

REVIEW

Tracking aquatic animals for fisheries management in European waters

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Abstract

Acoustic telemetry (AT) has emerged as a valuable tool for monitoring aquatic animals in both European inland and marine waters over the past two decades. The European Tracking Network (ETN) initiative has played a pivotal role in promoting collaboration among AT researchers in Europe and has led to a significant increase in the number of tagged and observed aquatic animals in transboundary European waters. While AT benefits decision-making and delivers essential data to management bodies, its potential for management decision-making mechanisms has yet to be fully harnessed. We reviewed existing research, studies, and organisational initiatives related to aquatic animal tracking and their utility in fisheries management in European waters. We found that AT has already contributed to many aspects of fisheries management, such as improved understanding of stock dynamics, identification of critical habitats, assessment of migration routes, and evaluation of the effectiveness of conservation

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measures. However, broader utilisation of tracking technologies is needed. By leveraging the full potential of AT, managers can make more informed decisions to protect, restore, and sustainably manage European waters and creatures that live therein.

KEYWORDS

acoustic telemetry, Europe, fisheries management, marine connectivity, marine spatial planning, migration

1 | INTRODUCTION

Aquatic ecosystems around the globe are threatened by many anthropogenic impacts, such as habitat degradation, pollution, warming, and overfishing, which includes bycatch of non-target species, some of which are threatened (Díaz et al., 2019; McCauley et al., 2015). Management strategies need to be identified that can reconcile conservation goals with maintaining or increasing fisheries yields for a growing human population (Gaines et al., 2010; Jupiter et al., 2017). Monitoring the status of resources and generating data for modelling population trajectories informs decision-making about regulating the exploitation of aquatic resources, including space, water (e.g. for energy production and carbon storage), or living resources in lakes, rivers, and oceans (Costa-Pereira et al., 2022; Hussey et al., 2015; Lennox et al., 2019; Vivian et al., 2017).

Biotelemetry is one technology that can provide valuable information to researchers and managers to track individuals for days, months, or years within a coverage area (Crossin et al., 2017). Biotelemetry is increasingly used to investigate diverse questions regarding the biology and ecology of fish, sharks, reptiles, invertebrates, and marine mammals (Florko et al., 2021; Hussey et al., 2015; Matley et al., 2022; McIntyre, 2014), but is underused to inform fisheries management (Crossin et al., 2017). Quantifying and describing animal movements and space use at various scales appears key to understanding the fundamental ecology of any aquatic organism, but is also essential for effective fisheries policy and conservation action (Cooke et al., 2016, 2022; Crossin et al., 2017). Acoustic telemetry is one of the most common types of biotelemetry to obtain these data (Lennox et al., 2023).

Acoustic telemetry is a widely used aquatic tracking method, in which signals transmitted from implanted or externally attached acoustic transmitters are detected and logged by nearby acoustic receivers. Continued advances and miniaturisation of transmitters have allowed researchers to quantify previously unobserved processes that are important for population dynamics, reproductive performance, and fitness for a wide range of taxa (Arnold & Dewar, 2001; Crossin et al., 2017; Lennox et al., 2023; Lucas & Baras, 2000). Introduced to European waters in the 1970s, telemetry is now widely used throughout Europe and neighbouring countries to monitor aquatic living resources and support research efforts to deliver essential data and insights to local, regional, national, and international management bodies (Abecasis et al., 2018; Alós et al., 2022; Young et al., 1972).

Fisheries management is an integrated process that includes determination of objectives, often in consultation with stakeholders or following legal mandates, information gathering, analysis, planning, consultation, decision-making, and allocation of resources, alongside the formulation, implementation, and enforcement of regulations and other rules that govern fisheries activities to ensure continued productivity of resources and accomplishment of other objectives (FAO, 1997). Any deficiency or weakness in one of these mutually reinforcing steps (e.g. information gathering) can adversely affect success of fisheries management. The European Union's Common Fisheries Policy (CFP) is the legal framework for management of marine European water. In inland waters, national and regional policies apply, but issues of fisheries management are generic. The CFP seeks to protect fish stocks and contribute to economically viable and competitive fisheries and aquaculture industries. In inland fisheries, and also some coastal sites, objectives of recreational fisheries are also important (Arlinghaus et al., 2019) as a broader conservation objective that are often derived from fisheries and nature conservation policies. In marine waters, with a focus on commercial fisheries, the European Union (EU) acts against the objective of meeting maximum sustainable yield (MSY) as part of the 2013 reform of the CFP. Against this objective and in light of historical overfishing, contemporary fisheries management in marine waters aims to regulate fishing mortality on a given stock to ideally produce MSY (O'Farrell & Botsford, 2006; Punt et al., 2014). Objectives for inland waters can differ from MSY-based objectives, especially if recreational fisheries are predominant and whose optimal experience is typically achieved at fishing mortality levels below MSY (Johnston et al., 2015). Besides a focus on fisheries, conservation objectives are also common in marine and fresh waters, sometimes conflicting and creating trade-offs with fisheries goals (Cowx et al., 2010).

To inform fisheries management, individual-level data provided by biotelemetry are useful information sources that can help to estimate difficult-to-estimate variables, such as population-level catchability, natural mortality, bycatch, catch-and-release mortality, or critical spawning habitats (Alós et al., 2022; Benaka et al., 2014; Donaldson et al., 2011; Lees et al., 2021). In most fisheries, the key spatial parameter is the stock unit, defined as all fish in an area that are part of the same reproductive process, with no immigration or emigration to or from the stock. In marine systems, data clearly delineating stock boundaries are often unavailable, and stock divisions are commonly assigned based on management convenience rather than relying on ecological data (Smedbol & Stephenson, 2001;

Stephenson, 1999). Such knowledge gaps, and challenges that impede effective fisheries management, can be partly overcome by using telemetry to quantify movement, migration timing, habitat use, and interactions among species and fishing gear. Thus, acoustic telemetry can be a relevant tool for scientists and managers to generate knowledge needed for decision-making. The present review builds on Crossin et al. (2017) to shed light on the key role of acoustic telemetry in research and management of European aquatic ecosystems. We non-exhaustively reviewed existing research, studies, and organisational initiatives related to aquatic animal tracking and discussed their utility in fisheries management in European waters.

2 | THE EUROPEAN CONTEXT

Acoustic telemetry is widely used in European lakes, rivers, fjords, and coastal areas of Atlantic and Arctic Oceans (Figure 1). Fewer studies have been in Mediterranean and central European rivers and lakes, although these areas contain some of the largest European ecosystems, such as the Danube and Rhine, and some of the most prominent lakes, such as Lake Balaton and Lake Constance (Abecasis et al., 2018). Most species studied are commercially or recreationally important fishes, such as Atlantic salmon (*Salmo salar*), brown trout

(*Salmo trutta*), Atlantic cod (*Gadus morhua*), European eel (*Anguilla anguilla*), northern pike (*Esox lucius*), and white seabream (*Diplodus sargus*). Focusing work on species of relevance to fisheries is a common feature of tracking research (Matley et al., 2022). Relative to fish, other taxa such as mammals, crustaceans, and cephalopods are currently less represented in European tracking studies (Abecasis et al., 2018; Cabanellas-Reboredo et al., 2012; Giacalone et al., 2019). Moreover, many existing studies have been designed for a particular species or a specific challenge, with tracking infrastructure deployed for short periods without capacity for long-term observation. Most existing studies are therefore temporary and limited in geographic and population scope (Table 1).

