

REVIEW

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The European tracking network through time: united efforts to advance aquatic conservation in Europe

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Abstract

Biotelemetry networks have transformed our capacity to study the movements and ecology of aquatic animals, yet their development has been geographically uneven over time. While North America and Australia (among others) already hosted mature, well-coordinated infrastructures in the early 2000s, Europe has long lacked a formal framework for collaboration. The European Tracking Network (ETN) emerged in 2017 as a grassroots response to this gap. Since then, ETN has grown tremendously and has become a sustainable network with a central data system and research infrastructure installed all across Europe, enabling collaborative research on a multitude of species and environments while maintaining a strong track record in capacity building. ETN operates through a decentralised model in which national and regional partners lead infrastructure deployment while contributing data to a shared data platform that adheres to FAIR principles and supports collaborative tools, interactive dashboards and a dedicated R-package. ETN has successfully enabled a growing body of transnational research on species movements, habitat connectivity and behavioural ecology, as well as meta-analyses that maximise data reuse and help reduce animal use. At the same time, ETN faces challenges common to large-scale telemetry initiatives, including the need for stable funding, potential equipment incompatibility, the risk of false-positive detections, a potential lack of community buy-in, and ongoing discussions around data ownership and proper attribution. By working proactively with the community and stakeholders, ETN could address most of these potential challenges through the development of open transmission protocols, by aligning data policies with community needs, and by enhancing stakeholder engagement. Looking ahead, ETN is positioning itself at the interface of digital twins, machine learning, multisensor integration and responsible stewardship. Together, these efforts are transforming ETN into a key component of a global aquatic animal observatory, supporting evidence-based management and conservation across European aquatic ecosystems and beyond.

Keywords European tracking network, Community collaboration, Aquatic animal tracking

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Aquatic animal tracking networks—the global landscape

Biotelemetry has become an essential tool for studying the spatial ecology of aquatic animals, playing a crucial role in informing management and conservation efforts [1–3]. Collaboration across administrative borders, facilitated by data sharing, enables researchers to track fish beyond a specific study area [4–7]. Acoustic telemetry is a particular animal biotelemetry technique that benefits greatly from international collaboration. The wide applicability of acoustic telemetry is partly due to the fact that it can be used in both freshwater and the marine environments as acoustic signals do not attenuate in high conductivity conditions, compared to radio signals. Acoustic telemetry uses acoustic transmitters that emit signals with a uniquely-coded ID which can be detected by a network of acoustic receivers if a transmitter is within the vicinity of those receivers (note that the detection range can differ according to the environmental circumstances [8–10]). Internationally coordinated acoustic receiver networks are therefore highly valuable for obtaining new fundamental knowledge about fish movement and informing adequate management.

Since the implementation of the Census of Marine Life Tagging of Pelagic Predators (TOPP) and Pacific Ocean Shelf Tracking (POST) projects, established in 2000 and 2002 respectively [11], several large-scale tracking networks have been established worldwide (Fig. 1). Collectively, they fostered rapid collaboration among researchers and enabled the deployment of wide-ranging monitoring arrays around the globe, covering both marine and freshwater environments. POST laid the groundwork for the Ocean Tracking Network (OTN), launched in 2008 and headquartered in Canada, which has since become one of the world's largest biotelemetry networks. OTN is a distributed scientific infrastructure, maintaining thousands of acoustic receivers around the world with dedicated annual maintenance of core arrays in the Pacific and Atlantic Oceans. Animal detection data are then archived in the OTN database, now holding over

2 billion animal detections from over 300 species [12]. As OTN nodes, many regional and national networks benefit from its resources (e.g. infrastructure, database) and contribute to the broader understanding of aquatic animal movements by matching tag data across broad scales.

There are now many other tracking networks operating across different regions in North America [13, 14] (Fig. 2). The Atlantic Cooperative Telemetry (ACT) network, launched in 2005, initially focused on Atlantic sturgeon and has since expanded its scope to all acoustic telemetry studies from Maine to North Carolina. The Great Lakes Acoustic Telemetry Observation System (GLATOS), established in 2010, is a bi-national (US-Canada) network of researchers aiming to understand fish behavior in the Great Lakes to support fisheries management [14]. The Northeast Pacific Acoustic Telemetry Network (NPACT) was established in 2024 and contributes to the study of movement ecology of marine species along the eastern Pacific coastline from Alaska to Baja California in Mexico. FACT, founded in 2007, was initially conceived to track coastal fish and sea turtles in east-central Florida, and has since expanded in geographic scope and membership to include state and federal wildlife agencies, universities, non-profit and private marine research organizations operating throughout the Southeastern U.S. [15]. Similarly, the Integrative Tracking of Aquatic Animals in the Gulf (iTAG), founded in 2014, fosters a collaborative scientific approach by bringing together movement ecologists, stock assessment scientists, and industry partners to advance the use of movement data for the management and conservation of aquatic animals across several U.S. States, with additional members from Mexico, Cuba and the Caribbean [16, 17].

Other initiatives use centralized databases to support collaborative research, offering tools for data sharing and visualisation as well as contributing to the coordination of tracking activities. The Pacific Aquatic Telemetry Hub (PATH) and the Riverine Acoustic Fish Telemetry Network (RAFT) are two such initiatives. PATH facilitates a collaborative data exchange network for data owned by

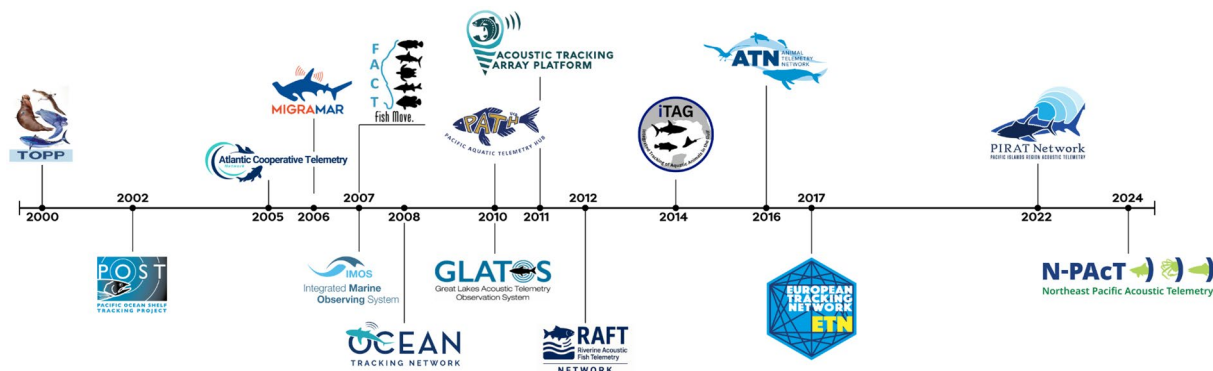


Fig. 1 Timeline of establishment of the animal biotelemetry network initiatives across the globe



Fig. 2 Areas of operation of the different animal biotelemetry networks

a variety of agencies and institutions. In contrast, RAFT was initially established to coordinate tracking of invasive carp in the Illinois River of the Midwest U.S. but has since expanded to support tracking of all fish species across the Mississippi River Basin. With the proliferation of telemetry initiatives across the United States, the U.S. Animal Telemetry Network (ATN) was established in 2016 to coordinate regional acoustic telemetry nodes under the IOOS Marine Life Program and to support these nodes through funding for infrastructure (both cyber- and detection infrastructure) and staff.

Other telemetry networks exist beyond North America (Fig. 2), with examples such as **MIGRAMAR**, a collaborative network of scientists focused on the conservation of marine migratory species in the Eastern Pacific Ocean, and the Pacific Islands Region Acoustic Telemetry (**PIRAT**) network, a consortium established to study the movements of aquatic animals in the Pacific Islands. In Australia, the **IMOS**-Animal Tracking Facility comprises a continental-scale monitoring array and a coordinated data repository that has supported tracking efforts since 2007 [18]. Similarly, in South Africa, the Acoustic Tracking Array Platform (**ATAP**), hosted by the South African

Institute for Aquatic Biodiversity, provides a backbone of acoustic telemetry hardware to facilitate the large-scale, long-term monitoring of acoustically tagged marine animals along the South African coastline [19, 20].

Despite the widespread use of acoustic telemetry and obvious advantages, large-scale tracking networks remain unevenly distributed. While North America, Australia, and South Africa have established collaborative networks, other regions such as South America, Asia and parts of Africa still lack comparable infrastructure or are in the early phases of developing it.

