Movement Ecology in Fisheries Management and Conservation

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Sumário pormenorizado da lição apresentada à Universidade do Algarve para obtenção do título de Agregado na área das Ciências do Mar, da Terra e do Ambiente, ramo Ciências do Mar, de acordo com o disposto na alínea c) do artigo 5º do Decreto-Lei nº 239/2007 de 19 de junho (Publicado no D.R. 1ª Série)

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Preamble

This lecture is part of the proposed Movement Ecology course unit, designed to be included in several Master programmes at the University of Algarve, namely the Master in Marine Biology, Master in Aquaculture and Fisheries, Master in Marine and Coastal Systems, and the International Master of Science in Marine Biological Resources (IMBRSea). This course responds to the growing scientific and relevance of movement ecology, an interdisciplinary field that combines animal tracking technologies, ecological analysis, and provides crucial information for biodiversity conservation and fisheries management.

The present lecture - Movement Ecology in Fisheries Management and Conservation - corresponds to one of the core theoretical classes of the course. Its objective is to demonstrate how movement ecology principles, particularly through the use of biotelemetry, can inform fisheries management strategies and marine conservation efforts. It integrates theoretical content together with case studies, enabling students to understand the direct application of key concepts to real-world management and conservation contexts.

Introduction

Movement, the change in spatial location through time, is one of the most fundamental and basic features of life (Nathan et al. 2008). It occurs in all species - including plants, algae, coral, and fish - at some point in their lifetime, and is a critical process for their survival and fitness.

The study of movement in animals has interested humans for centuries. From early times humans have noticed and registered information on the seasonal migration of birds and on the movements of anadromous fish up the rivers to spawn.

Movement is key in many ecological processes at the individual, population and ecosystem levels (Nathan et al. 2008). At the individual level movement defines habitat use, with consequences on energy and nutrient transfers between habitats. It also relates to species interactions such as competition, trophic interactions or symbiosis. Population dynamics are influenced by species movement as these have an important role in gene flow, population connectivity and spatial distribution (e.g., Abecasis et al. 2024).

But movement also contributes to many evolutionary processes. Gene flow and genetic diversity are highly associated with movement. Species with higher dispersal capabilities tend to have an increased genetic diversity within populations and reduced genetic differentiation (Gandra et al. 2021; Palumbi 2003). Furthermore, restricted movement can result in genetic isolation, which can lead to speciation (Palumbi 1994). Movement capabilities will determine how species react to the local environment and its selective pressures having a significant impact on local adaptation. For example, size selective fishing, an example of selective mortality, can have a significant impact on species evolution (Heino et al. 2015; Conover and Munch 2002).

Movement ecology is a relatively recent discipline that gained traction after the seminal work of Nathan et al. (2008) who proposed a unifying paradigm integrating conceptual, theoretical, methodological and empirical frameworks for studying species movements. It focuses on the study of how and why organisms move, the environmental and biological factors influencing their movement, and the consequences of movement for individuals, populations, and ecosystems. Movement ecology integrates concepts from ecology, behaviour, physiology, and environmental science to understand patterns of movement across different spatial and temporal scales (Nathan et al. 2008).

Movement ecology can support fisheries management by informing stock delineation, providing key parameter estimates (e.g., natural mortality) for complex population models, providing data on species' vulnerability to fishing, and enabling the monitoring of by-catch survival (Crossin et al. 2017; Brownscombe et al. 2022; Alós et al. 2022). In the context of conservation, particularly in the planning and management of marine protected areas (MPAs), movement ecology contributes essential insights into species' habitat use, residency, connectivity, and home range areas, which are critical for the effective design and evaluation of MPA networks (Abecasis et al. 2014b; Crossin et al. 2017; Alós et al. 2022).

Animal movement can be studied using a variety of methods, each offering different spatial and temporal resolutions. These include: direct observations of movement patterns (e.g., seasonal migrations of birds or fish); the use of natural markers such as genetic signatures (e.g., DNA), parasite assemblages, photo-identification, or chemical and structural features in hard tissues like otoliths or bones; remote sensing techniques (e.g., radars to track bird migration); and movement modelling approaches, including species distribution models and dispersal simulations (Figure 1). Additionally, tagging methods, ranging from conventional external tags (e.g., Petersen discs, T-tags) to electronic tags such as PIT (passive integrated transponder), satellite, and acoustic transmitters, are widely used to track individual animals (Hussey et al. 2015).