Acoustic telemetry can provide European fisheries management with key population parameters, such as survival and emigration, but is thought to be underutilised, as is the potential for investigating species interactions (e.g. fish vs marine mammals), fisheries interactions (e.g. the overlapping area of exploitation and harvest), and marine protected area (MPA) functionality (e.g. is the targeted fish species' home range actually covered by the MPA; Alós et al., 2022; Lees et al., 2021; Matley et al., 2022). This represents a potential loss in knowledge that is fisheries-independent (unlike many traditional sampling methods) and also potentially cheaper because the cost of launching marine surveys with research vessels is expensive and

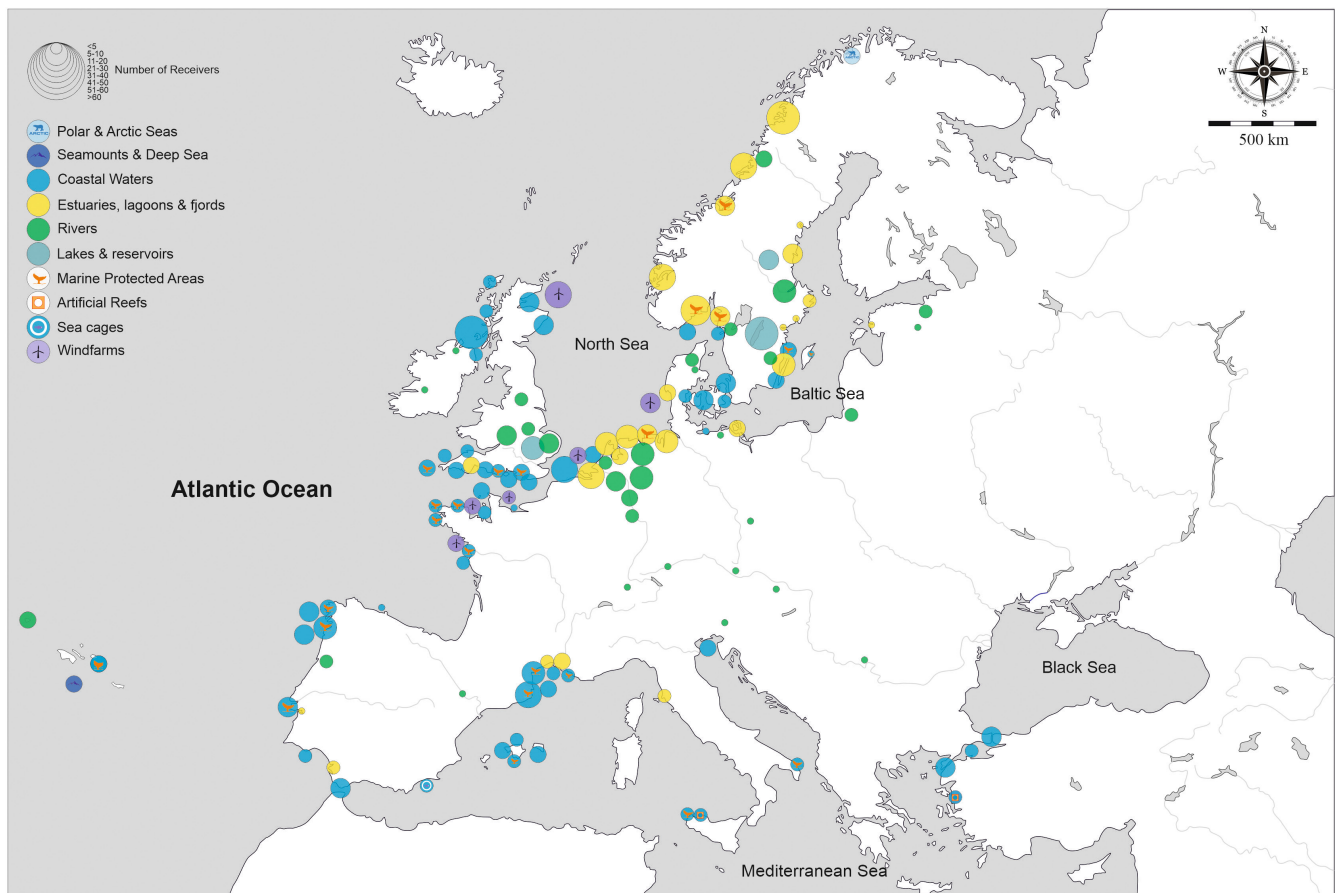


FIGURE 1 Locations of acoustic telemetry studies in European waters. Circle size indicates the number of receivers, and colours indicate area of use (data are from the European Tracking Network, <https://www.lifewatch.be/etn>).



TABLE 1 Applications of acoustic telemetry in European waters: Species, highlights, challenges and recommendations.

| Realm | Species | Highlights | Challenges | Recommendations | References |
|-----------------------------|--|--|---|---|--|
| Polar & Arctic seas | <ul style="list-style-type: none"> <i>Melanogrammus aeglefinus</i> <i>Salmo trutta</i> <i>Salvelinus alpinus</i> | <ul style="list-style-type: none"> Global warming Sea ice melting Interaction between species | <ul style="list-style-type: none"> Losses of acoustic performance Highly research costs Roughly environmental conditions | <ul style="list-style-type: none"> Raising awareness Review of management & conservation policies | <ul style="list-style-type: none"> Halvorsen (2019) Davidson et al. (2020) Davidson et al. (2021) |
| Sea mounts & deep sea | <ul style="list-style-type: none"> <i>Pagellus bogaraveo</i> <i>Pagrus pagrus</i> <i>Pseudocaranx dentex</i> | <ul style="list-style-type: none"> Conservation & management of the deep sea ecosystem Management of deep-sea fishery and regularization of fisheries restrictions | <ul style="list-style-type: none"> Difficulties of working with deep-water species Technological and logistical challenges | <ul style="list-style-type: none"> Improving equipment design & methodology Specialized tagging/surger techniques Development of custom-built acoustic equipment | <ul style="list-style-type: none"> Afonso, Fontes, Guedes, et al. (2009); Afonso, Fontes, Holland, & Santos (2009) Afonso et al. (2012) Afonso et al. (2014) |
| Coastal waters | <ul style="list-style-type: none"> <i>Anguilla anguilla</i> <i>Dicentrarchus labrax</i> <i>Gadus morhua</i> <i>Loligo vulgaris</i> <i>Merluccius merluccius</i> | <ul style="list-style-type: none"> Increase of water temperature & thermocline Urban development Overfishing Anthropogenic impact Conservation & spatial management Impact of invasive species | <ul style="list-style-type: none"> Loss of acoustic equipments due to overfishing Highly cost of long-term & large-scale studies Legal processes and licensing Lack of collaboration between cross-border countries Compatibility between research equipment | <ul style="list-style-type: none"> Revising the European Union recovery plan Re-organize fishery regulations and bans Long-term data collection from coastal waters Managing stakeholders in the coastal waters | <ul style="list-style-type: none"> Righton et al. (2007) Cabanelas-Reboredo et al. (2012) De Pontual et al. (2013) Neat et al. (2014) Bultel et al. (2014) Verheist et al. (2022) De Pontual et al. (2023) |
| Estuaries, lagoons & fjords | <ul style="list-style-type: none"> <i>Anguilla anguilla</i> <i>Clupea harengus</i> <i>Esox lucius</i> <i>Gadus morhua</i> <i>Platichthys flesus</i> <i>Salmo trutta</i> <i>Sarpa salpa</i> <i>Scophthalmus maximus</i> | <ul style="list-style-type: none"> Determination of migration & survival of key species Stock management Species-specific conservation and management Identifying and conserving spawning areas | <ul style="list-style-type: none"> Performance loss of acoustic equipment Natural or human-induced underwater noise Habitat loss due to land reclamation Variable water level and environmental conditions | <ul style="list-style-type: none"> Development of conservation & management strategy Frequent checking & cleaning of acoustic receivers Increasing the performance of acoustic equipment | <ul style="list-style-type: none"> Aarestrup et al. (2010) Abecasis et al. (2012) Eggers et al. (2015) Eldøy et al. (2019) Kristensen et al. (2021) Baden et al. (2022) Dhellemmes et al. (2023) |
| Rivers | <ul style="list-style-type: none"> <i>Alosa fallax</i> <i>Anguilla anguilla</i> <i>Barbus barbus</i> <i>Lampetra fluviatilis</i> <i>Leuciscus leuciscus</i> <i>Petromyzon marinus</i> <i>Platichthys flesus</i> <i>Salmo trutta</i> <i>Silurus glanis</i> | <ul style="list-style-type: none"> Determination of migration & survival of key species Fish passage Species-specific conservation and management Fisheries regulations Habitat selection & management | <ul style="list-style-type: none"> Natural or human-induced underwater noise Fragmentation & pollution Difficulty working in shallow water (<30cm) Decreased acoustic performance due to high water flow rate and turbulence Vandalism | <ul style="list-style-type: none"> Miniaturization of tags Fixed stations for long term studies Improving detection and noise filtering technology Collaboration between cross-border countries Labeling & citizen science | <ul style="list-style-type: none"> Aarestrup et al. (2010) Le Pichon et al. (2014) Aarestrup et al. (2015) Stein et al. (2016) Tummers et al. (2016) Silva et al. (2017) Gutmann Roberts et al. (2019) Barry et al. (2020) Flávio et al. (2020) Davies et al. (2021) Lenhardt et al. (2021) Davies et al. (2022) |



