Thorburn et al. Animal Biotelemetry (2024) 12:20
https://doi.org/10.1186/s40317-024-00370-5

RESEARCH

Open Access

Assessing the potential of acoustic telemetry to underpin the regional management of basking sharks (*Cetorhinus maximus*)

James Thorburn[1,2,3,4], Patrick C. Collins[1,2], Amy Garbett[1,2], Heather Vance[1,2], Natasha Phillips[1,2], Alan Drumm[5], Joseph Cooney[5], Catherine Waters[5], Niall Ó'Maoiléidigh[5], Emmett Johnston[1,24], Haley R. Dolton[6], Simon Berrow[7,23], Graham Hall[8], Jackie Hall[8], Diego Delvillar[9], Ross McGill[9], Fred Whoriskey[10], Nann A. Fangue[11], Alexandra G. McInturf[12,13], Andrew L. Rypel[11], Richard Kennedy[14], Jessie Lilly[15], Jessica R. Rodger[16,18], Colin E. Adams[16], Nienke C. F. van Geel[17], Denise Risch[17], Lorna Wilkie[18], Suzanne Henderson[19], Paul A. Mayo[20], Paul J. Mensink[21], Matthew J. Witt[22], Lucy A. Hawkes[22], A. Peter Klimley[11] and Jonathan D. R. Houghton[1,2*]

Abstract

Acoustic telemetry can provide valuable space-use data for a range of marine species. Yet the deployment of species-specific arrays over vast areas to gather data on highly migratory vertebrates poses formidable challenges, often rendering it impractical. To address this issue, we pioneered the use of acoustic telemetry on basking sharks (*Cetorhinus maximus*) to test the feasibility of using broadscale, multi-project acoustic receiver arrays to track the movements of this species of high conservation concern through the coastal waters of Ireland, Northern Ireland, and Scotland. Throughout 2021 and 2022, we tagged 35 basking sharks with acoustic transmitters off the west coast of Ireland; 27 of these were detected by 96 receiver stations throughout the study area ($n=9$ arrays) with up to 216 detections of an individual shark (mean = 84, s.d. 65). On average, sharks spent ~ 1 day at each acoustic array, with discrete residency periods of up to nine days. Twenty-one sharks were detected at multiple arrays with evidence of inter-annual site fidelity, with the same individuals returning to the same locations in Ireland and Scotland over 2 years. Eight pairs of sharks were detected within 24 h of each other at consecutive arrays, suggesting some level of social coordination and synchronised movement. These findings demonstrate how multi-project acoustic telemetry can support international, cost-effective monitoring of basking sharks and other highly mobile species. Decision support tools such as these can consolidate cross-border management strategies, but to achieve this goal, collaborative efforts across jurisdictions are necessary to establish the required infrastructure and secure ongoing support.

Keywords Spatial ecology, Highly mobile species, Multi-species array, Elasmobranchs, Regional monitoring, Conservation, Marine animal tracking, Spatial patterns, Synchronised movement, Cross-border collaboration

*Correspondence:
Jonathan D. R. Houghton
j.houghton@qub.ac.uk
Full list of author information is available at the end of the article

Introduction

Our understanding of large marine animal movement and behaviour gained significant momentum following the advent of satellite telemetry [5, 22, 23, 29, 49]. This technology has been used to investigate the ocean-scale movements of migratory species (e.g., [22, 29, 39]), identify critical habitats [5, 24, 40], reveal foraging behaviours (e.g., [53]), and identify hotspots of human/wildlife conflicts (e.g., [47, 48]). For managers, such information can underpin the implementation of effective conservation measures [12, 24]. While satellite telemetry has the potential to track animals over multiple years [49], studies using this technology typically focus on providing powerful snapshots of behaviour and movement over periods of less than one year [49], rather than acquiring long-term data sets. However, for long-lived species, spatial protection must be reinforced by monitoring over multiple years to understand behavioural plasticity and animal responses to changing environments [1, 2, 9, 11, 40]. Acoustic telemetry offers the potential to monitor individuals for up to 10 years [1, 29, 40]. This longevity has driven a proliferation of acoustic telemetry projects over recent decades [15, 40], deepening our understanding of animal movement patterns on a global scale [24].