Notably, Europe has long lacked a formal network organizational structure [21]. Although Europe's biotelemetry users were booming and publication records increased sevenfold in the span of a decade (2007–2017), it was not until 2017 that the first steps towards establishing a formal network initiative were taken. During a workshop (organised within the framework of the AtlantOS project) the potential structure of a European Tracking Network (ETN) was discussed. This led to four main actions: (i) capacity building, (ii) creation of a centralized database (iii) the identification of key sites for new infrastructure installations, and (iv) the identification of priority

species for telemetry research in European waters (Abecasis et al. [21]). Through a COST Action (CA18102), the implementation of these action points was initiated and from November 2018 until March 2023 much effort was devoted to capacity building and research coordination across Europe. Since its initiation in 2017 up to the present day, ETN has grown into an established network with a central data system, research infrastructure across Europe (Fig. 2) and four acoustic telemetry arrays implemented at key straits in Europe (STRAITS project) [22]. In addition, it performs collaborative research on a multitude of species and environments and has a strong capacity building record, ticking off all the action points proposed in 2017.

ETN has evolved into a grassroots collaborative international network of scientists in Europe that share expertise, infrastructure, and knowledge. The network uses primarily acoustic telemetry as a tool to learn how to better understand, protect and manage aquatic animals in support of European policy priorities, breakthrough science, and cutting-edge technological innovation. ETN aims to be a sustainable, efficient, and integrated pan-European aquatic biotelemetry network embedded within the international context, as we also collaborate intensively beyond Europe.

Many telemetry networks facilitate data sharing between their affiliated researchers and across networks. This inter-network sharing has created a global aquatic animal observatory. Currently we are extending this capability by linking ETN to intergovernmental initiatives like the Global Ocean Observing System (GOOS) and the Group on Earth Observations Biodiversity Observation Network (GEO BON). These initiatives are important vehicles for collecting observations and translating critical ocean data to policymakers, industry and the public. These observations and measurements are mainly translated in Essential Ocean Variables and Essential Biodiversity Variables, which both support reporting against internationally agreed conventions and treaties [23, 24]. Recently, the Animal Movement Biodiversity Observation Network (MoveBON) was initiated under GEO BON and will help the global aquatic animal observatory to transform the raw movement data and tracks into conservation policy at national and global scales.

ETN: a grassroots tracking initiative

ETN operates as a decentralised, bottom-up initiative where institutions, rather than a centralised governing body, lead infrastructure development and data collection. This structure allows for greater flexibility, innovation, and inclusivity, making it well-suited for managing the diverse and complex aquatic ecosystems and organisational setups in Europe.

However, to empower ETN members for active collaboration—ensuring a robust, flexible, and impactful network—ETN has some general principles that it should adhere to.

1. *Collaborate, communicate and disseminate knowledge*: ETN develops ways and opportunities for the aquatic animal tracking community within Europe and beyond to gather, develop ideas, train peers and collaborate. ETN fosters the building of bridges between the scientific user community, policy, industry and society on a European and global scale. ETN communicates in an open and inclusive way, and disseminates the knowledge gathered to diverse stakeholders.
2. *Implement a research infrastructure*: The network initiates, implements and supports telemetry research infrastructure at strategic locations across Europe, in all aquatic realms.
3. *Equipment compatibility*: ETN aims to improve the usefulness and inter-applicability of currently available technology, and foster technological advancements.
4. *Support FAIR and Open data*: The network centralises quality assured and quality controlled data in the ETN database. The ETN data platform allows for an efficient data preservation and curation, assures efficient data access through tools and services adopting FAIR (Findable, Accessible, Interoperable, Reusable) data principles.
5. *Care*: We work towards a future in which we strive to become more sustainable, provide input on how to improve animal welfare standards, and encourage Diversity, Equity and Inclusion (DEI) in our membership base.

These principles connect the ETN members and allow them to independently implement specific actions on a local and regional scale that serve the overall objectives of the network. Principles are explained in the following sections.

Celebrating successes

Success in numbers

Since its inception in 2017, ETN has grown in the number of users, receivers deployed, and free-swimming fish with active tags. Abecasis et al. [21] showed that the biotelemetry community in Europe was rapidly increasing, but without a formal network, accurate estimations of the infrastructure deployed in European waters was lacking. In less than a decade, ETN has grown from few to 626 users.

By the end of 2025, ETN had an infrastructure of almost 4000 acoustic receivers in the water, listening to

over 7000 active tags. There are currently 44 218 unique tags uploaded on the ETN database. For 21 379 deployed tags, their battery life has already ended, and 17 013 are already purchased and ready to be deployed.

As illustrated in Fig. 3, the number of active tags has strongly increased since ETN's establishment, with the number of active receivers showing a similar trend over time.

The momentum of aquatic animal tracking in Europe has been growing since ETN's establishment. It took 5 years for the number of tagged animals (and receiver deployments) to increase from 1000 to 5000, but only 2 years to increase from 20 000 to 25 000 animals tagged and from 15 000 to 20 000 deployments (Fig. 4a,b). The formalisation of ETN also resulted in a centralisation of data from ongoing projects in 2017 and encouraged researchers to use the ETN database as their data management platform, as exemplified by the consistent increase in acoustic detections gathered (Fig. 5b).

ETN is aware of more than 28,000 animals of 161 species that have been tagged in European waters, with diadromous species (mainly *Anguilla anguilla*, *Salmo salar* and *Salmo trutta*) being the most commonly tagged. These are followed by species from the Family Gadidae, Sparidae, Cyprinidae, Moronidae and Esocidae, with all other families having less than a thousand individuals tagged (Fig. 5). Species with decreasing population trends and endangered species have been an important focus of research conducted by ETN members, including various

diadromous species as well as several species of skates (Rajidae).

Since ETN's inception, receivers have been deployed at 5 778 fixed locations (i.e., stations) for a total of 19 950 deployments, of which 19 249 represent acoustic telemetry receivers and 701 as underwater acoustics (being C-PODs (341), F-PODs (130), soundtraps (118) and other hydrophones (95)) (Fig. 6a).

The ETN database holds a total of 1 billion 'raw' detections from animal-borne tags deployed on animals as well as internal receiver tags (typically used for positioning systems or range testing) (Fig. 6b). Of these, 350 M are "known" tags for which both tag and animal metadata are available in ETN.

Installed detection infrastructure

Unlike a centrally controlled system where decisions are made by a single governing entity, ETN uses a decentralised model for research infrastructure deployments. In ETN, different countries and institutions independently manage tracking arrays across the continent, resulting in almost 4000 active deployment stations (Fig. 3), and ensuring that detection infrastructure aligns with national research priorities and funding availability. This decentralised, bottom-up approach fosters adaptability and enables local researchers to take ownership of their projects, fostering innovation and investment in long-term research. In this way, individual research institutions and regional networks can respond swiftly to local ecological and management challenges. Unlike

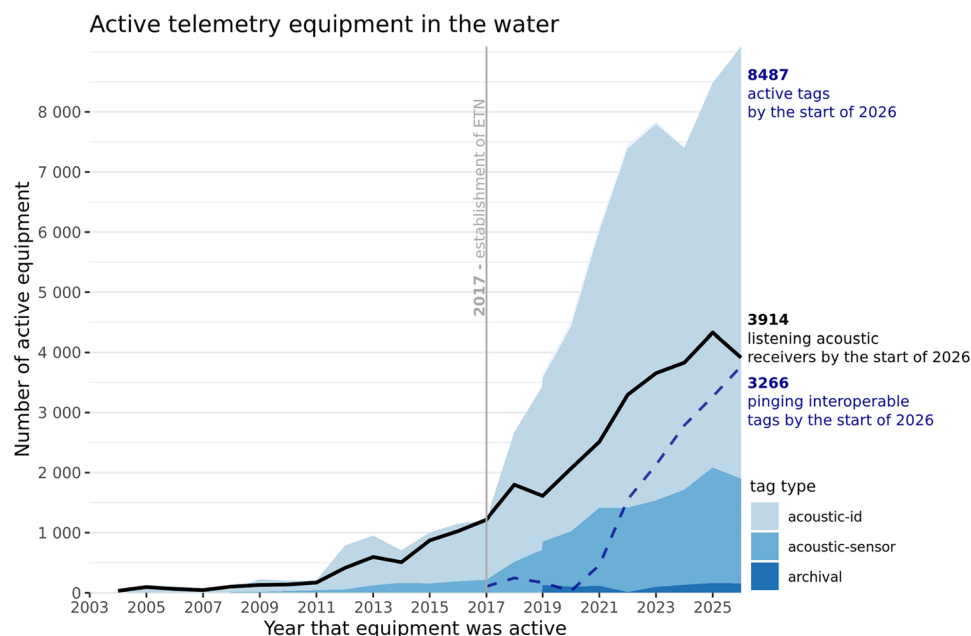


Fig. 3 The evolution of number of active tags and receivers deployed over time. Black line indicates active acoustic receivers in the water. Blue area represents number of active tags in the water over time, distinguished by tag type. Dashed blue line indicates the number of interoperable tags in the water (defined here as being either on Open Protocol (OP) or on the R64K protocol). The ETN database holds historical data (i.e. data older than its inception)

