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Use of Fish Telemetry in Rehabilitation Planning, Management, and Monitoring in Areas of Concern in the Laurentian Great Lakes

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Abstract Freshwater ecosystems provide many ecosystem services; however, they are often degraded as a result of human activity. To address ecosystem degradation in the Laurentian Great Lakes, Canada and the United States of America established the Great Lakes Water Quality Agreement (GLWQA). In 1987, 43 highly polluted and impacted areas were identified under the GLWQA as having one or more of 14 Beneficial Use Impairments (BUIs) to the physical and chemical habitat for fish, wildlife and humans, and were designated as Areas of Concern (AOC). Subnational jurisdictions combined with local stakeholders, with support from federal governments, developed plans to remediate and restore these sites. Biotelemetry (the tracking of animals using electronic tags) provides information on the spatial ecology of fish in the wild relevant to habitat management and stock assessment. Here, seven case studies are presented where biotelemetry data were directly incorporated within the AOC Remedial Action Plan (RAP) process. Specific applications include determining seasonal fish–habitat associations to inform habitat restoration plans, identifying the distribution of pollutant-indicator species to identify exposure risk to contamination sources, informing the development of fish passage facilities to enable fish to access fragmented upstream habitats, and assessing fish use of created or restored habitats. With growing capacity for fish biotelemetry research in the Great Lakes, we discuss the strengths and weaknesses of incorporating biotelemetry into AOC RAP processes to improve the science and practice of restoration and to facilitate the delisting of AOCs.

Keywords Habitat restoration · Fish habitat restoration · Fisheries management · Acoustic telemetry · Telemetry

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Introduction

The Laurentian Great Lakes basin (herein referred to as the Great Lakes) encompasses more than 765,000 km^2 and 17,000 km of shoreline and is within one of the most industrialised regions in North America (Hanson 1998). The basin is home to about 10% of the U.S. population and 30% of the Canadian population (Danz et al. 2007). Throughout the Great Lakes basin, human activities have led to drastic physical habitat alterations through activities, such as shoreline modification, coastal wetland draining and filling, and channelization of tributary streams (Jones et al. 2006). In addition, point source pollutants from industrial processes (largely from the 1800s and 1900s) and sewage outflows have caused localised sites (often harbours) to be severely contaminated. Non-point source pollution from activities that occur near tributaries (e.g., agriculture, stormwater management) deliver an excess of nutrients and other pollutants to the receiving waterbodies. These aforementioned stressors represent only a selection of the 50 stressors currently impacting the ecosystem goods and services that the great Lakes provide (see Smith et al. 2015).

As a result of the degraded condition of certain areas of the Great Lakes, the International Joint Commission (IJC), which manages the boundary waters of Canada and the United States of America (IJC 2012a), drafted the Great Lakes Water Quality Agreement (GLWQA). The GLWQA was signed by both the nations in 1972 to ensure commitment to the protection of the Great Lakes and St. Lawrence River drainage basin. By virtue of the GLWQA, 43 highly degraded (and often contaminated) sites, known as Areas of Concern (AOC), were identified and designated in 1987. AOCs are locations where local human activities have impaired certain beneficial uses of the lakes and connecting rivers, such as water quality and fish consumption, dredging, and loss of fish and wildlife habitat, all categorised into 14 Beneficial Use Impairments (BUIs; Table 1). Upon designation as an AOC, federal government partners (e.g., US Environment Protection Agency, US Fish and Wildlife Service, Environment Canada and Climate Change, Fisheries and Oceans Canada), with assistance from subnational agencies (e.g., Ontario Ministry of Natural Resources and Forestry (OMNRF), Conservation Authorities, Restoration Councils) are required to devise a Remedial Action Plan (RAP) representing a systematic and comprehensive ecosystem approach to restoring the AOC. The RAP is then submitted to the IJC over three stages; Stage 1: when a definition of the problem has been completed; Stage 2: when remedial and regulatory measures are selected; and Stage 3: when monitoring indicates that beneficial uses have been restored. AOCs are delisted when: (i) a delisting target has been met through remedial actions, which demonstrates that the beneficial use has been restored; (ii) it can be demonstrated that the impairment is not limited to the local geographic extent, but rather is typical of lake, region, or area-wide conditions, or; (iii) that the impairment is caused by sources outside of the AOC (USPC 2001). To date, seven AOCs have been delisted and two have been designated as in the recovery phase (http://ijc.org/en_/aoc).

Environmental monitoring programmes are developed to either measure the status and trends of specific chemical, physical, and biological characteristics over time, or to detect alterations in characteristics deemed to be indicators of a relevant change (Ekman et al. 2013). The RAP process can implement remedial actions effectively by using research and monitoring to track trends, promote adaptive management, develop interdisciplinary integration, and increase public accountability (Hall et al. 2006). Many AOCs have been exposed to anthropogenic disturbances for over one hundred years. Thus, rehabilitation of ecosystem services will likely take decades and maintaining momentum will be difficult. Monitoring programmes essential for the RAP delisting process also serve to motivate local, regional, and national stakeholders for these long-term goals (USPC 2001; Hall et al. 2006).

Currently, limited independent monitoring programmes exist within the Great Lakes, including the Mussel Survey and the Great Lakes Fish Monitoring Programme (Carlson and Swackhamer 2006) that support RAP processes. Specific monitoring programmes for various BUIs include sampling fish and wildlife populations, and their physical and chemical habitats (Table 1). Traditional physical habitat sampling involves hydroacoustic surveys of submerged aquatic vegetation (Leisti et al. 2012, 2016) or substrate, plant, and water chemistry analysis (Grabas et al. 2012). Assessment of the water chemistry associated with fish habitat involves surface-column and water-column sampling for temperature, dissolved oxygen (DO), sediment, contaminants, and metals. Current fish population monitoring schemes to quantify restoration success across multiple sites in the Great Lakes use local or regionally derived indices of biotic integrity, which consider the fish community trophic composition, including invasive species (Brousseau et al. 2011; Hoyle et al. 2012; Boston et al. 2016; Hoyle and Yuille 2016).

