Urban Ecosystems
https://doi.org/10.1007/s11252-024-01575-5

Evaluating ecological restoration in urban ecosystems with acoustic telemetry: marine and freshwater case studies

Morgan L. Piczak[1] · Saron Berhe[2] · Anne C. Knag[3] · Robert J. Lennox[2,4] · Knut Wiik Vollset[2] · Rick Portiss[5] · Jonathan D. Midwood[6] · Steven J. Cooke[1]

Accepted: 27 June 2024

Abstract

Around the globe, ecological restoration projects are being undertaken to mitigate anthropogenic impacts and recover lost biodiversity; however, evaluations of efficacy can lack robustness or, more often, are not completed at all. In this perspective piece, to demonstrate the utility of acoustic telemetry to assess ecological restoration in aquatic systems, we synthesize two case studies in coastal freshwater and marine urban ecosystems: Toronto, Canada, and Bergen, Norway. In Toronto Harbour, a Before-After-Control-Impact experimental design was instrumental in detecting differences attributed to ecological restoration across multiple species of fish. Additionally, acoustic telemetry data were paired with catch and community traits derived from electrofishing, which provided a more complete understanding of fish responses to restoration. In Bergen Harbour, the acoustic telemetry array was deployed before restoration, providing a Before-After comparison of habitat use by several fish species and European lobster (*Homarus gammarus*). In addition to acoustic telemetry, blood samples were taken from multiple fishes, to examine the levels of contaminants before and after restoration, adding an ecotoxicological dimension to the assessment. Incorporating these complementary methods contributed to a more holistic understanding of animal response to ecological restoration. Finally, we also identified indicators that could be calculated using acoustic telemetry data, including those derived from addition sensors (e.g., pressure). As we look to the future within the Anthropocene, it will be imperative that ecological restoration achieves intended goals and we contend that acoustic telemetry has a bigger role to play in the evaluation of efficacy as it provides continuous monitoring compared to more traditional, discrete sampling.

Keywords Fisheries management · Biotelemetry · Restoration ecology · Fish habitat · Movement ecology

Introduction

Both marine and freshwater ecosystems face increasing threats imposed by anthropogenic activities (Arthington et al. 2016). Across the many different types of stressors including non-native species, pollution, overexploitation, and global climate change, habitat alteration continues to be among the most damaging to fish populations for both freshwater (Dudgeon et al. 2006) and marine species (Musick et al. 2000). Anthropogenic alterations to habitats can be broadly categorized into fragmentation, degradation, and loss, each resulting in deleterious effects on species and the ecosystems they inhabit (see Piczak et al. 2023a). First, habitat fragmentation, related to habitat loss, occurs when contiguous habitat patches are altered, leading to smaller, isolated areas, which disrupts connectivity therefore impacting animal movements and life history processes (Jeffrey et al. 2015). Within both freshwater and marine

✉ Morgan L. Piczak
morganpiczak@gmail.com

1 Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Drive, Ottawa, ON, Canada

2 NORCE Norwegian Research Centre, Laboratory for Freshwater Ecology and Inland Fisheries, Nygårdsgaten 112, 5008 Bergen, Norway

3 Agency for Urban Environment, City of Bergen, Johannes Bruns gate 12, 5008 Bergen, Norway

4 Ocean Tracking Network, Dalhousie University, 1355 Oxford St, Halifax, Canada

5 Toronto and Region Conservation Authority, 101 Exchange Avenue, Concord, ON, Canada

6 Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Science, 867 Lakeshore Road, Burlington, ON, Canada

systems, an example of habitat fragmentation can include barriers from roads or bridges (Choy et al. 2018; Moore and Berejikian 2022). Next, habitat degradation occurs when anthropogenic activities reduce the quality of habitats, impacting their physical, chemical, or biological attributes, even if the quantity remains intact (Dudgeon et al. 2006). Examples of degradation can stem from the application of excessive road salts creating run-off into freshwater streams (Lawson and Jackson 2021) or the increase of hypoxic "dead zones" in marine systems stemming from increased nutrient run-off (Diaz and Rosenberg 2008), among others. Finally, habitat loss occurs when the destruction of areas no longer provide the necessary resources or conditions of the pre-existing ecosystem, leading to a decrease in habitat quantity (Pardini 2018). An example of habitat loss that applies to both marine and freshwater ecosystems is the infilling of fish habitat (Whillans 1979; Shen et al. 2016). Unfortunately, these habitat alterations often occur together, which can result in cumulative negative effects to aquatic ecosystems, of which remain poorly understood (Reid et al. 2019).

In response to anthropogenic habitat alterations, environmental managers have turned to ecological restoration. The goal of ecological restoration is to manage, conserve, or repair ecosystems in an attempt to return to a more natural state through deliberate management actions (Hobbs and Harris 2001). To date, negative impacts associated with anthropogenic activities have resulted in billions of dollars spent to restore aquatic habitat with the aim of conserving biodiversity and ecosystem services (Bernhardt 2005). Despite the promise of restoration ecology as a discipline, there remains work to produce robust, evidence-based data in support of efficacy (Cooke et al. 2018). Without these evaluations, environmental managers are left with minimal evidence as to the success of such efforts and how to improve and inform best practices (Wortley et al. 2013). Assessing the efficacy of ecological restoration has been undertaken with discrete sampling to estimate indicators such as richness, biomass, or abundance, which can provide a 'snapshot' in time (Ruiz-Jean and Mitchell Aide 2005). However, there remains opportunity to improve our understanding of ecological restoration with continuous monitoring longitudinally through space and time, as opposed to more traditional, discrete methods. Continuous monitoring can be achieved with acoustic telemetry (Brooks et al. 2017), which permits a level of detail that allows researchers to assess the efficacy of habitat restoration on an ecologically relevant scale.

As acoustic telemetry remains underutilized in the evaluation of ecological restoration projects (e.g., Lapointe et al. 2013; Crossin et al. 2017), it is our intention to highlight the utility of this technology to help guide more effective restoration efforts in the future. Here in this perspective piece, we examine the use of acoustic telemetry to assess restoration efforts within aquatic urban habitats to inform best practices for undertaking future evaluations and associated indicators. Specifically, we turned to two case studies for each a freshwater and marine ecosystem, to showcase the utility of acoustic telemetry for studying the response of diverse fish communities to ecological restoration. For each case study, we provide details of the ecological restoration including anthropogenic stressors, restoration goals, stakeholders involved, restoration techniques used, and target species. From there, we identify lessons learned and future opportunities to help refine the application of acoustic telemetry for evaluating restoration actions intended to benefit fish populations. We provide recommendations stemming from the case studies for users of acoustic telemetry that help address paucities in our understanding of ecological restoration across freshwater and marine ecosystems. Finally, we identify and describe indicators that could be calculated from acoustic telemetry data to assess the efficacy of ecological restoration. It is our hope that by showcasing the utility of acoustic telemetry, lessons learned through real world examples, and indicators, that this powerful technology could contribute to a more comprehensive understanding of fish responses to ecological restoration.

Acoustic telemetry

Acoustic telemetry is a rapidly growing method used across the globe to study the movements, behaviours, and spatial ecology of free-roaming animals across diverse aquatic habitats (Matley et al. 2022a, b). Briefly, acoustic telemetry involves the deployment of stationary or mobile receivers into the aquatic environment, which detect the presence of animals with encoded signals emitted from transmitters that are fixed to the animal either internally (e.g., gastrically, Kennedy et al. 2018; or surgically implanted, Gahagan and Bailey 2020) or externally (Jepsen et al. 2015). Acoustic telemetry arrays are highly customizable in that they can be deployed to cover habitats from small scales (e.g., ponds) to large areas (e.g., ocean wide; Hellström et al. 2022). Compared to discrete sampling (e.g., mark-recapture studies with nets), acoustic telemetry permits monitoring to occur near-continuously and longitudinally (e.g., up to 10 years) as opposed to a 'snapshot' in space and time (Heupel et al. 2006). This technology has become a mainstay in fisheries research and management as acoustic telemetry is low-cost, low-maintenance, and autonomous (Hellström et al. 2022). Acoustic telemetry also provides the opportunity to capture movements of animals beyond their home receiver array via extended telemetry networks such as the Great Lakes Acoustic Telemetry Observation System (GLATOS) or the Ocean Tracking Network (OTN; Lennox et al. 2023).

Acoustic telemetry can address diverse questions across both fundamental and applied topics. Specifically regarding fundamental questions, acoustic telemetry has been used to examine life history, survival, morphology, fitness, and energetics (Donaldson et al. 2014). On the other hand, acoustic telemetry has increasingly been used to aid in conservation and management by shedding light on topics such as habitat associations, environmental drivers, protected areas, non-native species control/management, stock assessments, marine spatial planning, and defining management units (Crossin et al. 2017). In addition to timestamped locational information, environmental (e.g., temperature or depth), behavioural (e.g., acceleration), and physiological (e.g., heart rate) data can also be collected with additional sensors on the transmitters (Crossin et al. 2017). As technological advances of acoustic telemetry continue to rapidly progress (e.g., additional sensors, miniaturization of tags), there will be further expansion of the biologging field (Hellström et al. 2022).

