Received: 17 March 2024 | Revised: 1 September 2024 | Accepted: 2 September 2024

DOI: 10.1111/faf.12861

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Long-term effects of tagging fishes with electronic tracking devices

Jordan K. Matley[1] | **Natalie V. Klinard**[2] | **Fabrice R. A. Jaine**[3,4] | **Robert J. Lennox**[2] | **Natalie Koopman**[2] | **Jan T. Reubens**[5] | **Robert G. Harcourt**[3] | **Steven J. Cooke**[6] | **Charlie Huveneers**[1]

[1]College of Science and Engineering, Flinders University, Adelaide, South Australia, Australia

[2]Department of Biology, Dalhousie University, Halifax, Nova Scotia, Canada

[3]Integrated Marine Observing System, University of Tasmania, Hobart, Tasmania, Australia

[4]School of Natural Sciences, Macquarie University, Sydney, New South Wales, Australia

[5]Marine Observation Center, Flanders Marine Institute, Ostend, Belgium

[6]Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, Ontario, Canada

Correspondence
Jordan K. Matley, College of Science and Engineering, Flinders University, Adelaide, SA 5042, Australia.
Email: jordan.matley@flinders.edu.au

Abstract

Tagging fishes with internal or external electronic tracking devices (acoustic, radio, satellite, or archival tags) is invaluable to behavioural, ecological, and welfare research, but may have adverse effects on the animals studied. While short-term responses to tagging (e.g., days to weeks) have often been investigated, less information is available on longer-term impacts (e.g., months to years) and the potential chronic effects of tagging on basic biological needs such as foraging and reproduction. Here, we synthesize existing knowledge from peer-reviewed acoustic, radio, satellite, and archival tagging articles ($n=149$) and anecdotal accounts ($n=72$) from 36 researchers to assess the effects of tagging over prolonged periods. We identified a dearth of research that has specifically measured or quantified the impacts of tagging over a period longer than a few weeks or months (e.g., median experimental study duration = 33 days; $n=120$ articles). Nevertheless, there was limited evidence to support a net negative long-term impact from the implantation or attachment of electronic devices. Considerations and future research directions are discussed with the goal of generating guidance to the research community and minimizing potentially detrimental impacts to study animals. Given the global application and relevance of electronic tagging research to inform conservation and management of fishes, it is imperative for scientists to continue evaluating how tagging procedures affect animal welfare, fate, and the interpretation of tracking data.

KEYWORDS
acoustic telemetry, animal tracking, biologging, radio telemetry, satellite telemetry, tagging effects

1 | INTRODUCTION

Implanting or externally attaching electronic devices to track the movements or characterize the biophysical environment of fishes (including Osteichthyes and Chondrichthyes) is now widespread in ecological research (Matley et al., 2022; Renshaw et al., 2023). The extent and resolution (in space and time) that animals can be monitored, as well as the ability to integrate electronic tagging with other sampling methods, is further expanding questions that tracking research can address (Espinoza et al., 2011; Lédée et al., 2021; Matley et al., 2023; Udyawer et al., 2023). Similarly, technological advancements, such as tag miniaturization and battery-life prolongation, as well as collaborative telemetry networks (e.g., Ocean Tracking Network; OTN, Integrated Marine Observation System; IMOS, European Tracking Network; ETN) have made tracking fishes of different sizes, morphologies, and life history or behavioural strategies more accessible than ever (Abecasis et al., 2018; Cooke et al., 2013; Hoenner et al., 2018; Lennox et al., 2017). Critically, the evolution of aquatic animal tracking has led to greater collaboration and engagement with various stakeholders within public and private organizations, as well as Indigenous communities (Gobin et al., 2023; Nguyen et al., 2019). In turn, electronic fish tracking, often originating from academic and government collaborations, is increasingly generating actionable knowledge that is informing fisheries management and environmental policy (Brooks et al., 2019; Hays et al., 2019; Taylor et al., 2017).

Tracking fishes with electronic devices involves implanting or externally fixing an acoustic, radio, satellite, or archival tag to a study animal (Thorstad, Rikardsen, et al., 2013). The process of tagging fishes also usually consists of several critical steps that may adversely impact the animal, such as capture and handling, applying anaesthetics, conducting surgical procedures, and evaluating recovery (Clemens et al., 2023). Such steps are often conducted by researchers without any formal veterinarian training and those involved in tagging will run the gamut of experience and knowledge of fish biology (e.g., students, local collaborators/stakeholders, established experts). The primary assumption of animal tagging research is that the implantation or attachment of a tracking device (e.g., transmitter or biologger) does not affect normal behaviour after the animal has recovered from the tagging procedure (Brown et al., 2011; Thorstad, Rikardsen, et al., 2013). This axiom implies that the impacts of the procedure will not compromise the animal during the study. This assumption has been subject to a multitude of studies that have evaluated the effects of tagging on the survival, behaviour, physiology, and growth (among others) of fish, but most studies are conducted in captive experimental trials and are short-term in scope (e.g., weeks to months) (reviewed in Bridger & Booth, 2003; Cooke et al., 2011; Vollset et al., 2020). Because many electronic tracking devices (or their attachment materials) remain within or attached to the animal beyond the study period, effects from tagging may also manifest in different ways (e.g., chronic/acute and lethal/sublethal) throughout the life of the animal. Animal welfare and research ethics are paramount to scientific research principles and social license for animal experimentation; investigators must avoid causing unnecessary harm to study animals and be responsible for refining the technology and techniques being applied to them (DeGrazia & Beauchamp, 2019; Niella et al., 2022).

Faced with the global expansion and uptake of fish telemetry and biophysical monitoring (e.g., biologging and environmental sensors), it is timely to critically evaluate current practices that may result in ethical dilemmas or restrict the interpretation of collected data. The purpose of this review is to synthesize available research to better understand the potential long-term effects of internal and external electronic tracking devices on fish. The specific objectives of this review are to (1) systematically characterize how tagging effects are evaluated in peer-reviewed studies, including quantifying durations of tag effects studies across tag types and uses; (2) describe and contextualize findings from existing long-term tagging effects studies and opportunistic observations from recaptures and resightings; (3) identify main long-term considerations concerning research and the long-term health and survival of tagged fishes; and (4) suggest ways forward for better integration of long-term tagging effects in future research. A more comprehensive understanding of the long-term effects of tagging on fishes will help inform future considerations from both logistical and ethical perspectives.

2 | DEFINING 'LONG-TERM' TAGGING EFFECTS

The main goal of this study was to evaluate long-term effects of electronic tagging of fishes in the wild. Yet, 'long-term' is inevitably a relative measure and difficult to define broadly. For example, 'long-term' will differ depending upon the study species as it relates to life expectancy or mortality rates in the wild. 'Long-term' may also be endogenous and vary by different stages of ontogenetic development, generation length, or genetic variation. Alternatively, it may vary exogenously with environmental cycles (e.g., seasons) or climatic shifts (e.g., climate change) at different scales. Researchers themselves may have subjective views of 'long-term'. A search for 'long-term' within the 149 reviewed electronic tagging articles (described in section below) revealed 26 instances of its usage in relation to the maximum duration of the study, ranging from 21 (Perry et al., 2013) to 4745 (Smukall et al., 2019) days. Given the variability and potential ambiguity of 'long-term', we have refrained from applying a strict definition in this study. Instead, we consider 'long-term' to be flexible and dependent on the scope of each study relative to the factors stated above (and any other applicable ones). Implicitly though, we consider 'long-term' to relate to direct and indirect effects of electronic tagging on animals after an initial period of recovery or re-acclimation (in the wild or holding environment) with potentially lasting or persistent ramifications throughout critical life stages, the expected tagged period, or the life of the animal.

3 | LONG-TERM TAGGING EFFECTS IN RESEARCH

To help gauge existing knowledge of long-term tagging effects on fishes, we identified peer-reviewed articles that investigated tagging effects across four electronic tagging types widely used in marine, freshwater, and estuarine environments: acoustic, radio, satellite, and archival tags (see below sections for specific definitions). We used distinct Web of Science™ (v.5.34) search criteria for each tagging type to identify relevant articles and only incorporated studies on fishes from 2010 onwards (Supporting Information). We also used TrackdAT (www.trackdat.org), an open-source metadata repository of peer-reviewed acoustic telemetry research (Matley et al., 2024) to identify additional articles on the effects of acoustic tagging. It was not our intention to incorporate every existing tagging effects study in this review, but to identify common themes across our search results. The following information was extracted from each study: tagging type (acoustic, radio, satellite, and archival), location of tagging (internal, external), maximum duration of experiment or monitoring period, and the method of evaluation. We identified three broad methods of evaluation (or a combination thereof): experimental, tracking, and recaptures. Experimental tagging effects studies consisted of trial-based treatments (e.g., tagged vs. untagged) within controlled (aquarium) and semi-controlled (e.g., pond) environments. Tracking studies evaluated effects based on animal movements and behaviour in the wild following tagging. Recapture studies consisted of dedicated or opportunistic efforts to capture animals that had been previously tagged to evaluate fate and defined endpoints.

We reviewed 149 electronic tagging articles, consisting of 112 acoustic, 16 radio, 9 satellite, and 15 archival investigations related to tagging effects. These articles examined species from 38 different families, with 40% of studies ($n=60$) on salmonids. Forty-seven per cent ($n=70$) and ~32% ($n=48$) of all articles tested juveniles and adults only, respectively (Figure 1), while internal tagging made up 81% ($n=121$) of studies. 'Experimental' trials (median study duration = 33 days; number of instances = 120) were the most common method of evaluation across all electronic tagging types, followed by 'tracking' (median study duration = 153 days; number of instances = 36) and 'recapture' (median study duration = 196 days; number of instances = 16) (Figure 2). The shorter duration of experimental trials compared to tracking and recapture approaches was consistent across all tagging types and is likely reflective of the different study designs between evaluation methods. For example, experimental trials usually required holding facilities and consistent monitoring, as well as repeated sampling throughout the study period, which are conducive to shorter studies. By contrast, tracking and recapture studies typically relied on resampling individuals from the wild (opportunistically or by design), and are often built into adjacent monitoring projects. Although conducted over shorter periods, experimental studies had greater capacity to examine and predict specific effects of tagging due to the manipulative study design. Meanwhile, the longer tracking and recapture studies were usually limited to broader investigations associated with changes in behaviour, growth, and survival, but were better suited to reflect conditions in the wild.

Below, we outline each tagging type investigated and provide examples associated with long-term tagging effects. Note that there is inherent bias in communicating examples of tagging effects as they may skew cases or reports of marginal or no effects within the same or other studies. Thus, examples listed below do not represent relative occurrence of adverse effects but are included to provide context for when they are identified—overwhelmingly, the studies we reviewed showed no major lasting effects.