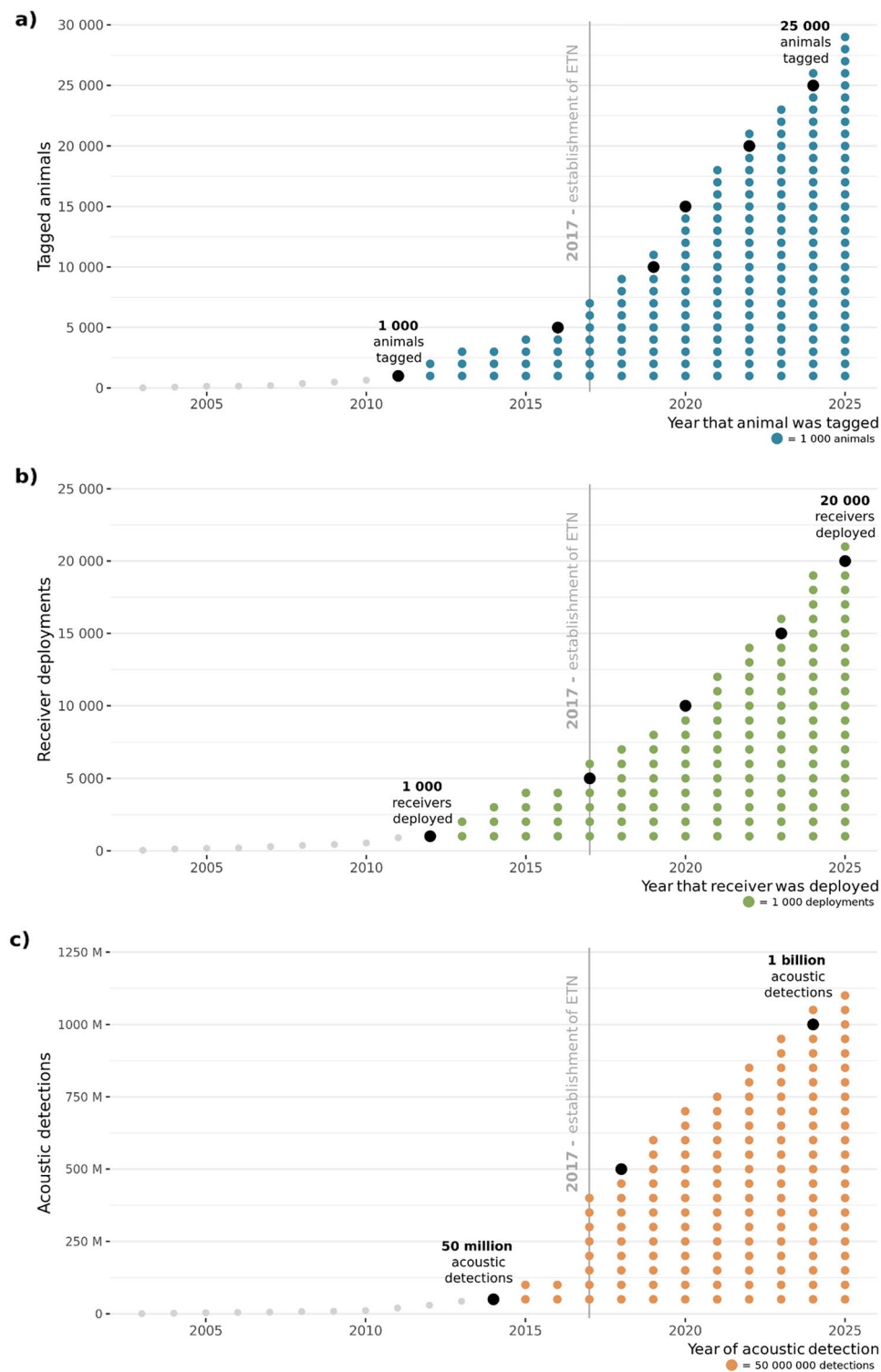


Fig. 4 Cumulative number of data and metadata uploaded to the ETN database over time, consisting of **a** animals tagged, **b** acoustic receivers deployed, **c** acoustic detections generated. Detections include data from tags deployed in animals, and non-animal related tags (sync tags, range test tags, etc.). Black dots represent milestones per **a** 5 000 animals tagged, **b** 5 000 receivers deployed, and **c** per 500 000 000 detections uploaded. Small grey dots represent data smaller than the unit represented by one colorful dot

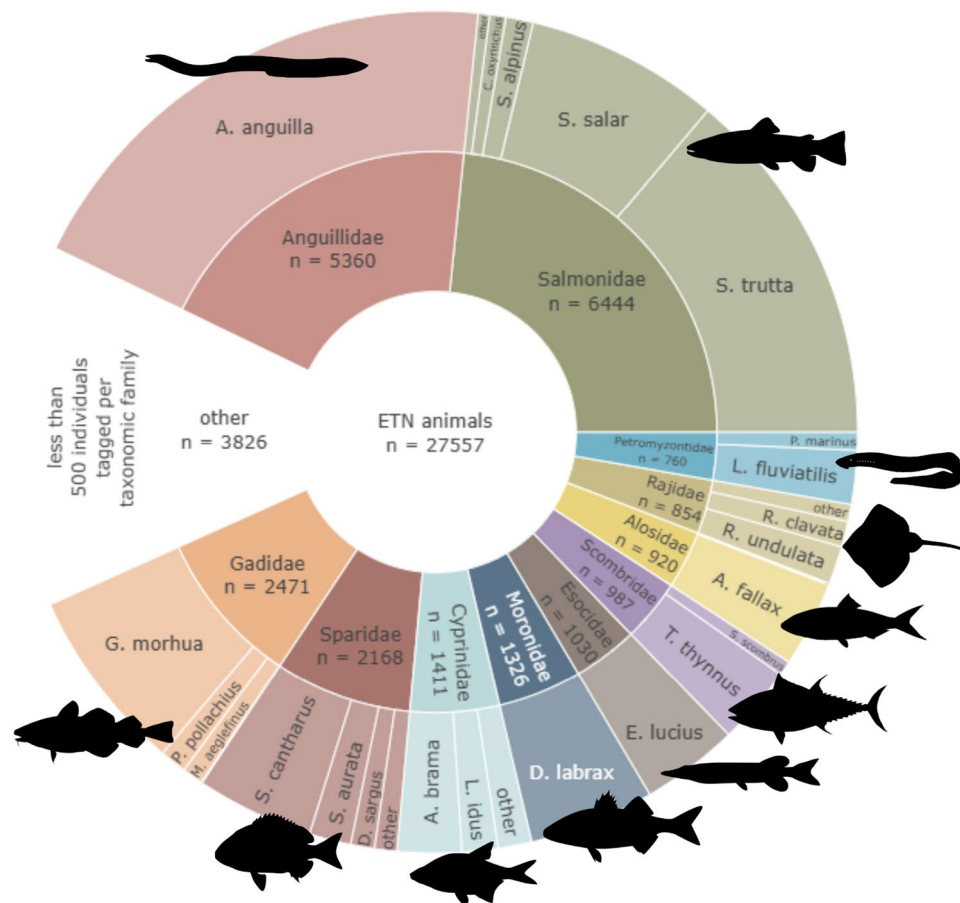


Fig. 5 Sunburst plot of number of tagged species and Family they belong to. As of 2025–12-05

centralised networks, which may suffer from bureaucratic inefficiencies and slow adaptation to emerging issues, decentralised initiatives empower institutions to develop solutions tailored to their specific environmental conditions [25]. Studies in environmental governance suggest that decentralised systems are more effective in addressing ecosystem variability because decision-making is closer to the field, and practitioners can experiment with locally suited methods before scaling up [26]. In ETN, telemetry arrays are operated independently, meaning that if one institution encounters funding challenges or technical issues, the rest of the network continues to function. This built-in redundancy is particularly valuable for tracking migratory species that traverse multiple jurisdictions, as no single entity holds the responsibility (or the risk) of maintaining the entire system. Additionally, by avoiding reliance on a single funding source, the network remains adaptable to changing financial landscapes, reducing the likelihood of systemic collapse. However, a decentralised infrastructure model also poses some dangers. A lack of long-term stable funding sources or non-compatible equipment across regions can have serious implications for the networks as a whole

(as explained in Sect. "Challenges ahead and potential solutions").

Installed data infrastructure

One of the key successes of ETN is the implementation of a sustainable central data infrastructure for the community that provides ETN with balanced data accessibility and institutional control. ETN adheres to the FAIR data principles [27], centralising data storage while allowing institutions to manage and control their own contributions. Unlike some databases where contributors have limited control over data access, ETN's model respects institutional autonomy while promoting data sharing, increasing overall research efficiency and innovation.

Research has shown that collaborative networks that prioritise open data policies, while still allowing contributors to maintain ownership, generate more impactful scientific insights [28]. By allowing institutions to upload data while maintaining governance over how it is accessed and cited, ETN enhances participation.