When assessing aquatic ecosystem health, fish are often the focal point due to their important economic and ecological ecosystem services (Holmlund and Hammer 1999; Lynch 2006), including supporting commercial, recreational, and subsistence fisheries. Fish also can be used as bio-indicators of aquatic habitat condition (see Whitfield and Elliott 2002, for full review). However, aquatic environments and fish in particular can be logistically difficult to study and observe directly. Past monitoring efforts have often focused on endpoints, such as changes in abundance and richness or community composition using sampling gear, such as gillnets, trapnets, traps, trawls, and electrofishing to collect data (Ford 1989; Murphy and Willis 1996; Lorenzen et al. 2016). These surveying techniques each have unique bias and only record animals at single points in time and space, and yield relatively few sightings for rare species living in inaccessible environments (Aarts et al.

Table 1 Current monitoring techniques for the 14 Beneficial Use Impairments and case studies where acoustic biotelemetry is being used to compliment these monitoring methods (Lower Menominee River (LMR); Manistique River and Harbour (MRH); St. Mary's River (SMR); St. Clair and Detroit Rivers (SCDR); Hamilton Harbour (HH); Toronto Harbour (TH); Niagara River (NR))

Beneficial use impairment	Current monitoring techniques	Biotelemetry?
Restrictions on fish and wildlife consumption	Samples from edible-sized fish and Young of Year for PCB, mercury, lead, etc.	Yes (HH, TH, MRH)
Tainting of fish and wildlife flavour	Samples from water column for volatile and semi-volatile organics and phenolics.	N/A
Degradation of fish wildlife populations	FISH: Electro-fishing, gillnet and trap net samples for species composition, abundance, size distribution and biomass. (IBI-Boston 2016) monitoring by RBG at the Cootes Paradise fishway	Yes (LMR, SCDR, HH, TH, NR)
	WILDLIFE: Visual surveys.	
Fish tumours or other deformities	E-fishing, gillnet for histological analysis from liver samples.	N/A
Bird or animal deformities or reproduction problems	WILDLIFE: Whole body tissue concentrations of contaminants (eggs, blood, liver, brain, muscle, stomach samples) FISH: Fish of a size and species considered prey for the wildlife under consideration must be sampled.	N/A
Degradation of benthos (organisms living on lake bottoms)	Benthic macroinvertebrate communities (abundance, composition, and size) & composite sediment samples/toxicity tests—Ponar grab.	N/A
Restrictions on dredging activities		Yes (MRH)
Eutrophication (undesirable algae)		N/A
Restrictions on drinking water consumption, or taste and odour problems		N/A
Beach closings		N/A
Degradation of aesthetics/visual appearance	Trash and contaminants, monitoring process?	N/A
Added costs to agriculture or industry		N/A
Degradation of phytoplankton and zooplankton populations		N/A
Loss of fish and wildlife habitat	PHYSICAL: Increase habitat and further establish and protect critical connective corridors for wildlife; CHEMICAL: Dissolved oxygen, current hypoxic and sometimes anaerobic conditions in AOC are primarily result of pollution, eutrophication and low flow.	Yes (LMR, SMR, HH, TH, NR)

2008). Also, the simple presence of animals at a site is not substantial evidence that the site contributes positively to the reproductive success and population replacement (Aldridge and Boyce 2007).

Studies of fish movement and spatial ecology within the Great Lakes have provided resource managers with important knowledge on the temporal and spatial distributions of fishes within and between the lakes and their tributaries. Following an individual's behaviour in these sites allows for comparisons of the ecosystem health based on behaviours that have fitness consequences, and can identify critical resources and provide information on the mechanisms through which species contribute to ecosystem functions (Lindell 2008). Landsman et al. (2011) have reviewed 112 fish movement studies within the Great Lakes between the years 1952 and 2010 and included methods, such as mark-recapture, biotelemetry, hydroacoustics, otolith microchemistry, and isotope analysis. These studies addressed questions relating to the reproductive biology of fishes (e.g. movements to and from spawning sites, locations of spawning activities, and spawning behaviour descriptions), environmental relations and disturbances, including natural (e.g. seasonal flooding, drought events) or anthropogenic (e.g. power plant discharge, barriers to fish movement), stocking success, identification of critical habitats, such as nursery areas, and the movements of invasive species.

With technological advancements over the past several decades, biotelemetry (the use of animal-borne electronic tags) has provided researchers opportunities to remotely track an animal's interactions with the ecosystem over scales of metres to thousands of kilometres, and over time frames of seconds to years (Cooke et al. 2013; Hussey et al. 2015). Numerous forms of biotelemetry can be used within freshwater fish research including, radio, acoustic, and satellite, and include some with biologging capabilities that can record temperature, pressure (depth), DO, heart rate, predation events, and acceleration. Each has its unique benefits for answering specific questions, but also has constraints including costs, labour required, climate conditions, and battery size requirements (for full review see Cooke et al. 2013).

In this paper, we discuss how knowledge about spatial ecology emanating from radio and acoustic telemetry studies, is being used in the restoration of AOCs and management of BUIs pertaining to fish and their habitats of the Great Lakes. To accomplish this, we describe seven case studies where biotelemetry is being used as a data gathering tool within various phases of AOC RAPs. Our purpose is to provide a critical review of the opportunities and limitations associated with biotelemetry for supporting AOC-related activities to inform future efforts given that biotelemetry is an emerging technology.

Biotelemetry in Ecosystem Management

Biotelemetry has typically been used to support ecosystem management with information on the spatial ecology of fish, including habitat requirements, migratory routes, foraging and reproductive sites, and dispersal characteristics of fish (reviewed in Cooke et al. 2013; Crossin et al. 2017). More specifically to habitat restoration, biotelemetry has provided a wealth of information on spatial and temporal habitat requirements for particular fish species, useful information for restoration design (Lucas and Baras 2000; Lapointe et al. 2013). However, until recently biotelemetry has not often been used in pre-restoration and post-restoration monitoring efforts in AOCs. Some examples of the successful applications of biotelemetry in AOCs are outlined under the AOC case studies.

Biotelemetry has unique characteristics relative to traditional fish and fish habitat sampling techniques (reviewed in Lucas and Baras 2000; Cooke et al. 2016), such as the ability to monitor individuals through time, quantify seasonal habitat and environmental preferences, and measure the internal physiological status of free-swimming fish. The 'snapshots' of fish abundance and community structure obtained through conventional sampling (e.g., use of netting or electrofishing surveys), is certainly important but fails to incorporate the aforementioned aspects (Ford 1989). Indeed, these approaches are complementary.