3.1 | Acoustic telemetry

Acoustic telemetry consists of tracking animal occurrences (and other sensor or biologging data) at defined locations remotely with sound. Specifically, an animal is internally (usually within the abdominal cavity) or externally tagged with a transmitter that emits a

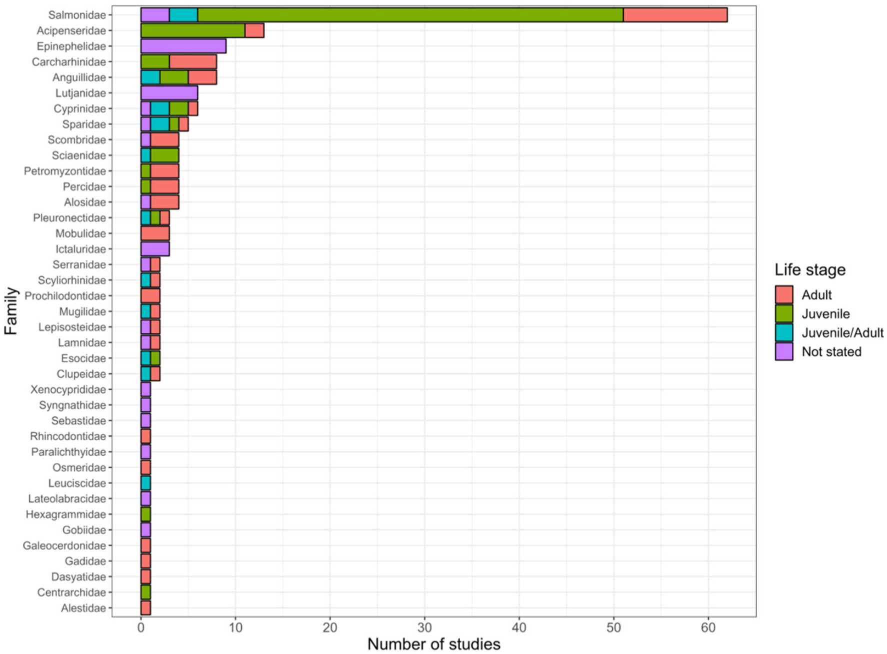

FIGURE 1 Number of tagging effects studies published between January 2010 and May 2024 ($n = 149$) identified by family and the life stage of the study animals.

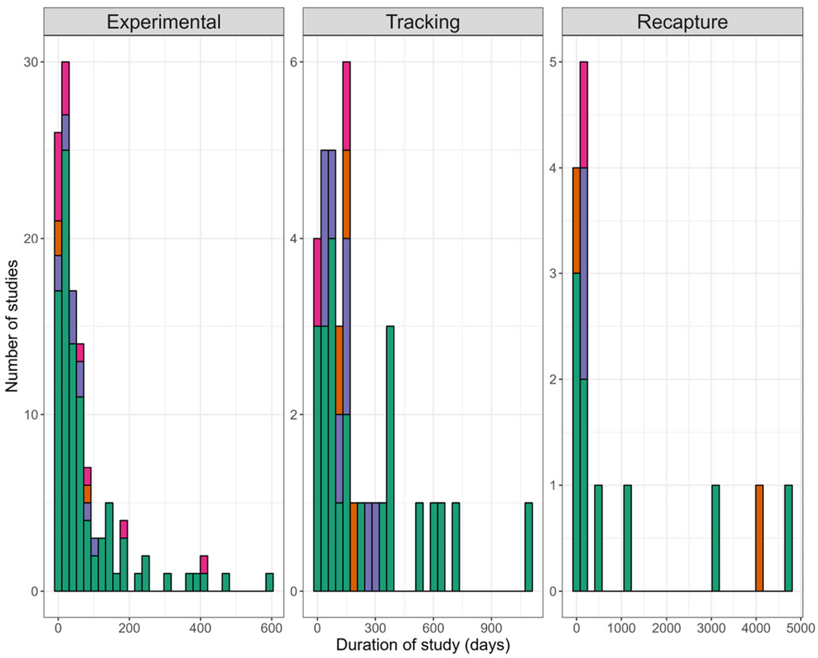

FIGURE 2 Distribution of tagging effects study durations distinguished by type of evaluation (i.e., experimental, tracking, and recapture). The median duration for experimental, tracking, and recapture studies was 33 days (n = 120), 153 days (n = 36), and 196 days (n = 16), respectively. Note the *x*- and *y*-axes scaling are unique to each subplot.

coded acoustic signal and is detected by a hydrophone (commonly moored underwater) when the fish swims nearby. Surgical insertion or attachment procedures vary but are often preceded by the disinfection of transmitters and incision sites, as well as anaesthetizing (including tonic immobility in sharks) the animal prior to and during the surgery. Animals are either released immediately following tagging or after a period of recovery. For more information about acoustic telemetry and tagging processes, see Matley et al. (2022) and Clemens et al. (2023).

Tagging effects studies associated with acoustic telemetry ($n = 112$) were carried out for a median duration of 36, 150, and 133 days for the experimental, tracking, and recapture methods of evaluation, respectively. There was considerable variety in the species and life history stages that were studied, as well as the parameter endpoints selected, although juvenile salmonids were common and experimental trials often focused on growth, tag retention, and survival as study endpoints. Seventeen articles self-identified the studies as 'long-term' with study durations ranging from 21 to 4745 days (Table S1). Most long-term studies concluded little to no long-term effects of tagging (Childs et al., 2011; Hubbard et al., 2021), and if negative effects were identified they often receded shortly after being tagged (Gardner et al., 2015; King & Stein, 2020). A few studies revealed poor tag retention over long-term periods, but survival in these studies was unaffected (Bodine & Fleming, 2013; Lawrence et al., 2023). The main long-term concerns that were identified pertained to foreign body response of the animal to the transmitter itself. For example, two related articles identified inflammatory cytokine expression in 70-day experimental trials of rainbow trout (*Oncorhynchus mykiss*) associated with the lack of biocompatibility with transmitter material, potentially leading to chronic fitness costs (Heath et al., 2023; Semple et al., 2018). Several studies <60 days in duration also identified lower rates of survival in tagged juvenile salmonids compared to controls, with tag burden (i.e., weight/volume of tag relative to size of fish) being the main factor driving differences during experimental trials (Bass et al., 2020; Collins et al., 2013; McKenna Jr et al., 2021). It is relevant to note that the effect of tag burden will vary considerably across species and life stages, and adverse effects in experimental trials often occur due to researchers testing threshold limits to ensure tags are suitable for animals released into the wild.

3.2 | Radio telemetry

Radio telemetry uses similar methodology as acoustic telemetry but relies on radio signals from transmitters to facilitate tracking with fixed or mobile receiver stations/antennas. Unlike acoustic telemetry, radio telemetry is not conducive to saltwater. Tagging fishes with radio transmitters follows similar practices as acoustic telemetry with transmitters of equivalent shape and size, although many types of radio transmitters have an antenna that extends outside the body cavity (when tagged internally). For more information about radio telemetry and tagging processes, see Thorstad, Rikardsen, et al. (2013).

Tagging effects studies associated with radio telemetry ($n=16$) were carried out for a median duration of 37 (experimental), 120 (tracking), and 146 (recapture) days. Two experimental articles self-identified the studies as 'long-term' with study durations of 21 and 98 days (Table S1). The former study found long-term effects of internal tag burden on the swimming performance of juvenile salmonids (Perry et al., 2013), while Spanos et al. (2023) found higher mortality risk associated with increased tag burden in adult Arctic lamprey (*Lethenteron camtschaticum*) beyond the 98-day experimental period (i.e., post-trial observations occurred for 35 weeks following surgery). Additionally, the impact of transmitter antenna protrusion worsened over the course of the study with severe inflammation and epidermal erosion in 42% and 16% of individuals at week 14, respectively. Although not identified as 'long-term' studies, recaptured (radio-tagged) adult African eels (*Anguilla* spp.) and adult salmonids were found in good health after prolonged periods at liberty in the wild (112 days—Hanzen et al., 2020 and 180 days—Naughton et al., 2018).

3.3 | Satellite telemetry

Satellite telemetry is the remote tracking of animal locations (and other sensor or biologging info) using radio signals that are transmitted to orbiting satellites, providing geolocated information that is relayed to the user. Given the power output required to transmit to satellites, satellite transmitters are typically heavier and larger than acoustic and radio transmitters, restricting the lower size range of animals that can be tagged. Satellite transmitters are almost exclusively attached externally (e.g., the dorsal fin of sharks) due to the payload of the tag but also because the tag needs to be at the surface to transmit. As a result, tagging practices (e.g., restraining the animal during tagging or tagging it while free-swimming) and attachment methods (e.g., subdermal darts, clamps, glue, screws) are varied, facilitating the capacity for both short- and long-term deployments. For more information about satellite telemetry and tagging processes, see Harcourt et al. (2019).

Tagging effects studies associated with satellite telemetry ($n=9$) were carried out for a median duration of 3 (experimental), 156 (tracking), and 1258 (recapture) days. Six articles self-identified the studies as 'long-term' with study durations ranging from 50 to 4015 days (Table S1). Four of these studies highlighted relatively long tag retention periods attached to sheepshead (*Archosargus probatocephalus*, 172 days; Naisbett-Jones et al., 2023), great hammerhead (*Sphyrna mokarran*, 323 days; Heim et al., 2023), and white shark (*Carcharodon carcharias*, 2192 and ~4015 days; Jewell et al., 2011 and Nasby-Lucas & Domeier, 2020) with no noticeable impact on growth and health, although there was evidence of external tissue trauma from the attachment method (e.g., due to abrasion) in some individuals. Otherwise, satellite tags had a negative effect on swimming ability of adult Atlantic salmon (*Salmo salar*) compared to acoustic or archival tags due to increased tag burden, with tracked individuals (up to 156 days) diving less frequently and to shallower depths, as well as having slower growth rates (Hedger et al., 2017).

3.4 | Archival tracking

Archival tags (also referred to as data loggers or biologgers) primarily record biological or environmental sensor information, but also spatial data (e.g., location via light or satellite). Unlike telemetry-based transmitters, the data are stored within the device requiring manual collection to retrieve the observations. Archival transmitters are constructed for different purposes and vary across size ranges and application methods (e.g., internal heart rate sensors and externally mounted depth-salinity-temperature tags). For the purposes of this review, archival transmission of stored data via satellite (e.g., pop-off satellite archival tags; PSATs) was categorized as satellite telemetry given the similar attachment methods as satellite transmitters. Also note that archival tagging in relation to spatial tracking was prioritized in this review. For more information about archival telemetry and tagging processes, see Harcourt et al. (2019).

Tagging effects studies associated with archival tracking ($n=7$) were carried out for a median duration of 17 (experimental), 79 (tracking), and 212 (recapture) days. Five articles self-identified the studies as 'long-term' with study durations ranging from 60 to 413 days (Table S1). Two separate experimental studies on European eel (*Anguilla anguilla*) found no evident negative effects of internal tagging on feeding and movement patterns (using nanosensors, volume: 5 mm^3, 60 days; Lee et al., 2019) or growth and survival (using data storage tags, diameter: 11 mm; length = 35 mm, 180 days; Thorstad, Økland, et al., 2013). Furthermore, ultrasounds showed no discernible change in tissue structure four weeks following tag implantation, indicating no substantial foreign body reaction (Lee et al., 2019). Growth and behaviour were also similar between tagged (temperature-depth-light internal tags) and control groups in a 413-day experimental trial of adult Pacific halibut (*Hippoglossus stenolepis*; Loher & Rensmeyer, 2011). However, after 59 weeks, most individuals dissected (82%, $N = 11$) had developed internal foreign body responses such as deposition of fibrous protein on tag surfaces, as well as tag encapsulation in the peritoneal wall or intestinal mesenteries for both fully internal tags and tags with electronic stalks penetrating the peritoneum, warning of the potential for delayed (>1 year) tag expulsion through the body wall (Loher & Rensmeyer, 2011).