Evaluations of ecological restoration are often not undertaken or provide weak evidence of success or failure, but acoustic telemetry could provide opportunities to assess responses of fish to interventions (Crossin et al. 2017). Reviewed in 2013, at the time there was only one study that used acoustic telemetry to assess restoration efforts (Lapointe et al. 2013), but since then there has been more research. Acoustic telemetry has been used in fresh water to assess the habitat use and predictors of movement for river blackfish (*Gadopsis marmoratus*) in a restored Australian river (O'Connor et al. 2023), and in marine ecosystems, to study the response of Atlantic cod (*Gadus morhua*) after reef restoration in Denmark (Kristensen et al. 2017). Acoustic telemetry has also been used successfully throughout the North American Laurentian Great Lakes to inform restoration designs and management by examining seasonal habitat associations, identifying exposure to pollutants and contamination sources, informing fish passage, and assessing use of restored/created habitat (Brooks et al. 2017). Further adoption of acoustic telemetry provides an opportunity to advance our understanding of restoration efficacy from the fish's perspective with acoustic telemetry.

Toronto harbour: area of concern

Site history

The Toronto Harbour (TH) and waterfront, located in the western portion of Lake Ontario, is directly connected to Canada's largest urban center (5 million people) and has experienced extensive aquatic habitat loss (400 ha; Whillans 1979; Fig. 1A). While fish species have historically suffered from overexploitation attributed to subsistence, recreational, and commercial fisheries (Christie 1972), other stressors have impacted populations more recently (Doka et al. 2018). The extensive habitat degradation and loss throughout the waterfront can be attributed to a number of anthropogenic activities including urbanization, port expansion, industrial activity, and transportation (Barnes et al. 2020). Specifically, aquatic habitat has been lost due to infilling, shoreline hardening, stonehooking, and dredging. Habitat fragmentation has also occurred through the burying of rivers, therefore impacting the connectivity of fish habitat (Eidelman 2018). Habitats in TH have also been degraded through impaired water quality stemming from pollution, salinization, urban runoff, and wastewater (overflow during storms; Howell et al. 2018). Additionally, there have been a number of non-native species that have further contributed to habitat degradation and altered food web dynamics within TH including dreissenid mussels (zebra mussels, *Dreissena polymorpha*; quagga mussels, *Dreissena rostriformis bugensis*), crustaceans (e.g., spiny water flea, *Bythotrephes longimanus*), and fish (e.g., common carp, *Cyprinus carpio*, see Piczak et al. 2023b; round goby, *Neogobius melanostomus*). Collectively, habitat loss, fragmentation, and degradation as well as the establishment of non-native species have contributed to the impairment of native fish populations (Midwood et al. 2022).

Ecological restoration

To mitigate the long history of anthropogenic impacts and associated negative ecological effects, the International Joint Commission drafted the Great Lakes Water Quality Agreement, which identified Toronto and Region as an Area of Concern (AOC), along with 42 other degraded areas across the Great Lakes (IJC 2012). As a part of the AOC designation, 13 different Beneficial Use Impairments (BUIs) were designated to act as indicators of change in chemical, physical, or biologist integrity. The main relevant BUIs that acted as goals throughout ecological restoration in TH include a) degradation of fish and wildlife populations, and b) loss of fish and wildlife habitat. The Toronto Waterfront Aquatic Habitat Restoration Strategy (TWAHRS) was developed to support habitat restoration efforts in support of these BUIs (Barnes et al. 2020). Aquatic Habitat Toronto (AHT), a consensus-based partnership across various agencies, was subsequently established to lead the implementation of the TWAHRS and facilitate research in support of aquatic habitat restoration via knowledge co-production (Piczak et al. 2022). Other involved agencies include the Toronto and Region Conservation Authority, which manages and monitors the land/water of TH, Environment and Climate Change Canada, which provides funding for research, and Fisheries and Oceans Canada, which undertakes supporting research with Carleton University using acoustic telemetry (Table 1).

Fig. 1 **A** Extent of urbanization throughout Toronto Harbour and **B** receiver network with colors according to receiver groupings. IH = Inner Harbour, OH = Outer Harbour, TTP = Tommy Thompson Park, TI = Toronto Islands and restoration sites are labeled (Toronto Islands are a control site). **C** Extent of urbanization throughout Bergen Harbour, and **D** receivers labeled according to restoration zone, whereby Restoration Zone 1 was from 2017–2018 (P = Puddefjorden), Restoration one 2 from 2023–2024 (Store Lungegårdsvannet), and Restoration Zone 3 (V = Vågen) which is in review for environmental measures

A large system (18 km^2) of open or exposed embayments, TH has four zones; Toronto Islands, Outer Harbour, Inner Harbour (IH), and Tommy Thompson Park (TTP; Fig. 1B). The Toronto Islands have remained relatively natural compared to the rest of the harbour and have not received as extensive ecological restoration efforts as other locations within TH. Next, the Outer Harbour has deeper habitat with low submergent aquatic vegetation, which has been dredged to accommodate shipping activities and has also not been the focus of extensive ecological restoration. The IH has undergone habitat restoration at two slips between 2007 and 2009, which has included increased complexity of habitat through the addition of large substrate, overhead coverage, and in-water structure (Barnes et al. 2020). Finally, TTP is a human-made peninsula consisting of a series of embayments and a confined disposal facility (CDF) comprised of three ponds, two of which were subsequently modified to enhance habitat for diverse aquatic species (Barnes et al. 2020). Specifically, the embayments have had restoration efforts including increases in shoreline complexity, creation of thermal refugia, construction of sheltering islands and berms, planting of aquatic vegetation, and installation of woody materials and substrate. With the exception of one embayment (2012 to 2015; Embayment D), restoration activities were undertaken at the embayments between 2009 and 2011. Next, dredged contaminated materials have been deposited in the CDF ponds, which ceased in the first two ponds (1985 and 1997), but is ongoing in the last pond. Subsequently, the first two ponds were capped and restored (2015–2020; Fig. 1B) with techniques designed to increase shoreline complexity, encourage the establishment of aquatic vegetation, increase structural habitat complexity, and use exclusion barriers to limit access for common carp (Barnes et al. 2020).

Table 1 Details of the main agencies involved with research using acoustic telemetry to assess ecological restoration for each Toronto Harbour, Canada and Bergen Harbour, Norway

Site	Agency Name	Type	Primary Role	Jurisdiction
Toronto Harbour	Fisheries and Oceans Canada	Government Department	Policy implementation and research in support of Canada's oceans and inland waters	Federal
	Environment and Climate Change Canada	Government Department	Funding in support of the natural environment and renewable resources	Federal
	Toronto and Region Conservation Authority	Agency	Local watershed management and regulator, research support and monitoring	Municipal
	Carleton University	Academic	Conduct research studies using acoustic telemetry in support of ecological restoration	N/A
	Aquatic Habitat Toronto	Consensus-based partnership	Implement the Toronto Waterfront Aquatic Habitat Restoration Strategy	Municipal
Bergen Harbour	Norwegian Research Centre	Research Institute	Conduct research studies using acoustic telemetry in support of ecological restoration	N/A
	University of Bergen	Academic	Ecotoxicological analysis: Analyzing blood samples of fish	N/A
	Institute of Marine Research	Research Institute	Ecotoxicological analysis: Analyzing tissue samples of fish and crustaceans	N/A
	Bergen Kommune	Municipal Government	Funding body and conducting the restoration efforts	Municipal
	Norwegian Environmental Directorate	Government Agency	Funding body	Federal
	Regional Research Fund	Federal Funding Body	Funding body	Federal

Acoustic telemetry & examination of restoration efficacy

While the ecological restoration efforts throughout TH in the IH and TTP have broadly focused on improving habitat conditions to increase native fish populations, the evaluation of ecological restoration using acoustic telemetry has been primarily focused on larger bodied species including largemouth bass (*Micropterus nigricans*, a warmwater piscivore), northern pike (*Esox lucius*, a coldwater piscovere; Fig. 2A), and common carp (a non-native benthivore). Close to 500 fish have been tagged throughout the entire project, where the main capture method was electrofishing with subsequent internal transmitter implantation (for surgery details see Piczak et al. 2023b). The majority of the telemetry array within TH was installed in spring 2011, with fluctuations thereafter in coverage due to the loss of receivers or expansion of coverage into new areas of interest. Key movement corridors, as well as various habitat types were strategically instrumented with VR2W 69 kHz acoustic receivers (Innovasea, Bedford, Nova Scotia; Fig. 1B). Receivers have been combined into 37 groups based on habitat consistency/proximity (Midwood et al. 2019; Fig. 1B), as well as range-testing results (conservative estimate of 350 m; see Veilleux 2014).

Acoustic telemetry has been used throughout TH to assess the efficacy of restoration efforts. As restoration within the IH at the two slips was completed prior to the deployment of the telemetry array, only post-restoration data were available and the amount of time spent within each slip was calculated for seven species using fine-scale positioning and contrasted with use of none-restored slips (Veilleux et al. 2018). Results from this study suggest that only northern pike use the slips, with clear preferences for the ones that have been restored, particularly during the spawning period. Degraded water quality at the two un-restored slips (i.e., habitat degradation) stemming from the highly urbanized Don River was proposed as one factor that may limit use, but in general the hardened shoreline and deeper water of the slips were not deemed suitable habitat for a majority of tracked species (Veilleux et al. 2018). Next, a multi-species evaluation of restoration within the embayments and ponds of TTP and Spadina Slip of the IH was undertaken; however, similar to the previous study, only post-restoration data were available as the restoration was completed prior to the deployment of the receiver array (Rous et al. 2017). In this study, the Toronto Islands acted as a control site, where the experimental design used was Control-Impact (i.e., restoration; Rous et al. 2017). The findings from this study found that restoration efficacy was species-specific, where yellow perch (*Perca flavescens*) and northern pike had higher site fidelity at restored sites compared to largemouth bass and common carp.