TABLE 1 (Continued)

| Realm | Species | Highlights | Challenges | Recommendations | References |
|--------------------------------|--|---|--|--|---|
| Lakes & reservoirs | <ul style="list-style-type: none"> <i>Anguilla anguilla</i> <i>Cyprinus carpio</i> <i>Esox lucius</i> <i>Perca fluviatilis</i> <i>Rutilus rutilus</i> <i>Salmo trutta</i> <i>Sander lucioperca</i> <i>Silurus glanis</i> <i>Tinca tinca</i> | <ul style="list-style-type: none"> Anthropogenic impact Eutrophication & acidification Management of recreational fisheries Habitat management & stock assessment Invasive species | <ul style="list-style-type: none"> Decreased acoustic performance due to macrophytes Natural or human-induced underwater noise Vandalism | <ul style="list-style-type: none"> Reservoirs management strategies Fixed stations for long term studies Frequent checking & cleaning of acoustic receivers Labeling & citizen science | <ul style="list-style-type: none"> Baktoft et al. (2013) Jacobsen et al. (2014) Trancart et al. (2018) Trancart et al. (2020) Monk et al. (2020) Monk et al. (2021) Říha, Gjelland, et al. (2021) Říha, Rabaneda-Bueno, et al. (2021) |
| MPA | <ul style="list-style-type: none"> <i>Diplodus sargus</i> <i>Epinephelus marginatus</i> <i>Homarus gammarus</i> <i>Labrus bergylta</i> <i>Palinurus elephas</i> <i>Raja brachyura</i> <i>Raja microocellata</i> <i>Raja undulata</i> <i>Sepia officinalis</i> <i>Serranus atricauda</i> <i>Solea senegalensis</i> <i>Sparisoma cretense</i> <i>Xyrichtys novacula</i> | <ul style="list-style-type: none"> Spatial management & conservation MPA efficiency & productivity Species-specific conservation & management Impact of invasive species Habitat management & stock assessment Habitat preference & site fidelity in the MPA Identifying and conserving spawning areas | <ul style="list-style-type: none"> Compatibility between research equipment Lack of collaboration between cross-border countries Vandalism Illegal fishery | <ul style="list-style-type: none"> Using acoustic telemetry data in MPA creation and management Fixed stations for long term studies Improving network between MPAs | <ul style="list-style-type: none"> Moland et al. (2011) Alós et al. (2012) La Mesa et al. (2012) Abecasis et al. (2013) Morel et al. (2013) Abecasis et al. (2014) Abecasis et al. (2015) Afonso et al. (2016) Aspillaga et al. (2016) Belo et al. (2016) Giocalone et al. (2019) Villegas-Ríos et al. (2020) Leeb et al. (2021) |
| Artificial reefs | <ul style="list-style-type: none"> <i>Diplodus sargus</i> <i>Gadus morhua</i> <i>Sciaena umbra</i> <i>Scorpaena porcus</i> <i>Scorpaena scrofa</i> | <ul style="list-style-type: none"> Habitat selection & residency Fisheries management Fish stock enhancement Conservation & spillover Site fidelity and habitat use | <ul style="list-style-type: none"> Losses of acoustic performance Difficulties in tracking cryptic animals Illegal fisheries | <ul style="list-style-type: none"> Fishery regulations and bans Improvement of AR design & location Fine-scale acoustic tracking systems Using powerful tags | <ul style="list-style-type: none"> Lino et al. (2009) D'Anna et al. (2011) Abecasis et al. (2013) Koeck et al. (2013) Reubens et al. (2013) Özgül et al. (2015) Özgül et al. (2019) |
| Sea cages, offshore structures | <ul style="list-style-type: none"> <i>Dicentrarchus labrax</i> <i>Gadus morhua</i> <i>Salmo salar</i> <i>Sparus aurata</i> | <ul style="list-style-type: none"> Fish welfare Fish behaviour Escapement Interaction wild fish & sea cage Fishery management Planning the feeding and culture regime | <ul style="list-style-type: none"> Decreased acoustic performance due to noise from cultured fish Need for high resolution data Decline in post surgery due to stress and disease | <ul style="list-style-type: none"> Improving equipment design & methodology Specialized surgery techniques Transmitters with different sensors Fine-scale acoustic tracking systems | <ul style="list-style-type: none"> Ugtem et al. (2010) Arechavala-Lopez et al. (2012) Muñoz et al. (2020) Svendsen et al. (2021) Alfonso et al. (2022) |

(Continues)



TABLE 1 (Continued)

| Realm | Species | Highlights | Challenges | Recommendations | References |
|------------|--|---|---|--|---|
| Wind farms | <ul style="list-style-type: none"> • <i>Gadus morhua</i> • <i>Pleuronectes platessa</i> • <i>Solea vulgaris</i> | <ul style="list-style-type: none"> • Fisheries management • Fish stock enhancement • Habitat selection & residency • Anthropogenic impact | <ul style="list-style-type: none"> • Natural or human-induced underwater noise | <ul style="list-style-type: none"> • Fine-scale acoustic tracking systems • Fishery regulations and bans • Fixed stations for long term studies | <ul style="list-style-type: none"> • Winter et al. (2010) • Reubens et al. (2013) • Reubens, De Rijcke, et al. (2014); Reubens, Degraer, & Vincx (2014) • Van der Knaap et al. (2022) • Buyse et al. (2022) • Buyse et al. (2023) |

limited in spatio-temporal scale (Matley et al., 2022) and because poor management decisions can be costly. Acoustic telemetry can also be developed further by moving beyond nearshore areas into the open sea via larger-scale deployments, at natural gates to fish migration, or into areas of aggregation after migration (Abecasis et al., 2018). Narrow access points between larger marine areas such as the Gibraltar Strait (between the Mediterranean Sea and the Atlantic Ocean), Dardanelles and Bosphorus Straits (between the Black Sea and the Mediterranean Sea), Danish Straits (between the Baltic Sea and the Atlantic Ocean), and the Bergen–Shetland corridor between Norway and Scotland (Lennox et al., 2022) are natural gates where acoustic arrays can enable study of local species and movement of animals on a wide scale. The value has already been demonstrated in the Danish Straits, where an array has provided Baltic countries studying European eel (*Anguilla anguilla*) migration in local systems, with additional detections for tagged eels that migrate through the Danish Straits system (Verhelst et al., 2022). However, arrays of this magnitude require investment over a longer timescale and beyond a single-study approach. Many species have the potential to move or migrate through these natural gates, so arrays or infrastructure in place enable many more species to be studied with the same array deployment cost. This calls for a more international collaboration and funding, such as EU funding schemes. Fine-scale telemetry can also inform fish ecology and responses to harvest in smaller freshwater systems, for example lakes (Lennox et al., 2021; Nathan et al., 2022), where fine-scale tracking can elucidate how fish interact with gear through fisheries-induced selection (Monk et al., 2021) and other relevant questions of management.