4 | ANECDOTAL LONG-TERM EFFECTS FROM RECAPTURES AND RESIGHTINGS

We reached out to the animal tracking community via social media (i.e., Twitter/X), by contacting national acoustic telemetry networks (e.g., ETN, IMOS, OTN), and by asking attendees of the 6th International Conference on Fish Telemetry held in Sète (France) in June 2023 to report anecdotal recaptures or resightings that could provide additional information about long-term tagging effects. We obtained observations from 36 scientists reporting recaptures and tagging effects for over 1600 individuals from 72 recaptures or resightings of 49 species with time-at-liberty ranging from 24 h to 10 years post-tagging (Table S2). Assessment of tagging effects varied and ranged from simple external observation of incision scars to dissection and internal examination of tagging sites (Figure 3). The effects of tagging were variable, but overall minimal. The incision from internal tagging healed rapidly, becoming unnoticeable as quickly as within 1–3 months post-tagging (e.g., in brown trout (*Salmo trutta*), gilt-head bream (*Sparus aurata*), and European seabass (*Dicentrarchus labrax*). On a few occasions, a faint scar could be seen ~3 years post-tagging (e.g., in undulate ray (*Raja undulata*); Figure 3a), twait shad (*Alosa fallax*), and European eel (Figure 3b) with one example of a scar still being detectable 8.5 years post-tagging in asp (*Leuciscus aspius*). Reports of inflammation or poor conditions were rare with inflammation observed in only seven species (<1% of cases reported) and records of individuals in poor body condition in three species (<0.5% of cases reported). Sutures dissolved or fell off as quickly as 1–2 months post-tagging (e.g., in sterlet sturgeon (*Acipenser ruthenus*), gilt-head bream, European seabass, and spotted catshark (*Scyliorhinus canicula*)), but were still present after 1.5 years in a couple of cases (i.e., in *Carassius auratus*; Figure 3c). Other deleterious effects reported included poorer condition of externally tagged spotted catshark compared to those tagged internally, a case where the suture of a northern pike (*Esox lucius*) seemed to have damaged a pectoral fin (Figure 3d), and a deformed fin 1-year post-tagging in a young-of-the-year white shark tagged with a satellite (SPOT) tag. Cases of transmitter encapsulation were reported in common chub (*Squalius cephalus*; Figure 3g), white seabream (*Diplodus sargus*), and ide (*Leuciscus idus*). Aside from these observations, most respondents observed no deleterious effects on individual health or condition. These observations are in line with previous studies documenting a lack of long-term effects on tagged individuals (Hubbard et al., 2021; Smukall et al., 2019).

While these reports do not in general provide a detailed assessment of fish behaviour or fitness (e.g., tagging impact on growth rate, reproductive output), they do suggest minimal macroscopic impact on tagged individuals with healed incisions, no inflammation, and no obvious reduction in body condition. We, however, acknowledge that these anecdotal reports have several limitations. Fish adversely impacted by tagging might be less likely to be resighted/recaptured if they suffer impaired swimming abilities or other changes in behaviour such as reduced appetite. Furthermore, individuals most severely impacted might have died—a concern often attributed over longer periods to natural events (i.e., predation, disease) or emigration rather than the effects of tagging (Klinard & Matley, 2020). Finally, most respondents provided information relating to acoustic telemetry resulting in skewed anecdotal information relating to tracking methods. Regardless of these limitations, anecdotal reports are an important contribution to the weight-of-evidence that tagged aquatic organisms can survive and indeed thrive despite tagging. The scientific community should promote the reporting of recaptures and ensure that where possible they include a macroscopic (e.g., photos) and even microscopic (e.g., bacterial swabs, histology) assessment of the tagging site, so that we can learn more about the long-term effects of tagging on aquatic animals.

5 | MAIN CONSIDERATIONS ASSOCIATED WITH LONG-TERM EFFECTS OF ELECTRONIC TAGGING

Across our literature synthesis, collection of anecdotal reporting, and personal experiences, several main themes stand out as poignant to consider from long-term animal health and research perspectives. Below, we outline these themes, which include external/internal tagging, infection risks and healing, tag characteristics (and associated concerns), data reliability, and ethical considerations.

5.1 | External vs. internal electronic tagging

External tagging with electronic tracking devices consists of attaching a transmitter to the outside of the body, usually using a dart and a tether made of plastic-coated stainless-steel wire or monofilament, often through the muscle below the dorsal fin or mounted to the

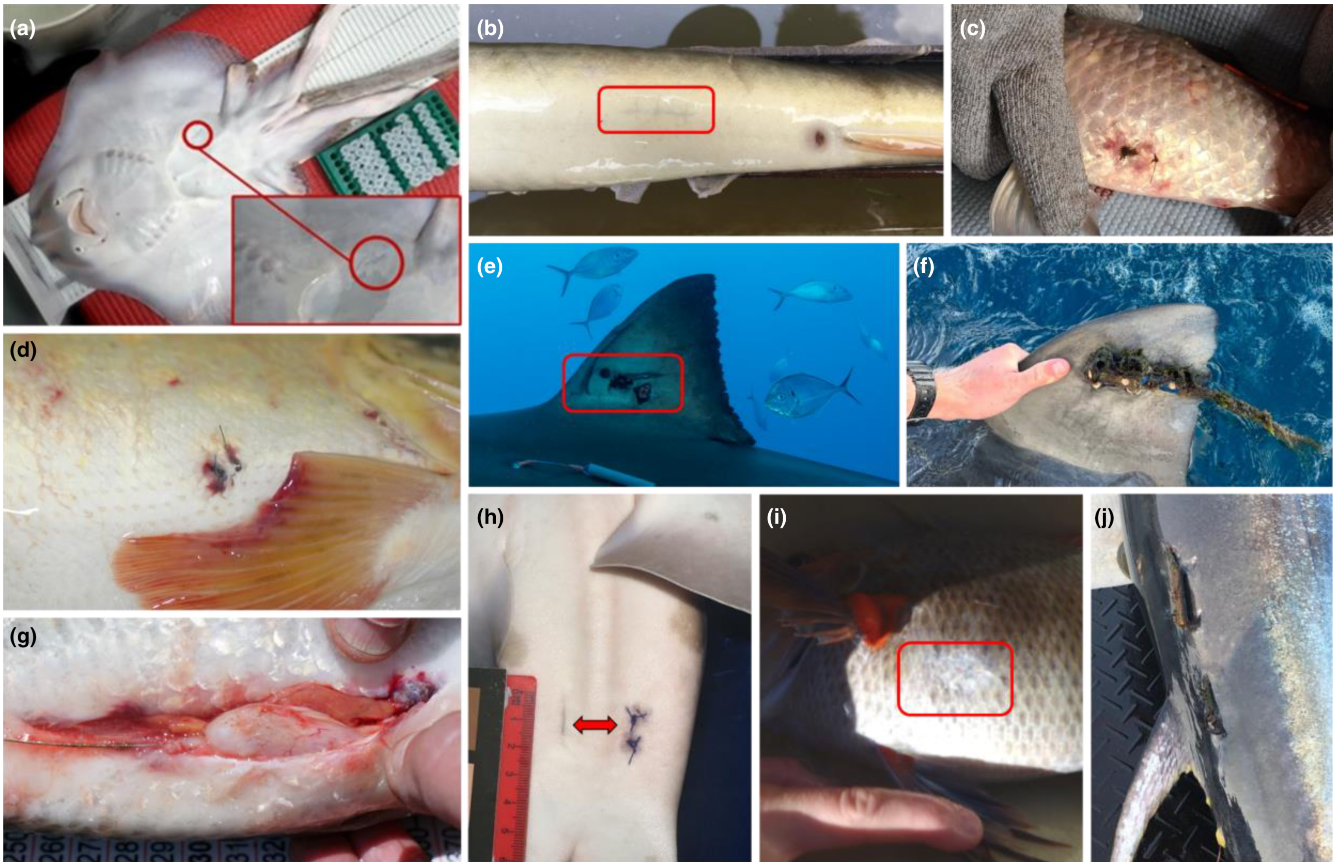

FIGURE 3 Photos of recaptured (from the wild) tagged individuals showing various levels of healing or lack thereof including (a) *Raja undulata*: Healed acoustic tag incision site 1085 days post-tagging (photo credit: Kenn Papadopoulo); (b) *Anguilla anguilla*: Scarring ~1 year post-acoustic tagging (photo credit: Pieterjan Verhelst); (c) *Carassius auratus*: Suture material remaining ~15 months post-acoustic tagging (photo credit: Sarah Larocque); (d) *Esox lucius*: Damaged pectoral fin presumably from suture irritation ~6 months post-acoustic tagging (photo credit: Jon Christian Svendsen); (e) *Carcharodon carcharias*: Wound healing on dorsal fin ~3 months following tagging with a temporary camera and accelerometer (biologger). External acoustic transmitter also visible (photo credit: Andrew Fox); (f) *Galeocerdo Cuvier*: Biofouled SPOT satellite transmitter that migrated horizontally after ~4.5 years (photo credit: Richard Fitzpatrick); (g) *Squalius cephalus*: Transmitter encapsulation ~1 year post-radio tagging (photo credit: Clemens Ratschan); (h) *Heterodontus portusjacksoni*: Acoustic tag incision sites (left: not sutured, right: sutured) 42 days post-surgery (experimental trial) showing limited inflammation and good healing, particularly at non-sutured site (photo credit: Brittany Heath); (i) *Lethrinus miniatus*: Healed incision site 132 days post-surgery (photo credit: Leanne Currey); (j) *Thunnus thynnus*: Attached acoustic transmitter (upper) and attachment site of pop-up satellite archival tag (PSAT) (lower; tag no longer present) several years following tagging (photo credit: Barbara Block).

dorsal fin directly in animals such as sharks that have robust dorsal fins (Heim et al., 2023). External tagging is common across all electronic tag types and is readily used for large species that are logistically more difficult to capture and internally tag (Niella et al., 2022). Internal tagging consists of implanting a transmitter within the body, typically within the coelom (or abdominal cavity). Internal tagging is a common attachment technique for acoustic and radio transmitters and is also used in archival monitoring (e.g., heart rate loggers). These two attachment methods have distinct advantages and disadvantages that may contribute to long-term tagging effects (summarized in Table 1).

Disadvantages of external tagging with potential long-term health implications include increased energy expenditure from drag, fouling which may lead to additional drag, scarring and fin deformation, entanglement, and increased predation risk or antagonistic interactions with conspecifics due to visibility of transmitter (Jepsen et al., 2015; Kerstetter et al., 2004; Nasby-Lucas & Domeier, 2020). Furthermore, Jepsen et al. (2015) identified concerns directly pertinent to long-term effects of external tagging including unsuitable method in the long-term for fast-growing or non-feeding fish; attachment methods may cause extensive long-term damage to muscle and integument; not suitable for measuring physiological variables in the long-term; and substantial tag loss possibility in long-term studies. Indeed, tag retention is typically short (weeks–months) when tagging externally, potentially avoiding deleterious long-term effects altogether (Jewell et al., 2011; Martins et al., 2019). Nevertheless, retention varies widely across species, habitat, and attachment technology (Jepsen et al., 2015) and high external tagging retention rates are relatively common in larger animals in which longer-lasting attachment methods can be used. For example, retention of externally attached archival depth-salinity-temperature tags was

TABLE 1 Summary of common advantages and disadvantages of external and internal electronic tagging methods based on Cooke et al. (2011) and Jepsen et al. (2015), as well as authors' experience.