Biotelemetry systems employ battery-powered acoustic or radio tags that produce a coded transmission and are attached externally to the body or are surgically implanted into animals (see Cooke et al. 2011 for details). Animals can be actively located and tracked by foot, boat, or plane using hydrophones for acoustic transmitters or antennas for radio transmitters. Passive tracking involves autonomous fixed-position receivers that decode transmissions and store the tag identity, sensor data, time, and date for each transmission when tagged fish are within range (Kessel et al. 2015). Passive tracking allows long-term monitoring of multiple individuals throughout all seasons with relatively little labour (see Heupel et al. 2006). If acoustic receivers are positioned in a grid-like pattern close to each other (~750 m), a fish's exact location can be determined for each acoustic transmission. Acoustic tags can also be equipped with sensors (Cooke et al. 2016) that measure environmental variables (e.g., depth, temperature, DO, pH), individual motion or activity (e.g., acceleration), or physiological status (e.g., heart rate). The combination of fish location, the surrounding environmental conditions, and internal status of the fish provides a more complete understanding of the environmental conditions encountered by fish, as well as drivers of fish movement (Nathan et al. 2008). This integrated data is valuable to managers of freshwater ecosystem rehabilitation and compliments traditional fish community and habitat sampling techniques.

Case Studies

Progress towards delisting an AOC is dependent on managers' having access to accurate ecosystem models produced with specific habitat requirements for fish and the ability to evaluate success of existing programmes (Hall et al. 2006). Here, we introduce seven case study examples (Fig. 1), where biotelemetry data is being directly used by State, Provincial, and Federal managers to: 1) determine seasonal fish–habitat associations to inform habitat restoration plans; 2) identify the distribution of pollutant-indicator species to identify exposure risk to contamination sources; 3) inform the development of fish passage facilities to enable fish to access fragmented upstream habitats; and 4) assess fish use of created or restored habitats. The presented biotelemetry projects have all been initiated, however they are at various stages of completion. We conclude by providing recommendations for scientists and managers that may consider the use of biotelemetry to inform AOC-RAP processes.

Lower Menominee River, USA (LMR)

Context

The Menominee River represents the boundary between northeast Wisconsin and the southern tip of Michigan's Upper Peninsula. The lower 4.8 km of the river and 5.0-km segments running north and south along the Green Bay (Lake Michigan) shoreline from the river's mouth were designated as an AOC in 1987 with six BUIs. Improper storage and disposal of arsenic combined with other industrial and municipal actions led to contamination of the lower river. Additionally, changes in habitat and lack of safe passage around dams limit access to important spawning and rearing habitat for fish species, such as lake sturgeon (*Acipenser fulvescens*). Park Mill and Menominee dams are within the AOC and serve as the initial upstream barriers to lake sturgeon passage from Green Bay, which contributes to the 'loss of fish and wildlife habitat' BUI. The Menominee Fish Passage Partnership, comprised of state and federal agencies, non-profit conservation organisations, and a private energy company, is developing safe and effective passage for lake sturgeon around these two dams

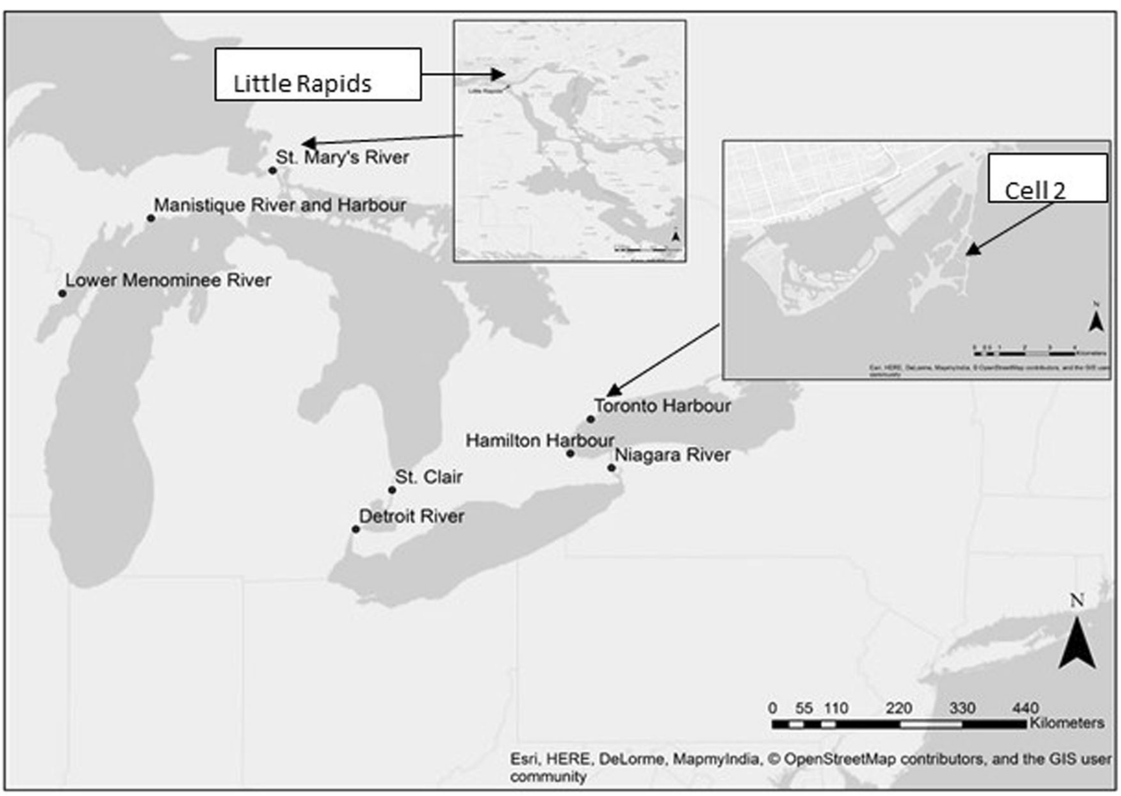

Fig. 1 Map of the Laurentian Great Lakes, including seven Areas of Concern that are using biotelemetry in Remedial Action Plans. Insets include Little Rapids section of the St. Mary's River, and the restored 'cell 2' site in the outer harbour of Toronto Harbour

using trap and transport of sturgeon captured in a fish lift built within Menominee Dam.