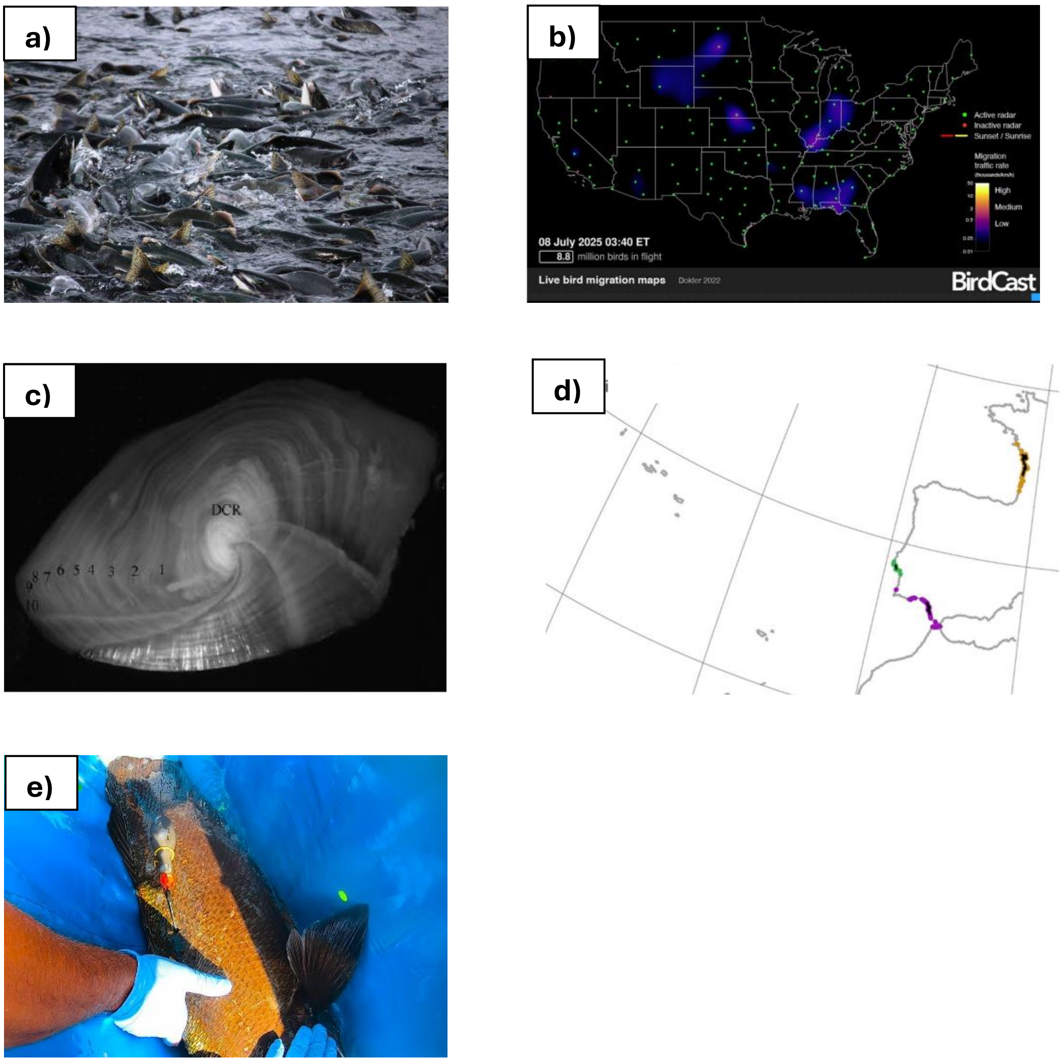

Figure 1. Examples of different methods to monitor animal movements: a) observations (from www.needpix.com), b) radars (www.birdcast.info) c), otoliths (D. Abecasis), d) modelling (adapted from Abecasis et al. 2024) and e) electronic tagging (D. Abecasis).

Electronic tagging, and in particular acoustic and satellite telemetry, has become the most widely used method to track the movement of aquatic species (Hussey et al. 2015). The use of these tools has been increasing steadily since the early 2000's and its application is widely spread across the world's oceans (Hussey et al. 2015; Matley et al. 2022). Recently, acoustic telemetry was recognized as playing an important role in advancing the United Nations Sustainable Development Goal 14 (Life Below Water), by contributing with data that supports the conservation and sustainable management of marine biodiversity (Alós et al. 2022).

Application of biotelemetry-based movement ecology in fisheries management

Movement ecology is a crucial field for fisheries science and management. Biotelemetry, and particularly acoustic telemetry, provides valuable data to researchers and managers by allowing them to track individual aquatic animals over large periods of time (up to several years) within a given coverage area (Hussey et al. 2015). This technology has gained rapid prominence due to advances that enable scientists to track animals in their natural environment aiding in the understanding of how aquatic animals interact with their seascape and anthropogenic activities (Hussey et al. 2015; Allen and Singh 2016).

Acoustic telemetry is a widely used method where signals from implanted or externally attached transmitters are detected and logged by acoustic receivers. This detection data can provide insights of difficult to estimate variables which are key for fisheries management, such as natural mortality, bycatch mortality, and identification of essential fish habitats (e.g., Block et al. 2019; Alonso-Fernández et al. 2022; Fairchild et al. 2013; Lees et al. 2021). However, despite its potential, acoustic telemetry is still considered underutilised in fisheries science and management (Crossin et al. 2017; Brownscombe et al. 2022). This may be due to telemetry studies often focusing on individual movement and differences in scale between telemetry data and management decisions (Brownscombe et al. 2022).

One of its key contributions lies in assessing habitat suitability. Understanding the properties of fish habitats - along with their function and the species they support - is fundamental for informed management (Brownscombe et al. 2022). Acoustic telemetry enables the development of comprehensive Habitat Suitability Index (HSI) models and Resource Selection Functions (RSFs) by continuously monitoring fish space use over extended periods (Brownscombe et al. 2021; Griffin et al. 2021). For instance, multivariate modelling techniques have been applied to telemetry data to generate HSI models for species such as largemouth bass, incorporating spatio-temporal dynamics (Brownscombe et al. 2021). Moreover, the use of transmitters equipped with environmental sensors (e.g., pressure/depth, temperature, acceleration) allows for remote measurements of fish behaviour and physiology (Hussey et al. 2015). These data provide insights into habitat function (e.g., foraging, spawning activities) as well as habitat suitability, including assessments of energetic costs and gains (Sims et al. 2006; Cooke and Hinch 2013).

Another important application of acoustic telemetry is in evaluating spatial scale and connectivity. These aspects are essential for management, influencing the effectiveness of marine protected areas (MPAs), habitat restoration efforts, fish passage designs, and population assessments. Telemetry is particularly well suited for capturing long-term data on fish space use, including estimates of home ranges and core activity areas (e.g., Abecasis et al. 2015a; Abecasis et al. 2015b; Kraft et al. 2024). Telemetry also facilitates the assessment of habitat connectivity by detailing individual movements between distinct habitats or management zones (Abecasis et al. 2009; Kraft et al. 2023; Hussey et al. 2017).

The high temporal resolution of acoustic telemetry enables the detailed exploration of spatial-temporal patterns in fish movements. Unlike traditional sampling methods, telemetry can track fish behaviour almost continuously over multiple years, providing a large temporal coverage. This allows researchers to identify seasonal patterns, site fidelity, and interannual repeatability in habitat use, such as repeated use of spawning sites (e.g., Abecasis et al. 2015a; Kraft et al. 2023).

Empirical Applications of Acoustic Telemetry in Fisheries Management

Specific examples highlight the diverse applications of acoustic telemetry in fisheries management. For stock delineation and structure, telemetry has been instrumental in revising assumptions about the seasonal movements of Greenland halibut (*Reinhardtius hippoglossoides*) in Canada (Hussey et al. 2017). This study showed that halibut regularly crossed the management boundary, contrary to the previous belief that they were resident in winter fishing grounds. The observed movements, strongly influenced by temperature, dissolved oxygen, and sea ice dynamics, prompted a revision of the management boundary in 2014 (Figure 2). This case study demonstrates how telemetry can inform spatial management boundaries based on empirical data.