Tagging concern	External tagging	Internal tagging	Examples from long-term studies
Tagging process	Relatively quick handling times Use of anaesthesia is common in fish, while less common in sharks and rays, which can reduce recovery time Highly variable attachment methods	Often considerable handling involved Typically requires laparotomy which demands that the fish is immobilized (e.g., using anaesthetics), except in sharks and rays where tonic immobility is often used Use of sutures for wound closure dominant	New external satellite transmitter attachment method outperformed (i.e., higher retention) previous methods over experimental (90 days) and tracking (172 days) trials in sheepshead (Naisbett-Jones et al., 2023) Wound healing and tag retention in internally tagged (acoustic) rainbow trout over a 12-week experimental trial was higher in unsutured vs. sutured wound closure treatments (Kelican et al., 2021)
Post-release activity	Quick recovery Commonly used in fishes showing high activity following tagging (e.g., upstream migrating salmonids)	Recovery time, especially for some anaesthetics, may be slow increasing predation risk and restricting normal behaviour	Retaining Atlantic salmon smolts for 75 days prior to release increased survival compared to releasing individuals into the wild within 24 hours of tagging (Daniels et al., 2021) Passage rates of twaite shad (Davies et al., 2023) and downstream spawning migrations of walleye Wilson et al. (2017) differed across tagging periods with recently tagged individuals resulting in lower passage rates and slower migrations, respectively
Species/habitat	Highest success in fusiform or laterally compressed fish Benthic or weedy habitats can be problematic due to entanglement Some species/life stages show poor affinity to external tagging Often used in large animals with robust skin and fin structures (e.g., rigid fins in sharks) Some technologies (e.g., radio) are better suited for external tagging and more effective in certain habitats (e.g., riverine systems)	Highly variable but generally effective for robust species Some species/life stages show poor affinity to internal tagging	Survival rates in common bream were highest when tagged with internal acoustic transmitters just prior to spawning compared to during spawning periods (Winter et al., 2020) Survival rates in northern pike were influenced by sex, with males generally surviving longer than females (Winter et al., 2020) Relatively slower growth rates in summer flounder compared to black seabass (both internally tagged with acoustic transmitters) under similar experimental conditions during trials >300 days (Fabrizio & Pessutti, 2007)
Tag retention	Typically lower than internal	Typically higher than external, but risk of expulsion still exists	More than 50% of captive silver perch rejected external radio tags after 146 days (O'Connor et al., 2009) Almost all (91%) adult American eel lost their attached sham tags during a 12-week experimental study (Loher & Rensmeyer, 2011) Expulsion rates were between 50% and 90% across internal acoustic and radio transmitter experimental trials in common carp (Daniel et al., 2009)
Tissue damage	Abrasions/infections at attachment site Drag can cause the attachment points to pull out or even 'cut' the tissue Fouling might increase drag or cause skin abrasion Potential for fish to engage in behaviours that attempt to remove the transmitter (e.g., rubbing against substrate)	Irritation from sutures Sutures often slow to be absorbed or fall out, especially in cold water environments	Some external tissue trauma from the attachment of satellite transmitters in sheepshead (172 days; Naisbett-Jones et al., 2023) and white shark (~4015 days; Nasby-Lucas & Domeier, 2020) Tissue necrosis at incision site (internal acoustic) of several largemouth bass 362 days post-surgery (Caputo et al., 2009) Absorbable sutures remained in acoustically tagged walleye (*Sander vitreus*) for up to 886 days following tagging (Schoonyan et al., 2017)

TABLE 1 (Continued)

Tagging concern	External tagging	Internal tagging	Examples from long-term studies
Infection risk and foreign body response	Dependent upon abrasion and tissue damage at tagging site	Moderate—but highly dependent upon the extent to which the handling and surgery adheres to good procedures	Prolonged foreign body response to internal acoustic tagging and transmitter coating in the form of chronic inflammatory cytokine expression in 70-day experimental trials of rainbow trout (Heath et al., 2023; Semple et al., 2018) Internal radio transmitter antenna protrusion worsened in arctic lamprey over the course of a 14-week study with severe inflammation and epidermal erosion in 42% and 16% of individuals at week 14, respectively (Spanos et al., 2023) After 59 weeks, 9/11 adult Pacific halibut had developed internal foreign body responses to archival transmitters such as tag encapsulation and warned of the potential of long-term (>1 year) tag expulsion (Loher & Rensmeyer, 2011) High expulsion rates in internal acoustic and radio transmitter experimental trials in common carp were attributed to ulceration and bacterial infection (Daniel et al., 2009)
Growth	Often high impact if tag burden or attachment method is beyond capacity of fish to tolerate	Often high impact if tag burden or attachment method is beyond capacity of fish to tolerate	Slower growth rates in adult Atlantic salmon tagged with external satellite transmitters compared to individuals tagged with internal acoustic and radio transmitters during 156 days of tracking (Hedger et al., 2017) Poorer condition of externally (acoustically) tagged catshark compared to those tagged internally (Papadopoulo et al., 2023)
Physiology/stress	Marginal impact if tag burden or attachment method is beyond capacity of fish to tolerate and proper tagging procedures followed	Marginal or short-lived impacts if tag burden or attachment method is beyond capacity of fish to tolerate and proper tagging procedures followed	No difference in physiological parameters of tagged (internal acoustic) and control largemouth bass sampled after 362 days post-surgery (Caputo et al., 2009) Long-term internal acoustic transmitter presence did not appear to increase serum cortisol levels in Siberian sturgeon more than in control fish (Boone et al., 2013) Resting heart rate took >3 weeks to stabilize in juvenile Atlantic salmon tagged internally with acoustic transmitters (Hvas et al., 2020)
Swimming performance	Drag can be high depending on shape and attachment technique Risk of biofouling Risk of entanglement (e.g., in aquatic macrophytes, corals)	Relatively low, unless high transmitter weight to body weight ratio	Tag burden impacted the swimming performance of internally tagged (acoustic and radio) Chinook salmon during a 21-day experimental trial (Perry et al., 2013) Less frequent and shallower dives in satellite-tagged (external) adult Atlantic salmon compared to internal acoustic and radio-tagged individuals during 156 days of tracking (Hedger et al., 2017)
Survival	Impact often considered to be marginal, particularly on larger animals, although impacts may be compounded if detrimental to healing or normal behaviour	Relatively higher risk of tagging-related mortalities compared to external tagging, mainly due to stress from handling or tagging procedures (but best practice should reduce this), higher infection risk, and tendency for internal implantation of smaller animals than external tags	Several studies <60 days in duration identified lower rates of survival in acoustically tagged (internal) juvenile salmonids compared to controls with tag burden as key factor (Bass et al., 2020; Collins et al., 2013; McKenna Jr et al., 2021) Higher mortality risk associated with high tag burden (internal; radio) in adult Arctic lamprey beyond the 98-day experimental period (Spanos et al., 2023)

Note: Specific examples of concerns from long-term studies are also included.

100% in a 6-month laboratory trial of Atlantic cod (*Gadus morhua*) using modified tags designed to reduce tension and cutting from wiring (Righton et al., 2006). Furthermore, satellite-linked radio transmitting (SLRT) and acoustic tags (both externally attached) have successfully tracked white sharks for >4 years (Nasby-Lucas & Domeier, 2020; Huveneers *pers. obs.*).

While internal tagging is typically more time-consuming and invasive (e.g., need for surgery/anaesthesia and pathogen entry risk) than external tagging, potentially causing acute health concerns, surgical implantation is often considered a more effective method in the context of long-term tagging because of increased tag retention and relatively low impact once healed (Haulsee et al., 2016; Jepsen et al., 2015). Still, internal tagging is not without issues (Clemens et al., 2023; Cooke et al., 2011; Gheorghiu et al., 2010), and some pressing long-term concerns exist (see section below). Ultimately, there is still a paucity in knowledge associated with long-term physiological, behavioural, and overall health effects of both internal and external tagging, but existing research largely shows that proper capture, surgical, and handling practices will not lead to adverse chronic impacts. The decision to tag internally or externally should be based on a combination of factors relating to animal welfare, logistics, feasibility, experimental constraints, environmental conditions, and study design, in addition to concerns outlined in this review.

5.2 | Tag characteristics

The physical presence of an electronic tag (or attachment/suture material) has the potential to influence organismal condition, health, and survival, particularly if the ratio between transmitter weight and fish weight (i.e., tag burden) is too large or the transmitter has specific characteristics (e.g., material, shape, or electronics used) that in some way impact the animal. Increasing tag burden beyond a critical limit has consistently shown significant impacts on survival, growth, and tag retention, and can also impact swimming performance and buoyancy (Collins et al., 2013; Macaulay et al., 2020; McKenna Jr et al., 2021; Perry et al., 2001). Internal transmitters that are, for example, too long relative to the swimming mechanics of a given organism can also impede certain swimming modes (Arnold & Holford, 1978). Similarly, external tags and associated drag, entanglement or biofouling (e.g., increased drag), can alter swimming performance (Hedger et al., 2017; Lear et al., 2018). A few studies have also raised concerns about the specific material of transmitters affecting immune responses (Heath et al., 2023; Semple et al., 2018), and the transmission of sound attracting predators has been raised as a long-term risk to fitness (Stansbury et al., 2015). The presence of the tag or incision may also disrupt internal body functions; for example, water intrusion in the body cavity (through the incision) caused loss in ovarian fluid and hardening of eggs in steelhead, resulting in higher post-spawning mortality and egg retention compared to non-tagged controls (Berejikian et al., 2007). The potential long-term implications of these impacts include deleterious effects on biological processes such as growth, reproduction, maintenance of homeostasis (i.e., stress response), energy acquisition, and predator avoidance. In all cases, it is reasonable to expect that tag burden and associated tag properties, if exceeding acceptable limits, become increasingly detrimental following tagging until mortality is incurred and may compound existing health concerns (Beeman et al., 2015).

Although limited, long-term studies tend to reveal negligible tag burden-associated impacts, suggesting biological needs of fishes are not significantly affected by tagging or are at least balanced. For example, Boone et al. (2013) found no transmitter impact on growth (or blood cortisol levels) in immature Siberian sturgeon (*Acipenser baeri*) during a 55-week captive trial. Similarly, Thorstad et al. (2009) found that specific growth rates of tagged and untagged tailor (*Pomatomus saltatrix*) did not differ after 144 days in a controlled tank experiment, although growth was hampered in fish tagged with large (13 × 50 mm vs. 9 × 28 mm) transmitters. Smukall et al. (2019) recaptured a lemon shark (*Negaprion brevirostris*) more than 13 years after initial internal tagging that showed signs of growth, pregnancy, and behaviour consistent with conspecifics. Long-term viability of internal tagging has also been supported from comparable physiological parameters (i.e., stress, tissue damage, and nutrition) between untagged and tagged (recaptured 335–1402 days post-release) wild largemouth bass (Caputo et al., 2009). Also, critical swimming speeds in internally tagged pikeperch (*Stizostedion lucioperca*) did not differ from controls following a year-long period in the wild (Koed & Thorstad, 2001). Finally, Hubbard et al. (2021) demonstrated no negative effects of tagging on survival, growth, or condition of lake trout by comparing tagged and untagged populations in three lakes during recapture efforts across 12 years (maximum recapture periods for tagged fish were ~6 years). Despite these findings, it is important to note that mortality, independent of occurring shortly after tagging or following a prolonged period, is a 'long-term' result of tagging; therefore, short-term studies evaluating survival also should be considered in this context (Hanzen et al., 2020; Naughton et al., 2018). Still, there has been a relatively large number of experimental investigations to understand the harmful effects of tag burden (particularly in juvenile salmonids) and while general rules (e.g., the 2% rule in acoustic and radio telemetry) may not be applicable to all circumstances (Jepsen et al., 2005), it is evident that researchers have consistently minimized negative impacts relating to tag characteristics by updating procedures and materials based on best available information (Cooke et al., 2011; Jepsen et al., 2015).