3 | HOW CAN TELEMETRY BE USED AS A FISHERIES MANAGEMENT TOOL?

3.1 | Exploitation and stock sizes

Telemetry can be used to assess whether fishery quotas are harvested, while providing an in-the-water estimate of the number of fish removed through harvest (Hightower & Harris, 2017; Monk et al., 2021). These critical insights can be derived from properly designed tracking data with arrays that cover large fractions of an ecosystem or even an entire ecosystem, which can support fisheries management by strengthening stock assessments and exploitation studies (Block et al., 2019; Byrne et al., 2017). Acoustic tags are expensive, so smaller numbers of fish are typically tagged than with standard external tags (e.g. T-bar, anchor, and spaghetti tags). This makes acoustic telemetry less optimal for mark-recapture studies, for estimating abundance. However, mark-resight models can be used to supplement or replace traditional mark-recapture methods by estimating stock abundance based on detection rates of tagged animals (Dudgeon et al., 2015; Lees et al., 2021; Sollmann et al., 2013). Such spatial models are, however, still challenging to parameterize and can be improved by accurate reporting of recaptured fish, which can be achieved by additional release of external



marks (either acoustic tag or standard tag) and incentives for fishers to report recaptures.

3.2 | Vital rates

Most fisheries are managed based on knowledge of total mortality (Z), which is the sum of natural (M) and fishing (F) mortality. Age-specific mortality of fish is critical to understanding the rate of population growth and resiliency to harvest, which are challenging to calculate. Tracking can provide an estimate of natural mortality based on attrition of tags (Alós et al., 2016; Hightower & Harris, 2017), fish movements and receiver configurations (Villegas-Ríos et al., 2020), or tracking a large number of individuals over long periods (Block et al., 2019). However, movement of fish outside arrays, tag failure, and natural predation that are difficult to detect, and intraspecific variation (e.g. sex and age), can affect estimates of natural mortality based on telemetry. For small species that must be tagged with relatively large transmitters, tag effects can particularly confound natural mortality estimates and short battery life can bias estimates of mortality (Brownscombe et al., 2019). Predation tags can differentiate mechanisms of natural mortality to provide a more synoptic view of vital rates of fish in the wild in support of fisheries management (e.g. Weinz et al., 2020). However, validation of methods is needed to fully support fisheries management.

3.3 | Critical habitat

Highly mobile species may move through or reside in multiple jurisdictions during their lifetimes, by using discrete regions for different biological needs for feeding, maturation, and spawning. For such species, connections between seasonally visited habitats can be difficult to recognise. Broad home ranges and associations of individuals with multiple distinct habitats can complicate conservation and management by expanding spatial scales over which threats are encountered and subsequent protective measures must be established (Bangley et al., 2020). Acoustic telemetry studies often rely on prior knowledge of species' spatial distributions to guide placement of acoustic receivers and tagged fish, so prior studies are valuable for identifying and quantifying the significance of critical habitats, such as spawning grounds, especially in nearshore or freshwater environments (Janssen et al., 2006; Le Pichon et al., 2014; Walters et al., 2009), connectivity among areas (Olsen et al., 2023). Simultaneous monitoring of multiple tagged individuals also allows new aggregation sites to be identified in obscure or unexpected locations within a given study area that can indicate trends in local residency and site fidelity (Edwards et al., 2022; Ramsden et al., 2017; Reubens et al., 2013). Although data collection is typically limited to existing acoustic arrays, combining data for individuals detected across multiple networks can significantly expand the spatial scale of monitoring, by encompassing home ranges that span international or ocean basins (Iverson et al., 2019; Reubens, Verhelst, Van

der Knaap, Wydooghe, et al., 2019). Furthermore, in contrast to traditional methods that provide a series of temporal snapshots in habitat use (e.g. habitat surveys using divers, Marsden et al., 2005; passive acoustics, Walters et al., 2009; and remotely operated vehicles, Janssen et al., 2006), acoustic telemetry can be used to monitor behavioural cycles over seasons or years (Nakayama et al., 2018). This can highlight the value of essential fish habitats over lifetimes of individuals and populations to reveal connections among distant habitats and potential migration corridors (Daley et al., 2015; Eldøy et al., 2019; Espinoza et al., 2021; Olsen et al., 2023).

3.4 | Stock boundaries and metapopulation structure

Delineation of population structure, or stocks, is a crucial aspect of successful fisheries management, though such information is often limited (Begg et al., 1999; Begg & Waldman, 1999). Fish movements are important determinants of population structure because they act as a mechanism through which populations mix and interact. Despite not being used systematically in fisheries management to identify stock structure, acoustic telemetry can be used to identify areas used by different populations and, if such areas overlap, to quantify connectivity among populations (Olsen et al., 2023) and thus identify boundaries among populations. Network analysis of acoustic telemetry data at a large scale may provide data that support or refute more commonly used genetic analyses, to offer new insights for improving management and conservation (Lédée et al., 2021; Lukyanova et al., 2024). Tagging Atlantic cod (*Gadus morhua*) with data storage tags (DSTs) enabled delineation of the boundary between two North Sea stocks, in direct support of fisheries management (Righton et al., 2007). Boundaries of many highly migratory species, including sharks such as spiny dogfish *Squalus acanthias*, porbeagle *Lamna nasus*, and basking shark *Cetorhinus maximus*, are still not well resolved within Europe, so tracking could help to differentiate between one panmictic population or multiple discrete stocks with unique vulnerabilities to local stressors (Cameron et al., 2018; Johnston et al., 2019; Lennox et al., 2022). In addition, telemetry can be used to identify population mixing and inform decisions about grouping populations together for management (Lukyanova et al., 2024). This approach can potentially save time and effort by considering large-scale dynamics of interconnected populations, rather than treating each population in isolation (Eggers, 2013; Källo et al., 2022).

3.5 | Interactions among invasive species and local fisheries

Controlling invasive species is a critical priority in fisheries management. Acoustic telemetry can be used to track movement and behaviour of native and invasive species to predict potential invasion hotspots and identify areas at high risk of invasion. One of the

major pathways for invasions in Europe is the Suez Canal, which connects the Red Sea and the Mediterranean Sea and leads to introductions of algae, invertebrates, and fishes, commonly referred to as Lessepsian migration (Kourantidou et al., 2021). More than 400 Lessepsian multicellular organisms have been introduced into the Eastern Mediterranean (Galil et al., 2021), including 93 fish species, at an alarming rate of 2.5 species per year (Golani, 2021). The lionfish *Pterois* sp. and pufferfish *Lagocephalus* sp. are among the notable invasive species that pose significant threats to the economy and ecology of coastal habitats (Ünal et al., 2015, 2018). Invasive crayfishes are also a major economic and conservation concern in European rivers (Lipták et al., 2023; Weiperth et al., 2020). Pink salmon (*Oncorhynchus gorbuscha*) are invasive in Norway, Scotland, and Finland, and telemetry can be used as part of a strategy to optimise removal of these species to benefit valuable Atlantic salmon fisheries in coastal rivers (Sandlund et al., 2019). Invasive crayfish species, Atlantic blue crab *Callinectes sapidus*, and the round goby *Neogobius melanostomus* are causing significant ecological disruptions in Europe (Clavero et al., 2022; Kornis et al., 2012; Lipták et al., 2023; Mancinelli et al., 2017). Implementing telemetry studies can enhance understanding and management of these invasions (e.g., Bergman et al., 2022; Carr et al., 2004; Florko et al., 2021).