The key strength in centralized data storage lies in its collaborative power. Since all detection data is in one database, people have access to detections of their

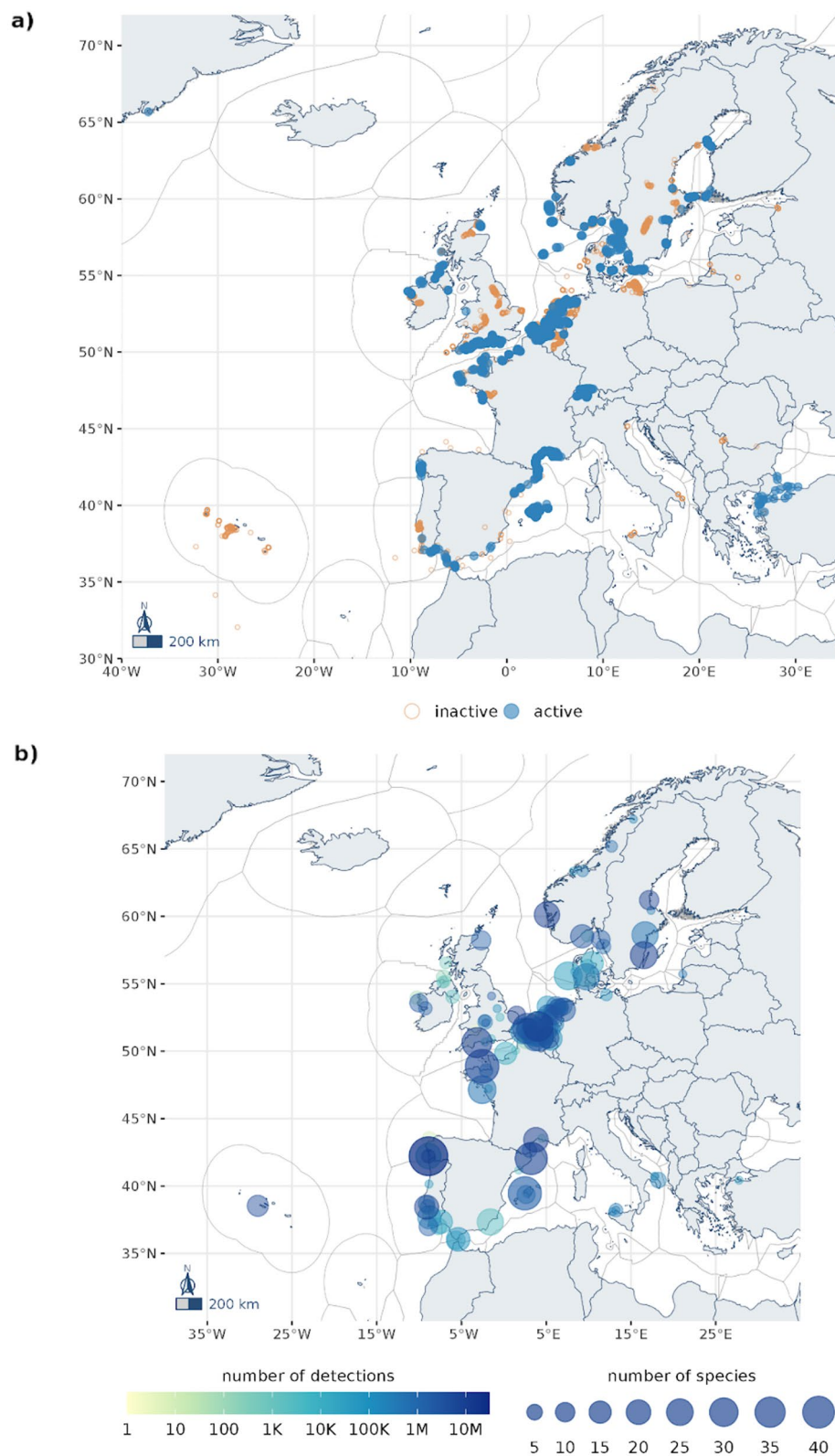


Fig. 6 **a** Spatial distribution of receivers deployments uploaded to the ETN, inactive deployments are shown in orange and deployments currently in the water are shown in blue (as of December 2025). For map clarity, only the latest deployment per station is shown. **b** Spatial distribution of detections (log 10 transformed) and number of species detected at each acoustic telemetry array. A detection constitutes a match between the tag IDs registered by a receiver and the animal metadata provided by the user, historical duplicate tag IDs, tag transmission collision and environmental noise may generate false detections that could be included in this figure (See 2.2.3)

animals beyond their receiver array and receivers owners have a potential to find the owners of detected tags. This represents an important incentive for researchers and institutions to collaborate and centralise their data. In addition, by archiving the data in a central repository, it is also preserved for the long-term and remains accessible for future (re)use [27].

The ETN data infrastructure consists of a central database to store the data, an online interface (ETN Data Platform) to upload or edit data, as well as several related services. ETN provides tools and procedures that ensure best practices in FAIR data management (Fig. 1 supplementary material).

Each ETN project has a linked (via unique identifier) metadata page in the Integrated Marine Information System (IMIS), [29] a public and searchable catalogue of metadata that links information on people, institutes, projects, datasets, publications and events related to marine, coastal, estuarine and riverine topics. Naming conventions (WoRMS, Marine Regions), thesaurus lists (ASFA Thesaurus List, CSA Technology Research Database Master Thesaurus, Transportation Research Thesaurus, etc.) and keywords are used in these metadata records to optimise findability and reusability. ETN also offers the possibility of creating a DOI (via DataCite) for completed and public datasets.

The ETN Data Platform is open to all telemetry users, with no cost. ETN makes a distinction between Public data, publicly accessible, and data under temporary embargo, restricted to data owners and collaborators for a specific period of time. Public data registered under an open licence (CC0, CCBY, CCNC or CCSA) are routinely reported to international biodiversity data repositories, as downdata in DarwinCore format, including the Ocean Biogeographic Information System (OBIS), the Global Biodiversity Information Facility (GBIF) and the European Marine Observation and Data Network (EMODnet). ETN collaborates with global and European Digital Twins (DTs) by creating essential data flows of Public Data registered under an open licence to these models. The European Digital Twin Ocean (EDITO) is one such example where the connection from ETN to EDITO allows us to design and run applications in the digital twin environment. By establishing a data flow from ETN to DTs, we support enhanced decision-making, resource management, and sustainable solutions, which are crucial for addressing global and local challenges. Further, data exchange between OTN and ETN is performed to ensure maximum connectivity across the different regional tracking data systems.

Another important part of the data-infrastructure is the ETN Virtual Research Environment [30], which is a digital environment of data exploration and reporting tools.

The requirements of large-scale collaborative projects, however, are more complex than the knowledge and data sharing already in place. Effectively answering research questions that involve species migration across borders requires an aligned setup of receivers and coordinated tagging efforts within international collaborations. To facilitate these efforts, interactive dashboards and automated reports provide a powerful toolbox [31]. The ETN-VRE is a set of standalone applications that feature interactive dashboards, automated reports and R-packages. Interactive dashboards allow users to get an intuitive, fast insight into their data while automated reports save time in documenting and communicating research efforts, which is relevant for reporting purposes or to attract funding. The ETN R-package [32] provides functions to access and process data from the ETN database, while the ETN-occurrences package contains scripts to publish fish tracking data from ETN to GBIF and OBIS.

Science

The ETN has played a role in expanding the spatial and thematic scope of acoustic telemetry research across Europe. By fostering transnational collaboration, facilitating data sharing, and offering collaborative infrastructure—including a secure database, data analysis tools and training—ETN has significantly strengthened the collective capacity to study aquatic animal movements, behaviours, and life-history traits at multiple scales. For example, Goossens et al. [5] used ETN infrastructure to reveal overwintering and potential spawning areas of seabass (*Dicentrarchus labrax*) in the southern North Sea, challenging assumptions of southward winter migration and raising concerns about the spatial mismatch between fisheries management and seabass ecology. In the English Channel, the FishIntel project [33] deployed an extensive acoustic receiver array across French, English, and Belgian coasts. Using the ETN data management platform and associated analytical tools, this work uncovered consistent seasonal site fidelity and highlighted the ecological importance of the Irish Sea for pollack (*Pollachius pollachius*) throughout the year, particularly during summer. Furthermore, Labourgade et al. [34] tagged *Scyliorhinus canicula* to investigate how offshore wind farm (OWF) infrastructure influences shark behaviour. The study found that most individuals displayed strong site fidelity and seasonal residency near a monopile structure with scour protection, especially during warmer months, underscoring the role of anthropogenic structures as potential habitats. Martorell-Barceló et al. [35] collected a multi-species dataset, spanning 34 species, to explore among-individual differences in circadian behavioural traits. This study revealed different chronotypes across 17 different species, thereby bridging scientific gaps between marine ecology and chronobiology. These case

studies illustrate how ETN is not only enabling novel biological and ecological scientific outputs but also reshaping how we approach the monitoring and management of aquatic species across national borders. As it continues to grow, ETN holds the transformative potential to revolutionize our collective capacity to study aquatic animal movements, behaviours, and life-history traits across spatial, temporal, and ecological scales, ultimately informing more adaptive and ecosystem-based management of marine and freshwater resources.