5.3 | Infection risks and healing

Internal insertion and external attachment of electronic tags have the potential to incur infection and cause injury from poor healing at insertion/attachment sites. Intracoelomic surgical implantation can result in incomplete healing and infection, especially without proper aseptic surgical procedures (Cooke et al., 2011; Rub et al., 2014). Affiliated responses to tagging can range from short-term minor irritation to chronic inflammation and infection in the days, weeks, or months following surgery (Wagner, 1999). In some instances, long-term consequences of incomplete healing and infection in tagged animals may include physical malformities, reduced swimming ability, altered behaviour, sustained immune burden, impaired health, and ultimately increased vulnerability to predation or mortality (Boone et al., 2013; Cooke et al., 2011; Semple et al., 2018). Inflammatory reactions around incision and suture insertion points following internal tagging are common, at least in the short-term, as materials for incision closure will likely be recognized as foreign by an animal's immune system (Rouch, 2003; Rub et al., 2014). Rate of suture absorbance and shedding is found to be slower in cool, temperate, or cold-water environments, resulting in the retention of absorbable suture material in fish beyond what might otherwise be expected (Rub et al., 2014). For example, absorbable sutures remained in acoustically tagged walleye (*Sander vitreus*) in the Great Lakes for up to 886 days following tagging even though incision sites were completely closed and healed within 2 months post-release (Schoonyan et al., 2017). While inflammation may be related to an immune response, lack of incision closure, or irritation from sutures, it has often been shown to subside over time as healing progresses (Miller et al., 2014; Thorstad, Økland, et al., 2013). Nevertheless, inflamed tissue can prolong incision closure, presenting an opportunity for bacteria to become trapped in exposed tissue and lead to infection and further complications (Hühn et al., 2014). For example, Caputo et al. (2009) observed wound adhesion and infection affecting long-term behaviour of largemouth bass (*Micropterus nigricans*), attributed to legacy impacts of tagging. Re-opening of incisions post-release may also allow for repeated infection and immune stress that negatively impact behaviour, physiology, and survival unbeknownst to researchers tracking the fish. Infections are probably the most urgent adverse impact of surgery with little known about their frequency, healing rates, or metabolic/physiological costs in the wild (Mulcahy, 2013).

Another long-term impact of internal tagging is the encapsulation of tags, a reaction of the body to encase foreign objects in connective tissue mediated by a chronic inflammatory response (Coleman et al., 1974). Encapsulation appears to be the primary pathway for transmitter expulsion either through the body wall, the gastrointestinal tract, or rupturing the incision area (Marty & Summerfelt, 1986). Overall, there is limited evidence indicating negative impacts of transmitter encapsulation or expulsion and in some cases, it may help restrict damaging movements of transmitters within the peritoneal cavity, in addition to removing a foreign body and initiating healing (Gheorghiu et al., 2010; Lucas, 1989). Intracoelomic transmitter encapsulation and expulsion appear to be common (at least in bony fishes) and may be underestimated in fish tracked in the wild. For example, 53% of artificial implants within channel catfish (*Ictalurus punctatus*) were expelled after only 23 days with 96% of all individuals showing at least some degree of encapsulation (Marty & Summerfelt, 1986). Gheorghiu et al. (2010) also found high rates of tissue encapsulation (100%) in PIT (passive integrated transponder) tags implanted in brown trout after 12 months of monitoring. The migration of transmitters, once encapsulated, near vital organs such as the heart and kidneys does pose some concern (Gheorghiu et al., 2010; Loher & Rensmeyer, 2011). Ultimately, the onset of encapsulation (and expulsion) as a chronic response to tagging may limit long-term studies if expulsion commonly occurs prior to the end of a study or tag battery life.

Overall, electronic tagging of fish may induce issues of infection risk or slow healing rate that can potentially negatively impact the health and survival of tagged animals, and in turn, the quantity and quality of data collected. Nevertheless, fish have high regenerative capability with skin and mucus layers providing innate immunity and protection with healing occurring relatively quickly (e.g., weeks to months; Vergneau-Grosset & Weber III, 2021). Research articles and anecdotal reports reviewed here suggest that such issues are relatively infrequent and standard practices for asepsis (in field or laboratory) can help reduce or prevent secondary infections (Rub et al., 2014).

5.4 | Reliability and interpretation of data

If the tagging of animals causes long-term deleterious effects associated with survival and biological processes such as growth, reproduction, maintenance of homeostasis (i.e., stress response), energy acquisition, and predator avoidance, then the ability to study those processes and interpret drivers of behaviour in wild animals is diminished. Wound healing and fighting infection consume energy and may negatively influence fish behaviour, and thus reliability of data. For example, Daniels et al. (2021) showed that retaining Atlantic salmon smolts for 75 days prior to release increased survival compared to releasing individuals into the wild within 24 hours of tagging. Space use patterns across successive years in relation to time since tagging has also been attributed to tagging effects. Passage rates of twaite shad at weirs in Great Britain were higher in returning migrants as opposed to newly tagged individuals, which was attributed, at least in part, to recent tagging affecting ability or motivation to pass weirs (Davies et al., 2023). Similarly, Wilson et al. (2017) compared movement patterns of walleye at different annual intervals following tagging and found that downstream spawning migration was slower in fish tagged during the same period as opposed to those tagged years earlier, again, suggesting that tagging effects were contributory.

Monitoring fish with electronic tags has a strong track record in answering challenging scientific questions by providing information on key fisheries or demographic parameters such as population and stock discrimination across a wide range of species (Lédée et al., 2021). Compared to conventional tagging, which requires recapture of the same animal to estimate spatial or biological parameters, most electronic tagging provides high recapture probabilities (albeit dependent on transmitter to receiver/satellite efficacy) allowing fishery-related estimates to be made more precisely with a smaller number of individuals (Lees et al., 2021). However, it is important to account for possible biases that arise from the process of handling, tagging, and tracking an animal as a long-term consequence of tagging when generating estimates. An important fishery component for stock assessments is the accurate estimation of natural mortality in populations (Kenchington, 2014). Telemetry has been used to quantify natural mortality of several key fish stocks (Block et al., 2019), but is challenged by disentangling the potential impacts of tagging as a contributor to mortality (Klinard & Matley, 2020). Any deviation in survival, movement, or reproduction between tagged and untagged populations could bias fishery estimates. Furthermore, failure to address tagging-induced mortalities, either short or long term, will likely overestimate natural mortality, as will falsely associating shed tags with a mortality occurrence (Lees et al., 2021). Alternatively, the ability to tag small individuals or species can lead to overestimates of survival associated with predator bias when tags are retained in the guts of predators for extended periods (Klinard et al., 2019). Ultimately, being wary of potential biases from tagging, in addition to following or contributing to accepted protocols for tagging, are the best paths forward to ensure data collected provides reliable information.

5.5 | Ethical responsibilities

Unless tagging studies are directly contributing to the determination of animal care regulations (e.g., testing appropriate tag burden limits), tagging should not unduly affect the behaviour, health, or survival of the study animal (Brown et al., 2011; Thorstad, Rikardsen, et al., 2013). When conducting scientific research with living animals, either in laboratory or field settings, researchers have a duty of care and should follow ethical guidelines. As such, it should fall on researchers to gain suitable knowledge concerning the animal's risk to tagging (e.g., life stage, physiology, predation risk, environmental conditions) so that associated procedures minimize negative effects on its welfare. In our experience, there are increasing concerns from animal care committees and the general public questioning whether animals are impacted by tagging beyond initial study periods. These concerns are especially common in species that are vulnerable to overexploitation or are at risk locally. We see this review as an initial effort to help researchers respond to queries about the long-term effects of tagging and account for such possible impacts when designing and undertaking tracking studies. Great care should be given when deciding sample sizes, study locations, tagging area, the persons conducting the tagging, the method of tagging, and type of tags to be used, and such decisions should be based on multiple levels of input including, in our opinion, recent literature, prior knowledge of primary investigators, transmitter manufacturers, animal care committees, specially trained veterinarians, and relevant knowledge from unbiased stakeholders.

6 | FUTURE DIRECTIONS TO BETTER UNDERSTAND LONG-TERM EFFECTS OF ELECTRONIC TAGGING

Throughout this review, we have highlighted research and collected new anecdotal observations to assess the long-term effects of electronic tagging across various technologies and tag types, and identified the main topics to consider when planning or conducting electronic tagging research. Below, we outline practical steps forward to better address long-term effects of electronic tagging in future research.

6.1 | Consolidation of best practices and historical tagging effects

We recommend that best practices for tagging fishes be consolidated and implemented across the research community to ensure animals are as minimally affected by tagging as possible—something that has been called on by others before (Brown et al., 2011) and transcends the idea of short- versus long-term effects. Not all species and life stages are equally robust in response to tagging. Some are very sensitive to specific aspects of the tagging process resulting in different impacts on recovery and survival across studies. Furthermore, there are multiple steps taken when tagging fishes (e.g., catch method, handling, surgery, anaesthesia, holding period; Clemens et al., 2023), each having potential to cause detrimental effects. For example, inter-individual variation in tagging proficiency among surgeons can lead to different outcomes (Heim et al., 2024). Collaboration, discussion, and training across veterinarians and non-veterinarian researchers are needed in greater capacity to hone skills so that there is less variation in outcomes and potential long-term effects. Similarly, the tagging effects literature, particularly veterinary principles (e.g., handling, aseptic technique, anaesthesia, implantation, and post-operative care), need to be better incorporated by new and established researchers alike. In this context, we recommend Harms and Lewbart (2000), Rub et al. (2014), and Vergneau-Grosset and Weber III (2021) as instrumental readings for any researcher tagging fish. Resources that provide practical advice across the various steps of tagging research (e.g., ethics applications, field methods, animal welfare considerations) should also be consulted (Smith et al., 2022). A dedicated repository of established tagging practices, specific to systems, species, and life stages would be a critical step forward to help evaluate risks associated with long-term animal tracking. A few examples already exist where experience and knowledge have been pooled to improve tagging procedures for specific species (Leroy et al., 2023). Collaborative animal tracking networks (e.g., OTN, IMOS, ETN) are an evident outlet to collate, disseminate, and update best practices for commonly studied species within different geographic regions. We also believe there to be a file drawer effect whereby failures (e.g., poor tagging results or no effect from tagging) are not reported in the literature. We encourage researchers to share both their successes and failures with our community through published case reports.