Managing biological invasions calls for an integrated approach based on scientific evidence about the biology of invasive species and social perspectives, because all non-native species are not considered invaders. Unlike native fishes, understanding movements and dynamics of invasive species can be more challenging because basic information about their life history and ecology is often lacking in newly colonised environments (Grubich & Odenkirk, 2014; Simberloff, 2003). Acoustic telemetry, however, has been used to predict and detect invasions, seek and destroy invaders, assess population structure, and evaluate harvest control rules (Lennox et al., 2016). Telemetry has been successfully used to manage invasions, such as in the Laurentian Great Lakes, where invasive sea lamprey (*Petromyzon marinus*) contributed to the collapse of valuable lake trout (*Salvelinus namaycush*) fisheries, and tracking of sea lamprey spawning movements was used to identify environmental drivers of movement and to adjust management strategies for capturing and removing sea lamprey from rivers (Holbrook et al., 2016).

4 | USING ACOUSTIC TELEMETRY TO INFORM MANAGEMENT OF AQUATIC SPECIES IN EUROPEAN WATERS

4.1 | Polar and Arctic seas

Polar and Arctic waters have become one of the most important frontiers in fisheries research because climate-induced melting of ice and increased access to the Arctic have led fisheries to expand into Europe's Arctic (Fauchald et al., 2021). These changes, termed borealisation or Atlantification (Ingvaldsen et al., 2021), will impact marine ecosystems and fisheries in unpredictable ways. Effects vary

from being optimistic with increasing productivity to feed the world (Sundby & Nakken, 2008), to problematic with north-ward expansions being truncated by geographic limitations and seasonality (Wiencke & Hop, 2016). Informing fisheries management in rapidly changing environments is crucial to accurately predict how much of Arctic ecosystems will be lost and how fast changes will progress (Harris et al., 2022; Wassmann & Reigstad, 2011). An important question to answer is whether changing ecosystems will impact Arctic keystone species, such as polar cod *Boreogadus saida*, and how newly arrived Atlantic species, such as haddock *Melanogrammus aeglefinus* and Atlantic cod, will interact with native species (Mueter et al., 2020). Future habitat refuge for Arctic species will depend on factors such as microclimatic conditions and habitat heterogeneity, so fine-scale tracking studies will be essential for shedding light on the details of these interactions. For example, limited acoustic telemetry research has already been used to study these topics in the Arctic (Barkley et al., 2018; Edwards et al., 2022; Kessel et al., 2016; Moore et al., 2016). Furthermore, despite a recent surge in studies of movement ecology of Arctic gadoids, major knowledge gaps still exist in the behavioural ecology of these fishes and how they will respond to future climate change as polar and boreal specialists increasingly overlap (Pettitt-Wade et al., 2021).

The Arctic environment is one of the least accessible environments to conduct fisheries research. Arguably, acoustic telemetry is one of the few remaining methods to apply that does not require the presence of humans for most of the study period and can be conducted under winter ice (Hussey et al., 2015; Song et al., 2014; Wartzok et al., 1992). With continuous development of robust acoustic release systems and long-lived batteries, deployment of long-term acoustic receiver arrays in the Arctic might be one of the most insightful methods to study fish ecology and inform fisheries management based on distributions, migration patterns, and natural and fishing mortality of polar species (Hammer et al., 2022; Moore et al., 2016). Although challenged by harsh winter conditions, underwater deployments are now functionally and economically viable and should be pursued to fill gaps affecting the capacity for effective management in the Arctic (Hussey et al., 2017; Kessel et al., 2016).

4.2 | Seamounts and the deep sea

Biotelemetry has seldom been used to support the management of deep-sea fisheries in comparison with freshwater or coastal environments (Alós et al., 2022). Yet, the use of biotelemetry, and specifically acoustic telemetry, holds great promise for addressing the large knowledge gaps which still subsists in relation to the vast majority of fished species and other ecologically important organisms inhabiting seamounts and other deep-sea environments (Morato et al., 2006). This lag results from multiple factors, including the technical difficulties in handling and tracking animals in the remote, cold, and pressurised environments of the deep sea and use of classical approaches for fisheries management that do not consider variation in individual ecology (Edwards et al., 2019). However, recent technical



and analytical advances have occurred fuelled by an increased interest in deep-sea species, including pelagic predators that venture into great depths (Braun et al., 2022), and the growing perception that effective, science-based conservation is needed to protect vulnerable deep-sea ecosystems, in particular, seamounts, which are considered oases of life and productivity (Morato et al., 2006).

Acoustic telemetry has been used to elucidate short- and long-term movements and habitat use of ecologically and commercially important deep-sea fishes on seamounts and slopes, such as black rockfish *Sebastes melanops* (e.g. Green & Starr, 2011), blackspot seabream *Pagellus bogaraveo* (Afonso et al., 2012), and halibut *Hippoglossus stenolepis* (Nielsen & Seitz, 2017). Such studies eventually allowed a new perception of individual variability, detailed tri-dimensional space use, and its ecological significance, such as for feeding or spawning (Afonso et al., 2014). Space use, site fidelity, and mortality estimates have been useful for understanding effects of fishing and management measures such as MPAs on seamounts, such as endangered bycatch species such as deep-water sharks (e.g. Fauconnet et al., 2023). Satellite telemetry has been mostly used to study the behaviour of large predators around deep-sea environments, including marine mammals, sharks, and fishes (Abecasis et al., 2018; Braun et al., 2022; Hussey et al., 2015). Miniaturisation of PSAT and fast improvements in acoustic transmitter battery life now enable the tagging of smaller fishes for longer periods (e.g. Brownscombe et al., 2022). Studies have increasingly combined multiple tracking techniques with high-resolution and multiple sensors across multiple scales of predator behaviour, from pursuit and tracking of prey on seamounts to deep diving during large-scale migrations (Braun et al., 2022). Therefore, one should expect a substantial increase in the use of biotelemetry in general and acoustic telemetry to fill large knowledge gaps in the biology and ecology of fished species (and other species of importance) on seamounts and in the deep sea.

4.3 | Coastal waters

The European coastal zone is dynamic and diverse, by encompassing a wide range of highly productive ecosystems relevant for fisheries. These ecosystems, including seagrass beds, salt marshes, soft sediments, and biogenic structures, play vital roles as nurseries, breeding areas, and foraging grounds for numerous commercially and ecologically important fish and invertebrate species (Seitz et al., 2014). Despite such unique and intrinsic ecological values, an extensive history of coastal development and continued habitat degradation has drastically reduced the functional capacity of European coastal habitats (Airoldi & Beck, 2007; EEA, 2006; Lotze et al., 2006) with implications for population dynamics and commercial and recreational yields (Arlinghaus et al., 2023; Seitz et al., 2014).

Management of coastal European fisheries has relied heavily on traditional methods, such as stock assessments and conventional mark-recapture programmes to define species distributions and abundance. For example, mark-recapture studies in the early 2000s

provided evidence of localised residency and homing of a highly exploited commercial species, the European hake (*Merluccius merluccius*), which resulted in significant changes to stock assessments by the International Council for the Exploration of the Sea (ICES) (De Pontual et al., 2013). However, study limitations, including differential reporting rates among fishing fleets and partial spatial coverage of the population's distribution by tagging, impeded the observation of seasonal movements or spatio-temporal structure potentially exhibited by the target stock with potential implications for estimates of natural mortality (De Pontual et al., 2013). By eliminating the need for fish recapture and providing more detailed information on individual movements, acoustic telemetry can address these and other challenges encountered by conventional mark-recapture studies, while also estimating demographic parameters (e.g., natural mortality, apparent survival, and absolute abundance), sometimes with greater precision (Dudgeon et al., 2015; Lee et al., 2014; Lees et al., 2021).