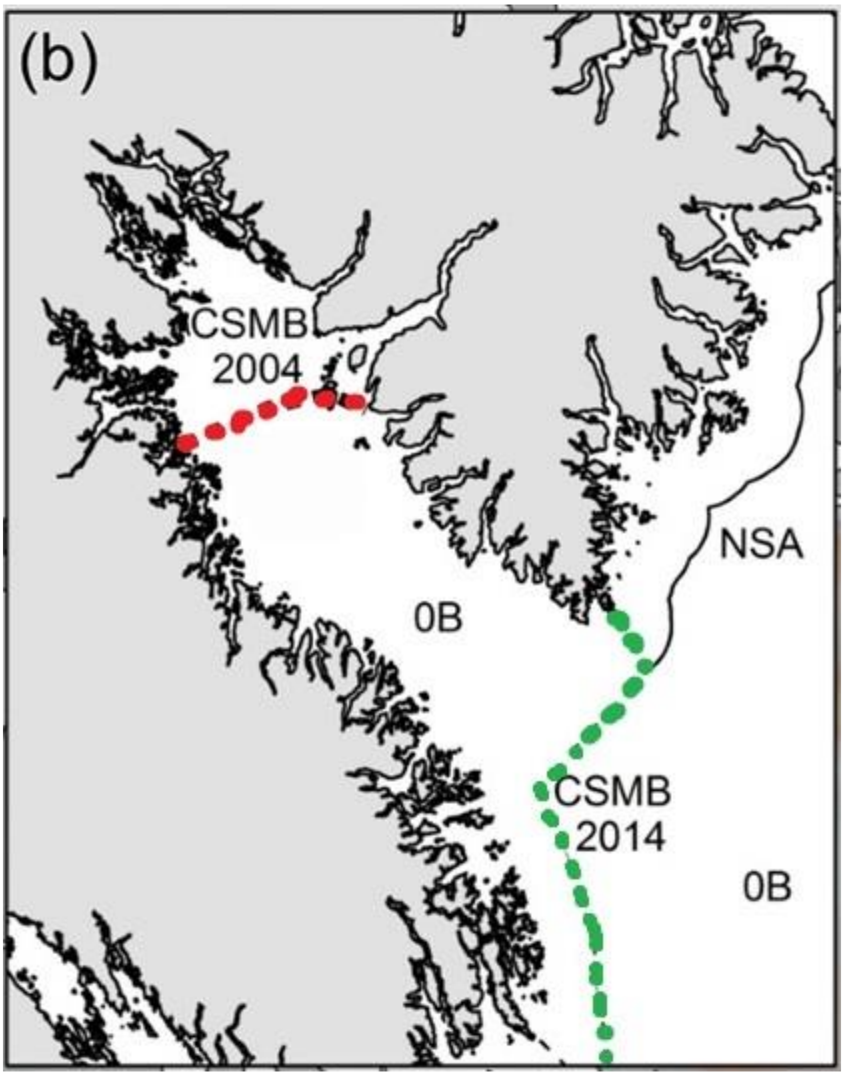

Figure 2. Changes to the management boundaries of Greenland halibut in Cumberland Sound based on a biotelemetry study (adapted from Hussey et al. 2017).

Acoustic telemetry also contributes to estimating vital rates such as natural mortality (M), a key parameter in stock assessment models. For example, tagging of Atlantic bluefin tuna (*Thunnus thynnus*) enabled the application of a spatially structured Bayesian mark-recapture model, based on high detection rates up to 1700 days post-tagging (Block et al. 2019). The resulting estimate of median annual natural mortality offers a valuable fisheries-independent input for refining population models and improving management decisions.

Understanding species-specific vulnerability to fishing gear is another important application. For example, a study on cuttlefish (*Sepia officinalis*), Senegalese sole (*Solea senegalensis*) and white seabream (*Diplodus sargus*) combined acoustic telemetry and species distribution models to infer on the size of suitable areas and vulnerability to fishing inside the Prof. Luiz Saldanha Marine Park (Figure 3; Abecasis et al. 2014b). Results indicated that this MPA provides variable protection to these species strongly linked to the species home range size and the distribution of suitable habitats (Abecasis et al. 2014b).

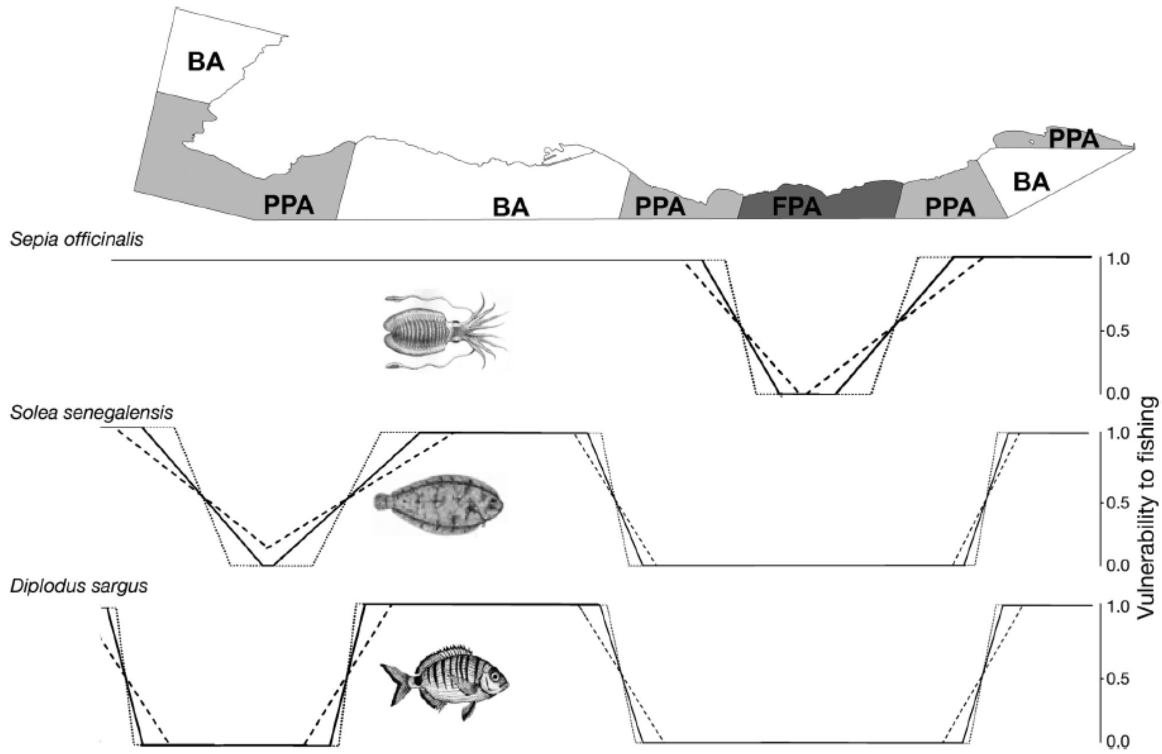

Figure 3. Vulnerability to fishing of *Sepia officinalis*, *Solea senegalensis* and *Diplodus sargus* throughout the Prof. Luiz Saldanha Marine Park. (adapted from Abecasis et al. 2014b).