6.2 | Addressing less-studied tag effects

As discussed throughout this review, there are several topics that have received less attention in tag effects research compared to others (e.g., effects on growth, tag retention, survival), but still pose a concern given the limited information available regarding their impacts. These topics mainly centre around the immune response and associated costs from transmitter implantation (Heath et al., 2023; Semple et al., 2018). Specific areas for further investigation include the prevalence of infections in the wild (from incisions and wound closure), energetic costs to fight infection, extent that transmitter encapsulation and expulsion inhibit other bodily functions, and impact of chronic inflammatory responses. There is an increasing need for better understanding of infections and immune response brought on directly from surgery (primary) and those that later develop as a result of implantation or attachment (secondary), as well as how these contribute to any lack of reliability of tagging data. Testing for differences in infection rates and immune responses between freshwater and saltwater environments, elasmobranchs and bony fishes, and across temperatures and fish sizes, among other variables, is also needed to evaluate tagging risks across studies. Exploring immune responses in greater detail to understand what scenarios lead to disease or mortality is vital for long-term viability of research. Immune responses are not as easily measured as common tag effects metrics, but their implications may be no less important, and may also be more common than presumed.

6.3 | Studies outside closed or controlled environments

Research outside of closed study systems and controlled experimental settings is needed to generate more knowledge of how reliable tracking data is under different scenarios and how long tagging effects are likely to impact behaviour, and thus data interpretation. Cooke et al. (2011) analysed 108 studies solely focused on evaluating the effects of tagging fish for intracoelomic implantation and determined the modal duration to be 1 month, while we identified a median duration of 33 days in experimental trials. Clearly, captive studies could be extended to improve understanding of long-term tagging effects, but they only provide baseline knowledge—they are not representative of wild conditions such as predator–prey interactions, courtship and mating behaviour, habitat use, biofouling, or long-distance migrations. Experimental conditions, where exposure to stressors or biophysical parameters can be controlled, are also not likely representative of the wild in terms of healing; for example, veterinary procedures usually call for fishes to be kept near their upper thermal tolerance following surgery to optimize healing (Vergneau-Grosset & Weber III, 2021)—something that is not reproducible in the wild.

Teasing apart or identifying long-term impacts from tagging (e.g., tag burden, immune responses, physiological stresses) in the wild remains a major challenge. Experimental ponds or mesocosms are probably some of the best facilities for initial efforts focused on long-term tagging effects comparable to the wild. Fish can be exposed to challenge tests (e.g., swim performance, artificial infestation with pathogens, thermal fluctuations, predator introduction) and ponds can be drained at the end of a study and fish can be recovered. In the wild, long-term tagging effects can still be addressed by comparing endpoints of tagged and untagged conspecifics or contrasting comparable studies across distinct temporal periods. Moreover, recapturing tagged fish in the wild can help identify long-term effects because biological measurements associated with growth or body condition, physiology and stress (e.g., blood chemistry), and reproduction (e.g., maturity) can be compared before and after release (Hubbard et al., 2021). Practical ways to enhance capacity for long-term tagging effects research in the wild are, in some ways, simple because much of the groundwork to support such efforts already exists. For example, transmitters used on large fishes commonly have battery lives of up to 10 years and miniaturization is increasingly extending the duration that smaller fish can be monitored. Satellite transmitters, if retained by the animal, will continuously be detected during their battery life as long as they are supported by satellite networks such as ARGOS. Acoustic and radio telemetry are limited by user input since receivers/antennae need to be deployed and maintained locally. Nevertheless, collaborative acoustic tracking networks offer a vital way to conduct long-term tracking research by providing centralized storage and access to data across user projects (e.g., obtaining detections on receivers within and outside an investigator's own deployments), as well as supporting receiver deployments in critical ecological areas, and providing equipment loan/sharing opportunities to researchers. Several instances of collaborations to advance electronic tracking capacity have been shown at regional (Matley et al., 2020), continental (Huveneers et al., 2021) and global (Queiroz et al., 2019) scales, and demonstrate how pooling resources (e.g., transmitter and receiver data) can reveal novel findings.

7 | CONCLUSION

It is always important to consider logistical, ethical, and practical viewpoints when evaluating methods used in research. There are many possible effects of tagging on fish, most of which have the potential to contribute to long-term changes in behaviour, health, and survival. It is evident that more research is needed to investigate long-term concerns of tagged fish in the wild. Nevertheless, existing research and anecdotal findings, in large, indicate that the implantation or attachment of electronic tracking devices do not unduly affect a fish's behaviour, physiology, biology, or survival, particularly when study-specific considerations about the tagging process (e.g., tag size, species, anaesthesia, recovery) are taken. Outlined above is a synopsis of current knowledge regarding the long-term effects of electronic tagging on fishes, as well as suggested areas to focus future research. Future advancements will require ongoing research commitment aimed at greater longevity in research monitoring, infrastructure, and collaboration, as well as study objectives.

ACKNOWLEDGEMENTS

We kindly thank all individuals that provided anecdotal information (and photos) pertaining to Figure 3, Table S2, and associated text, including O. Slavik, C. Ratschan, R. Verspui, B. Wolfe, A. Barnett, U. Krumme, J. Gardiner, R. O'Neill, A. Gooden, K. Aarestrup, T. Henke, K. Papadopoulo, L. Couturier, D. Abecasis, S. Larocque, R. Smith, J. Bergman, P. Verhelst, A. Fox, R. Fitzpatrick, B. Block, S. Hont, J. Rees-Jones, J. Christian Svendsen, G. Mucientes, J. Davidsen, J. Dainys, M.

Smederevac-Lalic, J. van Eerbeek, B. Koeck, B. Hereu, J. Bourjea, K. Adams, L. Currey-Randall, B. Heath, and K. Birnie-Gauvin, as well members of the Integrated Marine Observing System (IMOS) Animal Tracking Facility and TrackdAT. Open access publishing facilitated by Flinders University, as part of the Wiley - Flinders University agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data used in this study to quantify tagging effects can be accessed from 'tagging effects' articles listed at www.trackdat.org.

ORCID

Jordan K. Matley https://orcid.org/0000-0003-4286-597X

REFERENCES

Abecasis, D., Steckenreuter, A., Reubens, J., Aarestrup, K., Alós, J., Badalamenti, F., Bajona, L., Boylan, P., Deneudt, K., Greenberg, L., & Brevé, N. (2018). A review of acoustic telemetry in Europe and the need for a regional aquatic telemetry network. *Animal Biotelemetry*, *6*, 1–7.

Arnold, G. P., & Holford, B. H. (1978). The physical effects of an acoustic tag on the swimming performance of plaice and cod. *ICES Journal of Marine Science*, *38*(2), 189–200.

Bass, A. L., Stevenson, C. F., Porter, A. D., Rechisky, E. L., Furey, N. B., Healy, S. J., Kanigan, A. M., Lotto, A. G., Welch, D. W., & Hinch, S. G. (2020). In situ experimental evaluation of tag burden and gill biopsy reveals survival impacts on migrating juvenile sockeye salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, *77*(12), 1865–1869.

Beeman, J. W., Hansen, A. C., & Sprando, J. M. (2015). Observational data on the effects of infection by the copepod *Salmincola californiensis* on the short-and long-term viability of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) implanted with telemetry tags. *Animal Biotelemetry*, *3*, 1–7.

Berejikian, B. A., Brown, R. S., Tatara, C. P., & Cooke, S. J. (2007). Effects of telemetry transmitter placement on egg retention in naturally spawning, captively reared steelhead. *North American Journal of Fisheries Management*, *27*(2), 659–664.

Block, B. A., Whitlock, R., Schallert, R. J., Wilson, S., Stokesbury, M. J., Castleton, M., & Boustany, A. (2019). Estimating natural mortality of Atlantic bluefin tuna using acoustic telemetry. *Scientific Reports*, *9*(1), 4918.

Bodine, K. A., & Fleming, B. P. (2013). Evaluation of an alternative technique for attaching external transmitters to blue catfish. *North American Journal of Fisheries Management*, *33*(5), 950–955.

Boone, S. S., Divers, S. J., Camus, A. C., Peterson, D. L., Jennings, C. A., Shelton, J. L., & Hernandez, S. M. (2013). Pathologic and physiologic effects associated with long-term intracoelomic transmitters in captive Siberian sturgeon. *North American Journal of Fisheries Management*, *33*(5), 869–877.

Bridger, C. J., & Booth, R. K. (2003). The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. *Reviews in Fisheries Science*, *11*(1), 13–34.

Brooks, J. L., Chapman, J. M., Barkley, A. N., Kessel, S. T., Hussey, N. E., Hinch, S. G., Patterson, D. A., Hedges, K. J., Cooke, S. J., Fisk, A. T., & Gruber, S. H. (2019). Biotelemetry informing management: Case studies exploring successful integration of biotelemetry data into fisheries and habitat management. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(7), 1238–1252.

Brown, R. S., Eppard, M. B., Murchie, K. J., Nielsen, J. L., & Cooke, S. J. (2011). An introduction to the practical and ethical perspectives on the need to advance and standardize the intracoelomic surgical implantation of electronic tags in fish. *Reviews in Fish Biology and Fisheries*, *21*, 1–9.

Caputo, M., O'Connor, C. M., Hasler, C. T., Hanson, K. C., & Cooke, S. J. (2009). Long-term effects of surgically implanted telemetry tags on the nutritional physiology and condition of wild freshwater fish. *Diseases of Aquatic Organisms*, *84*(1), 35–41.

Childs, A. R., Næsje, T. F., & Cowley, P. D. (2011). Long-term effects of different-sized surgically implanted acoustic transmitters on the sciaenid *Arygyrosomus japonicus*: Breaking the 2% tag-to-body mass rule. *Marine and Freshwater Research*, *62*(5), 432–438.

Clemens, B. J., Matley, J. K., Klinard, N. V., Lennox, R. J., Sortland, L. K., & Cooke, S. J. (2023). The need for reporting rationale and detailed methods in studies that surgically implant fish with electronic tracking devices. *Fisheries*, *48*(9), 388–394.

Coleman, D. L., King, R. N., & Andrade, J. D. (1974). The foreign body reaction: A chronic inflammatory response. *Journal of Biomedical Materials Research*, *8*(5), 199–211.

Collins, A. L., Hinch, S. G., Welch, D. W., Cooke, S. J., & Clark, T. D. (2013). Intracoelomic acoustic tagging of juvenile sockeye salmon: Swimming performance, survival, and postsurgical wound healing in freshwater and during a transition to seawater. *Transactions of the American Fisheries Society*, *142*(2), 515–523.

Cooke, S. J., Midwood, J. D., Thiem, J. D., Klimley, P., Lucas, M. C., Thorstad, E. B., Eiler, J., Holbrook, C., & Ebner, B. C. (2013). Tracking animals in freshwater with electronic tags: Past, present and future. *Animal Biotelemetry*, *1*, 1–9.

Cooke, S. J., Woodley, C. M., Brad Eppard, M., Brown, R. S., & Nielsen, J. L. (2011). Advancing the surgical implantation of electronic tags in fish: A gap analysis and research agenda based on a review of trends in intracoelomic tagging effects studies. *Reviews in Fish Biology and Fisheries*, *21*, 127–151.

Daniel, A. J., Hicks, B. J., Ling, N., & David, B. O. (2009). Acoustic and radio-transmitter retention in common carp (*Cyprinus carpio*) in New Zealand. *Marine and Freshwater Research*, *60*(4), 328–333.

Daniels, J., Brunsdon, E. B., Chaput, G., Dixon, H. J., Labadie, H., & Carr, J. W. (2021). Quantifying the effects of post-surgery recovery time on the migration dynamics and survival rates in the wild of acoustically tagged Atlantic Salmon *Salmo salar* smolts. *Animal Biotelemetry*, *9*, 1–4.