Acoustic telemetry determines the presence and location of the study species via a two-component system: (i) static or mobile receivers, which can detect (ii) transmitters (tags), either internally or externally attached to the animals, which emit an encoded acoustic signal. In its simplest form, when a tagged individual moves into the detection range of a receiver (typically less than 1,000 m), its unique ID code is recorded, along with a date and time stamp. Arrays of receivers are usually deployed at a given location depending on the research question [1, 2, 40] and the scale of the animal movements to be tracked, which can range from high-resolution movements over small spatio-temporal scales to pan-oceanic migrations [1, 2, 17, 29, 35, 40, 51]. For example, the long battery life of acoustic tags [1] enables studies of inter-year seasonal site fidelity, ontogenetic variation in movement patterns and overall space use (e.g., [19, 46]). However, for highly migratory marine vertebrates, the logistical and financial challenges of deploying species-specific acoustic telemetry arrays over large geographic ranges are frequently beyond the capacity and/or resources of a single research team. To address this issue, a host of collaborations and infrastructure and data-sharing agreements have emerged so that receivers deployed to study a given species can add value to other projects by detecting and sharing information on non-target species [1, 11]. However, for this approach to work, a formalised network needs to be in place to connect acoustic telemetry users and streamline the transfer of data [1, 11]. To meet this global need, the acoustic telemetry community has been cultivating partnership platforms, such as the Ocean Tracking Network (OTN) [11] and the European Tracking Network [1], to create a global formalised network. These platforms and collaborations greatly expand the coverage of effective acoustic telemetry arrays with minimised additional resource requirements, to the benefit of all concerned [1].

The SeaMonitor project (2019–2023) was developed based on this collaborative approach, spanning the territorial waters of the Republic of Ireland, Northern Ireland (UK), and Scotland (UK). A key aim of the project was to use acoustic telemetry to produce regionally coherent management recommendations for a range of migratory species that habitually exhibit trans-boundary movements across multiple jurisdictional boundaries. The centrepiece of SeaMonitor was an acoustic telemetry array ($N = 108$ receiver stations across 65 km) spanning the Malin-Islay front that linked the north coast of Ireland with the west coast of Scotland. While this array was primarily deployed to estimate the survivorship of Atlantic salmon (*Salmo salar*) smolts at sea, we wanted to assess its value for studies of other highly mobile species. Basking sharks (*Cetorhinus maximus*) were selected as a target species given their conservation priority status (e.g., an EC-wide moratorium on target fishing, Republic of Ireland (ROI) Wildlife Act 1976, Wildlife (Northern Ireland) Order 1985, Nature Conservation (Scotland) Act 2004, International Appendices I and II of the Convention on Migratory Species (CMS), Appendix II of the CITES, Endangered on the IUCN Red List) and seasonal occurrence in all three jurisdictions [14–16, 21, 31, 32, 54, 58–61, 70].

To date, spatial-based management for basking sharks has been based primarily on protecting established hotspots identified through effort-corrected visual observation and satellite telemetry, leading to the designation of the Sea of Hebrides Marine Protected Area in Scotland [46] and a network of marine reserves in the Isle of Man. However, less attention has been paid to basking shark conservation at a multi-national scale which is pertinent given their frequent, wide-ranging movements across borders [14–16, 21, 31, 32, 54, 58–61, 70]. To meet this need, we capitalised on the extensive acoustic telemetry network around the island of Ireland and off western Scotland, including the Malin-Islay array, to establish a basking shark acoustic tracking programme in 2020.

The rationale for acoustically tracking basking sharks was to assess the technology's efficacy as a long-term monitoring tool to support the management of this protected species. Thus, we posed five primary questions: (1) What proportion of the acoustic telemetry receivers deployed in the Ireland/Western Scotland region detected basking sharks? (2) What proportion of tagged animals were subsequently detected at arrays beyond the tagging location within the same year? (3) Was there any evidence of inter-annual site fidelity to particular areas? (4) How long were individual sharks detectable within given locations, providing estimates of individual residency? (5) Was tag retention adequate to record inter-annual movements?