The Atlantic cod has been a commercially valuable species for decades. Cod are distributed across the continental shelves of the North Atlantic, as distinct self-sustaining populations (ICES, 2020). Cod are economically high in value and are also culturally important (Meager et al., 2018). However, stocks declined due to overfishing and warming temperature, so management plans were developed to promote stock recoveries, with limited success (Kraak et al., 2013). ICES has a long record of research on population structure of cod in the North Sea and adjacent areas, but stock identity remains unclear, with multiple populations in the North Sea that extend into neighbouring areas that complicate assessment of stock status and fisheries management needed to restore healthy stocks (ICES, 2021). Telemetry can help to resolve these issues and improve assessments (Kristensen et al., 2021). For example, cod population structure around the British Isles based on animal tracking to map movements suggested that population structure was at a finer scale than was currently recognised (Neat et al., 2014). Different stocks also experience different environmental conditions that influence life history, growth, and reproduction (Olsen et al., 2023; Reglero et al., 2018). Recent work combining telemetry and genomics identified behavioural ecotypes based on chromosomal inversions in cod (Pampoulie et al., 2022), thereby suggesting that telemetry could identify stocks and predictive tools to understand how different fisheries might selectively harvest genetically distinct ecotypes.

4.4 | Estuaries, lagoons, and fjords

Estuaries, lagoons, and fjords are spatially and temporally complex critical transition zones linking open marine habitats with land and fresh water, where salt water and fresh water mix intra- and inter-annually. Estuaries and lagoons, especially, are highly productive systems used by numerous organisms (Arlinghaus et al., 2023; Beck et al., 2001; Garrido et al., 2011). Despite their ecological significance, estuaries and lagoons are also among the most anthropogenically degraded habitats on Earth (Blaber, 2002; Edgar et al., 2000;

Webster & Harris, 2004), as preferred locations for human settlement because of their natural connections between inland and over-sea destinations. Thus, human activities drive pressures on physical functioning, habitats, and ecosystem services in these habitats.

Estuaries, lagoons, and fjords are excellent locations for acoustic telemetry studies because they are spatially explicit and confined. The detection range of acoustic transmissions from tags is limited, so estuaries and lagoons that are smaller than most oceans can be covered effectively by acoustic receivers (Dhellemmes et al., 2023). However, estuaries are mixing areas where temperature, pressure, salinity, and sediments that mix across small spatial scales create barriers to tag detection ranges (Bruneel et al., 2023; Kessel et al., 2014; Reubens, Verhelst, Van der Knaap, Deneudt, et al., 2019). Moreover, flow close to river mouths or tidal velocity in macrotidal estuaries can make receiver deployments challenging, especially as sediments shift and damage or bury receivers (Abecasis et al., 2012). Fish tracking data in estuaries, lagoons, and fjords can be used to inform stakeholders on spawning sites, connectivity, and survival (Aarestrup et al., 2010, 2015; Flink et al., 2023), as when planning locations of open net-pen Atlantic salmon farming (Crossin et al., 2017; Davidsen et al., 2019) or land reclamation (Davidsen et al., 2021).

4.5 | Rivers

Rivers are among the most threatened ecosystems worldwide, with river fragmentation by anthropogenic structures being a primary cause of decline (Grill et al., 2015; Tickner et al., 2020). In Europe, more than 1 million barriers fragment rivers, 68% of which are small barriers with a height of less than 2 m (Belletti et al., 2020). Together with pressures from chemical pollution, invasive species, channelisation, and transportation, rivers differ considerably from those that fish adapted to through millennia (Finlayson et al., 2005). The fast pace of change may not be aligned with evolutionary processes, so behavioural changes are expected to be the first immediate detectable response (Munday et al., 2013). Human-made structures can delay migration and result in retreat behaviour to search for alternative upstream migration routes, as for acoustic-tagged sea lamprey in the River Severn (Davies et al., 2022). Moreover, anadromous species often must pass multiple impediments during freshwater migrations, where telemetry can be used to estimate survival and behaviour of downstream (Aarestrup et al., 1999) and upstream (Davies et al., 2021) migrants. The EU Water Framework Directive considers river connectivity key to good ecological status, so assessing impacts of human-made obstacles and efficacy of mitigation measures is needed when removal is not possible (Water Framework Directive, 2024). Acoustic telemetry, especially if coupled with Passive Integrated Transponder (PIT) or radio telemetry, is a good and well-established tool to undertake such research (Silva et al., 2017; Tummers et al., 2016).

For fisheries management in rivers, acoustic telemetry can inform stock assessments and connectivity. Out-migrating salmon smolts are among the most studied species and life forms (Thorstad

et al., 2012). Mortality and out-migration timing has been used directly to inform stock assessments and fisheries management. For example, out-migrating Atlantic salmon smolts and returning adults were counted and tagged to estimate survival at sea at a trap 3.5 km upstream of the ocean in the River Bush, Northern Ireland, although survival of acoustically tagged smolts (32% to 68%) within this short stretch of river suggested that many smolts assumed to have migrated to sea died before reaching the sea (Flávio et al., 2020). Acoustic telemetry studies of seaward migration of European eel, since dramatic population declines that were partly attributed to interactions with human infrastructure, have led to a classification as critically endangered by the International Union for Conservation of Nature and Natural Resources (IUCN) and legislation for their protection (Regulation EC 1100/2007). Tagged European eels migrated using a discontinuous, stepwise migration over an extended period of time, with only 28% migrating clearly downstream (Stein et al., 2016).

4.6 | Lakes, reservoirs, and ponds

Many lakes are threatened by eutrophication, warming, and invasive species. Lake ecosystems may also be entirely human-created, such as ponds, water-supply reservoirs, and gravel-pit lakes. Lakes offer excellent environments for high-resolution tracking and can help elucidate crucial insights for population biology (see review in Lennox et al., 2021).

Telemetry is a powerful tool for management of fish communities in lakes and artificial waters. Recent studies in newly created post-mining lakes, for example, have shown the importance of macrophyte presence on the behaviour and population dynamics of the apex predator, the northern pike (Říha, Gjelland, et al., 2021), besides the potential impact on the overall fish community (Vejříková et al., 2017, 2022). Results were used to modify pike stocking in similar lakes (Peterka, 2021a, 2021b). Another study of space use by three predator fish species (northern pike, pikeperch *Sander lucioperca*, and European catfish *Silurus glanis*) identified specific areas of the reservoir and seasons when predatory fish were most likely to be present and at risk from illegal fishing (Říha, Rabaneda-Bueno, et al., 2021). These findings are of special importance in drinking water waterbodies such as the Římov Reservoir, where the study was conducted and where a long-term predator stocking programme for biomanipulation is applied (Jůza et al., 2022; Říha et al., 2009). For assessing threats, high-resolution telemetry has been used to assess impacts of boating, angling, and handling on several species-specific changes in activity, swimming speed, and behaviour (Jacobsen et al., 2014). For example, temperature-dependent activity of angled pike changed following handling but lasted less than 48 h (Baktoft et al., 2013). High-resolution tracking has also been used to quantify fishery-induced selection (Monk et al., 2021) and study behavioural and fitness outcomes of introduced predators that mimic stocking experiments (Monk et al., 2020). Telemetry can help in the management of carp (*Cyprinus carpio*) in aquaculture by providing a better



insight into the feeding activity of the fish and the utilisation of the feeding ground in a pond (Jurajda et al., 2016). Such telemetry studies can help managers better assess how fish cope with human-induced stressors such as angling or stocking, predict likely post-release survival, and infer the potential for fisheries-induced timidity of exploited fish stocks (Arlinghaus et al., 2017; Monk et al., 2021).