Biotelemetry applications

The two BUIs being monitored with acoustic biotelemetry are: 'degradation of fish and wildlife populations' and 'loss of fish and wildlife habitat'. From 2014 to 2016, lake sturgeon was captured from below Menominee Dam using a fish elevator constructed within the dam and by electrofishing. Adult lake sturgeon ($N = 120$) ready to spawn was implanted with 10-year acoustic transmitters and released above the two lowest dams (Park Mill and Menominee) on the Menominee River. Fish passed upstream were expected to spawn in the next available spawning period (usually early to mid-May). Spawning habitat and habitat for juvenile lake sturgeon are more abundant in the section of river above the two dams. Fixed acoustic receivers located throughout the river are being used to determine if: (1) lake sturgeon remain above both dams to spawn at least once; (2) tagged fish eventually return downstream; and (3) sturgeon use downstream passage facilities. Determining if lake sturgeon remain upstream of dams to spawn is an important first step in assessing whether passage efforts have the potential to increase the lake sturgeon population in the lower Menominee River AOC, Green Bay, and Lake Michigan as a whole. If fish do not remain above both dams to spawn, then improvements in recruitment resulting from passage cannot occur. Additionally, potential improvements in recruitment may be offset if adult fish do not return downstream after passage. Results of this research will help in defining passage strategies in terms of numbers and sex of fish and the time of year passage should occur in order to maximise potential for increased recruitment.

Manistique River and Harbour, Lake Michigan (MRH)

Context

The Manistique River and Harbour Area of Concern is a 2.7 km river reach and harbour on the northern shore of Lake Michigan in the Upper Peninsula of Michigan, USA. The site was designated an AOC in 1987 due to sediments contaminated with polychlorinated biphenyls (PCBs) and heavy metals (Michigan DNR 1987, Michigan Department of Environmental Quality 2011). The PCB contamination has been the subject of study and remediation since the 1980s, including large-scale sediment dredging efforts from 1996 to 2000 and again in 2016 and 2017. Two BUIs remain at this AOC: 'restrictions on dredging' and 'restrictions on the consumption of fish and wildlife'. The most stringent fish consumption advisory is a 'do not eat' advisory on common carp (*Cyprinus carpio*), due to the high PCB content in the fish tissue (Michigan Department of Health and Human Services 2016). The fish consumption advisories are considered a 'beneficial use impairment' that needs to be removed before an area can be delisted as an AOC (U.S. Policy Committee 2001). For this case study, the residency of common carp was studied to evaluate the extent to which fish tissue contaminants can be associated with the AOC or derived from areas outside the AOC.

Biotelemetry applications

In 2015, adult common carp was captured from the AOC and implanted with integrated acoustic and radio transmitters (Model MM-MC-16-50, Lotek Wireless, Newmarket Ontario), with the objective of establishing their residency in the harbour and identifying their specific locations while in the harbour. A fixed array of receivers was in place from early June (pre-spawning) to late October 2015. The array has a hybrid design, intended to indicate the presence or absence of fish in some areas of the harbour and to determine high-resolution two-dimensional positions of fish in other areas, depending on harbour geometry. Additionally, aerial radio tracking was used to locate fish after they left the harbour into Lake Michigan. The study showed that common carp was generally transient to the harbour, with residency ranging from only a few days to several months. Preferred locations of fish (while resident in the harbour) were also identified. Results have been used to establish that common carp were not a reliable indicator of the restriction on fish consumption BUI because their contaminant burdens cannot be directly attributed to the Manistique River and Harbour AOC.

St. Marys River, Lake Huron/Superior (SMR)

Context

The St. Marys River, the largest tributary to Lake Huron, is a 112 km long braided channel that connects Lake Superior and Lake Huron. The river contains a diversity of habitats (high energy rapids, fringing wetlands, and warm embayments) for fishes, yet a succession of anthropogenic impacts resulted in the river being listed as an AOC in 1987 with 10 identified BUIs (Bray 1996; Ripley et al. 2011). Key impacts on the fish community included extensive habitat loss to support shipping and hydroelectric industries, high industrial discharges that continue to influence benthic communities, and water quality degradation from point sources, such as water treatment facilities (Ripley et al. 2011). The fish community was originally listed as degraded in part due to concerns about habitat loss and aquatic invasive species, declines in native species, and high sea lamprey (*Petromyzon marinus*) abundance (Remedial Action Plan 1992). Ongoing remediation efforts have included reductions in point source pollution, sediment remediation, and habitat restoration including the ongoing restoration of the Little Rapids area (Fig. 1). Fish populations are generally healthier and more stable than most other AOCs, though reductions in the populations of some desired native fishes are suspected (Schaeffer et al. 2011; Pratt and O'Connor 2011). Efforts to rehabilitate degraded walleye (*Sander vitreus*) and lake sturgeon and to combat sea lampreys are ongoing in the river, and include the provision of more natural flow regimes to improve spawning habitat for fishes, and enhanced bayluscide treatments in areas of high larval sea lamprey density (IJC 2012b; Robinson et al. 2016).