Transnational scientific collaborations, empowered by ETN, have catalyzed large-scale, multinational research initiatives that go beyond individual case studies. Collaborative work in aquatic telemetry is not new [36], but the establishment and maturation of ETN has dramatically expanded the geographic and thematic reach of such efforts [7, 37, 38]. ETN members have successfully secured multiple rounds of funding to develop continent-wide tracking infrastructures and conduct ambitious research programs. It has also fostered a vibrant scientific exchange through the organization of the bi-annual ETN Symposium (initiated in 2019), which has become an excellent platform for knowledge sharing, interdisciplinary collaboration, and the development of innovative approaches in aquatic animal tracking and ecology.

Meta-analyses offer another interesting pathway to go beyond the potential of individual or spatially restricted studies. Combining data from independent tagging studies can fill fundamental and applied knowledge gaps on the wider geographical distribution area of a species [39]. This is particularly relevant for widely distributed species or those whose feeding and spawning habitats are far apart, as impacts in one part of their range can affect the whole population. However, bringing ‘independent’ datasets together is not trivial, as they are often stored on local (i.e. institutional) servers or even personal drives. It is therefore beneficial to upload telemetry data to a central data repository to support broader uptake and align with the FAIR principles [27]. This not only reduces the chance that data gets lost but can also stimulate the reuse of ‘dormant’ data that can be found and applied by others in large-scale spatio-temporal analyses. Another important advantage is that when extracted from a central repository, all the data have the same standardized formats, reducing the effort of data processing substantially before proceeding to data visualisations and analyses. It is likely that in the near future, data visualisation and analysis software will be developed based on the data formats from international repositories, facilitating complex analyses. In addition, reusing data prevents studies from being duplicated and/or reduces the number of tagged animals. This is in compliance with the three ‘R’ principles in European animal welfare, i.e. reduction, replacement and, especially, refinement [40].

Together, these efforts of collaborative science, collaborative projects, and meta-analyses illustrate how ETN has evolved into a transformative force in aquatic research, fostering a new era of cross-border collaborations to go towards an ecosystem-scale understanding of aquatic animal behaviour. As the network grows, so too does its potential to reshape the conservation and management of aquatic species and environments in Europe and beyond.

Training

Developing the capacity to monitor ocean life requires sustained, long-term investment in people and their institutions [41]. ETN is committed to providing continuous training and networking opportunities and promoting knowledge transfer, with a particular focus on early-career researchers (ECRs). To achieve this goal, ETN offers training schools, webinars, online platforms, and opportunities for travel grants.

To identify training needs within the community, ETN conducts surveys that engage researchers as well as key stakeholders, including NGOs, resource managers, and representatives from the fisheries sector. These surveys help identify the most pressing capacity gaps and emerging priorities, thereby guiding the strategic selection and prioritization of training topics that best serve the community’s evolving needs. By also assessing the willingness of community experts to act as trainers, ETN facilitates the development of training activities across a range of formats, including webinars, online courses, and hands-on workshops.

In addition, ETN promotes short-term scientific stays and conference participation for ERCs. These exchange visits provide valuable opportunities for researchers and are great opportunities for researchers to share techniques and acquire skills that may not be available at their home institutions. ETN also develops and shares training materials via its YouTube channel and continues to seek funding through philanthropic initiatives and dedicated programs to sustain these efforts.

Challenges ahead and potential solutions

The organisation of large-scale network initiatives introduces challenges and limitations specific to interjurisdictional telemetry networks that are less pronounced at smaller scales. Identifying these challenges and proposing potential solutions is a first step towards successful, long-term implementation.

Sustainable funding sources

Large, interjurisdictional telemetry networks now exist to serve aquatic industry and management worldwide, demonstrating a clear track record of success and reinforcing the ETN as a strong investment in science that

supports the United Nations Sustainable Development Goals (UN SDG) and a sustainable blue economy in European seas [1]. The ETN has not been a top-down initiative by the European Union nor has it been advocated for as a tool that could support Regional Fisheries Management Organisations (RFMOs) like North Atlantic Salmon Conservation Organization (NASCO), International Commission for the Conservation of Atlantic Tunas (ICCAT), International Council for the Exploration of the Sea (ICES), General Fisheries Commission for the Mediterranean (GFCM) and North-East Atlantic Fisheries Commission (NEAFC) or conventions (like the Oslo-Paris Convention (OSPAR)).

Our vision for the ETN is to maintain a compatible data system headquartered at a central facility and to build out an infrastructure network that operates and maintains tracking infrastructures to observe animals across the European seascape. Efforts to identify the key points for instrumentation were formalised by Abecasis et al. [21]. However, a tracking infrastructure network is expensive to deploy and maintain, particularly in remote areas, offshore, and deep-sea environments. A high initial capital investment is needed for equipment and deployment logistics, and maintaining receiver networks requires continued investment in the form of skilled personnel, battery replacements and a high turn-over rate of infrastructure replacements (as a result of the harsh environmental conditions the equipment is exposed to). Most available research grants are based on short-term funding cycles of three to four years, creating a mismatch between funding needs and availability of infrastructure. Since individual institutions are responsible for securing their own financial support, disparities can also arise between well-funded research groups and those with limited resources. This imbalance can create data gaps in certain geographic areas and in time, limiting the ability of ETN to provide comprehensive tracking coverage for migratory species. Smaller institutions may face particular difficulties in maintaining long-term receiver arrays, as sustaining such infrastructure often requires ongoing financial and technical support [3], and access to large vessels and expertise for working at sea. It is therefore critical that ETN transitions towards long-term funding models, as exemplified by other networks North America and Australia. Looking ahead, ETN seeks to establish a fully coordinated and standardized approach to animal tracking across spatial and temporal scales, positioning it as a powerful tool for advancing ocean observation and supporting sustainable marine management. In addition, ETN should seek inclusion in national and EU-coordinated monitoring programs (e.g. European Strategy Forum on Research Infrastructures) or frameworks including options such as MoveBON, GEOBON and GOOS. Partnerships with community stakeholders from

both the public and private sector should also be stimulated (see challenge 2.2.3), as engagement with fisheries, offshore industry companies and eco-tourism operators can lead to shared stewardship through increased awareness (helping to reduce equipment loss or damage), support in equipment maintenance (e.g. diving operator or fishing vessel maintaining a receiver at a remote location), and the stimulation of ocean literacy.

Equipment compatibility

A major challenge for large acoustic telemetry networks has been the lack of compatibility between infrastructure from different manufacturers. Effective tracking networks should ensure that tagged organisms are detectable across receivers regardless of their brand or who manages them. Proprietary and encrypted protocols have been introduced by manufacturers to prevent ID duplication, but have ultimately restricted cross-brand compatibility. As a result, research initiatives, particularly in Europe, have faced significant collaboration challenges, as independently managed receiver arrays often used incompatible equipment, limiting the potential of large-scale studies on species movement, habitat connectivity, and ecosystem monitoring [42].

ETN has worked to address this issue by promoting the development and implementation of Open Protocols (OP) for acoustic telemetry, which were designed in collaboration with equipment manufacturers to ensure interoperability [42]. OP are a set of standardized, open transmission protocols that enable seamless operation between acoustic telemetry devices at the 69 kHz frequency. Field testing in the main aquatic environments, including rivers, coastal lagoons and open sea locations, has demonstrated that OP devices perform comparably to proprietary systems in terms of detection range and efficiency while also exhibiting lower rates of false detections compared to older shared protocols such as R64K [10].

The implementation of OP represents a significant step toward greater collaboration in aquatic animal tracking, reducing technological barriers and making the field more accessible to a broader scientific community. By shifting from proprietary constraints to a shared standard, OP not only facilitates data collection but also encourages innovation by fostering a more competitive and cooperative fair market. This development highlights the power of bottom-up technological advancements, where researchers and manufacturers collaborate to develop solutions tailored to scientific needs rather than being restricted by commercial interests.

However, the currently available OP (i.e., OPi and OPs) represent only a mid-term solution to a broader structural challenge. Future efforts should focus on expanding OP adoption while also promoting the development

of a community-driven, entirely open-source telemetry framework that is not dependent on manufacturer-specific limitations. This next step should include other signal encoding systems beyond 69 kHz PPM and ensure long-term interoperability, cost efficiency, and greater flexibility for researchers.

By increasing accessibility and control over tracking technologies, there are multiple advantages for the scientific community both in terms of innovation (products easier to bring to the market, more potential manufacturers), economies of scale (avoiding overlapping receivers between different research groups and bulk buying), and collaboration on streamlining deployment. Hence, such an approach would greatly benefit the study and conservation of aquatic species on a global scale.