Movement ecology also plays a vital role in identifying essential fish habitats and supporting connectivity-based conservation strategies. For species like meagre (*Argyrosomus regius*), which exhibits high genetic fragmentation, biotelemetry was used to locate critical habitats such as feeding grounds, nursery areas, and spawning aggregation sites (Figure 4; Abecasis et al. 2024; Gandra et al. 2024). This knowledge, particularly when coupled with data on spatio-temporal overlap with fishing activity, is fundamental for identifying and protecting essential fish habitats, minimising anthropogenic impacts, and preserving habitat connectivity and gene flow through marine corridors.

Biotelemetry is equally important in assessing bycatch and discard survival. In the small-scale fisheries off Galicia (Spain), acoustic telemetry was used to estimate discard survival rates for coastal elasmobranchs such as *Scyliorhinus canicula*, *Raja undulata*, *Raja clavata*, and *Raja brachyura (Alonso-Fernández et al. 2022)*. These results are crucial for informing discard mortality exemptions in European fisheries regulations.

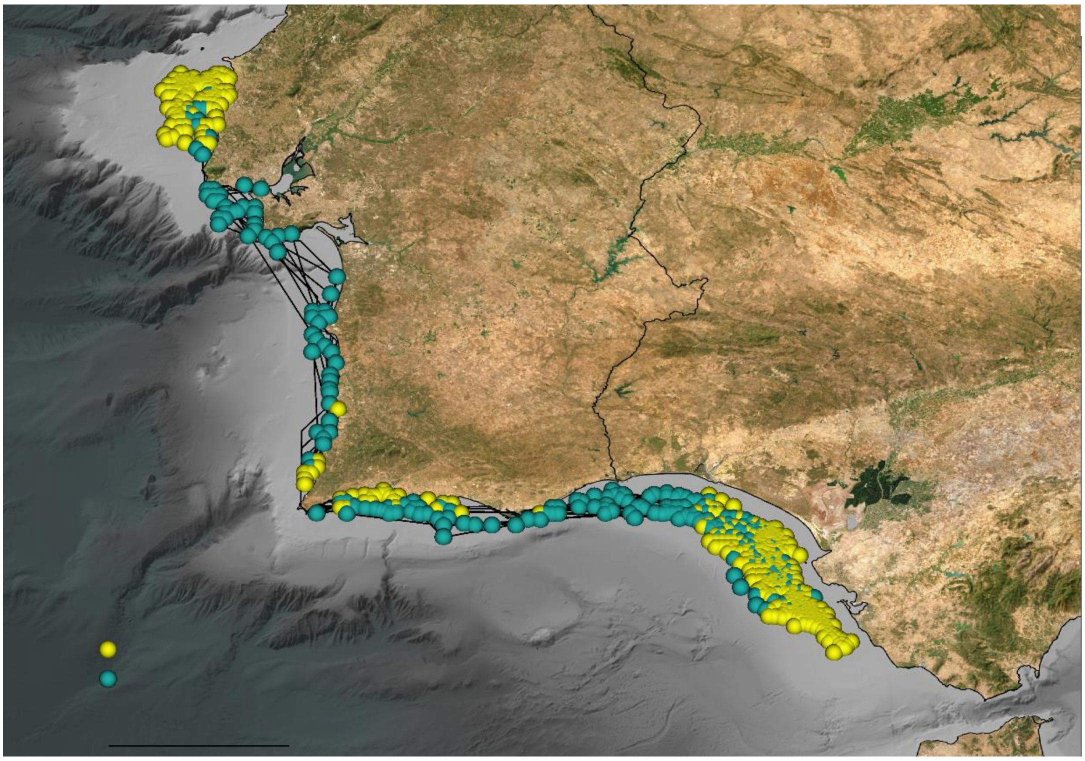

Figure 4. Behavioural states of *Argyrosomus regius* (● - area restricted and ● - transiting) by location area identified based on biotelemetry data and nonparametric Bayesian framework (adapted from Gandra et al. 2024).

Finally, biotelemetry is increasingly being used to understand how fishing pressure affects movement behaviour and potentially drives evolutionary changes. For example, in snapper (*Pagrus auratus*), acoustic telemetry revealed that individuals within marine reserves exhibited unimodal home ranges averaging 900 metres, while those outside had larger, bimodal home ranges (~2100 metres) (Parsons et al. 2010). These findings suggest that protected areas may promote site fidelity or select for particular behavioural traits. More broadly, telemetry offers the unique potential to assess harvest selection on behavioural and life-history traits in the wild, contributing to our understanding of fisheries-induced evolution (Moland et al. 2019).

Collectively, these examples illustrate how acoustic telemetry supports data-driven decision-making in fisheries management.

Application of biotelemetry-based movement ecology in conservation

Biotelemetry has significantly advanced the field of movement ecology, offering vital information for addressing numerous conservation and management challenges in marine ecosystems (Brooks et al. 2018; Fraser et al. 2018).

Movement ecology aims to understand the causal relationships between environmental conditions, animal movements, species interactions, and biodiversity patterns (Nathan et al. 2008). These are key elements for the implementation of adequate and effective conservation measures.

A key conceptual tool is the movement–management framework, which demonstrates how knowledge of animal movement can improve management strategies (Allen and Singh 2016). This framework highlights the importance of understanding key movement attributes - such as food availability, predator avoidance, and environmental drivers - that influence a species' survival and reproduction. Effective management relies on identifying movement pathways and essential fish habitats such as spawning and nursery areas. Such data are crucial for the appropriate spatial planning of MPAs, ensuring that protected areas encompass key habitats at ecologically relevant scales (Moffitt et al. 2011).