4.7 | Marine protected areas (MPAs)

Conventional fisheries management based on maximum sustainable yield (e.g., quotas, minimum landing size, and gear restrictions) has often been insufficient to sustainably manage world fisheries (Pauly et al., 1998; Roberts, 1997). MPAs have been advocated as a tool for fisheries management and conservation, particularly to expand from a conventional species-specific approach to fisheries management to a more ecosystem-based approach (Gaines et al., 2010; Roberts, 1997), to overcome uncertainties of complex interspecific relationships. Importantly, MPAs only function from a conservation perspective if the MPA is large enough to encompass the home range of fish and can only deliver fisheries benefits if fish spill over boundaries (Abecasis et al., 2015; Di Lorenzo et al., 2020). Both issues can be studied well with telemetry.

For fisheries, the main benefits of MPAs come from the recruitment effect (net larval export) and the spillover effect (net adult export), which should increase fishing yield outside the MPA, particularly in nearby areas (Russ, 2002). Information on species habitat use, home range areas, and movement is important for designing MPAs, assessing their effectiveness, and implementing adaptive management strategies (Grüss et al., 2011; Pomeroy et al., 2005), but is usually limited to movements of large-sized fish. Efficiency of MPAs is highly dependent on size and target species. For example, acoustic telemetry studies in the Arrábida MPA (Portugal) indicated that the MPA was large enough to protect home ranges of *Diplodus sargus* (Abecasis et al., 2015) and Senegalese sole *Solea senegalensis* (Abecasis et al., 2014), but too small for cuttlefish *Sepia officinalis* (Abecasis et al., 2013). Other studies of European MPAs showed that even small marine reserves provided relevant spatial and temporal protection for commercial and recreational fish species, particularly site-attached species (e.g. Afonso et al., 2016; Alós et al., 2012; Aspillaga et al., 2016; Belo et al., 2016; Koeck et al., 2014; La Mesa et al., 2012; Moland et al., 2011; Villegas-Ríos et al., 2013). Acoustic telemetry studies of other species suggested that a network of MPAs, together with traditional fishing effort management measures, were needed (red porgy *Pagrus pagrus*, Afonso, Fontes, Guedes, et al., 2009; white trevally *Pseudocaranx dentex*, Afonso, Fontes, Holland, & Santos, 2009; and some ray species, Leeb et al., 2021; Morel et al., 2013). Acoustic telemetry holds great potential for elucidating connectivity between MPAs, identifying migration corridors, and understanding density-dependent movements outside of protected areas (Alós et al., 2022). To harness this potential effectively, collaboration and knowledge exchange are needed between researchers and managers, to translate research

findings into practical management measures that support long-term conservation and sustainable use of European marine ecosystems (Brownscombe et al., 2019). However, results of studies in European MPAs have seldom been applied to effective protected area or fisheries management (Huserbråten et al., 2013; Marques et al., 2024).

4.8 | Artificial reefs

Protection and restoration of fish habitats is an important component of fisheries management (Brownscombe et al., 2022). Artificial reefs (ARs) have been used for decades around the world for many purposes, such as habitat restoration, stock enhancement, tourism, recreation, fisheries management, and research areas (Addis et al., 2013; FAO, 2015). ARs were first used in Monaco, Europe, in the 1960s and have since been widely used in fisheries management by more than 20 countries, especially in the Mediterranean Sea (FAO, 2015). The recent increase in ARs necessitates development of a management model for artisanal and recreational fishing at these sites (Pioch et al., 2011). Small-scale fisheries on ARs should be controlled using a management model as in other fishing areas (Polovina, 1991; Santos & Monteiro, 2007). Otherwise, establishment of ARs might result in net negative outcomes, rather than ensuring economic and ecological benefits (Becker et al., 2018; Brickhill et al., 2005; Lök et al., 2011). Fisheries are commonly regulated in ARs to ensure sustainability of the reef area by implementing seasonal or spatial closures and fishing gear restrictions (BSGM, 2020). Nevertheless, characteristics of fishing fleets (fishing power, fishery methods, etc.), stakeholders (diving clubs, aquaculture, etc.), socio-economic conditions of the coastal zone, effective area of ARs, home range areas, and movement patterns of reef species, are major factors to be considered in management of ARs (Addis et al., 2013; Koeck et al., 2013; Kramer & Chapman, 1999).

Understanding the home range and residency of reef species can greatly influence success of fisheries management in ARs. Determining the variance of fish behaviour on artificial reefs is essential for evaluating reef design and determining effective conservation and management strategies after the reef is settled (Powell, 2000; Wiens, 2000). Acoustic telemetry has recently been used to detect fine-scale movements of reef species at ARs and in surrounding habitat (Pincock & Johnston, 2012; Voegeli et al., 2001). Acoustic telemetry has been used to investigate behaviour of many fish species in ARs, including common dolphinfish *Coryphaena hippurus* (Josse et al., 2000), yellowfin tuna *Thunnus albacares*, skipjack tuna *Katsuwonus pelamis* (Doray et al., 2006), big-eye tuna *Thunnus obesus* (Hallier & Gaertner, 2008), *Diplodus sargus* (D'Anna et al., 2011), northern red snapper *Lutjanus campechanus* (Topping & Szedlmayer, 2011), copper rockfish *Sebastes caurinus* and Lingcod *Ophiodon elongatus* (Reynolds et al., 2010), bluespotted sea bass *Cephalopholis taeniops* (Lino et al., 2011), Atlantic cod (Reubens et al., 2013), brown meagre *Sciaena umbra* (Özgül et al., 2015), black scorpionfish *Scorpaena porcus*, and red scorpionfish *Scorpaena scrofa* (Özgül et al., 2019). Similar to artificial reefs, telemetry has been

used in lakes to study how predators aggregate on artificial structures (Ahrenstorff et al., 2009).

4.9 | Sea cages and other offshore structures

Aquaculture plays a significant role in European waters, with a focus on farming sea gilthead seabream *Sparus aurata* and European sea bass *Dicentrarchus labrax* in the Mediterranean Sea and *Salmon salar* on the Atlantic coast (Barnabé & Dewavrin, 2019; Scientific, Technical and Economic Committee for Fisheries (STECF), 2023). However, escapement of cultured fish from sea cages challenges the aquaculture industry (Arechavala-Lopez et al., 2013; Dempster et al., 2007; Jensen et al., 2010). Cultured fish escape due to various factors, including storms, infrastructure failures, operational errors, and biological causes such as net-biting, and can impact wild fish populations and ecosystems (Jensen et al., 2010). Fish escaping from marine fish farms have always been a major socio-economic and ecological concern, as a vector for genetic introgression, invasive species, and pathogens (Fleming et al., 2000; Heggberget et al., 1993; Naylor et al., 2005). Studies on the prevention or reduction of fish escape are ongoing in many countries (Izquierdo-Gomez & Sanchez-Jerez, 2016). However, the fate of fish escaping from net cages is highly controversial (Arechavala-Lopez et al., 2011, 2012; Izquierdo-Gomez & Sanchez-Jerez, 2016). Acoustic telemetry enables the study of behaviour of different sizes and species escaping from aquaculture facilities (Arechavala-Lopez et al., 2012; Uglem et al., 2010), to inform researchers and fish farms about behaviour of fleeing fish with trials under different conditions, perhaps to capture escaped fish that remain near sea cages (Dempster et al., 2018). Telemetry has also been used to study migration of fish past fish farms to assess the impact of disease and parasites in aquaculture facilities on the mortality of wild fish populations (Vollset et al., 2018). Migratory timing and pathways from telemetry (Vollset et al., 2022) are directly used to inform models of disease transfer (Johnsen et al., 2021; Stige et al., 2022) and to estimate mortality for informing management of these populations.