False-positive detections

Acoustic telemetry can be prone to false-positive detections wherein a receiver decodes and stores a transmitter ID that is different from the ID actually transmitted by the tag [43, 44]. False-positives can result from the collision of two or more transmitter signals, but also from ambient noise (interfering with the transmitter signals or with the receivers themselves) or transmitter signal reflections in reflective environments (e.g., concrete canal banks; Vergeynst et al., [45]). In some cases, false-positives can be confidently identified, for example when a detection occurs outside the time window than the transmitter was active in, when a detection is picked by just one receiver in a dense network, or if the detection location is impossible (e.g. the detection of a marine fish in freshwater, a detection far outside the distribution range of a species, or a single detection past a series of receivers without any detections on these devices). However, in some cases it is difficult to address false-positives and to distinguish them from real detections.

With the implementation of large-scale detection networks allowing tracking tagged animals beyond a single study area, and the accompanying data sharing, the identification of false-positive detections becomes more challenging, yet particularly important. False-positives can have substantial negative impacts on data analyses and potentially even on management advice [46]. Therefore, it is important to perform quality control on the data to prevent false-positive detections from being used in data analyses or integrated in other data platforms. For instance, (open) data flows from ETN to GBIF, OBIS and the European digital twin of the ocean. The latter can be used for scenario testing of potential consequences of human impacts (see section 'Envisioning the future') making it crucial that false-positives are not integrated in the data analyses.

Consequently, it is necessary to perform data controls and quality checks to avoid false-positive detections being

included in analyses. One approach that is frequently used, is to remove detections that occur only once on a receiver [43]. However, these may still be true detections, especially in areas with low detectability and/or transmitters with a large signal transmission delay. Removing these single detections may therefore result in the loss of true, sometimes even crucial detections. Therefore, the implementation of a thorough algorithm to identify false-positive detections is urgently needed [44].

With the further development of acoustic telemetry, more recent protocols are less prone to false-positive detections. Especially with the evolution towards digital signal transmission (i.e., BPSK signals) the problem may become less important.

Community buy-in

The ultimate strength of the ETN will depend on community buy-in from the different stakeholders and how ETN, its users, and its data are used in the quintuple helix framework of academia, industry, government, society, and the environment [47]. Research indicates that effective collaboration between scientific communities and policymakers significantly improves the practical application of environmental data in decision-making [48, 49]. The ultimate goal of the network is to generate data usable in innovation, decision-making and policy creation [38] that supports society and the natural environment. To do so, we need a multi-stakeholder engagement. Academic research supports this approach, suggesting that stakeholder engagement in the data interpretation process increases the likelihood of scientific insights being integrated into policy framework [50]. However, bridging the gap between telemetry data products, decision-making, and policy is a challenge and not yet at its maximum potential. ETN could, for instance, support decision making in RFMOs and additional efforts to interact are needed. An important lesson learned in recent projects has been the importance of early engagement with non-ETN stakeholders to foster a sense of shared ownership and encourage data-sharing. In the Turkish STRAITS Array, for example, the project team successfully navigated complex licensing requirements by proactively engaging Turkish government agencies and the local fishing community. This engagement not only facilitated necessary permissions but also helped to reduce the risk of equipment loss due to fishing activities. Similarly, in the Irish North Channel, delays in marine licensing highlighted the need for stronger relationships with national regulatory authorities to streamline future deployment processes. In an earlier telemetry project, SeaMonitor (2019–2023), local angling clubs were engaged from the beginning of the project which led to some of the clubs purchasing additional acoustic transmitters to bolster datasets as part of the project.

Moving forward, ETN aims to strengthen stakeholder mapping efforts, ensuring that the right data products are developed to meet user needs. Subsequently, by delivering short presentations to regulators and expert groups, we aim to highlight potential use cases for telemetry data to inform stock assessments and species management action plans.

Finally, an important lesson learned from ETN's projects is that collaborating with existing environmental monitoring networks can enhance data uptake and increase overall stakeholder participation. In Gibraltar, STRAITS successfully integrated its telemetry network with oceanographic monitoring initiatives, increasing both efficiency and reach. Similar strategies have been recommended in the literature on European Research Infrastructures, where leveraging existing networks and regulatory frameworks has been shown to improve data integration and stakeholder engagement [51, 52]. By ensuring that telemetry data aligns with legislative frameworks like the Marine Strategy Framework Directive (MSFD) and the EU Biodiversity Strategy 2030, ETN can further improve community buy-in and long-term sustainability.

Data-ownership

While efforts to improve network participation and equipment compatibility continue, the long-term success of ETN also hinges on the development of data-sharing policies that provide guidance in balancing open-access policies with the need to protect individual research investments. Data should be as open as possible (which is a requirement of many funding organisations) but also needs to be as closed as needed to protect data ownership. At times, these data ownership and collaboration dynamics can create friction between network participants. Researchers may be hesitant to share their detection data, fearing that their contributions will not be adequately acknowledged or that their findings could be used without proper credit [28]. It is equally important to acknowledge the contributions of both tag owners and the owner-operators of independent receiver arrays. It has broadly been accepted that detection data are attributed to the owner of the detected animal tags – a system that works well in regions with shared management of large-scale arrays, few independently operated arrays, or infrequent animal movements between discrete arrays. However, in European waters, where numerous independent arrays operate in close proximity and animal movements often span multiple countries, an evolution of the procedures used to determine data ownership is needed. The consequences of these procedures is made greater by the grassroots structure of the ETN, where individual research groups shoulder the responsibility of producing scientific output, while also establishing and maintaining

their own receiver array infrastructure – often at considerable personal and financial cost. An opinion piece entitled, *People behind the “pings”*, [53] highlights the challenge of ensuring fair attribution for array owners and operators. Central to their message is the lack of standardised procedures for acknowledging array operators despite significant investment required for ongoing data collection and receiver array maintenance, which are essential to telemetry research. They further assert that a lack of recognition could exacerbate the financial burden placed on array operators by impeding their ability to acquire necessary funding for maintaining (semi-)permanent networks. Furthermore, limitations restricting the number of people eligible to receive credit or co-authorship places underrepresented groups (including ethnic and gender minorities, as well as early career researchers) at greater risk of being overlooked, hindering career development and funding opportunities (Jordan et al. in prep.).

To assess community perspectives on data sharing and ownership, a survey was conducted, eliciting responses from 94 telemetry users from across the globe. Survey participants were primarily scientists (94%) at various career stages (senior researchers with 52% best represented) and from multiple continents, with the majority based in Europe (84%). Most correspondents were members of one or more telemetry networks, including 70% from ETN.

Survey responses indicated a gradual shift in the community's perspective on data ownership, moving away from the traditional model that attributes detection data solely to tag owners. While 94% supported traditional data ownership – granting tag owners access to detections recorded by receivers outside their study – 70% believed receiver owners should have similar access to data on animals detected by their receivers but tagged in other studies (Fig. 7). In this context, 'external receiver owners' refer to those operating receivers that detect animals from other tagging studies, while 'external tag owners' are those whose tagged animals are detected by receivers outside their study. Recognition of external receiver owners for scientific outputs varied, with 35% in favor of acknowledgment for significant contributions, 31% supporting general acknowledgment, and others preferring case-by-case discussions between tag and receiver owners. Meanwhile, external tag owners were more often seen as warranting guaranteed (44%) or conditional acknowledgment (27%), determined by significant contribution, with 27% favoring case-by-case discussions. Co-authorship was generally seen as negotiable, with most correspondents advocating for discussions between tag and receiver owners. For the inclusion of external receiver owners as co-authors, 56% advocated a need for discussions, 32% supported inclusion based on

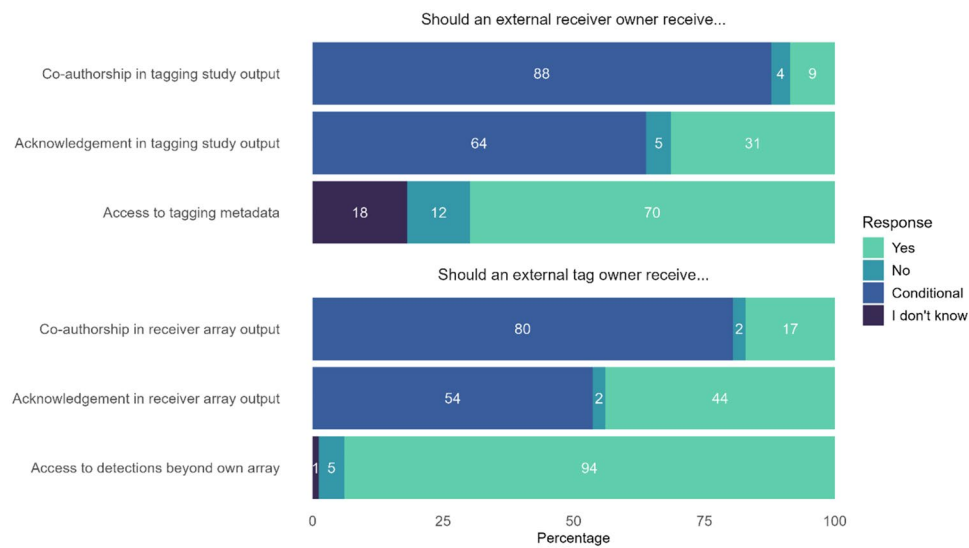


Fig. 7 Survey responses reflecting the views of telemetry users on co-authorship, acknowledgement, and data access between studies. Questions address two scenarios: (i) scientific outputs include data from tagged fish detected by receivers owned by a different research group (external receiver owner), and (ii) scientific outputs include detections of fish tagged by another research group (external tag owner)

significant input, while only 8% supported automatic co-authorship and 4% opposed it entirely. A similar pattern emerged for including external tag owners as co-authors in outputs related to a receiver array, with 43% favoring discussions, 38% supporting conditional inclusion, 17% agreeing outright, and 2% opposing.