Biotelemetry applications

Acoustic biotelemetry is being used to address 'the degradation of fish and wildlife populations' and 'loss of fish and wildlife habitat' BUIs in the St. Marys River. Three recent studies examined how to limit the impacts or potential impacts of aquatic invasive species. Successfully controlling sea lampreys remains a critical management goal on the river, and two studies used acoustic biotelemetry to examine why sea lamprey trapping rates remain lower than other locations. The first study examined sea lamprey temporal and spatial migration dynamics, determining existing migration pathways and demonstrating that many sea lampreys were not vulnerable to traps (Holbrook 2015). The second study used 3-D positioning to test if manipulation of discharge from a hydro-generating station could increase sea lamprey trap success at traps immediately downstream (Rous et al. 2017a). The main finding identified a spatial (vertical) mismatch between the space use of sea lampreys and the locations of traps and increasing discharge did not alter space use in a manner that increased trap success (Rous et al. 2017a). A third study, which began in 2013 examined the potential for invasive fishes (notably Asian carps) to use the shipping locks in the St. Marys River as a potential invasion pathway into Lake Superior. This study identified that surrogate, large-bodied fishes passed upstream and downstream using both the US and Canadian locks, and given their history of lock usage for dispersal in the Mississippi River system, it was hypothesised that Asian carps would have a high probability of dispersal through the locks on the St. Marys River if established below the locks (Kim et al. 2016). A number of acoustic biotelemetry studies examining walleye and lake sturgeon habitat use and movement are either completed (Gerig et al. 2011) or underway in the St. Marys River and will help address habitat loss concerns, and identify locations for protection or future remediation. For example, Gerig et al. (2011) identified in 2006–07 that lake sturgeon was exclusively using the north channel of the river through Lake George and as far south as East Neebish Island with core activity centred where the Garden River enters the north channel and upper Lake George, and were avoiding the south channel where the shipping channel is located. The Anishinabek/Ontario Fisheries Resource Centre followed up that research in 2016, and with the help of acoustic telemetry identified a lake sturgeon spawning location in the Garden River. This has resulted in changes in sea lamprey control activities in the river over concerns that age-0 lake sturgeon can be susceptible to lampricide mortality under certain physiochemical conditions (O'Connor et al. 2016). Another ongoing study, using acoustic telemetry study initiated in 2015 by Fisheries and Oceans Canada and the Ontario Ministry of Natural Resources, is assessing the potential for at lake sturgeon movement between lakes Superior and Huron, as genetic data indicates that spawning populations from south-eastern Lake Superior and the North Channel of Lake Huron are a meta-population, and at least at one time populations from this broad area mixed by migrating through the St. Marys River.

St. Clair and Detroit rivers (SCDR)

Context

The Detroit and St. Clair rivers together with Lake St. Clair form the connecting channel that links Lakes Huron and Erie. The Detroit and St. Clair rivers once provided important spawning habitat for lake sturgeon, lake whitefish (*Coregonus clupeaformis*), cisco (*C. artedii*), and walleye, but after decades of navigational dredging, shoreline development, and pollution, spawning runs of these migratory species declined or ceased altogether (Bennion and Manny 2011; Roseman et al. 2011; Hondorp et al. 2014). Thus, in 1987, both rivers (but not Lake St. Clair) were listed as AOCs with the 'loss of fish habitat' and 'degradation of fish populations' as key BUIs. A primary emphasis of restoration efforts in both rivers has been the construction of rock-rubble spawning reefs that mimic natural spawning shoals that were the preferred spawning sites of migratory fish. To date, a total of six spawning reefs have been constructed in the main channels of the Detroit and St. Clair Rivers (Manny et al. 2015).

Biotelemetry applications

Acoustic telemetry data is beginning to inform the site selection process for fish spawning reef construction in the SCDR. Historically, candidate sites for reef construction were selected and prioritised using a biophysical model that predicted spawning habitat quality from site-specific current velocities and bathymetry (Bennion and Manny 2014). More recently, however, a study using acoustic telemetry to describe lake sturgeon population structure in the Lake Huron-to-Lake Erie corridor has provided information on lake sturgeon movements in the vicinity of potential reef construction sites. The acoustic telemetry data enabled fishery managers to identify construction sites that would maximise lake sturgeon encounters with newly constructed reefs and to determine a priori which lake sturgeon populations would benefit from a spawning reef constructed at a given location. As an example, movements of acoustic-tagged lake sturgeon identified the North Channel of the St. Clair River between the Chenal a bot Rond confluence and Pte aux Tremble as an ideal location for the construction of spawning reefs due to heavy lake sturgeon use of this 5.0-km section of river. Similarly, acoustic telemetry data was used to confirm that lake sturgeon was likely to encounter man-made spawning reefs at a proposed site near Grassy Island in the Detroit River.

Hamilton Harbour, Lake Ontario (HH)

Context

Hamilton Harbour, a 21-km² embayment in the western end of Lake Ontario (Figs. 1, 2c), is Canada's largest contaminated site in the Great Lakes (with regard to polycyclic aromatic hydrocarbons (PAHs), Graham et al. 2012) and designated as AOC in 1985 with 11 BUIs (see Hamilton Harbour RAP 2003). Historically, the harbour was a productive wetland area; however, it has lost 65% of available fish and wildlife habitats since industrialisation in the early 1900s (Hamilton Harbour RAP 2003). In nearshore zones, non-native species have become dominant, altering fish community composition and trophic balances such that benthic fish generalists are favoured over piscivores (Brousseau and Randall 2008). The Hamilton and Burlington areas have five waste-water treatment plants introducing high levels of phosphorus and nitrogen into the harbour, leading to eutrophication and extremely low levels of DO in many areas (Gertzen et al. 2016; Yerubandi et al. 2016). Remediation efforts include 376 ha of restored fish and wildlife habitats, 12-km of new shoreline (Hamilton Harbour RAP 2003), and new and strict regulations on waste-water treatment outflows. Fish community surveys to assess the status of the littoral fish community in the Harbour have been conducted since 1988. Using an Index of Biotic Integrity (IBI), a score that considers species richness and abundance, survey results have shown that the trophic composition continued to reflect a degraded fish community. The biomass of generalist fish species, such as common carp and bullheads (*Ameiurus nebulosus*) was high, while the average biomass of piscivores was low (Brousseau and Randall 2008). In an attempt to increase the levels of piscivores, OMNRF has over the last two decades stocked walleye, a previously extirpated native predator. Monitoring the behaviours of native and reintroduced fish is necessary for further restoration projects and delisting purposes.