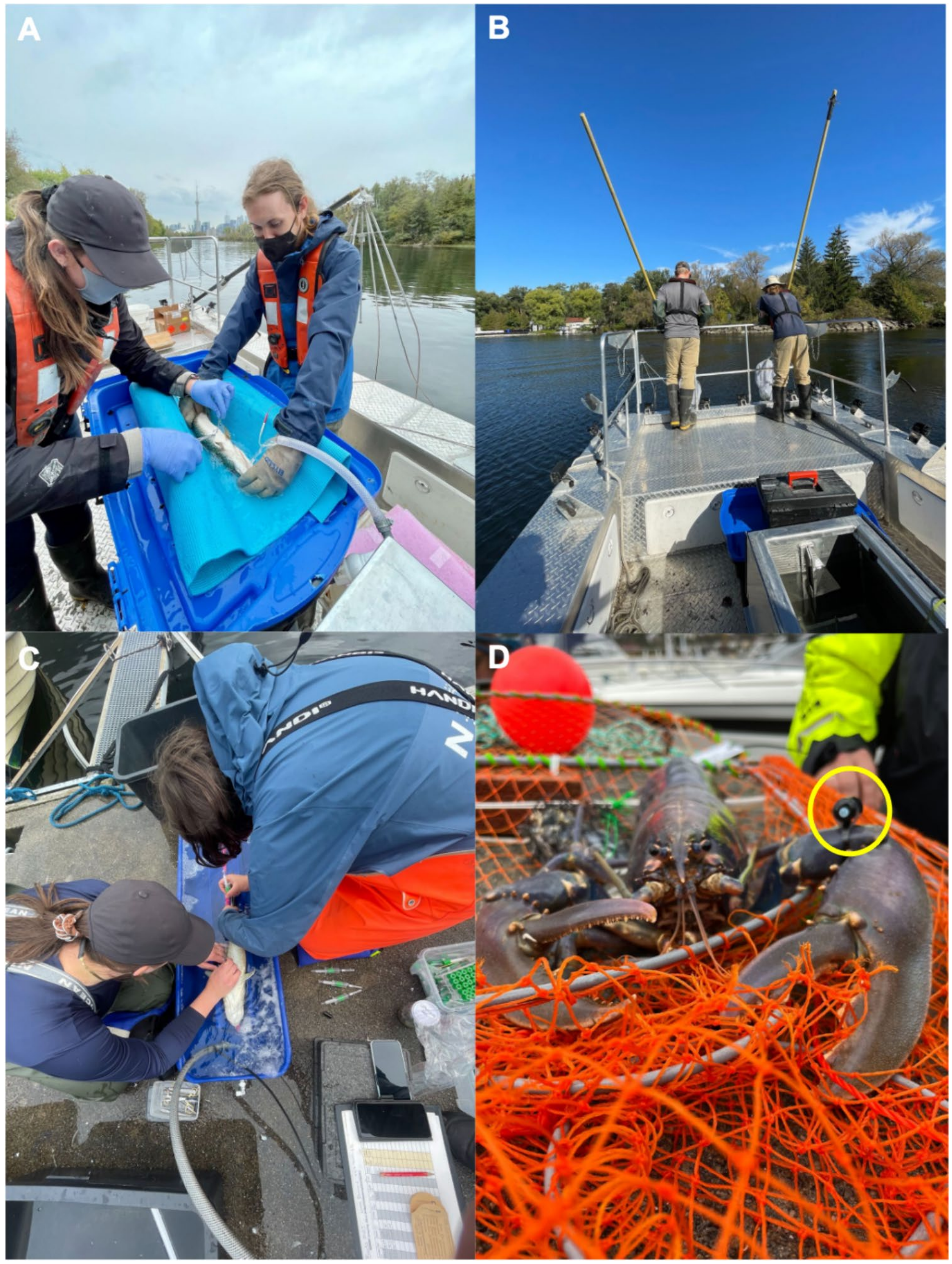

Fig. 2 **A** Transmitter implantation within a northern pike (*Esox lucius*) in Toronto Harbour. **B** Long-term electrofishing sampling throughout Toronto Harbour, Canada has complemented the acoustic telemetry data, with discrete indicators such as biomass and community indices. **C** Transmitter implantation in Atlantic cod (*Gadus morhua*) with simultaneous blood sampling to examine individual endocrine disruption within Bergen Harbour, Norway. **D** European lobster (*Homarus gammarus*) with acoustic tag (yellow circle) to examine efficacy of restoration efforts on invertebrate species in Bergen Harbour

In response to previous limitations of experimental design (i.e., lack of before-restoration data), more recent studies have aimed to implement a Before-After-Control-Impact design (Piczak 2024). Specifically, later restoration projects occurring in Embayment D (2012–2015) and Cell 2 (2015–2020; Fig. 1B) permitted an examination of fish response to restoration both before and after restoration as the acoustic receiver array had been operational, with the Toronto Islands acting as a control throughout the entire study period: 2010 to 2023. To assess the response of fishes to restoration, habitat use was examined by calculating the proportion of tagged individuals present (i.e., residency index; see Kessel et al. 2016), and depth use with pressure sensors (Table 2). In addition to acoustic telemetry, long-term monitoring data from electrofishing transects across the restoration and control sites were also included in this evaluation. Specifically, to complement the acoustic telemetry data, catch of target species and community indices derived from the electrofishing data were calculated for a more complete picture of fish response to restoration. Results indicated that at both restoration sites there was continued use by largemouth bass; however, there was also reduced access to both systems for northern pike and non-native common carp as a result of the installation of carp barriers (Piczak 2024). In addition to the acoustic array within the harbour, fish movements beyond TH were captured via the extended receiver network through GLATOS (see Piczak et al. 2023b).

Table 2 Comparison of acoustic telemetry projects to evaluate ecological restoration across each Toronto Harbour, Canada and Bergen Harbour, Norway

Aspect	Toronto Harbour	Bergen Harbour
Ecosystem Type	Freshwater coastal wetlands	Marine fjords
Fish Capture	Electrofishing	Angling (both conventional and fly) and nets/traps
Sedation	Electroimmobilization Chemical (eugenol)	Chemical (MS-222)
Species	Multiple fish species including both native and non-native fishes	Multiple fish species, as well as benthic invertebrate (European lobster)
Size of Tags	Due to tag burden, both projects were limited in terms of fish tagged, where small-bodied species and juveniles were tagged less frequently	
Complementary Methods	Discrete sampling: Electrofishing monitoring contributed to estimates of catch (catch-per-unit-effort) and community traits (e.g., abundance of warmwater species).	Ecotoxicological studies including muscle tissue (biopsies) and vitellogenin (necropsies) to study contamination levels across both fish and crustaceans
Challenges associated with Urban Setting	Tampering with acoustic receivers and potential high rates of angling	Tampering with nets and traps used for capture
Use of Controls	The Toronto Islands did not receive any major ecological restoration and remained relatively natural, these sites acted as a control.	No control or reference sites were available
Experimental Design	Before-After-Control-Impact	Before-After

Lessons learned

The TH telemetry project has been a valuable resource for furthering our understanding of the spatial ecology of fishes and how it relates to ecological restoration; however, there is some room for improvement and lessons learned. Initial studies (i.e., Veilleux et al. 2018 and Rous et al. 2017) were limited in terms of data availability in that the acoustic array was deployed after ecological restoration had been completed, so there was not 'before' data and they were limited to a Control-Impact design. The Before-After-Control-Impact (BACI) design is the 'gold standard' for assessing changes in the environment to determine the effects of the treatment (i.e., ecological restoration; Smokorowski and Randall 2017). Further, it is important to have sufficient sample sizes to ensure statistical power, ideally with an even amount of time across time periods (i.e., before and after restoration; see Smokorowski and Randall 2017). Unfortunately due to the COVID-19 pandemic (i.e., disrupted sampling) and potentially high rates of angling, the sample size for the post-restoration period was relatively small compared to before, therefore limiting the statistical power. To mitigate this issue, it is important to ensure a sufficient number of individuals tagged at regular intervals (as transmitters used last three years) across both restoration and control sites. Adding to our small sample sizes, it is highly likely that many of the tagged fish were angled and removed from the system. Although t-bar anchor tags were initially used to help externally identify tagged fish, we noted poor retention and this was stopped. Recent works have noted poor long-term retention for this type of external tag and recommended the use of internal anchor tags (Colborne et al. 2024), which should be adopted. Although the acoustic telemetry array was used to assess ecological restoration on a larger spatial scale (i.e., site-level), determining which specific restoration techniques benefitted fish the most could be examined with more fine-scale approaches such as the positioning using hyperbolic multilateration (see Vellieux et al. 2018).