A key takeaway from these responses is the shared belief in the need for ongoing discussions among independent telemetry users to establish terms for acknowledgement and co-authorship. Hawkes et al. [53] similarly identified the risk of losing such discussions due to the ‘depersonalisation’ of centralised databases, which could impact telemetry networks like ETN. While communication remains essential for ensuring fair recognition and fostering collaboration, clearer guidelines on how receiver and tag owners should be properly accredited and solutions for balancing open-access principles with fair attribution are still needed.

To accommodate the identified risks and incorporate the community needs/requests, ETN has established standardised guidelines based on FAIR data principles. In addition, it updated its data policy [54] in 2025, moving away from the traditional detection owner vision, allowing a more balanced ownership. The ETN data policy offers guidance while allowing room for discussion and self-governance among telemetry users. Fundamentally, ETN’s policy follows the traditional approach, granting tag owners access to all detections of their tags, regardless of receiver ownership. However, receiver owners also gain access to species information for tags from external studies that are detected by their receivers. The policy also clearly states that proper attribution should be given to all contributing data providers (through

project citation or referencing the DOI of datasets). An additional clause states that parties must agree on a suitable level of attribution (including but not limited to co-authorship and acknowledgement) if certain conclusions cannot be stated without the detection data provided by external data contributors. This addition should promote inclusion and fair accreditation for all contributors without free-riding in co-authorship, which should be avoided to continue to meet academic standards. Citation guidelines [55] are available to help steer the data users to properly acknowledge and cite data collaborators.

Envisioning the future

Animal tracking networks are dynamic and must continually adapt to keep pace with contemporary developments in tracking hardware and software, data storage capabilities, and evolving best practices in data and animal welfare, while maintaining strong connections with stakeholders, funding opportunities, and scientific development. Long-term solutions for the many of the aforementioned challenges have already been suggested and are currently being implemented (Table 1). New opportunities lie ahead, but maximising their potential requires anticipating future developments and understanding their associated benefits and challenges. Identifying relevant near-term changes will allow ETN to assess their potential impacts and determine how best to integrate them into its objectives and long-term goals.

Digital twins

The European Tracking Network is now well-positioned to contribute to ongoing efforts to create Digital Twins of the Ocean (DTO). Digital twins (DTs) are digital

Table 1 Summarizing the challenges encountered by the collaborative tracking networks and (potential) solutions that ETN envisions

	Challenges encountered by collaborative tracking networks	Solutions the ETN is incorporating or envisioning to do in the future
Funding	Networks have long-term funding needs, while funding sources are often short-term, insufficient or unequally accessible	Advocacy for long-term funding models and inclusion within European Strategy Forum on Research Infrastructures in combination with grass-roots institute/researcher driven local coordination and advocacy. In addition, promote a centralised, shared infrastructure and strategic arrays/straits
Equipment compatibility	Proprietary/encrypted coding schemes preventing interoperability of equipment across manufactures, preventing cross-network detections	Creation of standardised open transmission protocols (OPI and OPs) to ensure interoperability among different systems. Have an MoU and licence agreement in place and have an independent ID allocation authority
False-positive detections	Identifying false-positive detections is challenging in a network context. Can have negative consequences in management and scenario-testing	Shift towards more recent protocols, potentially using other decoding technologies. Implement robust algorithms to identify false-positive detections
Community buy-in	Achieving strong community buy-in from diverse stakeholders is challenging	Adopt the Quintuple Helix Framework and promote multi-stakeholder engagement from early on in the process. Map your stakeholders
Data sharing	Balancing open-access data sharing with protection of individual research investment and ownership is challenging. Definitely if data, authors and institutes are not properly cited or, acknowledged	ETN Survey to assess perception of the community. ETN data-policy in place and easily accessible citation guidelines provided to the community

counterparts to physical objects or phenomena and can play a key role in learning more about the functioning of our marine ecosystems, exploring future scenarios and supporting decision-making and policy development. DTs represent real physical objects or processes by using data streams to continuously update models to reduce uncertainty and improve realism [56]. DTs usually consist of data pipelines (consisting of sensor data, historical

data and other DT data), a model or models, predictions, and a user interface [57].

The recognition that DTs have great potential to improve our understanding of the natural world and improve decision making has resulted in their interest at high-political levels [57]. Although this concept originated in spacecraft engineering, DTs have more recently been adapted to other domains such as earth and environmental sciences [58]. Specifically, in 2022 the European Commission announced the objective to build a European Digital Twin of the Ocean (EDITO), with two projects at the core—EDITO-Infra and EDITO-Model lab—forming the data-service and modelling components of the public DT infrastructure in Europe respectively. Several major DTO initiatives, including the Iliad project [59], and DITTO [60], are also ongoing both within Europe and globally and will simultaneously integrate with EDITO. Beyond ocean environments, DTs such as the European Commission’s programme Destination Earth are also being developed and may be integrated to create a global DT [61].

While major efforts are underway to produce DTOs worldwide including the EU [60], incorporation of marine animal movement from multiple species is in the early phases. Big-Data inputs can be critical for the success of such DTs [62], consequently requiring broad spatiotemporal data inputs and infrastructure that enables frequent updating from newly acquired data. In the case of marine animal movement, only a large network such as the ETN is capable of addressing these needs. As such, the ETN and collaborators are working to develop DTs of animal movement, demonstrated by initiatives such as DTO-Bioflow [63] and DTOTrack [64], and the contribution of quality controlled open datasets to EDITO. Importantly, detection data contributed to DTOs can be linked with environmental data as well as future environments from other DTs. The ETN can also contribute their experience in animal movement data analysis and visualization by developing new modelling techniques, core to DTs, and interactive data platforms. Existing modelling approaches for bringing aquatic acoustic telemetry data into a digital twin are already wide-ranging, and are expected to continually improve. Current candidates involve ensemble based species distribution models, integrated step selection, and machine-learning approaches. Overall the DT efforts can provide a clear link between the ETN infrastructure and decision making and policy development in Europe.

Machine-learning and Artificial Intelligence (AI)

With the DTs gathering and centralising huge amounts of data, advanced techniques are needed to analyse and understand the large amount of newly generated data, resulting in a rapid expansion of the use of AI-based

methods by researchers across disciplines [65] including ecology [66, 67], and enabling major scientific advancements [68]. For example, machine-learning, a subfield of AI that enables systems to learn and improve from data, has been used to solve the protein folding problem far earlier than anticipated [69]. Machine-learning methods are, however, data-hungry and often scale in performance with increasing data availability [70], provided that any additional data are properly quality-controlled. Concurrently, movement ecology is undergoing a big-data revolution, reflected in the growth rate of detections within the ETN (Fig. 6) where the amount of data per project is orders of magnitude larger than it was two decades ago and the cost-per-animal-position has been steadily declining [71]. In this way, data generated by acoustic telemetry are well suited to benefit from machine-learning approaches, particularly when aggregated across a coordinated network.

To support cutting-edge research, the ETN must maintain a proficiency and expertise in machine-learning methods, and as a community, pioneer new ways of applying these approaches to the datasets that have been collected. A first step in embracing this revolution is to continue providing expert-led tutorials that introduce and integrate machine-learning methods into acoustic telemetry data analysis and workflows. Furthermore, foundational models such as large language models (e.g., Claude, ChatGPT, DeepSeek, and Gemini) can now facilitate the broader uptake of new methods by enabling rapid access to information, fast prototyping of tools, and streamlined data analysis through AI-based code assistants. They also provide powerful deep-research capabilities and help overcome traditional language barriers — an essential advantage for international networks that involve many countries. When used thoughtfully, these tools will accelerate the pace-of-discovery using acoustic-telemetry and reduce the training time needed for students and early career researchers to gain proficiency in working with acoustic-telemetry data.