Biotelemetry applications

The two BUIs being monitored with acoustic biotelemetry are: 'degradation of fish and wildlife populations' and 'loss of fish and wildlife habitat'. Beginning in fall 2015, sexually mature walleye was captured and tagged with acoustic transmitters with pressure (depth) sensors. Fixed acoustic biotelemetry receivers were placed throughout and adjacent to the harbour to determine residency patterns of walleye, including both sides of the shipping canal, with a particular focus on identifying aggregation areas during the spawning season (Fig. 3). Results will help assess whether stocking efforts have been effective and will also help to direct future habitat protection and enhancement efforts. In addition to walleye, fish from multiple trophic levels (e.g., channel catfish (*Ictalurus punctatus*), longnose gar (*Lepisosteus osseus*), and freshwater drum (*Aplodinotus grunniens*)) have been tagged to characterise seasonal habitat use with a particular emphasis on use of restored habitats. Pressure sensor data from these individuals will also help to establish their seasonal depth distribution, which can be paired with extensive DO mapping and modelling efforts to evaluate changes in the amount of available habitat for fishes and whether fishes are using anoxic zones. In the future, fish will be equipped with newly developed acoustic transmitters that have integrated DO sensors (see Svendsen et al. 2006) to obtain more detailed information on use of anoxic or near-anoxia waters. Also, collaborations with researchers working in the nearby Toronto Harbour and Niagara River AOCs (see following case studies TH and NR) are planned to explore connectivity among these spatially distinct systems. Finally, efforts have been made to engage the public through social media activity, public events, and school visits because results from telemetry studies such as this can be easily understood and disseminated through mapping and fish movement visualisation. Preliminary findings have shown that reintroduced walleye is residing within the Harbour for the majority of the year, and highlighted areas of high use during the spawning season, both of which provides an important next step for research into the natural recruitment prospects (Brooks et al., in preparation).

Fig. 2 **a** Electro-fishing a northern pike (*Esox lucius*) in Toronto Harbour, ON, for acoustic transmitter surgery (photo credit Jeff Dickie); **b** Inserting an acoustic transmitter into a lake sturgeon (*Acipenser fulvescens*) in the Detroit River, MI; **c** Downloading an acoustic receiver near steel plant, Hamilton Harbour, ON (photo credit Jill Brooks); **d** grappling for receivers near the city of Buffalo, NY (photo credit Jonah Withers); e Inserting an external identification floy tag into a lake sturgeon (photo credit D. Gorsky)

Toronto and Region, Lake Ontario (TH)

Context

Situated along the north shore of western Lake Ontario, the Greater Toronto Area is the most densely urbanised area in Canada (Figs. 1, 2). The watersheds and extensive coastal waters (42 km of shoreline) in and around the City of Toronto have a long history of agricultural and urban disturbance that led to this region being designated as an AOC in 1987 with 11 BUIs, eight of which are still listed as impaired. These BUIs are linked to stormwater and combined sewer overflows (e.g., excess nutrients, bacteria), contaminants related to industry and legacy pollutants (e.g., lead, PCBs, mercury), and changes to or a loss of habitat and biodiversity (Toronto Region RAP 2007). Guided by the RAP, extensive restoration efforts have been undertaken throughout the AOC including: improvements to wastewater infrastructure (e.g., combined sewer separation), tree and riparian vegetation planting, removal of instream barriers to fish migration, addition of aquatic habitat structure to hardened slips and shorelines, and the creation and restoration of coastal wetland habitat (Toronto Region RAP 2007). From a habitat perspective, the central waterfront of Toronto has experienced some of the largest changes in the AOC with a net loss of over 600 ha of wetland habitat through infilling and shoreline hardening (Whillans 1982). Restoration efforts to date have increased the amount and

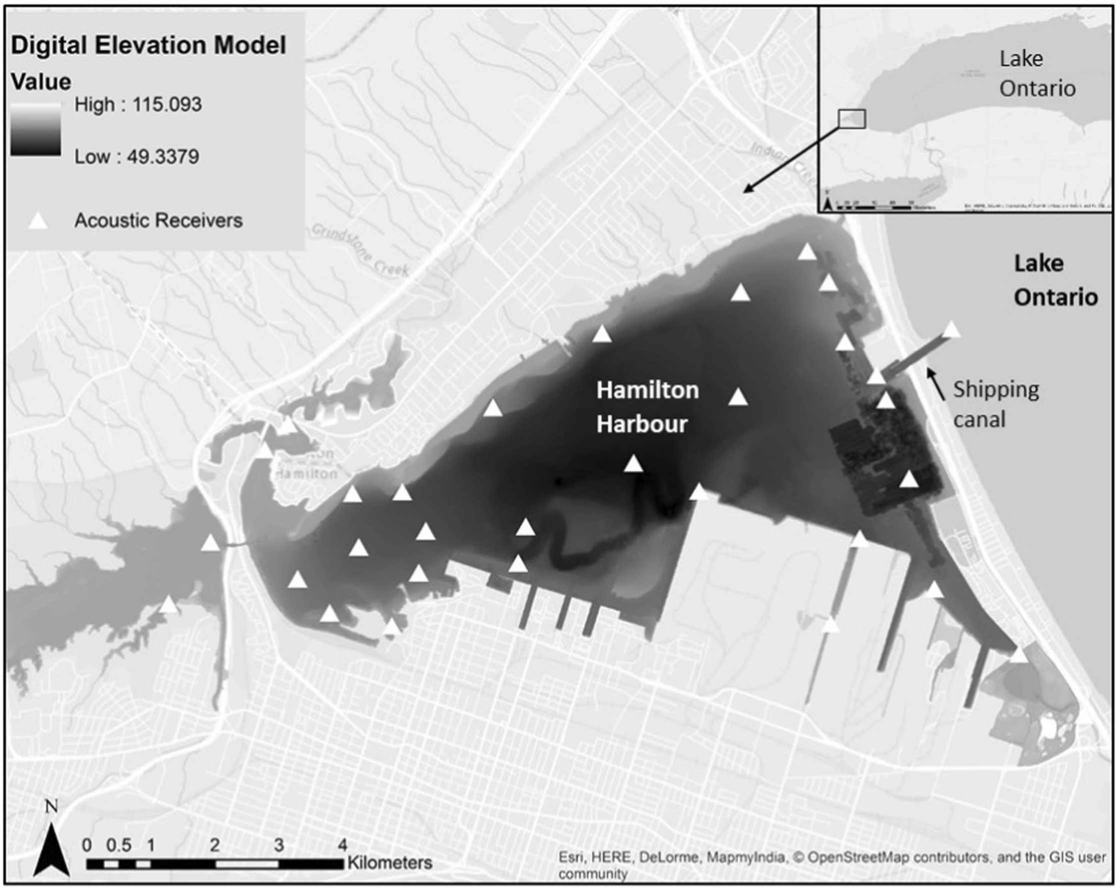

Fig.3 An example of an array of fixed acoustic biotelemetry receivers placed throughout and adjacent to Hamilton Harbour to determine residency patterns of walleye (*Sander vitreus*), including both sides of the shipping canal, with a particular focus on identifying aggregation areas during the spawning season

quality of aquatic habitat, but an understanding of how fish has responded to the increased habitat is needed to support RAP targets.