Recognising different types of movement - sedentary, migratory, or nomadic - is fundamental, as these determine the appropriate management actions, including preserving connectivity or creating MPAs. Animal movement also plays an integral role in marine ecosystem processes by facilitating the transfer of nutrients across habitats. As marine animals migrate or forage, they transport energy and organic matter - through excretions, gametes, carcasses, or undigested food - linking areas such as coastal zones, reefs, and the open ocean (Roman and McCarthy 2010). These movements enrich nutrient-poor environments, support food webs, and contribute to ecosystem productivity and resilience (Allgeier et al. 2016; Roman and McCarthy 2010). However, these services are increasingly threatened by anthropogenic impacts to seascape connectivity.

Understanding the scale at which species move, including home range sizes and habitat requirements, is critical to match conservation efforts with ecological processes (Moffitt et al. 2011). Management interventions that fail to align with the spatiotemporal scales of species movement are often less effective (e.g., Abecasis et al. 2013).

Despite its growing relevance, integrating movement ecology into conservation policy is hindered by several challenges. These include limited spatial and temporal scope in studies, insufficient data sharing, perceived unreliability of data by decision-makers, and poor communication of the practical utility of movement data (Ogburn et al. 2017; Brooks et al. 2018; Fischer 2024).

To overcome this, it is essential to engage with practitioners and stakeholders from the start, co-create research agendas, and ensure studies meet the needs of end-users (Arseneault-Deraps et al. 2024; Ogburn et al. 2017). Clear communication, effective data visualisation, and directly addressing uncertainties can further improve uptake. Interdisciplinary teams that integrate biotelemetry with genetics, physiology, and oceanography contribute to more robust scientific insights and enhance relevance for policy. Ultimately, building trust and maintaining active relationships with stakeholders is crucial for ensuring that scientific data lead to real-world conservation outcomes.

Empirical Applications of Acoustic Telemetry in Conservation

Acoustic telemetry enables long-term monitoring of individual movements, generating datasets that guide the design phases of MPAs, and help evaluate the effectiveness of conservation actions and guide adaptive management (Abecasis et al. 2014b; Alós et al. 2022).

One major application is the estimation of home range areas, site fidelity, and habitat connectivity for designing Marine Protected Areas (MPAs). For instance, studies on the Senegalese sole (*Solea senegalensis*) in the Prof. Luiz Saldanha Marine Park (LSMP) – a small coastal MPA - revealed that most individuals occupy small areas (average 95% KUD = 1.2 km^2), supporting the effectiveness of this small coastal MPAs for the protection and spillover of this important resource (Abecasis et al. 2014a). Additionally, research on white seabream (*Diplodus sargus*) found that this same MPA can increase abundance and biomass when species have small home ranges and high site fidelity (Abecasis et al. 2015a; Abecasis et al. 2015b).

In contrast, the meagre (*Argyrosomus regius*), a large migratory predator, travels long distances (over 2,000 km) along the Iberian Peninsula (Gandra et al. 2024) suggesting that the implementation of small MPAs will provide limited protection. Thus, identifying key aggregation sites for spawning, feeding or overwintering is critical for the spatial management of this species. Similarly, acoustic telemetry in the LSMP showed that common stingrays exhibit seasonal site fidelity and migrations between the park and the nearby Sado estuary (Figure 5), suggesting the need for protected corridors beyond MPA boundaries (Kraft et al. 2023).

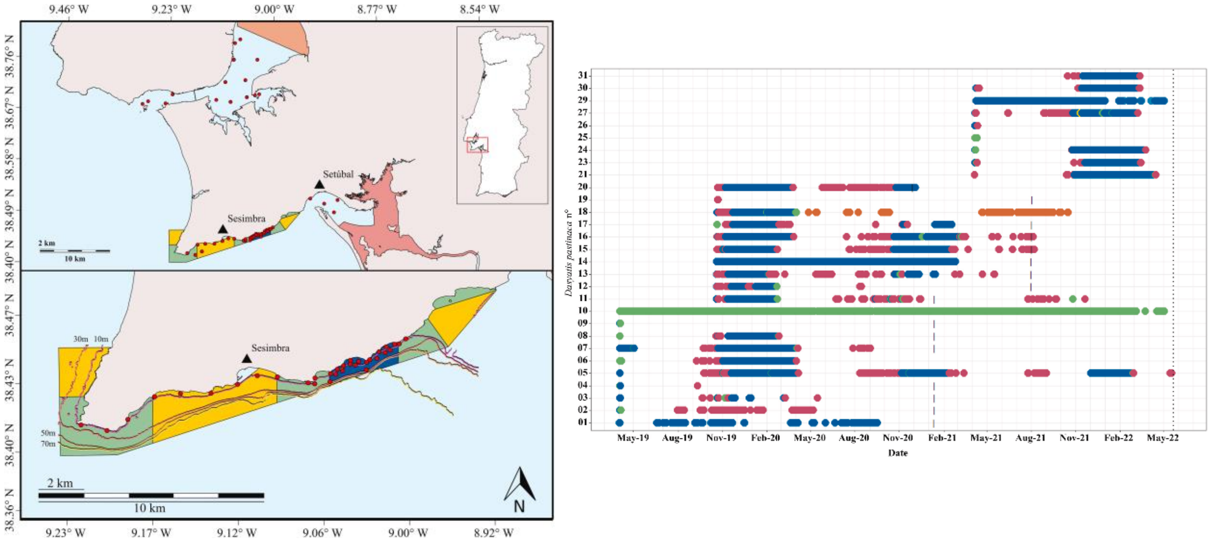

Figure 5. Seasonal movement patterns and residency of *Dasyatis pastinaca* in the Prof. Luiz Saldanha Marine Park and the nearby Sado estuary (adapted from Kraft et al. 2023).

Habitat selection studies reveal species-specific preferences that are essential for informing the effective design of Marine Protected Areas (MPAs). For instance, research on the Senegalese sole (*Solea senegalensis*) identified a clear preference for shallow sandy bottoms (Figure 6). The study also demonstrated that the LSMP contains sufficient areas of this preferred habitat to offer effective protection for the species (Abecasis et al. 2014a). Habitat selection studies should account for the influence of environmental conditions, as these can strongly shape species' spatial behaviour. For example, Freitas et al. (2016) found that sea temperature significantly affects habitat use and selection by Atlantic cod (*Gadus morhua*) along the Norwegian Skagerrak coast.