Machine-learning based methods offer numerous potential advancements to acoustic telemetry research. Specifically, these methods commonly perform well at classification tasks, and with the development of attention-based approaches like transformer algorithms [72] that capture long-term patterns within time-series, we anticipate that machine-learning will improve our ability to segment and interpret animal behaviours from acoustic positions and movement trajectories. Furthermore, deep-learning, as a subfield of machine learning, uses multi-layered artificial neural networks to automatically learn intricate patterns from raw data, capturing relationships within highly complex systems. In the near future, this might allow us to better predict animal movements by combining acoustic telemetry data with

environmental datasets that include abiotic, biotic, and anthropogenic variables. Such approaches would help to clarify future climate impacts or anthropogenic stressors on movement and migrations of aquatic animals, and subsequently, these predictive models could be used directly to construct or contribute to digital twins. In realms outside of marine ecology, transformers have been shown to successfully classify [73] and predict mobility [74]. It therefore appears likely that similar approaches will eventually be adapted for marine and/or freshwater acoustic telemetry-based datasets.

Despite these powerful opportunities, machine-learning and artificial intelligence also present new challenges [75] that the ETN must confront. Regulations around artificial intelligence are in their early stages, but the EU has recently adopted the AI Act (EU 2024/1689) by which uses of AI will be assessed based on risk level, and high risk applications must comply with a set of standards including performing a risk assessment, mandatory usage high quality data, logging of activity, inclusion of human oversight, high quality documentation, adequate information to any deployed, and robust cybersecurity measures. Most applications of AI in relation to aquatic telemetry would currently be considered of minimal or no risk, but in some cases where AI might enhance poaching or negative ecological exploitation, high-risk threats could be possible. Additionally, the EU has released guidelines for best practice by researchers, institutions, and funding agencies [76]. Of particular relevance are the responsible use of intellectual property and compliance with data privacy and licensing agreements. As a community, the ETN will need to work hard to guarantee that data is not uploaded to train new models without required permissions [77]. Finally, the ETN will need to weigh the ecological impacts of data centres behind the use of many foundational models with the research benefits [75].

Stewardship

Effective stewardship of animal tracking networks is vital for the sustainable management of wildlife populations. It requires a balanced approach that integrates ecological science, technology, ethics, policy, and community engagement to ensure that tracking efforts contribute not only to the long-term conservation of species and their habitats, but also to equity in science. Animal tracking networks can fulfill an important community stewardship role, which carries key responsibilities: promoting the suitability of equipment and practices, ensuring high standards of animal welfare, and encouraging diversity, equity, and inclusion (DEI) in its membership base (Table 2). These principles are embedded in ETN's core values. Through our network of infrastructure, scientists,

Table 2 Key stewardship aspects of animal tracking networks, their role & responsibilities and recommended actions a network can take

Animal tracking network Stewardship:		
Key aspects	Role & responsibility	Recommended actions
Sustainability	Represent the tracking network in pushing for suitability of equipment and actions	Voice the need to improve product sustainability to the manufacturers. Establish relationships with other initiatives working on equipment sustainability. Provide up to date information on actions network members can take to improve their sustainability. Centralise meeting points to facilitate sustainable travel
Animal welfare	Guard the (ethical) obligations toward good animal welfare practices in the field	Provide up to date information on best practice on animal handling. Enable network community discussions to learn and improve on best practices
DEI (diverse, equitable and inclusive)	Embracing a diverse, equitable and inclusive tracking community and represent the diversity within the community	Create a mission statement that includes network vision on DEI. Perform a network wide DEI GAP analysis. Take directed actions to bridge the gaps identified

data, and knowledge, we undertake the following actions to fulfill this stewardship role.

Critically, we encourage sustainability in acoustic telemetry infrastructure, including the technology used (animal tags, receivers), associated materials (anchoring and deployment), and our actions (e.g., the centrality of bi-annual meeting locations). At the 2024 ETN meeting, a moderator-led session [78] with representatives from each leading animal tag manufacturer discussed current steps and identified potential avenues for enhanced sustainability in manufacturing and technological streamlining (e.g., integrated tag sensors, co-deployment platforms, rechargeable receiver batteries). Future efforts will be focused on “greening” technologies and materials. For example, non-recoverable receiver moorings are commonplace given the prohibitive cost and often logistics of mooring recovery. Also, decreasing the environmental hazard posed by lithium tag batteries should be considered both by researchers and manufacturers [79]. As a platform with many members, ETN encourages manufacturers to offer more cost-efficient mooring recovery systems, enabling users to reduce their research footprint. In addition, we provide guidance on sustainability practices for network members through an information page on the ETN webpage.

In recent years, significant steps have globally been taken to improve the welfare of animals used in science and to develop guidelines for best practice for a range of aquatic species (e.g., cetaceans [80]; batoids [81]; tunas [82], general reporting [83]). Within aquatic tracking, studies have investigated the effects of animal capture [84], handling [85], tagging effects [86–89], and provided guidelines on when tagging is appropriate [90,91]. The ETN aims to add to this knowledge and improve welfare standards by enabling the community to record and store data on the methodology of animal capture, tagging (i.e., internal versus external tagging and type of anaesthetic and/or analgesic used), and recovery. By gathering this information in a central database, meta-analyses can be performed to identify current approaches and provide recommendations for future research. ETN also supports the three Rs of animal research (replace, reduce and refine) [92,93] by hosting a central database. Researchers can *replace* the need to tag animals through the use of existing data, *reduce* tag numbers by identifying existing data holders, and *refine* animal use protocols through contacting current project holders with experience working with the proposed species. As we enter the 9th year of ETN, we aim to support further integration between tracking networks to promote data sharing and collaboration and co-develop best practice approaches to animal protocols. The next step is to communicate best practices to improve animal welfare, which we will do through our website and quarterly newsletter. We will further facilitate the exchange of information on best practices by enabling network community discussions during the bi-annual ETN meeting.

ETN strives to improve diversity, equity, and inclusion (DEI) within its member group. We promote fair treatment and pan-European participation by providing an accessible platform for researchers to promote their projects and foster collaborations. In addition, we provide opportunities for early-career researchers from European countries to participate in workshops, meetings, and conferences by offering reduced attendance rates and travel grants. By making the infrastructure, databases, and knowledge network available to all, we work to diversify our member group, promote data use for different purposes, and promote knowledge sharing. However, we need to take further steps and ensure that DEI approaches are operationalized throughout the community. We will begin by identifying areas for improvement by performing a network-wide GAP analysis, which we will use to take directed actions to bridge the gaps.

Multi-sensor integration and ocean best practices

The next phase of ETN will be defined by its ability to combine diverse sensor technologies into an integrated observation framework that serves both science

and policy. Acoustic telemetry remains the backbone of coordinated aquatic animal tracking, providing scalable, long-term monitoring across European waters. However, addressing complex, management-based questions, ranging from climate-driven distribution shifts to fisheries sustainability, requires complementing existing approaches with additional tools. This can initially be achieved by extending the available tracking technologies (e.g. data-storage tags, passive integrated transponders, radio telemetry), and later by deploying integrated suites of biotic and abiotic sensors capable of measuring (semi-)continuous over longer time scales (weeks to months). Such approaches offer significant advantages by linking movement patterns to environmental drivers in near real time. When collected at appropriate scales and resolutions, these observations provide valuable contributions to the ocean observing community and to monitoring Essential Ocean Variables [24, 94]. For instance, Calonge et al. [95] combined passive acoustic monitoring with telemetry arrays to simultaneously track fish and detect marine mammals, revealing patterns of species co-occurrence relevant to ecosystem-based management. In addition, the advent of real-time detection systems across telemetry arrays, passive acoustic monitoring devices, and environmental sensors would allow immediate cross-referencing of biological and physical data streams, enabling quicker responses to unusual movements, environmental anomalies or potential threats. Such capability would transform the network from a retrospective research tool into a dynamic, operational monitoring system.

The challenges ahead are not purely technological. Standardising protocols, ensuring interoperability across networks, and fostering open data sharing will be critical [42], as will addressing the cultural and structural barriers to multi-disciplinary collaboration. Ocean Best Practices System (OBPS) repository can help to easily discover and access best practices in ocean observing [96]. And the ETN community, with its extensive experience in ocean-going activities can help improve existing practices and develop new methods on a broad range of topics (including infrastructure deployments, FAIR data-management and stewardship activities). Realising the full potential of a multi-sensor ETN will require biologists, oceanographers, engineers, data scientists and policy specialists to work in truly collaborative frameworks—an approach that is still too rare in marine monitoring [3]. For example, integrating ecological datasets with high-resolution oceanographic measurements demands shared research priorities, compatible workflows, and mutual understanding of disciplinary constraints and opportunities [97]. Without deliberate investment in cross-disciplinary capacity building and joint governance mechanisms, multi-sensor systems risk becoming technologically

advanced yet institutionally siloed. Embedding collaboration at the core of network design and operations will allow ETN to deliver not only richer datasets, but also the integrative science needed to inform complex, cross-sectoral marine policy.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40317-026-00475-z>.

Additional file1 (DOCX 71 KB)

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Author contributions

JR: paper conceptualization; writing original draft; writing review; conceptualization of maps, plots and figures LP, CM: writing original draft; writing review; conceptualization and creation of maps, plots and figures JER, RMCG: writing original draft; writing review; language and grammar check All other authors: writing original draft; writing review.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

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