Biotelemetry application

The acoustic biotelemetry project for the Toronto and Region AOC is focused on the central waterfront (Toronto Harbour) and aimed at supporting two BUIs, the 'degradation of fish and wildlife populations' and the 'loss of fish and wildlife habitat'. The harbour has been the focus of many of the aquatic habitat creation and restoration efforts in the AOC, which have primarily occurred in the slips along the north shore, among the comparatively natural Toronto Islands, and at Tommy Thompson Park (created from surplus fill and dredged material). Starting in 2010, the acoustic biotelemetry project was implemented to help assess the efficacy of the restoration efforts completed in the harbour by evaluating the use and residency of native fishes (e.g., northern pike (*Esox lucius*), largemouth bass (*Micropterus salmoides*), walleye, yellow perch, white sucker (*Catostomus commersonii*), brown bullhead and bowfin (*Amia calva*)) and the non-native common carp using a passive acoustic telemetry array. Clear evidence of use of restored areas by a subset of fishes has since been documented (Rous et al. 2017b); however, increased use of restored areas relative to un-restored areas has been more challenging to confirm due to a lack of historical data. Results from the acoustic biotelemetry project will provide baseline data for restoration projects currently underway in the harbour. In addition to tracking residency and habitat use at the level of fish community, the biotelemetry project has provided more detailed insight into seasonal habitat preferences (depth, temperature, aquatic vegetation; Midwood et al., in sub; Peat et al. 2016) of tagged fishes, as well as their behavioural responses to extreme events, such as the frequent intrusions of cold Lake Ontario water into the harbour (Hlevca et al. 2015). This type of core fish ecology information has been used since to refine the design of habitat restoration projects. For example, for Cell 2 in Tommy Thompson Park (Fig. 1), restoration plans were modified to include deeper water habitat (2–5 m) based on the telemetry-informed use of this depth strata by walleye and northern pike in the spring and by largemouth bass and northern pike in the winter. Moving forward with the Toronto Harbour project, tagging efforts and the array design will continue to support the assessment and refinement of restoration actions. Additional effort may also be directed towards an additional BUI, 'restrictions on fish and wildlife consumption'. White sucker continues to show elevated levels of PCBs in the AOC and in a similar manner as the Manistique River and Harbour AOC, and tracking their movements and residency within the harbour may help to determine whether the source of these contaminants is within the harbour and, if so, where more detailed sampling is required to isolate the source. This evaluation will partially be accomplished through the expansion of acoustic biotelemetry arrays in the Toronto and Region AOC and in the nearshore of western Lake Ontario, as well as with support from collaborators managing acoustic arrays in the Hamilton Harbour and Niagara River AOCs.

Niagara River, Lakes Erie, and Ontario (NR)

Context

The Niagara River is the connecting channel between Lake Erie and Lake Ontario (Fig. 1). The river drains inputs from the upper Great Lakes basin into Lake Ontario. The availability of the water for transportation and power generation led to the industrialisation within and around the major cities Buffalo, New York and Niagara Falls, Ontario. The upper Niagara River is generally a shallow and wide river system with high currents in the channels and slow water near several islands that split the waterway. The lower Niagara River has a large gorge section below the falls with fast flowing deep waters. Approximately 7.0 km below the falls, the river exits the gorge and opens into a wider sinuous river section before entering Lake Ontario. The upper Niagara River has been most impacted by industrialisation. Contaminated sediment contributes to several BUIs in the Niagara River AOC (Niagara River RAP Stage 2 Addendum 2012). Additionally, dredging, shoreline development, and harbour development have removed or degraded many essential fish habitats within the AOC. Efforts to restore fish habitat are pending a resolution from the severe contamination from legacy chemicals. Considerable progress has been made in remediation of chemical contamination by reducing discharges and removal of contaminated sediments at multiple locations within the AOC.

Biotelemetry applications

Two BUIs are currently being addressed with the use of acoustic telemetry: 'the degradation of fish and wildlife populations' and 'loss of fish and wildlife habitats'. Since 2014, acoustic receivers have been deployed in an array at the headwaters of the Niagara River and a series of curtains throughout the Niagara River to fill critical information gaps pertaining to lake sturgeon life-history parameters and recovery impediments. Objectives of the study include: (1) elucidating lake sturgeon distribution within Lake Erie, Lake Ontario, and the Niagara River, (2) determining lake sturgeon residency within the AOC, (3) assessing lake sturgeon habitat availability and use, and (4) identify whether spawning occurs within the AOC. To date, 52 lake sturgeons in the upper Niagara River and 67 individuals in the lower Niagara River have been implanted with acoustic transmitters with estimated battery lives of 10 years. Early results suggest lake sturgeon rely on areas within the AOC for spawning and show high site fidelity to the AOC during staging events. As discussed in the Niagara River RAP, dramatic habitat alterations within the upper Niagara River likely have reduced available spawning and nursery habitats proximate to discovered spawning locations (Neuenhoff et al. J. Withers unpublished data). Current and future efforts work towards assessing and quantifying available habitat availability within the AOC.

Synthesis In this review, we presented several examples of how biotelemetry has and is being used to support the Great Lakes' AOC RAP process. Biotelemetry has been incorporated during both the planning (Stage 2) and monitoring (Stage 3) stages of the RAP management process for the BUIs involving fish and wildlife populations. We included biotelemetry projects funded specifically to support the RAPs and cases where pre-existing but relevant animal movement data have also been incorporated.

During the planning stage of the RAP process (Stage 2), habitat preference information for various species of concern was incorporated into planning for physical habitat remediation. In Toronto Harbour, seasonal habitat and depth preferences for two focal species, northern pike and largemouth bass, were determined and then incorporated into the project designs of physical habitat restoration. In other AOCs, walleye and lake sturgeon movements will similarly be used to identify locations for further protection and remediation efforts. Biotelemetry was used during the post-restoration monitoring stage (Stage 3) for the majority of the case studies. In Lower Menominee River, lake sturgeons have been acoustically tagged to determine their upstream spawning habits, and the successful use of downstream passage facilities at the two dams within the AOC. In Manistique River and Harbour, common carps were traditionally used as bio-indicators for PCB contamination issues; however, radio and acoustic telemetry established that their residency times within the AOC boundary were too short and they were no longer considered a reliable indicator of the 'fish consumption' BUI. This application represents an important frontier in ecological risk assessment and begins to question the assumption that fish sampled in a given location is representative of contaminant burdens from that location (Van der Oost et al. 2003).