Davies, P., Britton, J. R., Castro-Santos, T., Crundwell, C., Dodd, J. R., Nunn, A. D., Velterop, R., & Bolland, J. D. (2023). Tracking anadromous fish over successive freshwater migrations reveals the influence of tagging effect, previous success, and abiotic factors on upstream passage over barriers. *Canadian Journal of Fisheries and Aquatic Sciences*, *80*(7), 1110–1125.

DeGrazia, D., & Beauchamp, T. L. (2019). Beyond the 3 Rs to a more comprehensive framework of principles for animal research ethics. *ILAR Journal*, *60*(3), 308–317.

Espinoza, M., Farrugia, T. J., Webber, D. M., Smith, F., & Lowe, C. G. (2011). Testing a new acoustic telemetry technique to quantify long-term, fine-scale movements of aquatic animals. *Fisheries Research*, *108*(2–3), 364–371.

Fabrizio, M. C., & Pessutti, J. P. (2007). Long-term effects and recovery from surgical implantation of dummy transmitters in two marine fishes. *Journal of Experimental Marine Biology and Ecology*, *351*(1–2), 243–254.

Gardner, C. J., Deeming, D. C., Wellby, I., Soulsbury, C. D., & Eady, P. E. (2015). Effects of surgically implanted tags and translocation on the movements of common bream *Abramis brama* (L.). *Fisheries Research*, *167*, 252–259.

Gheorghiu, C., Hanna, J., Smith, J. W., Smith, D. S., & Wilkie, M. P. (2010). Encapsulation and migration of PIT tags implanted in brown trout (*Salmo trutta* L.). *Aquaculture*, *298*(3–4), 350–353.

Gobin, J., Duncan, A. T., & Lauzon, R. (2023). Saugeen Ojibway nation community input and action: Initiating a two-eyed seeing approach for dikameg (*Coregonus clupeaformis*) in Lake Huron. *Journal of Great Lakes Research*, *49*, S160–S171.

Hanzen, C., Lucas, M. C., O'Brien, G., Calverley, P., & Downs, C. T. (2020). Surgical implantation of radio tags in three eel species (*Anguilla* spp.) in South Africa. *Journal of Fish Biology*, *96*(3), 847–852.

Harcourt, R., Sequeira, A. M., Zhang, X., Roquet, F., Komatsu, K., Heupel, M., McMahon, C., Whoriskey, F., Meekan, M., Carroll, G., & Brodie, S. (2019). Animal-borne telemetry: An integral component of the ocean observing toolkit. *Frontiers in Marine Science*, *6*, 326.

Harms, C. A., & Lewbart, G. A. (2000). Surgery in fish. *Veterinary Clinics: Exotic Animal Practice*, *3*(3), 759–774.

Haulsee, D. E., Fox, D. A., Breece, M. W., Clauss, T. M., & Oliver, M. J. (2016). Implantation and recovery of long-term archival transceivers in a migratory shark with high site fidelity. *PLoS One*, *11*(2), e0148617.

Hays, G. C., Bailey, H., Bograd, S. J., Bowen, W. D., Campagna, C., Carmichael, R. H., Casale, P., Chiaradia, A., Costa, D. P., Cuevas, E., & de Bruyn, P. N. (2019). Translating marine animal tracking data into conservation policy and management. *Trends in Ecology & Evolution*, *34*(5), 459–473.

Heath, G., Semple, S. L., Rodríguez-Ramos, T., Hardy, S., Harrison, P., Mulder, I. M., Power, M., & Dixon, B. (2023). Surface material of acoustic transmitters influences the inflammatory response of rainbow trout (*Oncorhynchus mykiss*) during long-term implantation. *Veterinary Immunology and Immunopathology*, *264*, 110660.

Hedger, R. D., Rikardsen, A. H., & Thorstad, E. B. (2017). Pop-up satellite archival tag effects on the diving behaviour, growth and survival of adult Atlantic salmon *Salmo salar* at sea. *Journal of Fish Biology*, *90*(1), 294–310.

Heim, K. C., Withers, J., & Castro-Santos, T. (2024). Tagger effects in aquatic telemetry: Short-term and delayed impacts of surgery in Atlantic salmon smolts. *North American Journal of Fisheries Management*, *44*, 262–275.

Heim, V., Grubbs, R. D., Smukall, M. J., Frazier, B. S., Carlson, J. K., & Guttridge, T. L. (2023). Observations of fin injury closure in great hammerheads and implications for the use of fin-mounted geolocators. *Journal of Aquatic Animal Health*, *35*(2), 53–63.

Hoenner, X., Huveneers, C., Steckenreuter, A., Simpfendorfer, C., Tattersall, K., Jaine, F., Atkins, N., Babcock, R., Brodie, S., Burgess, J., & Campbell, H. (2018). Australia's continental-scale acoustic tracking database and its automated quality control process. *Scientific Data*, *5*(1), 170206.

Hubbard, J. A., Hickie, B. E., Bowman, J., Hrenchuk, L. E., Blanchfield, P. J., & Rennie, M. D. (2021). No long-term effect of intracoelomic acoustic transmitter implantation on survival, growth, and body condition of a long-lived stenotherm in the wild. *Canadian Journal of Fisheries and Aquatic Sciences*, *78*(2), 173–183.

Hühn, D., Klefoth, T., Pagel, T., Zajicek, P., & Arlinghaus, R. (2014). Impacts of external and surgery-based tagging techniques on small northern pike under field conditions. *North American Journal of Fisheries Management*, *34*(2), 322–334.

Huveneers, C., Niella, Y., Drew, M., McAuley, R., Butcher, P., Peddemors, V., Waltrick, D., Dowling, C., Mountford, S., Keay, I., & Braccini, M. (2021). Continental-scale network reveals cross-jurisdictional movements of sympatric sharks with implications for assessment and management. *Frontiers in Marine Science*, *8*, 697175.

Hvas, M., Folkedal, O., & Oppedal, F. (2020). Heart rate bio-loggers as welfare indicators in Atlantic salmon (*Salmo salar*) aquaculture. *Aquaculture*, *529*, 735630.

Jepsen, N., Schreck, C., Clements, S., & Thorstad, E. B. (2005). A brief discussion on the 2% tag/bodymass rule of thumb. *Aquatic telemetry: Advances and applications* (pp. 255–259).

Jepsen, N., Thorstad, E. B., Havn, T., & Lucas, M. C. (2015). The use of external electronic tags on fish: An evaluation of tag retention and tagging effects. *Animal Biotelemetry*, *3*, 1–23.

Jewell, O. J., Wcisel, M. A., Gennari, E., Towner, A. V., Bester, M. N., Johnson, R. L., & Singh, S. (2011). Effects of smart position only (SPOT) tag deployment on white sharks *Carcharodon carcharias* in South Africa. *PLoS One*, *6*(11), e27242.

Kelican, A. N., Huysman, N., Van Rysselberge, L. A., Voorhees, J. M., & Barnes, M. E. (2021). Assessment of a novel surgical technique for acoustic transmitter insertion. *Open Journal of Veterinary Medicine*, *11*(7), 247–257.

Kenchington, T. J. (2014). Natural mortality estimators for information-limited fisheries. *Fish and Fisheries*, *15*(4), 533–562.

Kerstetter, D. W., Polovina, J., & Graves, J. E. (2004). Evidence of shark predation and scavenging on fishes equipped with pop-up satellite archival tags. *Fishery Bulletin*, *102*(4), 750.

King, S. M., & Stein, J. A. (2020). Effective anesthetic dosage and recovery from specialized surgical methods in shortnose gar. *North American Journal of Fisheries Management*, *40*(6), 1486–1498.

Klinard, N. V., & Matley, J. K. (2020). Living until proven dead: Addressing mortality in acoustic telemetry research. *Reviews in Fish Biology and Fisheries*, *30*(3), 485–499.

Klinard, N. V., Matley, J. K., Fisk, A. T., & Johnson, T. B. (2019). Long-term retention of acoustic telemetry transmitters in temperate predators revealed by predation tags implanted in wild prey fish. *Journal of Fish Biology*, *95*(6), 1512–1516.

Koed, A., & Thorstad, E. B. (2001). Long-term effect of radio-tagging on the swimming performance of pikeperch. *Journal of Fish Biology*, *58*(6), 1753–1756.

Lawrence, M. J., Wilson, B. M., Reid, G. K., Hawthorn, C., English, G., Black, M., Leadbeater, S., McKindsey, C. W., & Trudel, M. (2023). The fate of intracoelomic acoustic transmitters in Atlantic salmon (*Salmo salar*) post-smolts and wider considerations for causal factors driving tag retention and mortality in fishes. *Animal Biotelemetry*, *11*(1), 40.

Lear, K. O., Gleiss, A. C., & Whitney, N. M. (2018). Metabolic rates and the energetic cost of external tag attachment in juvenile blacktip sharks *Carcharhinus limbatus*. *Journal of Fish Biology*, *93*(2), 391–395.

Lédée, E. J., Heupel, M. R., Taylor, M. D., Harcourt, R. G., Jaine, F. R., Huveneers, C., Udyawer, V., Campbell, H. A., Babcock, R. C., Hoenner, X., & Barnett, A. (2021). Continental-scale acoustic telemetry and network analysis reveal new insights into stock structure. *Fish and Fisheries*, *22*(5), 987–1005.

Lee, M. A., Nguyen, F. T., Scott, K., Chan, N. Y., Bakh, N. A., Jones, K. K., Pham, C., Garcia-Salinas, P., Garcia-Parraga, D., Fahlman, A., & Marco, V. (2019). Implanted nanosensors in marine organisms for physiological biologging: Design, feasibility, and species variability. *ACS Sensors*, *4*(1), 32–43.

Lees, K. J., MacNeil, M. A., Hedges, K. J., & Hussey, N. E. (2021). Estimating demographic parameters for fisheries management using acoustic telemetry. *Reviews in Fish Biology and Fisheries*, *31*(1), 25–51.

Lennox, R. J., Aarestrup, K., Cooke, S. J., Cowley, P. D., Deng, Z. D., Fisk, A. T., Harcourt, R. G., Heupel, M., Hinch, S. G., Holland, K. N., & Hussey, N. E. (2017). Envisioning the future of aquatic animal tracking: Technology, science, and application. *Bioscience*, *67*(10), 884–896.

Leroy, B., Scutt Phillips, J., Potts, J., Brill, R. W., Evans, K., Forget, F., Holland, K., Itano, D., Muir, J., Pilling, G., & Nicol, S. (2023). Recommendations towards the establishment of best practice standards for handling and intracoelomic implantation of data-storage and telemetry tags in tropical tunas. *Animal Biotelemetry*, *11*(1), 4.

Loher, T., & Rensmeyer, R. (2011). Physiological responses of Pacific halibut, *Hippoglossus stenolepis*, to intracoelomic implantation of electronic archival tags, with a review of tag implantation techniques employed in flatfishes. *Reviews in Fish Biology and Fisheries*, *21*, 97–115.

Lucas, M. C. (1989). Effects of implanted dummy transmitters on mortality, growth and tissue reaction in rainbow trout, *Salmo gairdneri* Richardson. *Journal of Fish Biology*, *35*(4), 577–587.

Macaulay, G., Wright, D., Oppedal, F., & Dempster, T. (2020). Buoyancy matters: Establishing the maximum neutral buoyancy depth of Atlantic salmon. *Aquaculture*, *519*, 734925.