We also learned via acoustic telemetry that the exclusion barriers installed as a part of the ecological restoration aimed at decreasing passage to common carp may also be blocking movements of native species (i.e., largemouth bass and northern pike; Piczak et al. 2023c). Beyond the acoustic telemetry, the evaluation of ecological restoration benefitted from monitoring with electrofishing throughout all restoration periods, where indicators including catch and community indices were able contribute to a more comprehensive understanding of fish response (Fig. 2B; Piczak 2024). Another aspect that contributed to the success of the TH telemetry project was that the science produced was conducted using knowledge co-production with AHT (see Piczak et al. 2022). Specifically, benefits to this approach that aided in ecological restoration included access to diverse expertise and local knowledge, increased understanding of regional fish habitat, adoption of novel restoration techniques and improved knowledge exchange across agencies. Finally, acoustic telemetry data have also been paired with habitat information (i.e., water temperatures, submerged aquatic vegetation, depth, and fetch) to determine species-specific habitat associations (Midwood et al. 2018a, b; Midwood et al.

2019; Brownscombe et al. 2023) that can in turn identify habitat supply limitations. These works, while informative, have relied on static habitat information (i.e., missing seasonal senescence of vegetation) and not explicitly assessed restoration status. To better understand fish response to changes in habitat, we recommend pairing acoustic telemetry data with habitat information on a finer temporal scale (i.e., at least seasonally).

Bergen harbour

Site history

The city fjord of Bergen in Western Norway has undergone significant changes during the last decades to accommodate urban use (Fig. 1C). This includes excavation for ship passage, sea wall construction, and the construction of docks and piers. These urban developments have contributed to the degradation of the marine ecosystem. Issues like urban runoff, boat pollution, and the effects of sewage channels have arisen, along with concerns about the disposal of industrial waste, including organic pollutants and heavy metals as drainage from the city pours into the harbour. Sources of such pollution range from road traffic around the city centre to facade materials and old paint, collectively impacting the water quality and general ecological condition of the harbour (COWI 2019).

Store Lungegårdsvannet (SL) is a 44 ha fjord basin with a maximum depth of 26 m in the inner part of the city fjord (Fig. 1D). The inner basin is connected to the outer part of the city fjord via a small and relatively shallow area leading into Puddefjorden. Tidal influx of seawater is combined with a top layer of freshwater running in from the river Møllendalselva south-east of the basin (Fig. 1D). However, Møllendalselva is greatly affected by channelisation and water removal that limits freshwater input. Indeed, the river is mostly a concrete channel, which supports a small population of spawning sea trout (*Salmo trutta*) that use the concrete features (Pulg, personal communication). The sea bottom of SL is highly polluted, and portions of the bottom layer of water is anoxic, due to the historical urbanization of the city fjord system and the buildup of polluted sediments near the mouth of the fjord around the bridges, limiting the water exchange. In addition, replenishment of the water basin in SL is limited due to its tenuous link to Puddefjorden and the outer fjord. SL is thereby especially predisposed to accumulation of organic pollutants and heavy metals. Despite these poor conditions, the system surprisingly hosts a diverse community of aquatic species, such as European lobster (*Homarus gammarus*), crabs (e.g., *Cancer pagurus*), European eel (*Anguilla anguilla*), Atlantic cod, Atlantic pollock (*Pollachius pollachius*), brown trout, and multiple species of wrasse (*Labrus* spp). The sea bottom is primarily characterized by soft sediment, but larger rocks on the side along the water basin promotes growth opportunities for kelp forests, and creates natural habitats that function as refugia for aquatic animals.

Ecological restoration

To prevent the further dispersal of environmental toxins and pollution to both human populations and the aquatic environment, the municipality of Bergen collaborated together with the Environmental Directorate of Norway on the project Renere Havn Bergen ("A Cleaner Harbour Bergen") in 2008. Now that most pollution has either ceased or been heavily reduced, the project focuses on preventing new spread, and in later years, capping pre-existing pollution on the seabed. The area of interest, Bergen Harbour, is divided into the three sub-areas (1) Puddefjorden, (2) SL and (3) Vågen (Fig. 1D). Various research has been conducted within these sub-areas in support of restoration. The city fjord study, which included quantitative benthic surveys, revealed changes in species composition due to sewage cleanup efforts, offering valuable insights into benthic fauna before clean masses were applied (COWI 2017). Dietary surveys of fish filet, liver samples, and crustaceans like edible crab and mussels showed elevated levels of pollutants such as mercury, PCBs, and dioxin-like PCBs, resulting in advisories against consumption (COWI 2017). An assessment of habitat types in Puddefjorden and SL highlighted a heavily modified area, with lack of valuable species or habitats, except for the red-listed European eel (*Anguilla anguilla*) in the system (COWI 2017). The current biodiversity in the soft-bottom environment was assessed as negligible to low, and previous evaluations of pollutants in sand trap material from Bergen's stormwater system have shown contamination with PCBs, PAHs, heavy metals, and, in some instances, tributyltin (COWI 2017).

Area 1, Puddefjorden, was the first to undergo restoration efforts in July 2017, and restoration was completed in August 2018. The comprehensive process of cleaning up the sea bottom combined traditional and innovative methods: the sea bottom was covered using crushed stone masses (from the construction of a new tunnel), which was environmentally friendly as the materials were reused in the restoration process. Since restoration, Puddefjorden has now moved into a phase of monitoring the response. In addition, the seabed is also surveyed for the recolonization and regeneration of benthic fauna and species diversity. Area 2, SL, is currently in the last phase of seabed restoration. Since 2021, the municipality of Bergen has mapped the seabed conditions and habitats, removed > 80 tons of scrap metal, shipwrecks, and garbage off the seabed, and begun the process of covering the seabottom with sand and gravel. In addition, the municipality is simultaneously running a second project to restore the river Møllendalsel, which drains into SL (Asplan Viak 2010), improving spawning ground for fish and creating public park areas around the river as part of the Renere Havn Bergen project. Area 3, Vågen, will be the next area to be restored in the project.

Acoustic telemetry & examination of restoration efficacy

In order to achieve Renere Havn Bergen's environmental goals (i.e., reduce toxic levels in fish and seafood, improve habitat conditions for the marine community, and enhance the use of harbor areas for the local community), it is crucial to know the state of the environment and how it is used by marine species before any restoration measures have been done. That way, responses can be documented following major changes to the environment, with an assessment of the ecological impact of the restoration efforts.

In the period from 2021–2023, movement, behavioral, and physiological data were collected for various marine species in SL as part of a Before-After study. A total of around 125 individual fish of corkwing wrasse (*Symphodus melops*) and ballan wrasse (*Labrus bergylta*), Atlantic cod, pollock, and European lobster were tagged either internally (vertebrates) or externally (invertebrates) with acoustic transmitters (methods as per Nilsen et al. 2022). Over the course of the tracking period, an array with approximately 50 acoustic receivers of the types TBR800, TBR700 and TBR700L 69 kHz (Thelma Biotel AS, Trondheim, Norway) were deployed, and covered both SL, Puddefjorden, and Vågen to track tagged species. Capture gear and methods varied between the target species: traditional spinning rods and trap nets were used for Atlantic cod and pollock, and traps were used for both lobster and wrasse. For the larger bodied animals (i.e., cod, pollock, wrasse, and lobster), tags were equipped with additional sensors including acceleration and temperature. These tags are both larger, with long lasting batteries (lifetime of 3–5 years), which enables continuous monitoring of tagged individuals not only throughout the entire restoration process, but also in the subsequent period after restoration. In addition to using acoustic telemetry, ecotoxicological samples were also taken to examine trends in contaminant levels and estrogen exposure before and after the seafloor was restored. Specifically, blood (for vitellogenin, a biomarker for environmental estrogen) and tissue (for mercury levels) samples were taken from tagged fish (Fig. 2C).

As the Renere Havn Bergen project is nearly finished with the completion of the seabed restoration phase in SL, more individuals of the target species will be sampled, tagged, and tracked during the subsequent phase of the Before-After study. The plan will be to investigate differences in estimated habitat use, residence time, and physiological samples of the target species over the course of the restoration efforts. Combined with a monitoring phase after restoration, these results can contribute to understanding how the organisms within the city fjord system respond to major changes to their environment.