Rapid advances in technology have also led to the miniaturisation of tags enabling researchers to study earlier life stages of fishes (relevant for recruitment questions), and an increase in sensor capabilities has resulted in tags that can record acceleration, depth, temperature, and DO (Cooke et al. 2004, 2016; Hussey et al. 2015). These sensor and biologging capabilities allow researchers to determine not only the location of fish but also the conditions of their local environment, potential drivers behind movements, and linking movement with physiology, providing a better understanding of the whole picture (Nathan et al. 2008). Currently these technologies are being used to assess how fish in Hamilton Harbour use the water column in response to varying DO levels (pressure sensors). Results from pressure sensor tags have also led to deeper embayment construction based on depth preferences of several species in Toronto Harbour. Finally, also in Toronto Harbour, accelerometer sensors are being used to determine the energy expenditure for fish in various habitat types, as animals that occupy sub-optimal habitats may experience increased expenditure of energy (Jeffrey et al. 2015).

Another additional benefit to biotelemetry is the possibility to engage with members of the public. As previously mentioned, with such long-term remediation projects, maintaining stakeholder momentum is an important aspect of the monitoring stage (Hall et al. 2006). Biotelemetry is an exciting tool to engage a broad public audience (McGowan et al. 2016) and can provide tangible and almost 'real time' proof that animals are surviving and using these newly restored habitats. Citizens of AOCs are ultimately affected by remedial efforts, therefore, it is important that these stakeholders participate in the activities of research and monitoring (Hall et al. 2006). Several biotelemetry users surveyed by Nguyen et al. (2017), mentioned an increase in public interest after they had shared their animal movement data online, leading to an increase in support and outreach opportunities. An example of this specific to the Great Lakes AOCs is a collaborative pilot project with the Great Lakes Fishery Commission, where walleye movement data from Hamilton Harbour were shared with local school groups as part of outreach efforts to involve the local community.

Constraints to biotelemetry use exist in the study of freshwater fish including problems with attaching devices to animals, the performance of electronic technology, and methods of analysing data (Cooke et al. 2013). Biotelemetry is regarded as a relatively expensive technology and can vary in total system costs dependent on the equipment selected, the complexity required in the ecosystem, and scope of the study and may not be suitable for short-term management questions. However, a growing collaborative research community has developed and is willing to share resources (e.g., expertise and equipment), such that this approach may now be accessible even if a specific project is not well funded (e.g GLATOS; Ocean Tracking Network). Performance of biotelemetry equipment can be impaired by various environmental conditions, such as high flow and turbulent systems, depth (deep water is problematic for radio telemetry, shallow water can be problematic for acoustic telemetry), highly vegetated, and high traffic areas, all considerations required when choosing the type of technology for the project (Heupel et al. 2006; Kessel et al. 2014). Biotelemetry can also result in large datasets that require significant post-processing and analytical efforts, often beyond the capabilities of simple spreadsheet applications (Heupel et al. 2006).

Guidelines for using telemetry in RAPs As with any study, the most important first step is to define clear project objectives and then to consider the best way to address the objectives. If biotelemetry is identified as a likely tool, defining the specific type of data required from a biotelemetry project will dictate the type of equipment required, and how best to deploy the selected technology (Heupel et al. 2006). Fine-scale habitat use on a scale of meters, either for habitat preference data, contaminated site use, or for monitoring the use of restored habitats may be best served using active tracking or an acoustic fine-scale positioning array (Niezgoda et al. 2002; Roy et al. 2014). The addition of pressure sensor tags allows for a 3D position of the fish when combined with a Vemco Positioning System (VPS) array and high-resolution bathymetry data, determining the use of water column in relation to known water quality conditions or contaminated sites (for example, Hamilton Harbour). If data are required to determine the duration that an animal remains within a set region (e.g., a protected area, or an AOC boundary), fine-scale or 3D positioning may not be necessary and a simple set of receivers to monitor exit or return may suffice (Lacroix 2005, for example array see Fig. 3). Alternatively, determining directed linear paths or migration routes requires a series of curtain or gate systems (Hayden et al. 2014). With the expanding use of biotelemetry in the Great Lakes, a collaborative group of researchers have formed the GLATOS allowing users of the same technology to share and exchange their data. Through this organised collaboration, tag detection coverage for individual projects is not limited to only the project's receivers. Managers can answer more broad-scale questions regarding the long-range migrations of fishes and the connectivity of AOC sites and other freshwater ecosystems, well beyond the geographic scope of individual projects.

For most research questions, a combination of telemetry and conventional research methods is recommended to ensure the desired level of population sample size and study power to achieve a complete picture of fish behaviour and physiology in relation to the environment (Bridger and Booth 2003). Lapointe et al. (2013) noted several studies where telemetry was successfully combined with diet studies, mark-recapture, creel surveys, and underwater video analysis to strengthen the evaluation of restoration success. Well considered and planned experimental design is essential when using all forms of biotelemetry. Lapointe et al. (2013) reviewed habitat restoration success studies and determined an ideal design would include pre-restoration animal movement data, or a control site for 'before and after' comparisons. This is, however, difficult to obtain at this point as many of the AOC restoration efforts are already underway.

Conclusion

Monitoring the success of habitat restoration is often difficult, in particular when little or no information exists on how fish used the site prior to restoration. However, when used in combination with other techniques, biotelemetry is proving useful in the AOC RAP process. It has allowed managers to answer questions important to the planning and monitoring of habitat restoration within the Great Lakes, as well as allowing researchers to ask broad scale questions, with potential relevance across AOCs and other freshwater habitat restoration efforts. Throughout these case studies, we have demonstrated that biotelemetry has been successfully incorporated into the RAP adaptive management process, with results from habitat preference studies directly integrated into further restoration designs. With consideration to the previously mentioned strengths and weaknesses to biotelemetry and the various technologies available, we suggest RAP managers consider including biotelemetry as an assessment tool and work to combine telemetry results from other AOC sites into their habitat management and restoration planning and monitoring processes.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no competing interests.

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