OTN and the Integrated Marine Observation System—two telemetry networks at the global and continental scale, respectively. Release of the "glatos" R package in 2017 (Holbrook et al. 2017) also supported growing use of acoustic telemetry in the Great Lakes by providing a means to handle large, complex datasets and manipulate data to streamline analyses. As GLATOS has expanded over the last decade, it has provided further support through data management, equipment loans, and servicing, planning, and structuring collaborations, connecting researchers and practitioners, and stimulating science transfer initiatives (Krueger et al. 2018).

## Overall challenges integrating acoustic telemetry into management

Despite the numerous examples of effective application, communication, and uptake of acoustic telemetry research within the Great Lakes, barriers still exist that limit linking research to management actions (Nguyen et al. 2018, 2019*a*, 2021). This knowledge–action gap is a persistent challenge in fisheries management (Arseneault-Deraps et al. 2024; Cooke et al. 2024). Commonly reported barriers to incorporating telemetry into fisheries management include skepticism of the tool, complexity of interpreting data, lack of awareness and access to results, institutional challenges, time and cost limitations, and lack of management relevance in study design (Young et al. 2013, 2018; McGowan et al. 2017; Nguyen et al. 2019*b*). In our experience, the lack of management relevance in research objectives or operability of findings are major hindrances. Of the 101 ecology studies identified in this review, it is doubtful that the findings from most have been actively integrated by managers. This disconnect is not surprising and appears to be ubiquitous across most ecological fields, particularly considering that academic and government research often have distinct goals (e.g., exploratory vs. applied; Kadykalo et al. 2021; Sabo et al. 2024). Still, to some extent, contemporary research, independent of the organization conducting the research, could follow objectives that will contribute to conservation or management needs and collaborate with others to ensure output is practicable. For example, given the history of water quality impairment in the Great Lakes and concern surrounding the growing impacts of climate change (IJC 1972; Zhong et al. 2016; Collingsworth et al. 2017), it is noteworthy that very few studies examined these topics (i.e., Kelso 1974; Kraus et al. 2023), potentially requiring more dedicated work that fish tracking can address or supplement (Matley et al. 2023). Furthermore, several research/management themes can be areas for future research, particularly in lakes that are strongly impacted by human activities, such as fishing and development.

Although carrying out and communicating research that is useful to managers is a key step forward, uptake of research also falls upon the responsibility of managers. Increasing the capacity of managers to access, stay up-to-date, and interact with the research material and researchers is an area that could be better developed. There is concern that a lack of implementation may be due to an absence of established mandates or even resolve to adapt existing protocols in response to the best-available science. For example, the SCAA model implemented by the Lake Erie Committee's Walleye Task Group still incorporates a natural mortality estimate from mark–recapture methods from the mid-1990s, despite the more recent studies (some including acoustic telemetry; Vandergoot and Brenden 2014; Peterson 2023) available. Ultimately, science transfer (from researchers) and uptake (by managers) is a two-way interaction that requires action and commitment from both parties. For example, to have management impact, researchers need to design studies that address management needs and ensure managers understand key aspects of the research findings, including the uncertainty involved. Concomitantly, managers need to convey specific program goals and questions of interest to researchers, while ensuring pertinent findings are supported through administrative and legislative avenues. Lake Committee Meetings provide a significant foundation for researchers and managers (and other stakeholders) to establish or strengthen relationships to bridge knowledge–action gaps. The overall perception of acoustic telemetry in the Great Lakes basin is largely positive among managers and researchers alike (Nguyen et al. 2021), with the primary concerns of costs and communication between stakeholders being similar to other regions in North America where acoustic telemetry is used (Young et al. 2018).

There are also limits to what acoustic telemetry has or can accomplish, which may hinder the achievement of research or management priorities. The effectiveness of acoustic telemetry is dependent on spatial and temporal factors (e.g., receiver coverage) as they relate to the behaviour of the animals tagged. As a result, an existing understanding of the biology (e.g., ontogeny) and behaviour (e.g., migration), as well as areas that are commonly used, is often needed as a starting point for tracking studies aimed at providing high-level management advice. While current array coverage in the Great Lakes provides globally unparalleled information on the timing and extent of large-scale movements by fishes, such an array design is limited in the spatial resolution of fish positions. The lack of spatial resolution can confound attempts to address questions related to significant topics such as fish habitat selection, reproductive behaviours, and localized disturbances, which are critical to informing restoration, stock assessments, and mitigation measures (Brownscombe et al. 2023; Larocque et al. 2024*b*). Similarly, the movements of less mobile or more resident species (e.g., round goby *Neogobius melanostomus*) will remain obscure without spatially representative receiver arrays. Fine-scale positioning can resolve this challenge and has been used in the Great Lakes to explore spawning habitat (Binder et al. 2018), define home ranges (Withers et al. 2021), and document fish interactions with human activities (Veilleux et al. 2018). However, fine-scale tracking requires considerable effort (and often incurs considerable expense), which could affect wide-scale deployment that benefits the larger network of receivers and tagged fishes within the Great Lakes. Acoustic telemetry is also just one tool at the disposal of researchers, and although movement is intrinsic to the ecology of fishes, acoustic telemetry may not always be best suited to answer certain questions that are of interest to managers.

# Conclusion

Use and application of acoustic telemetry has grown throughout the Great Lakes basin over several decades and demonstrates the potential to inform fisheries management and conservation in various capacities. Quantifying trends in research and identifying specific examples that characterize successes or failures in bridging knowledge gaps revealed a collection of factors that have shaped acoustic telemetry research and its impact in the Great Lakes. Successful integration of research with management can be attributed to a focus on active collaboration with managers, development of research–practitioner networks, regular and frequent in-person meetings with diverse stakeholder groups, an adaptive multijurisdictional management regime, funding and programs that target science transfer initiatives, ongoing public engagement and collaboration, traditional and newer forms of knowledge dissemination, and support provided by a dedicated acoustic telemetry observation network. Barriers also remain that limit the optimal integration of acoustic telemetry findings, including applicability and communication of study findings, stakeholder perceptions, accessibility of research materials, institutional avenues for uptake, and spatiotemporal scale alignment with research or management priorities. Ongoing and future telemetry research in the Great Lakes could be most successful when research objectives can be directly related to management questions. Although some factors that have contributed to the successes of acoustic telemetry with management in the Great Lakes are inherent to the system, the Great Lakes are proving to be one of the leading applications of acoustic telemetry globally.

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### Data availability

Data analyzed during this study are available from TrackdAT (www.trackdat.org).

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The authors declare there are no competing interests.

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## Supplementary material

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