Lessons learned

SL has been a beneficial area to implement a Before-After study with its accessible location, historical time series documenting abiotic and biotic factors, and a diverse ecosystem to track multiple organisms. Based on these characteristics, several important knowledge gaps were filled through acoustic telemetry, which permitted an examination of movement and behavior of marine species in response to ecological restoration. To examine the responses to major habitat changes, it would have been beneficial to track tagged animals *during* the restoration efforts, yielding a unique insight into the *in-situ* behavioral responses. Unfortunately, this could not be implemented due to practical difficulties with receivers becoming buried during the sea floor capping. The dataset is therefore limited to tracking marine species before and after the restoration efforts. Next, the study revealed a robust population of the red-listed European lobster in SL through capture for tagging. Invertebrates are at a high risk of being buried in the sandy bottom during such a restoration of the sea bottom, and therefore a key group for assessing the response to restoration efforts (Fig. 2D). It was also beneficial to experimentally assess the activity sensor in the transmitter on some of our study species (Atlantic cod and European lobster) within a controlled environment: the Bergen Aquarium. Here, we conducted trials with underwater video cameras to observe the behavior of the species when they were instrumented with accelerometer transmitters. Video recorded behaviour was then linked with the acceleration signals sent to a receiver to use these sensors to assess behavioral states in different habitats. This approach introduces an additional dimension to the study, in which evaluating acoustic sensors can provide a more comprehensive explanation of the marine species' behavior. In terms of tagging procedures, the brackish water basin in SL also posed challenges for handling marine fish. Species such as Atlantic cod and pollock were typically caught in lower salinity layers and then brought to upper freshwater layers for tagging. Handling protocols during this process should therefore prioritize maintaining similar water quality at the location of capture to maximize animal welfare. Fine-scale positions were calculated for multiple species from the acoustic telemetry data (see Baktoft et al. 2017), which will provide crucial insights into the high resolution habitat use, particularly emphasizing the role of habitat structure. Despite the importance of fine-scale positioning, smaller tags (7 mm) proved ineffective for positioning, possibly due to environmental noise. Therefore, thorough consideration of target species (i.e., tag burden) and range testing of the acoustic array is essential prior to the deployment of tags. Finally, one goal of the ecological restoration was to decrease the biological availability of environmental toxins by capping the sea floor using sediments. Initial attempts to collect muscle tissue samples (biopsies) from Atlantic cod and pollock for ecotoxicological studies were unsuccessful due to inadequate size, therefore, necropsies were required to collect larger samples. To examine ecotoxicological trends in crustaceans, brown crabs (*Cancer pangerus*) were euthanized (i.e., necropsy for tissue samples) as an alternative to European lobster, since this species is red-listed (see Oug et al. 2006). This highlights the necessity of exploring alternative methods (i.e., necropsies) and species (brown crab), particularly when studying threatened species where not all individuals may be suitable for sampling.

Comparison of evaluations

There are many decisions to be made when planning and undertaking evaluations of efficacy for ecological restoration in terms of experimental design and methods; here we explore differences across each project (Table 2). First, as these projects occurred in different ecosystems (i.e., freshwater versus marine), capture methods differed whereby electrofishing was used in Toronto Harbour and in Bergen Harbour fish and invertebrates were caught with nets and angling. Next, sedation protocols were different in that in Toronto, fish were primarily sedated with electroanesthesia (see Rous et al. 2015), which is generally associated with quick recovery time and increased welfare (Jennings and Looney 1998); whereas in Bergen, MS-222 was used to sedate fish for surgery, with a longer recovery period. Both harbours used a multiple-species approach (which is a benefit of acoustic telemetry), but in Bergen an invertebrate was also tagged and samples for ecotoxicological assessment were harvested from brown crab, resulting in a broader understanding of the impacts of ecological restoration on the ecosystem. The size of taggable fish was limited for both Toronto and Bergen, whereby small-bodied and/or juvenile individuals were tagged less frequently, but as transmitters continue to miniaturize (see Lennox et al. 2017), adding these smaller fishes to evaluations of efficacy could lead to more comprehensive understanding of response to ecological restoration. Complementary methods (see Matley et al. 2022a) for both harbours also contributed to further understanding of the response to ecological restoration: in Toronto Harbour, electrofishing (i.e., discrete sampling) permitted an examination of trends in catch and community indices and in Bergen Harbour, blood and tissue samples of target species contributed to a ecotoxicological dimension to examine trends in contaminants in response to seafloor restoration. Logistical challenges arose for both projects stemming from the urban settings, whereby receivers and nets were tampered with, and in Toronto there were high rates of presumed angling of tagged fishes, therefore limiting sample sizes in some studies (see Piczak et al. 2024). Fortunately in Toronto Harbour, there was a comparator site that did not receive major ecological restoration and remained relatively natural (i.e., Toronto Islands), which was used as a control to compare to the ecological restoration sites before and after. Finally, both harbours were able to deploy the acoustic telemetry arrays prior to some of the ecological restoration efforts, which provided a baseline to compare to after ecological restoration: BACI and Before-After for Toronto and Bergen, respectively.

Recommendations

Based on the professional experience derived from undertaking evaluations of ecological restoration with acoustic telemetry, we have compiled recommendations to effectively undertake future studies. First, we reinforce long-standing guidance that using a BACI experimental design to detect changes attributable to ecological restoration is essential (Underwood 1991). Unfortunately, monitoring before ecological restoration to establish a baseline is rarely prioritized or resourced, and can often suffer from poor design (Block et al. 2001). We emphasize the importance of conducting monitoring as a part of a BACI design before, during, and after, ecological restoration ideally with even sampling periods (i.e., configuration; same number of years and sample sizes before and after restoration; see Smokorowski and Randall 2017) and at both control and treatment sites. Within the large system of embayments throughout TH, we were fortunate to have a control site, which has remained relatively intact despite a long history of anthropogenic degradation throughout the harbour. As the availability of control sites within ecological restoration sites can be rare, an alternative could include the use of a reference site (White and Walker 1997), which should approximate the conditions of the restoration site. Although selecting appropriate reference sites can be challenging; traditional and local ecological knowledge could help guide site selection by identifying the most relevant target species and providing historical knowledge about land management (Uprety et al. 2012). In Toronto, it was difficult to maintain sufficient sample sizes of fish possibly due to a number of reasons: the COVID-19 pandemic, high rates of angling or the openness of the system (fish forays from the area). Because our restoration and control sites were not accessible by boat for electrofishing, we resorted to capturing and tagging fish outside these site throughout the harbour; however, it would have been more ideal to capture fish from the study sites instead (especially given that both largemouth bass and northern pike tend to be resident). Taken together, we highlight the need to tag additional individuals to compensate for losses in sample size and to capture individuals from the study sites (i.e., treatment and control).

In Bergen, surgery protocols and investigations of tag burden were undertaken prior to studies in the wild, which improved animal welfare. In addition to the acoustic telemetry, both projects benefited from additional complementary methods: electrofishing (i.e., discrete fisheries sampling) and blood sampling (i.e., biological sampling). Moreover, electronic tags can be equipped with sensors (e.g., acceleration, temperature, depth) to provide additional information on fish-environment interactions. Depth sensors in particular have proven to be critical additions to base sensors because they support more accurate determination of fate (i.e., dead/alive) of tagged individuals. These are just a few examples of additional types of complementary sampling that could be undertaken to bolster animal tracking with acoustic telemetry (see Matley et al. 2022a). We also recommend pairing the acoustic telemetry data with habitat information that is scaled temporally (e.g., across seasons and restoration periods) and spatially (e.g., each receiver group). Finer-scale investigations with tools such as position solvers (see Orrell and Hussey 2022; Baktoft et al. 2017; Lennox et al. 2023) could provide additional details to determine which restoration techniques are contributing the most to habitat use.

Data processing and indicators

Prior to data analysis and calculation of indicators, it is essential to filter the detection data to increase accuracy. False detections attributable to transmission error (e.g., ambient noise or multiple transmitter collisions) are common and need to be removed based on criteria such as realism of distance moved or speed (see Brownscombe et al. 2019). Next, the fate of animals should also be assigned, which can be inferred from tag signals (Villegas-Rios et al. 2020) or probabilistically (e.g., mark-recapture models; McQueen et al. 2022). Examples of realistic fates include departure from the study area, removed from the system via angling, faulty transmitter, or death (Villegas-Ríos et al. 2020). Further, death can be interpreted carefully through investigations of depth or location (Klinard and Matley 2020).

Across both projects, we used multiple indicators that could be calculated with data collected using acoustic telemetry detections to assess animal responses to ecological restoration (Table 3). A number of different indicators including time spent, site fidelity, and residency indices provide insight into the timing, duration, and spatial distribution of habitat use, which can be compared before and after restoration as an experimental evaluation of the effectiveness of measures. The proportion of tagged individuals present can also help understand lag times between restoration action and the ecological response, where the amount of time taken for animals (i.e., lag times) to access restored sites can be estimated. A residency index (see Appert et al. 2023; Kraft et al. 2023) was calculated on a seasonal basis in Toronto Harbour to examine how habitat use changed across seasons throughout the restoration process and highlighted a change in the springtime habitat use by largemouth bass after restoration, which is the known spawning period of the species and suggests a shift towards increased usage for reproductive habitat (see Piczak 2024). At a larger spatial scale, whole system residence can be estimated to determine what proportion of tagged animals stay within the system after ecological restoration (e.g., Piczak et al. 2023a, b). Home ranges calculated with methods such as kernel density estimates or generalized additive modeling can highlight hotspots of habitat use across restoration periods, thereby shedding light on if the restored habitat is suitable. Movement paths (e.g., network analysis) have been used in Toronto Harbour to identify important movement corridors or routes used by animals to access restored sites.

Positioning, either with specialized arrays (e.g., Vemco Positioning Systems) or with modeling (e.g., Yet Another Positioning Solver-YAPS), are particularly valuable in that these methods can measure responses habitat associations in response to specific restoration techniques (e.g., the addition of spawning shoals) at a higher spatial resolution than a configuration of receivers providing detection data. For example, in Toronto, while a detection at a single receiver would have suggested northern pike were using a restored boat slip, a fine-scale array showed that they were using the margins or central portion of the slip rather than directly interacting with the root wads and tree structures that had been added during restoration (Veilleux et al. 2018). Having precise locations calculated from these approaches can allow the identification of habitat associations to determine what types of habitats could be created or restored (e.g., Brownscombe et al. 2021) If more detail is desired, behavioural states can be derived from continuous time data derived from positioning using hidden Markov models. Bacheler et al. (2019) identified behavioural states of grey triggerfish (*Balistes capriscus*) from fine-scale positioning data and mapped how these behaviours occurred on different habitats. This framework is conducive to an experimental design where behavioural states are estimated before and after restoration to determine changes in resting and active times and locations within a study area; a very promising tool for evaluating restoration *in-situ* using instrumented animals as reliable ecological indicators.