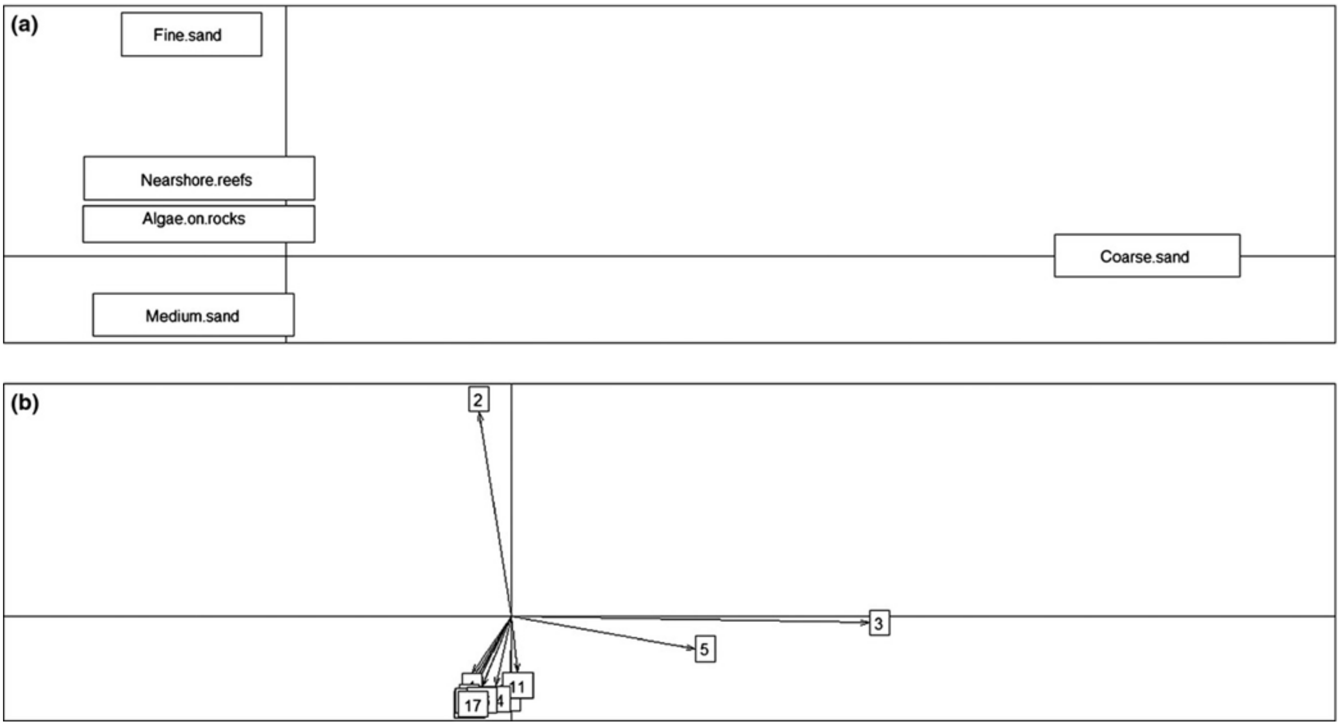

Figure 6. Eigen analysis of selection ratios of habitat selection by 17 *Solea senegalensis* on five different habitats. (a) Habitat type on the first two factorial axes. (b) Animal scores on the first factorial plane. (Adapted from Abecasis et al. 2014a).

Biotelemetry also helps identify Essential Fish Habitats (EFHs), such as feeding grounds, nursery areas, and aggregation sites. For lemon sharks (*Negaprion brevirostris*), biotelemetry and genetic data showed predictable aggregation patterns and population structure, supporting the designation of a Habitat Area of Particular Concern and the redefinition of EFH boundaries (Figure 7; Brooks et al. 2018).

MPA monitoring and assessment is another key application of acoustic telemetry data (Abecasis et al. 2014b). Although small MPAs may not fully encompass the movement ranges of more mobile species, they can still enhance the size and abundance of sedentary fish. In the LSMP, some reef-associated species have shown signs of recovery (Abecasis et al. 2015b). However, limited effects have been observed for more mobile or soft-bottom species such as cuttlefish (Martínez-Ramírez et al. 2021; Sousa et al. 2018;

Abecasis et al. 2013). The fact that the LSMP provides only seasonal protection for certain species, such as the common stingray (Kraft et al. 2023), highlights the need for more comprehensive and spatially inclusive planning. Acoustic telemetry can also help to detect changes in animal behaviour and movement patterns related with climate change and other anthropogenic factors, and thus contribute to adaptive management.

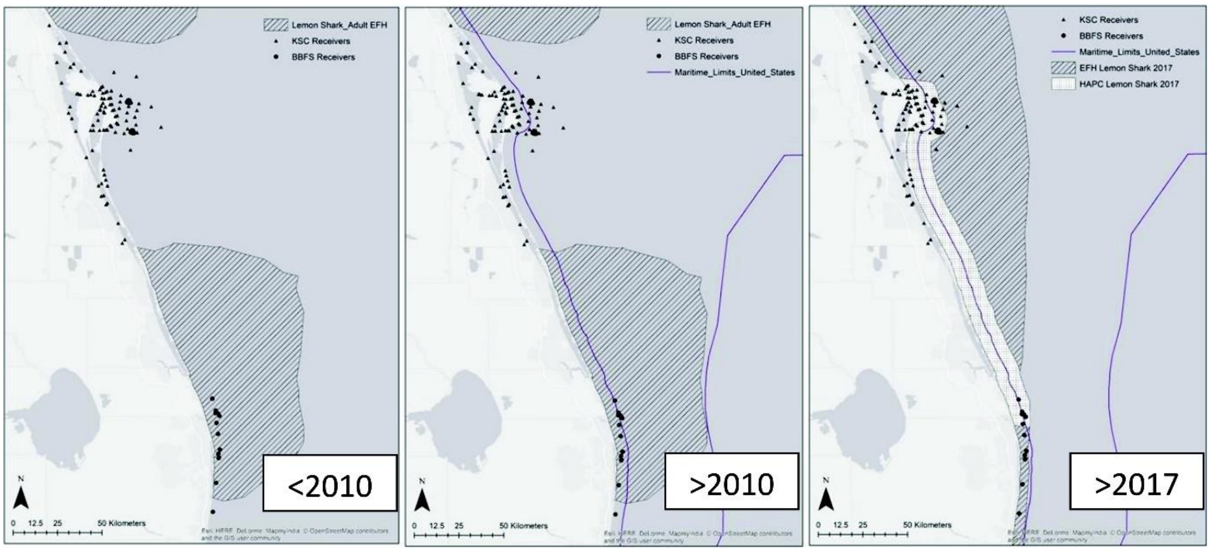

Figure 7. Evolution of *Negaprion brevirostris* management and essential fish habitat boundaries in Florida (USA), based on acoustic telemetry and genetic data (Adapted from Brooks et al. 2018).