Martins, A. P. B., Heupel, M. R., Oakley-Cogan, A., Chin, A., & Simpfendorfer, C. A. (2019). Towed-float GPS telemetry: A tool to assess movement patterns and habitat use of juvenile stingrays. *Marine and Freshwater Research*, *71*(1), 89–98.

Marty, G. D., & Summerfelt, R. C. (1986). Pathways and mechanisms for expulsion of surgically implanted dummy transmitters from channel catfish. *Transactions of the American Fisheries Society*, *115*(4), 577–589.

Matley, J. K., Faust, M. D., Raby, G. D., Zhao, Y., Robinson, J., MacDougall, T., Hayden, T. A., Fisk, A. T., Vandergoot, C. S., & Krueger, C. C. (2020). Seasonal habitat-use differences among Lake Erie's walleye stocks. *Journal of Great Lakes Research*, *46*(3), 609–621.

Matley, J. K., Klinard, N. V., Larocque, S. M., McLean, M. F., Brownscombe, J. W., Raby, G. D., Nguyen, V. M., & Barbosa Martins, A. P. (2023). Making the most of aquatic animal tracking: A review of complementary methods to bolster acoustic telemetry. *Reviews in Fish Biology and Fisheries*, *33*(1), 35–54.

Matley, J. K., Klinard, N. V., Martins, A. B., Oakley-Cogan, A., Huveneers, C., Vandergoot, C. S., & Fisk, A. T. (2024). TrackdAT, an acoustic telemetry metadata dataset to support aquatic animal tracking research. *Scientific Data*, *11*(1), 143.

Matley, J. K., Klinard, N. V., Martins, A. P., Aarestrup, K., Aspillaga, E., Cooke, S. J., Cowley, P. D., Heupel, M. R., Lowe, C. G., Lowerre-Barbieri, S. K., & Mitamura, H. (2022). Global trends in aquatic animal tracking with acoustic telemetry. *Trends in Ecology & Evolution*, *37*(1), 79–94.

McKenna, J. E., Jr., Sethi, S. A., Scholten, G. M., Kraus, J., & Chalupnicki, M. (2021). Acoustic tag retention and tagging mortality of juvenile cisco *Coregonus artedi*. *Journal of Great Lakes Research*, *47*(3), 937–942.

Miller, E. A., Froehlich, H. E., Cocherell, D. E., Thomas, M. J., Cech, J. J., Klimley, A. P., & Fangue, N. A. (2014). Effects of acoustic tagging on juvenile green sturgeon incision healing, swimming performance, and growth. *Environmental Biology of Fishes*, *97*, 647–658.

Mulcahy, D. M. (2013). Legal, ethical, and procedural bases for the use of aseptic techniques to implant electronic devices. *Journal of Fish and Wildlife Management*, *4*(1), 211–219.

Naisbett-Jones, L. C., Branham, C., Birath, S., Paliotti, S., McMains, A. R., Joel Fodrie, F., Morley, J. W., Buckel, J. A., & Lohmann, K. J. (2023). A method for long-term retention of pop-up satellite archival tags (PSATs) on small migratory fishes. *Journal of Fish Biology*, *102*(5), 1029–1039.

Nasby-Lucas, N., & Domeier, M. L. (2020). Impact of satellite linked radio transmitting (SLRT) tags on the dorsal fin of subadult and adult white sharks (*Carcharodon carcharias*). *Bulletin of Marine Science*, *96*(1), 23–30.

Naughton, G. P., Keefer, M. L., Clabough, T. S., Knoff, M. J., Blubaugh, T. J., & Caudill, C. C. (2018). Tag effects on prespawn mortality of chinook salmon: A field experiment using passive integrated transponder tags, radio transmitters, and untagged controls. *North American Journal of Fisheries Management*, *38*(1), 96–103.

Nguyen, V. M., Young, N., Brownscombe, J. W., & Cooke, S. J. (2019). Collaboration and engagement produce more actionable science: Quantitatively analyzing uptake of fish tracking studies. *Ecological Applications*, *29*(6), e01943.

Niella, Y., Simes, B., Fox, A., Wright, A., Waller, M., Riley, M., Meyer, L., Drew, M., Pederson, H., & Huveneers, C. (2022). Short-term response of research activities on white shark behaviour. *Wildlife Research*, *50*(4), 260–271.

O'Connor, J. P., Koehn, J. D., Nicol, S. J., O'Mahony, D. J., & McKenzie, J. A. (2009). Retention of radio tags in golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*) and carp (*Cyprinus carpio*). *Marine and Freshwater Research*, *60*, 334–340.

Papadopoulo, K., Villegas-Ríos, D., Mucientes, G., Hillinger, A., & Alonso-Fernández, A. (2023). Drivers of behaviour and spatial ecology of the small spotted catshark (*Scyliorhinus canicula*). *Aquatic Conservation: Marine and Freshwater Ecosystems*, *33*(5), 443–457.

Perry, R. W., Adams, N. S., & Rondorf, D. W. (2001). Buoyancy compensation of juvenile Chinook salmon implanted with two different size dummy transmitters. *Transactions of the American Fisheries Society*, *130*(1), 46–52.

Perry, R. W., Plumb, J. M., Fielding, S. D., Adams, N. S., & Rondorf, D. W. (2013). Comparing effects of transmitters within and among populations: Application to swimming performance of juvenile Chinook salmon. *Transactions of the American Fisheries Society*, *142*(4), 901–911.

Queiroz, N., Humphries, N. E., Couto, A., Vedor, M., Da Costa, I., Sequeira, A. M., Mucientes, G., Santos, A. M., Abascal, F. J., Abercrombie, D. L., & Abrantes, K. (2019). Global spatial risk assessment of sharks under the footprint of fisheries. *Nature*, *572*(7770), 461–466.

Renshaw, S., Hammerschlag, N., Gallagher, A. J., Lubitz, N., & Sims, D. W. (2023). Global tracking of shark movements, behaviour and ecology: A review of the renaissance years of satellite tagging studies, 2010–2020. *Journal of Experimental Marine Biology and Ecology*, *560*, 151841.

Righton, D., Kjesbu, O. S., & Metcalfe, J. (2006). A field and experimental evaluation of the effect of data storage tags on the growth of cod. *Journal of Fish Biology*, *68*, 385–400.

Rouch, J. K. (2003). Biomaterials and surgical implants. In D. H. Slatter (Ed.), *Textbook of small animal surgery* (pp. 141–148). Elsevier Health Sciences.

Rub, A. M., Jepsen, N., Liedtke, T. L., Moser, M. L., & Weber, E. S. (2014). Surgical insertion of transmitters and telemetry methods in fisheries research. *American Journal of Veterinary Research*, *75*(4), 402–416.

Schoonyan, A., Kraus, R. T., Faust, M. D., Vandergoot, C. S., Cooke, S. J., Cook, H. A., Hayden, T. A., & Krueger, C. C. (2017). Estimating incision healing rate for surgically implanted acoustic transmitters from recaptured fish. *Animal Biotelemetry*, *5*, 1–8.

Semple, S. L., Mulder, I. M., Rodriguez-Ramos, T., Power, M., & Dixon, B. (2018). Long-term implantation of acoustic transmitters induces chronic inflammatory cytokine expression in adult rainbow trout (*Oncorhynchus mykiss*). *Veterinary Immunology and Immunopathology*, *205*, 1–9.

Smith, B. P., Waudby, H. P., Alberthsen, C., & Hampton, J. O. (2022). *Wildlife research in Australia: Practical and applied methods*. CSIRO Publishing.

Smukall, M. J., Kessel, S. T., Franks, B. R., Feldheim, K. A., Guttridge, T. L., & Gruber, S. H. (2019). No apparent negative tagging effects after 13 years at liberty for lemon shark, *Negaprion brevirostris* implanted with acoustic transmitter. *Journal of Fish Biology*, *94*(1), 173–177.

Spanos, M. C., Cunningham, C. J., Drew, K. A., & Sutton, T. M. (2023). Evaluating the viability of the use of T-bar and radiotelemetry tags on prespawn Arctic lampreys. *North American Journal of Fisheries Management*, *43*(6), 1631–1647.

Stansbury, A. L., Götz, T., Deecke, V. B., & Janik, V. M. (2015). Grey seals use anthropogenic signals from acoustic tags to locate fish: Evidence from a simulated foraging task. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1798), 20141595.

Taylor, M. D., Babcock, R. C., Simpfendorfer, C. A., & Crook, D. A. (2017). Where technology meets ecology: Acoustic telemetry

in contemporary Australian aquatic research and management. *Marine and Freshwater Research*, *68*(8), 1397–1402.
Thorstad, E. B., Kerwath, S. E., Attwood, C. G., Økland, F., Wilke, C. G., Cowley, P. D., & Næsje, T. F. (2009). Long-term effects of two sizes of surgically implanted acoustic transmitters on a predatory marine fish (*Pomatomus saltatrix*). *Marine and Freshwater Research*, *60*(2), 183–186.
Thorstad, E. B., Økland, F., Westerberg, H., Aarestrup, K., & Metcalfe, J. D. (2013). Evaluation of surgical implantation of electronic tags in European eel and effects of different suture materials. *Marine and Freshwater Research*, *64*(4), 324–331.
Thorstad, E. B., Rikardsen, A. H., Alp, A., & Økland, F. (2013). The use of electronic tags in fish research–an overview of fish telemetry methods. *Turkish Journal of Fisheries and Aquatic Sciences*, *13*(5), 881–896.
Udyawer, V., Huveneers, C., Jaine, F., Babcock, R. C., Brodie, S., Buscot, M. J., Campbell, H. A., Harcourt, R. G., Hoenner, X., Lédée, E. J., & Simpfendorfer, C. A. (2023). Scaling of activity space in marine organisms across latitudinal gradients. *The American Naturalist*, *201*(4), 586–602.
Vergneau-Grosset, C., & Weber, E. S., III. (2021). Fish surgery. In R. Avery Bennett, & Geoffrey W. Pye (Eds.), *Surgery of exotic animals* (Vol. *24*, pp. 46–62).
Vollset, K. W., Lennox, R. J., Thorstad, E. B., Auer, S., Bär, K., Larsen, M. H., Mahlum, S., Näslund, J., Stryhn, H., & Dohoo, I. (2020). Systematic review and meta-analysis of PIT tagging effects on mortality and growth of juvenile salmonids. *Reviews in Fish Biology and Fisheries*, *30*, 553–568.
Wagner, G. N. (1999). Investigation of effective fish surgery techniques. MSc. Thesis. Zoology Department, University of Guelph, Ontario, Canada.
Wilson, A. D., Hayden, T. A., Vandergoot, C. S., Kraus, R. T., Dettmers, J. M., Cooke, S. J., & Krueger, C. C. (2017). Do intracoelomic telemetry transmitters alter the post-release behaviour of migratory fish? *Ecology of Freshwater Fish*, *26*(2), 292–300.
Winter, E. R., Hindes, A. M., Lane, S., & Britton, J. R. (2020). Predicting the factors influencing the inter-and intraspecific survival rates of riverine fishes implanted with acoustic transmitters. *Journal of Fish Biology*, *97*(4), 1209–1219.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Matley, J. K., Klinard, N. V., Jaine, F. R. A., Lennox, R. J., Koopman, N., Reubens, J. T., Harcourt, R. G., Cooke, S. J., & Huveneers, C. (2024). Long-term effects of tagging fishes with electronic tracking devices. *Fish and Fisheries*, *25*, 1009–1025. https://doi.org/10.1111/faf.12861