Table 3 Indicators that have been calculated using acoustic telemetry in Toronto and Bergen Harbour to assess the efficacy of ecological restoration

Indicators	Description	Example of Application for Restoration Efficacy	Reference
Time spent	Total time (hours) spent at each receiver grouping	Longer duration could indicate more suitable habitat conditions	Veilleux et al. (2018)
Site fidelity	Proportion of detections per individual per receiver station per day to estimate relative use	Repeated use during specific times could indicate use for life history events (e.g., spawning)	Rous et al. (2017)
Proportion of tagged individuals	The total number of individuals detected per week at each site over the total number of individuals active within the array per year	Spikes in proportions could indicate higher use during specific times for life history events	Piczak (2024)
Residency Index	The number of days an individual fish was detected at each receiver or receiver group divided by the total number of days the fish was detected anywhere within the acoustic array	Higher Residency Index is reflective of habitat selection at a given location	Kessel et al. (2016), Midwood et al. (2019), Piczak (2024)
System residence	Proportion of tagged fishes that remained within the array	Higher proportion of tagged individuals remaining within the array could indicate suitable habitat conditions	Midwood et al. (2019), Piczak et al. (2023b)
Movement paths	Likely path of movement for fishes within a system based on sequential detections on the array	Identification of important movement corridors or routes taken to access restored areas	Midwood et al. (2018a, b)
Kernel density estimates	Heat maps of home ranges derived density of animal detections	Increased density could reflect higher use	Veilleux et al. (2018), Midwood et al. (2019)
Habitat association	Derived from telemetry data paired with habitat information to identify the habitat conditions fishes are selecting or associated with. Can be calculated at different temporal scales (e.g., seasonal, during spawning)	Can inform or guide habitat restoration efforts, but if applied to habitat conditions after works are completed can also identify the types of species that are likely to be associated with the site	Brownscombe et al. (2021), Brownscombe et al. (2023)
Positioning	Gridded receiver array with overlapping detection radii to estimate animal positions using time of arrival (e.g., YAPS) or time difference of arrival (e.g., VPS) of transmissions at receivers	Fine-scale positioning can provide a level of detail necessary to estimate animal responses to restoration at fine scales	Baktoft et al. (2017), Veilleux et al. (2018)
Depth Use[a]	Mean depth use (m) which can be binned across various temporal scales (e.g., seasonal)	Differences in depth use before and after restoration could highlight response to change in bathymetry	Midwood et al. (2019), Olsen (2023), Piczak (2024)
Temperature Use[a]	Body temperature that can be summarized at various temporal scales (e.g., hourly, daily, seasonally)	Determination of preferred thermal ranges; evidence for deviation above or below these ranges in created habitats	Peat et al. (2016)
Locomotor Activity[a]	Accelerometers can be used to estimate movement of animals (m/s^2) based on summarized transmissions of tri-axial accelerometers on board acoustic tags	Higher acceleration could reflect unsuitable habitat, while lower acceleration could reflect higher habitat quality	Rous et al. (2023)

[a]Indicates that additional sensors are required on the acoustic transmitters

YAPS Yet Another Positioning Solver, *VPS* Vemco Positioning System

Acoustic transmitter sensor data can be an essential piece of a puzzle when evaluating restoration (see Wilson et al. 2015). Pressure sensors used to identify depth use can highlight the response of organisms to changes in bathymetry over the course of ecological restoration. Moreover, broader environmental drivers (e.g., water temperature, light levels, food availability, dissolved oxygen) can influence depth use making it a logical indicator to measure. Indeed, fish live in a 3-dimensional environment and presumably view habitat and its restoration through such a lens. Temperature data from tagged fishes is both informative of the types of habitat they are using (i.e., thermal regime), but since reflective of internal body temperatures, are also useful for supporting evaluations of bioenergetics. Acceleration sensors on tags could provide information on the energetic consequences of habitat selection (e.g., optimal versus sub-optimal habitat) and thus enable use of bioenergetics as another indicator of restoration success (Rous et al. 2023; Cooke et al. 2016). Acceleration sensors, if calibrated, can also be used to detect events such as spawning or feeding which yields information on the ecological function of habitats (e.g., Danylchuk et al. 2011).

Conclusion

As urbanization of aquatic ecosystems continues across the globe (Alberti et al. 2007), ecological restoration will continue to play an integral role to mitigate the negative impacts and increase biodiversity. In this perspective piece, we contend that the assessments of efficacy for ecological restoration are imperative to advancing the evidence base and that acoustic telemetry has a bigger role to play. Despite the potential utility of acoustic telemetry to evaluate ecological restoration, there remains few examples in the literature and we aimed to fill this paucity with two case studies across each a freshwater and marine ecosystem: Toronto, Canada, and Bergen, Norway, respectively. Acoustic telemetry permitted the use of various indicators to estimate fish response to ecological restoration including habitat use across various spatial and temporal scales. Although we focused on two case studies dealing with restoration in urban areas, these same tools are equally relevant to systems impacted by other forms of human development or activity and related restoration efforts. As billions of dollars have been spent on ecological restoration across the globe so far (BenDor et al. 2015), it is essential that ecological restoration achieves intended goals and acoustic telemetry can help advance the evidence base.

Author contributions Morgan Piczak: conceptualization, writing- original draft, writing- review & editing, visualization. Saron Berhe: writing- original draft, writing- review & editing, project administration. Anne Knag: writing- review & editing, project administration. Robert Lennox: resources, writing- review & editing, supervision, project administration. Knut Vollset: resources, writing- review & editing, supervision, project administration. Rick Portiss: resources, project administration, writing- review & editing. Jonathan Midwood: resources, writing- review & editing, supervision, project administration. Steven Cooke: conceptualization, resources, writing- review & editing, supervision, project administration.

Funding This work was conducted as part of a Mitacs Globalink Research Internship completed by M Piczak. The BOATS project in Bergen was supported by Bergen Kommune and by the Regionale Forskningsfond Vestland.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Alberti M, Booth D, Hill K, Coburn B, Avolio C, Coe S, Spirandelli D (2007) The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. Landsc Urban Plan 80(4):345–361

Appert C, Udyawer V, Simpfendorfer CA, Heupel MR, Scott M, Currey-Randall LM et al (2023) Use, misuse, and ambiguity of indices of residence in acoustic telemetry studies. Mar Ecol Prog 714:27–44

Arthington AH, Dulvy NK, Gladstone W, Winfield IJ (2016) Fish conservation in freshwater and marine realms: status, threats and management. Aquat Conserv Mar Freshwat Ecosyst 26:838–857. https://doi.org/10.1002/aqc.2712

Asplan Viak (2010) Møllendalselven forprosjekt. Fagrapport 523506005:44. Available from https://www.bergen.kommune.no/politikere-utvalg/api/fil/bksak/2012092966-3322892/Forprosjekt-Elveparken-Park-1

Bacheler NM, Michelot T, Cheshire RT, Shertzer KW (2019) Fine-scale movement patterns and behavioral states of gray triggerfish Balistes capriscus determined from acoustic telemetry and hidden Markov models. Fish Res 215:76–89

Baktoft H, Gjelland KØ, Økland F, Thygesen UH (2017) Positioning of aquatic animals based on time-of-arrival and random walk models using YAPS (Yet Another Positioning Solver). Sci Rep 7:14294. https://doi.org/10.1038/s41598-017-14278-z

Barnes, K., Cartwright, L., Portiss, R., Midwood, J. D., Boston, C. M., Granados, M., Sciscione, T., Gibson, C., & Obembe, O. (2020). Evaluating the Toronto Waterfront Aquatic Habitat Restoration Strategy (Toronto and Region Conservation Authority Report) p. 157

BenDor TK, Livengood A, Lester TW, Davis A, Yonavjak L (2015) Defining and evaluating the ecological restoration economy. Restor Ecol 23(3):209–219

Bernhardt ES (2005) ECOLOGY: Synthesizing U.S. River Restoration Efforts Science 308:636–637. https://doi.org/10.1126/science.1109769