Understanding connectivity between habitats is crucial for effective conservation planning, particularly for species that use multiple habitats throughout their life cycles. For instance, the common stingray exhibits seasonal migrations between the LSMP and the Sado estuary, underscoring the need for protected corridors or networked MPAs to ensure adequate year-round protection (Kraft et al. 2023). Similarly, acoustic telemetry studies on juvenile dusky kob (*Argyrosomus japonicus*) revealed a dual pattern of space use, with some individuals showing strong estuarine residency while others undertook marine excursions (Childs et al. 2015). This suggests the existence of distinct estuarine and marine contingents, with estuarine-resident individuals being particularly vulnerable to exploitation (Childs et al. 2015). Comprehending the intraspecific variability is crucial to ensure that it is not eroded with protection-induced selection introduced by MPAs (Villegas-Ríos et al. 2017).

Other species also demonstrate varying degrees of connectivity and mobility beyond MPA boundaries. The Senegalese sole has been observed to make regular excursions outside the LSMP, facilitating moderate levels of adult spillover (Abecasis et al. 2014a). In the Ria Formosa coastal lagoon, white seabream (*Diplodus sargus*) and two-banded seabream (*Diplodus vulgaris*) exhibited high residency, reinforcing the importance of this lagoon as a nursery area (Abecasis et al. 2009). Yet, as these fish grow, they migrate to nearby coastal areas where they settle down as adults. In a more extreme case, winter skates (*Leucoraja ocellata*) tagged offshore New York displayed long-distance seasonal dispersal exceeding 1000 km (Frisk et al. 2019), lending support to the "adult-mediated population connectivity" hypothesis, which posits that large-scale biomass connectivity is driven by the movement of adult individuals (Frisk et al. 2014).

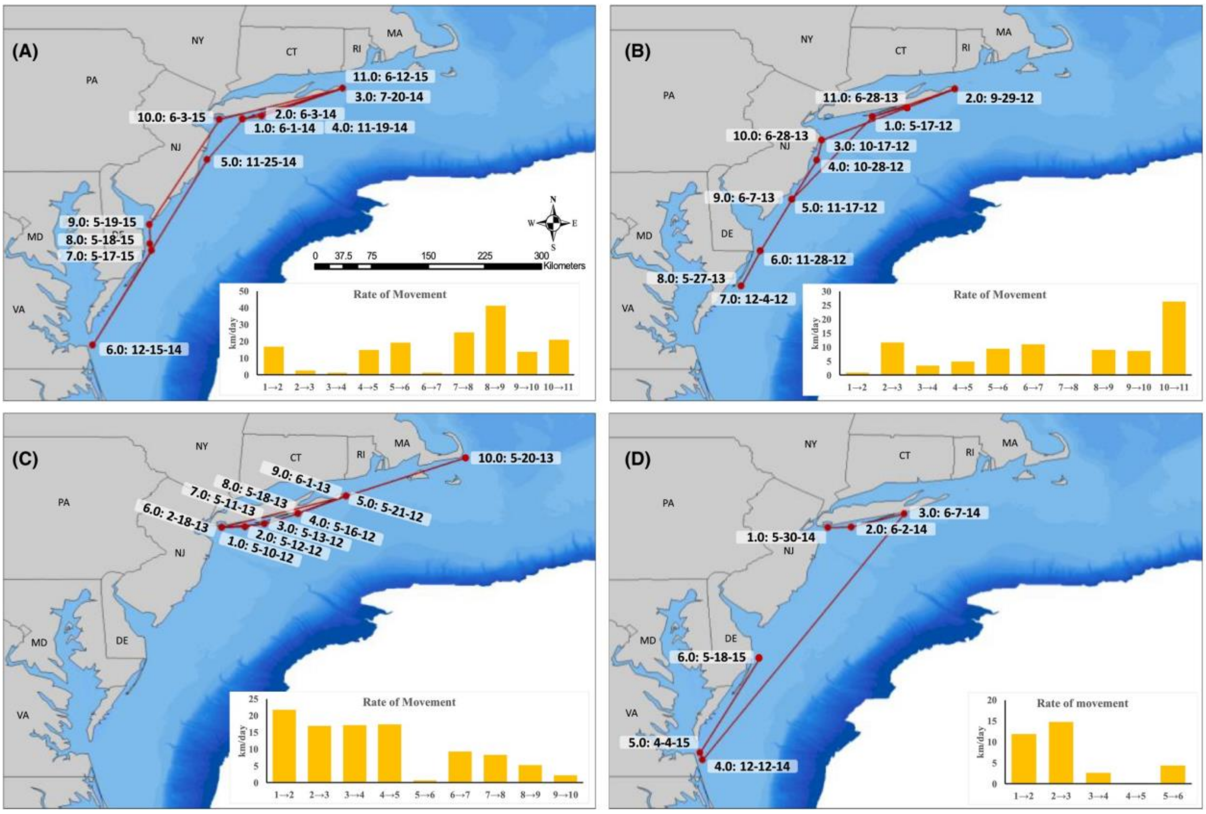

Figure 8. Long-distance migrations of *Leucoraja ocellata* in the Northwestern Atlantic (adapted from Frisk et al. 2019).

Acoustic telemetry has also been instrumental in assessing anthropogenic impacts. In Sydney harbour, telemetry linked fish movements to contamination with polychlorinated dibenzodioxins and furans (Taylor et al. 2018). Exposure to contaminated areas explained up to 98% of tissue contaminant concentrations, highlighting the role of movement in bioaccumulation and implications for human health risk assessments.

Combining data from biotelemetry and animal-borne sensors is crucial for monitoring ocean health and anticipating ecosystem responses to climate stressors (Matley et al. 2023). For example, a study on blue sharks (*Prionace glauca*) showed that hypoxic zones lead to habitat compression and increased vulnerability to fishing (Figure 9; Vedor et al. 2021).