4.10 | Wind farms

Offshore wind energy is expanding rapidly globally, with significant developments already in shallow waters of the North Sea and along European coastlines (Arapogianni et al., 2011). Significant effects of offshore wind farms (OWFs) on marine ecosystems include changes to local biodiversity and ecosystem functioning (Andersson et al., 2009; Lindeboom et al., 2011). For fish, costs and benefits of wind farms include the exclusion of fisheries (Buyse et al., 2022; Leonhard et al., 2011; Van Hal et al., 2012) and addition of submerged structures as artificial reefs (windmill artificial reefs, WARs) that provide refuge and increase habitat complexity that attract and support production of benthopelagic fish species (Bergström

et al., 2013; Langhamer et al., 2009; Methratta & Dardick, 2019; Reubens, De Rijcke, et al., 2014; Winter et al., 2010). Benthic and pelagic fish communities can also be disturbed during construction, operation, and decommissioning of wind farms, in the form of habitat destruction, generation of underwater sound, and human-induced electromagnetic fields (Gill et al., 2005; Raoux et al., 2017; Thomsen et al., 2006).

Small-scale acoustic telemetry studies have revealed strong residency and site fidelity of demersal species, such as Atlantic cod, sole *Solea solea*, and plaice *Pleuronectes platessa* around wind turbines (Buyse et al., 2023; Reubens et al., 2013; Reubens, Degraer, & Vincx, 2014; Winter et al., 2010). However, exposure to sounds produced within these areas (seismic surveys and pile driving) can also alter the behaviour of tagged fish, with potential consequences for individual survival (Van der Knaap et al., 2021, 2022). Continued study of fish movements within and around wind farms will illustrate effects of local attractants and stressors on individual fish (Gimpel et al., 2023; Wang et al., 2023). Details of fish residency, recurrence rates, and fine-scale behaviour from presence-absence data or positional tracking can also reveal the functional role of wind farms in fish life cycles and highlight their potential contribution to ecosystem-based marine spatial planning (MSP) (Hammar et al., 2015). Additionally, acoustic telemetry networks such as the ETN will be essential for observing the potential influence of wind farms on fish distributions and migratory behaviours over broader spatial scales (Reubens, Verhelst, Van der Knaap, Wydooghe, et al., 2019).

5 | TRACKING NETWORKS AND CENTRALISED DATABASES: BENEFITS TO FISHERIES MANAGEMENT

Globally, fish tracking communities are organising themselves into networks. The leading global tracking network is OTN (Ocean Tracking Network), a global aquatic research, data management, and partnership platform with a mission to inform stewardship and sustainable management of aquatic animals by providing knowledge on their movements, habitats, and survival in the face of changing global environments (Iverson et al., 2019). OTN has partner nodes (e.g. the Florida Atlantic Coast Telemetry (FACT), the Integrated Tracking of Aquatic Animals in the Gulf of Mexico (iTAG), and the Acoustic Tracking Array Platform (ATAP)) at different places in the world, which form a large network of tracking infrastructure across the globe. In Australia, the Integrated Marine Observing System Animal Tracking Facility (IMOS ATF) established a permanent array of acoustic receivers around Australia, a centralised national database to foster collaborative research across the user community and quantify individual behaviour across a broad range of taxa that uses animal tracking to support of fisheries management, marine spatial planning, and human health and safety to learn about shark interaction risks (Hoenner et al., 2018). In Europe, a tracking network initiative was long missing (Abecasis et al., 2018), and with



ETN, the network idea was supported in 2018. ETN's mission is to track aquatic animals across Europe to better understand, protect, and manage them. ETN is both an infrastructure and research network that provides necessary capacity building, enhances collaborations, and maintains a centralised database for aquatic animal tracking data (Abecasis et al., 2018). Having such a centralised data system for all aquatic animal tracking data generated across Europe is key to produce necessary knowledge for decision-making related to fisheries management. ETN also offers both the ability to easily access data for meta-analysis (e.g. on a particular species investigated in several places) and legacy analysis over time to investigate decadal changes in movement. Furthermore, linking with larger arrays allows researchers working locally with migratory fish to document survival and behaviour over a larger scale at low extra cost. This may prove valuable particularly for longer migrating species, but also offers new insight into species migration and species normally assumed to be resident. ETN currently maintains movement information of almost 20,000 individuals of over 120 different species tagged by institutes across Europe. By having access to data gathered at the European network level, better and more insights can be generated on movement, migration, important habitats, and species interactions, while linking to environmental factors that might influence presence.

Benefits of tracking networks are maximised by using compatible equipment throughout the network, ensuring easy access to data by all network users, and using common best practices in all network projects. First, equipment must be compatible across different telemetry studies to ensure unique scientific benefits of networking. Open Protocol (OP) advocated by ETN provides robust and energy-efficient transmission protocols that can be used by all manufacturers after signing a memorandum of understanding and a licence agreement. IDs of the protocols are controlled by an independent third party (Reubens et al., 2021). Protocols contribute to standardised data collection, sharing, and collaboration among researchers, institutions, and management bodies in Europe. FAIR data (findable, accessible, interoperable, and reusable) principles ensure access to data by all users by (1) emphasising use of standardised data formats and metadata to ensure consistency and compatibility across different telemetry studies that enables researchers to easily share and integrate data, thereby fostering collaboration and facilitating large-scale analyses, and (2) encouraging data sharing through open-access platforms (FAIRification) by making data openly available, enhancing transparency, reproducibility, and data reuse, to facilitate cross-disciplinary research that supports evidence-based decision-making in aquatic species management. Furthermore, harmonisation of telemetry methodologies and best practices should be promoted within tracking networks, to provide guidelines and recommendations for data collection and standardisation to enhance comparability of results across studies and facilitate development of robust management strategies. By fostering collaboration, standardisation, and data sharing, acoustic tracking networks promote a holistic and informed approach to fisheries management in European waters.

6 | CONCLUSIONS

We reviewed the important role that acoustic telemetry plays in research and management of European aquatic ecosystems, particularly fisheries. We reviewed selected research, studies, and organisational initiatives pertaining to aquatic animal tracking and its utility in fisheries management of European waters. Acoustic telemetry plays a crucial role in informing management of aquatic species in European waters by providing valuable insights into migration patterns, habitat use, behaviour, fishery impacts, and climate change impacts. Incorporating these realms into fisheries and conservation management strategies can help to ensure long-term sustainability and conservation of European aquatic ecosystems.

To better protect, manage, and monitor European waters, bio-telemetry and acoustic telemetry technologies still have an unused potential, particularly in southern Europe, especially in the Mediterranean and Black Seas, and broadly in freshwater and coastal areas. Within ETN, collaboration among researchers from different European countries should increase. Developments are positive. Acoustic telemetry infrastructures are and will be established across Europe with the Strategic Infrastructure for Improved Animal Tracking (STRAITS) project that emerged as a result of the ETN network. Tracking large-scale movements of key species can provide critical information about when, where, and why animals move, when, where, and how much fishing should be allocated, how animals are responding to climate change and other anthropogenic threats, overall health of ecosystems, and provide knowledge needed for industries and policy setters to develop spatial protections and other marine management directives in line with EU policies (e.g. Marine Strategy Framework Directive, Common Fisheries Policy, CFP; Natura 2000 Directives). However, this network established among telemetry researchers across Europe, thanks to ETN, needs to be strengthened and sustained, with particular emphasis on scientific policies for monitoring migratory and endangered species.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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