Block WM, Franklin AB, Ward JP, Ganey JL, White GC (2001) Design and Implementation of Monitoring Studies to Evaluate the Success of Ecological Restoration on Wildlife. Restor Ecol 9:293–303. https://doi.org/10.1046/j.1526-100x.2001.009003293.x
Brooks JL, Boston C, Doka S, Gorsky D, Gustavson K, Hondorp D, Isermann D, Midwood JD, Pratt TC, Rous AM, Withers JL, Krueger CC, Cooke SJ (2017) Use of Fish Telemetry in Rehabilitation Planning, Management, and Monitoring in Areas of Concern in the Laurentian Great Lakes. Environ Manage 60:1139–1154. https://doi.org/10.1007/s00267-017-0937-x
Brownscombe JW, Midwood JD, Cooke SJ (2021) Modeling fish habitat: model tuning, fit metrics, and applications. Aquat Sci 83:1–14
Brownscombe JW, Midwood JD, Doka SE, Cooke SJ (2023) Telemetry-based spatial–temporal fish habitat models for fishes in an urban freshwater harbour. Hydrobiologia 850(8):1779–1800
Brownscombe JW, Lédée EJ, Raby GD, Struthers DP, Gutowsky LF, Nguyen VM et al (2019) Conducting and interpreting fish telemetry studies: considerations for researchers and resource managers. Rev Fish Biol Fish 29:369–400
Choy M, Lawrie D, Edge CB (2018) Measuring 30 years of improvements to aquatic connectivity in the Greater Toronto Area. Aquat Ecosyst Health Manage 21(3):342–351
Christie WJ (1972) Lake Ontario: Effects of Exploitation, Introductions, and Eutrophication on the Salmonid Community. Journal of the Fisheries Board of Canada 29:913–929. https://doi.org/10.1139/f72-134
Colborne SF, Faust MD, Brenden TO, Hayden TA, Robinson JM, MacDougall TM et al (2024) Estimating internal transmitter and external tag retention by Walleye in the Laurentian Great Lakes over multiple years. N Am J Fish Manag
Cooke SJ, Brownscombe JW, Raby GD, Broell F, Hinch SG, Clark TD, Semmens JM (2016) Remote bioenergetics measurements in wild fish: opportunities and challenges. Comp Biochem Physiol A Mol Integr Physiol 202:23–37
Cooke SJ, Rous AM, Donaldson LA, Taylor JJ, Rytwinski T, Prior KA, Smokorowski KE, Bennett JR (2018) Evidence-based restoration in the Anthropocene-from acting with purpose to acting for impact: Evidence-based restoration. Restor Ecol 26:201–205. https://doi.org/10.1111/rec.12675
COWI (2017) Forundersøkelse. Spredning av miljøgifter i Puddefjorden og Store Lungegårdsvann. Rapport nr. A079577–2017–02, pp 55
COWI (2019) Kartlegging av landkilder, Store Lungegårdsvann. Mulige kilder til ny tilførsel av miljøgifter fra land til sjø. Rapport nr. A109463–2019–04, pp 68
Crossin GT, Heupel MR, Holbrook CM, Hussey NE, Lowerre-Barbieri SK, Nguyen VM, Raby GD, Cooke SJ (2017) Acoustic telemetry and fisheries management. Ecol Appl 27:1031–1049. https://doi.org/10.1002/eap.1533
Danylchuk AJ, Cooke SJ, Goldberg TL, Suski CD, Murchie KJ, Danylchuk SE et al (2011) Aggregations and offshore movements as indicators of spawning activity of bonefish (Albula vulpes) in The Bahamas. Marine Biol 158:1981–1999
Diaz RJ, Rosenberg R (2008) Spreading Dead Zones and Consequences for Marine Ecosystems. Science 321:926–929. https://doi.org/10.1126/science.1156401
Doka SE, Munawar M, Midwood JD, Wells MG (2018) The state of Toronto and Region's ecosystem: Synthesis and highlights. Aquat Ecosyst Health Manage 21(3):362–367
Donaldson MR, Hinch SG, Suski CD, Fisk AT, Heupel MR, Cooke SJ (2014) Making connections in aquatic ecosystems with acoustic telemetry monitoring. Front Ecol Environ 12:565–573. https://doi.org/10.1890/130283
Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev 81:163. https://doi.org/10.1017/S1464793105006950
Eidelman G (2018) Failure When Fragmented: Public Land Ownership and Waterfront Redevelopment in Chicago, Vancouver, and Toronto. Urban Affairs Review 54:697–731. https://doi.org/10.1177/1078087416671429
Gahagan BI, Bailey MM (2020) Surgical Implantation of Acoustic Tags in American Shad to Resolve Riverine and Marine Restoration Challenges. Marine and Coastal Fisheries 12:272–289. https://doi.org/10.1002/mcf2.10108
Hellström G, Lennox RJ, Bertram MG, Brodin T (2022) Acoustic telemetry. Curr Biol 32:R863–R865. https://doi.org/10.1016/j.cub.2022.05.032
Heupel MR, Semmens JM, Hobday AJ (2006) Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Mar Freshw Res 57:1–13. https://doi.org/10.1016/S0960-9822(97)70976-X
Hobbs RJ, Harris JA (2001) Restoration Ecology: Repairing the Earth's Ecosystems in the New Millennium. Restor Ecol 9:239–246. https://doi.org/10.1046/j.1526-100x.2001.009002239.x
Howell ET, Dahmer SC, Chomicki KM, Benoit N, Boyd D, Bowen GS (2018) Monitoring water quality on the central Toronto waterfront: Perspectives on addressing spatiotemporal variability. Aquat Ecosyst Health Manage 21(3):255–267
International Joint Commission [IJC] (2012) Great Lakes Water Quality Agreement. Available from: https://www.ijc.org/sites/default/files/2018-07/GLWQA_2012.pdf
Jeffrey JD, Hasler CT, Chapman JM, Cooke SJ, Suski CD (2015) Linking Landscape-Scale Disturbances to Stress and Condition of Fish: Implications for Restoration and Conservation. Integr Comp Biol 55:618–630. https://doi.org/10.1093/icb/icv022
Jennings CA, Looney GL (1998) Evaluation of two types of anesthesia for performing surgery on striped bass. North Am J Fish Manag 18(1):187–190
Jepsen N, Thorstad EB, Havn T, Lucas MC (2015) The use of external electronic tags on fish: an evaluation of tag retention and tagging effects. Animal Biotelemetry 3:49. https://doi.org/10.1186/s40317-015-0086-z
Kennedy RJ, Allen M, Wilson R (2018) Tag retention and mortality of adult Atlantic salmon *Salmo salar* gastrically tagged with different sized telemetry transmitters. J Fish Biol 92:2016–2021. https://doi.org/10.1111/jfb.13622
Kessel ST, Hussey NE, Crawford RE, Yurkowski DJ, O'Neill CV, Fisk AT (2016) Distinct patterns of Arctic cod (Boreogadus saida) presence and absence in a shallow high Arctic embayment, revealed across open-water and ice-covered periods through acoustic telemetry. Polar Biol 39:1057–1068. https://doi.org/10.1007/s00300-015-1723-y
Klinard NV, Matley JK (2020) Living until proven dead: addressing mortality in acoustic telemetry research. Rev Fish Biol Fisheries 30(3):485–499
Kraft S, Gandra M, Lennox RJ, Mourier J, Winkler AC, Abecasis D (2023) Residency and space use estimation methods based on passive acoustic telemetry data. Mov Ecol 11(1):12
Kristensen LD, Støttrup JG, Svendsen JC, Stenberg C, Højbjerg Hansen OK, Grønkjær P (2017) Behavioural changes of Atlantic cod (Gadus morhua) after marine boulder reef restoration: Implications for coastal habitat management and Natura 2000 areas. Fish Manage Ecol 24:353–360. https://doi.org/10.1111/fme.12235
Lapointe NWR, Thiem JD, Doka SE, Cooke SJ (2013) Opportunities for Improving Aquatic Restoration Science and Monitoring through the Use of Animal Electronic-Tagging Technology. Bioscience 63:390–396. https://doi.org/10.1525/bio.2013.63.5.12
Lawson L, Jackson DA (2021) Salty summertime streams—road salt contaminated watersheds and estimates of the proportion of

impacted species. FACETS 6:317–333. https://doi.org/10.1139/facets-2020-0068

Lennox RJ, Aarestrup K, Cooke SJ, Cowley PD, Deng ZD, Fisk AT et al (2017) Envisioning the future of aquatic animal tracking: technology, science, and application. BioScience 67(10):884–896

Lennox RJ, Whoriskey FG, Verhelst P, Vandergoot CS, Soria M, Reubens J, Rechisky EL, Power M, Murray T, Mulder I, Markham JL, Lowerre-Barbieri SK, Lindley ST, Knott NA, Kessel ST, Iverson S, Huveneers C, Heidemeyer M, Harcourt R, Griffin LP, Friess C, Filous A, Fetterplace LC, Danylchuk AJ, Daly R, Cowley P, Cooke SJ, Chávez EJ, Blaison A, Whoriskey K (2023) Globally coordinated acoustic aquatic animal tracking reveals unexpected, ecologically important movements across oceans, lakes and rivers. Ecography. https://doi.org/10.1111/ecog.06801

Matley JK, Klinard NV, Larocque SM, McLean MF, Brownscombe JW, Raby GD, Nguyen VM, Barbosa Martins AP (2022a) Making the most of aquatic animal tracking: a review of complementary methods to bolster acoustic telemetry. Rev Fish Biol Fisheries 33(1):35–54. https://doi.org/10.1007/s11160-022-09738-3

Matley JK, Klinard NV, Barbosa Martins AP, Aarestrup K, Aspillaga E, Cooke SJ, Cowley PD, Heupel MR, Lowe CG, Lowerre-Barbieri SK, Mitamura H, Moore J-S, Simpfendorfer CA, Stokesbury MJW, Taylor MD, Thorstad EB, Vandergoot CS, Fisk AT (2022b) Global trends in aquatic animal tracking with acoustic telemetry. Trends Ecol Evol 37:79–94. https://doi.org/10.1016/j.tree.2021.09.001