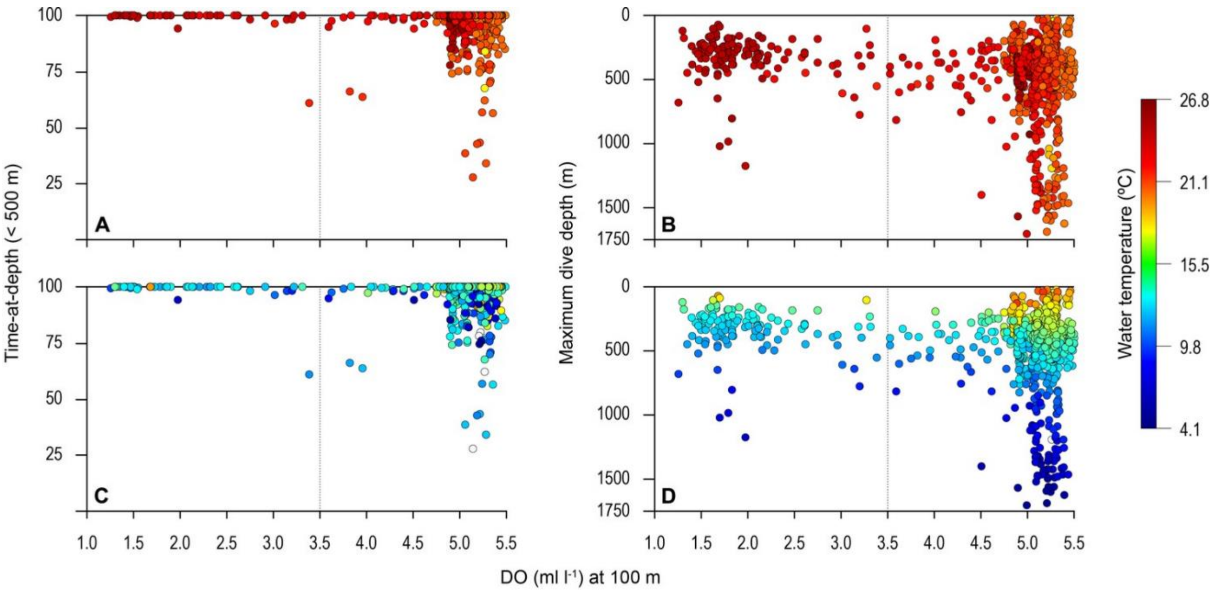

Figure 9. Percentage of time spent in the upper 500m of the water column (A and C) and maximum daily dive depths (B and D) in relation to the dissolved oxygen concentration at 100m depth. Time at depth and maximum depth in relation to sea surface temperature (A *and B) and temperature at depth (C and D). The dashed line indicates the dissolved oxygen concentration below which maximum dive begins to decrease. (Adapted from Vedor et al. 2021)*

Biotelemetry can also be used to assess the effects of human-made structures, like offshore wind farms (OWFs), in fish behaviour and movement patterns (Alós et al. 2022). In France's first OWF, lesser spotted dogfish (*Scyliorhinus canicula*) exhibited site fidelity and seasonal residency around monopiles, indicating that such structures may serve as refuges or food sources (Labourgade et al. 2024). The increasing development of offshore infrastructures could lead to changes in the behaviour of some fish species potentially leading to cascading effects in the ecosystem.

Conclusions

Biotelemetry provides robust empirical data on animal movement, habitat use, and spatial connectivity, offering essential information for the scientific understanding and management of marine ecosystems. These insights are essential for both conservation and fisheries management.

From a fisheries management perspective, acoustic telemetry supports more accurate stock assessments through empirical estimates of key parameters such as natural mortality, habitat use, and species-specific vulnerability to fishing gear. It enables the delineation of biologically meaningful management units and helps revise spatial management boundaries. Biotelemetry data also informs the designation of essential fish habitats (EFHs) and helps to assess discard survival, contributing directly to the design of more effective, evidence-based fisheries policies. Additionally, biotelemetry allows the monitoring of fishing impacts on movement behaviours, revealing potential fisheries-induced evolutionary changes.

In the conservation realm, acoustic telemetry enhances MPA design and assessment by providing detailed information on home range, site fidelity, and habitat preferences. It supports the identification of key areas for protection - such as spawning, nursery, and foraging sites - and informs connectivity-based conservation strategies. Biotelemetry is also increasingly used to assess the ecological consequences of anthropogenic stressors, including pollution, climate change, and the expansion of offshore infrastructure.

Continued integration of acoustic telemetry with other scientific tools - such as genomics, environmental sensors, and remote sensing - and sustained collaboration with stakeholders will be essential to address the multifaceted challenges in the management and conservation of aquatic ecosystems.

Future directions

Future research in biotelemetry should prioritise the integration of movement data with environmental, physiological, genetic, and fisheries datasets to better understand the drivers of animal movement and their implications for management and conservation. This requires advancing analytical frameworks that move beyond descriptive approaches to inferential, predictive models capable of supporting species-specific and ecosystem-based management.

Methodologically, efforts should focus on expanding the use of biotelemetry to a broader range of species, including smaller-bodied and data-deficient taxa, and improving cost-efficiency and data sharing across research networks. Combining biotelemetry with complementary tools - such as oceanographic sensors, biologging, and remote sensing - will improve our capacity to assess species' responses to environmental variability and anthropogenic pressures, including climate change and fishing.

Strengthening collaborations through large-scale initiatives such as the Ocean Tracking Network (OTN - https://oceantrackingnetwork.org/) and the European Tracking Network (ETN - https://www.europeantrackingnetwork.org/) will be critical to harmonise methodologies, support long-term monitoring, and address transboundary management challenges, especially for highly migratory and commercially important species.

Finally, ensuring that research outputs are actionable requires stronger engagement with policymakers and managers. Future work must prioritise co-designed studies, targeted communication, and the development of decision-support tools that facilitate the uptake of telemetry data into fisheries management and conservation planning.

In the context of my research programme, I aim to contribute to this growing field by advancing the integration of biotelemetry with other methodological approaches, fostering collaboration through international tracking networks, and promoting the translation of movement ecology research into actionable conservation and management strategies. In doing so, my goal is to bridge the gap between fundamental ecological research and applied conservation, supporting evidence-based decision-making for the sustainable management of marine biodiversity.

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