McQueen K, Meager JJ, Nyqvist D, Skjæraasen JE, Olsen EM, Karlsen Ø, Kvadsheim PH, Handegard NO, Forland TN, Sivle LD (2022) Spawning Atlantic cod (Gadus morhua L.) exposed to noise from seismic airguns do not abandon their spawning site. ICES J Mar Sci 79(10):2697–2708

Midwood JD, Gutowsky LF, Hlevca B, Portiss R, Wells MG, Doka SE, Cooke SJ (2018a) Tracking bowfin with acoustic telemetry: Insight into the ecology of a living fossil. Ecol Freshw Fish 27(1):225–236

Midwood JD, Blair SG, Boston CM, Brown E, Croft-White MV, Francella V, Gardner Costa J, Liznick K, Portiss R, Smith-Cartwright L, van der Lee A (2022) First assessment of the fish populations beneficial use impairment in the Toronto and Region Area of Concern. Can Tech Rep Fish Aquat Sci 3503:xvii + 283

Midwood JD, Gutowsky LFG, Hlevca B, Portiss R, Wells MG, Doka SE, Cooke SJ (2018b) Tracking bowfin with acoustic telemetry: Insight into the ecology of a living fossil. Ecol Freshw Fish 27:225–236. https://doi.org/10.1111/eff.12340

Midwood JD, Rous AM, Doka SE, Cooke SJ (2019) Acoustic telemetry in Toronto Harbour: assessing residency, habitat selection, and within-harbour movements of fishes over a five-year period. Can Tech Rep Fish Aquat Sci 3331:xx + 174

Moore ME, Berejikian BA (2022) Coastal infrastructure alters behavior and increases predation mortality of threatened Puget Sound steelhead smolts. Ecosphere 13(4):e4022

Musick JA, Harbin MM, Berkeley SA, Burgess GH, Eklund AM, Findley L, Gilmore RG, Golden JT, Ha DS, Huntsman GR, McGovern JC, Sedberry GR, Parker SJ, Poss SG, Sala E, Schmidt TW, Weeks H, Wright SG (2000) Marine, Estuarine, and Diadromous Fish Stocks at Risk of Extinction in North America (Exclusive of Pacific Salmonids). Fisheries 25:6–30. https://doi.org/10.1577/1548-8446(2000)025%3c0006:MEADFS%3e2.0.CO;2

Nilsen CI, Vollset KW, Velle G, Barlaup BT, Normann ES, Stöger E, Lennox RJ (2022) Atlantic salmon of wild and hatchery origin have different migration patterns. Can J Fish Aquat Sci 80(4):690–699

O'Connor J, Morrongiello J, Ayres R, Amtstaetter F, Koster W, Kitchingman A, Cowell T, Bowler M, Hale R (2023) Understanding movement and habitat-use to guide reintroductions and habitat rehabilitation for a nonmigratory freshwater fish. Restor Ecol 31:e13869. https://doi.org/10.1111/rec.13869

Olsen C (2023) Habitat niche differentiation of Ballan wrasse (Labrus bergylta) and Corkwing wrasse (Symphodus melops) revealed by acoustic telemetry: Implication for an urban restoration project. MSc Thesis, University of Bergen, pp 47

Orrell DL, Hussey NE (2022) Using the VEMCO Positioning System (VPS) to explore fine-scale movements of aquatic species: applications, analytical approaches and future directions. Mar Ecol Prog Ser 687:195–216

Oug E, Djursvoll P, Aagaard K, Brattegaard T, Christiansen ME et al (2006) "Krepsdyr - Crustacea. In: Kålås JA, Viken Å, Bakken T (eds) Norsk Rødliste 2006–2006 Norwegian Red List (in Norwegian). Trondheim, Artsdatabanken, pp 197–206

Pardini R (2018) OBSOLETE: Fragmentation and habitat loss, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier p B9780124095489098000. https://doi.org/10.1016/B978-0-12-409548-9.09824-9

Peat TB, Gutowsky LF, Doka SE, Midwood JD, Lapointe NW, Hlevca B, Cooke SJ (2016) Comparative thermal biology and depth distribution of largemouth bass (Micropterus salmoides) and northern pike (Esox lucius) in an urban harbour of the Laurentian Great Lakes. Can J Zool 94(11):767–776

Piczak, M. L. (2024). Advancing restoration ecology for freshwater fish habitat of the Laurentian Great Lakes. [Doctoral dissertation, Carleton University]. Carleton University Research Repository

Piczak ML, Theis S, Portiss R, Ruppert J, Midwood J, Cooke SJ (2024). Evaluating the efficacy of ecological restoration of fish habitat in coastal waters of Lake Ontario (#STOTEN-D-24-10265)

Piczak ML, Theÿsmeÿer T, Doka SE, Midwood JD, Cooke SJ (2023c) Knowledge of spawning phenology may enhance selective barrier passage for wetland fishes. Wetlands 43(6):72

Piczak ML, Perry D, Cooke SJ, Harrison I, Benitez S, Koning A et al (2023a) Protecting and restoring habitats to benefit freshwater biodiversity. Environ Rev 00:000–000

Piczak ML, Anderton R, Cartwright LA, Little D, MacPherson G, Matos L, McDonald K, Portiss R, Riehl M, Sciscione T, Valere B, Wallace AM, Young N, Doka SE, Midwood JD, Cooke SJ (2022) Towards effective ecological restoration: Investigating knowledge co-production on fish–habitat relationships with Aquatic Habitat Toronto. Ecological Solutions and Evidence 3:e12187. https://doi.org/10.1002/2688-8319.12187

Piczak ML, Brooks JL, Boston C, Doka SE, Portiss R, Lapointe NWR, Midwood JD, Cooke SJ (2023b) Spatial ecology of non-native common carp (*Cyprinus carpio*) in Lake Ontario with implications for management. Aquat Sci 85:20. https://doi.org/10.1007/s00027-022-00917-9

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev 94:849–873. https://doi.org/10.1111/brv.12480

Rous AM, Forrest A, McKittrick EH, Letterio G, Roszell J, Wright T, Cooke SJ (2015) Orientation and Position of Fish Affects Recovery Time from Electrosedation. Trans Am Fish Soc 144:820–828. https://doi.org/10.1080/00028487.2015.1042555

Rous AM, Midwood JD, Gutowsky LFG, Lapointe NWR, Portiss R, Sciscione T, Wells MG, Doka SE, Cooke SJ (2017) Telemetry-Determined Habitat Use Informs Multi-Species Habitat Management in an Urban Harbour. Environ Manage 59:118–128. https://doi.org/10.1007/s00267-016-0775-2

Rous, A. M. (2023). Biotelemetry-based Monitoring of Fish-habitat Interactions as an Informative Window into Habitat Management in a Multi-species Fish Community in Toronto Harbour. Doctoral Thesis, Carleton University

Ruiz-Jaen MC, Mitchell Aide T (2005) Restoration success: how is it being measured? Restor Ecol 13(3):569–577
Shen C, Shi H, Zheng W, Li F, Peng S, Ding D (2016) Study on the cumulative impact of reclamation activities on ecosystem health in coastal waters. Mar Pollut Bull 103(1–2):144–150. https://doi.org/10.1016/j.marpolbul.2015.12.028
Smokorowski KE, Randall RG (2017) Cautions on using the Before-After-Control-Impact design in environmental effects monitoring programs. FACETS 2:212–232. https://doi.org/10.1139/facets-2016-0058
Underwood A (1991) Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. Mar Freshw Res 42:569–587
Uprety Y, Asselin H, Bergeron Y, Doyon F, Boucher J-F (2012) Contribution of traditional knowledge to ecological restoration: Practices and applications. Écoscience 19(3):225–237. https://doi.org/10.2980/19-3-3530
Veilleux, M. (2014). Spatial ecology of fish in Toronto Harbour in response to aquatic habitat enhancement (MSc dissertation, Carleton University)
Veilleux MAN, Midwood JD, Boston CM, Lapointe NWR, Portiss R, Wells M, Doka SE, Cooke SJ (2018) Assessing occupancy of freshwater fishes in urban boat slips of Toronto Harbour. Aquat Ecosyst Health Manage 21:331–341. https://doi.org/10.1080/14634988.2018.1507530
Villegas-Ríos D, Freitas C, Moland E, Thorbjørnsen SH, Olsen EM, Codling E (2020) Inferring individual fate from aquatic acoustic telemetry data. Methods Ecol Evol 11:1186–1198
Whillans TH (1979) Historic Transformations of Fish Communities in Three Great Lakes Bays. J Great Lakes Res 5:195–215. https://doi.org/10.1016/S0380-1330(79)72146-0
White PS, Walker JL (1997) Approximating Nature's Variation: Selecting and Using Reference Information in Restoration Ecology. Restor Ecol 5(4):338–349
Wilson AD, Wikelski M, Wilson RP, Cooke SJ (2015) Utility of biological sensor tags in animal conservation. Conserv Biol 29(4):1065–1107
Wortley L, Hero J-M, Howes M (2013) Evaluating ecological restoration success: A review of the literature. Restor Ecol 21:537–543. https://doi.org/10.1111/rec.12028