Methods

Array

All acoustic receivers were deployed sub-surface using acoustic release units with no surface markers. The location of all receivers was marked via GPS positioning at the site of deployment. This study used two types of receivers: Innovasea VR2W units, deployed with separate Innovasea Ascent Acoustic Releases (Ascent AR) units, and Innovasea VR2AR units, which had built-in acoustic releases. The VR2AR and Ascent AR units were connected to 70 kg of sacrificial ballast via a 1-m-long, 15-mm-diameter sea-steel leash. For both VR2AR and Ascent AR units, two × 2 m lengths of 10-mm sea steel were attached to the bolt holes at the top of the units. These were plaited together approximately 30 cm above the units, and two 12-in. (30 cm) hard plastic buoys were threaded onto the opposite end of the rope and knotted in place. For Ascent AR units, a VR2W unit was cable tied to the plaited 10-mm riser rope between the Ascent AR and the floats. The SeaMonitor project deployed a central main receiver "curtain", linking Malin Head to the Isle of Islay (Fig. 1). Additional arrays were deployed to monitor the presence of tagged basking sharks at known Irish hotspots around Malin Head, Tory Island and Achill Island (Fig. 1). The SeaMonitor arrays were complemented by networks of receivers deployed by the West Coast Tracking Project [63], MEFS [64], COMPASS [10], and SAMOSAS [68] in the marine waters of western Ireland, north-western England, and west Scotland (Fig. 1). Combined, the deployed arrays consisted of 637 receiver stations, spanning a latitudinal distance of ca. 480 km and a longitudinal distance of ca. 470 km. All receivers operated at 69 kHz.

Deployment of acoustic tags

Tagging was undertaken on free-swimming sharks in May (n = 11), August (n = 3) and September (n = 9) 2021, and April 2022 (n = 12). All tagging was conducted from either an Orkney 4.87 m (16 foot) fibreglass boat with a 50-hp outboard or a 6 m XS 600 RHIB with a 115-hp outboard. Basking sharks were tagged with externally mounted Innovasea V16-4 × ID tags inside the manufacturer's external casing (length = 87 mm, diameter = 18 mm, weight in air = ~ 12 g). All tags transmitted at 69 kHz with a nominal tag delay of 120–240 s and an estimated tag life of 3650 days. Tag cases were attached to a 5-cm stainless steel aviation wire tether. A 5-cm Wildlife Computers titanium anchor was used for each tag to secure the device in the dorsal musculature at the rear of the shark's dorsal fin using a 2-m fibreglass pole with an applicator pin attached to one end to dart the tag into place. The tagger was stationed at the bow of the vessel. The total length of each tagged animal was estimated with reference to the boat [6] (i.e. 0–2 m; 3–4 m; 5–6 m; 7–8 m; > 8 m). Tagging was conducted off Achill Island, County Mayo (latitude: 53.945°N, longitude: -10.102°W) and Loop Head, County Clare (latitude: 52.729°N, longitude: − 9.679°W; Fig. 2) by experienced staff under the auspices of an HPRA project license (Number: AE /19121/P003) held at the Marine Institute, Ireland.

Data processing and analysis

The detection data were sorted to remove all detections of tags not associated with this study and then further filtered to remove possible false detections, identified as a single detection within a 24-h period. These were identified using the false_detections function in the R package GLATOS [27]. Receiver arrays were grouped based on geographic location (see Fig. 2), and summary data were calculated, including the total number of detections, detections per shark, detections per receiver, and detections per array. Discrete residency periods within an array were determined using the detection_events function from the GLATOS package. A break duration of one week was employed to determine a residency event whereby a break between detections exceeding one week was deemed to represent separate residency events. To investigate the potential of acoustic telemetry data to reveal whether basking sharks travel through coastal waters in groups, we identified "group detection events" per array. These were defined as detections of two sharks or more at a single array with less than a 24-h break between detections.

Results

In total, 35 basking sharks were tagged at two sites off the west coast of Ireland during the SeaMonitor project, 23 in 2021 (Achill Island, County Mayo and Loop Head, County Clare) and 12 in 2022 (Achill Island). The sharks ranged from 4 to > 8 m in estimated total length (see Appendix Table S1). Of these, 27 were subsequently detected (77%). In total, there were 2304 detections between 14 May 2021 and 06 Oct 2022. Of these, 47 (1.9%) detections from 23 sharks (ranging from 1 (n = 14 sharks) to 7 for shark #11) were removed as possible false detections. The SeaMonitor main array had the greatest number of possible false detections (n = 17), with 12 other

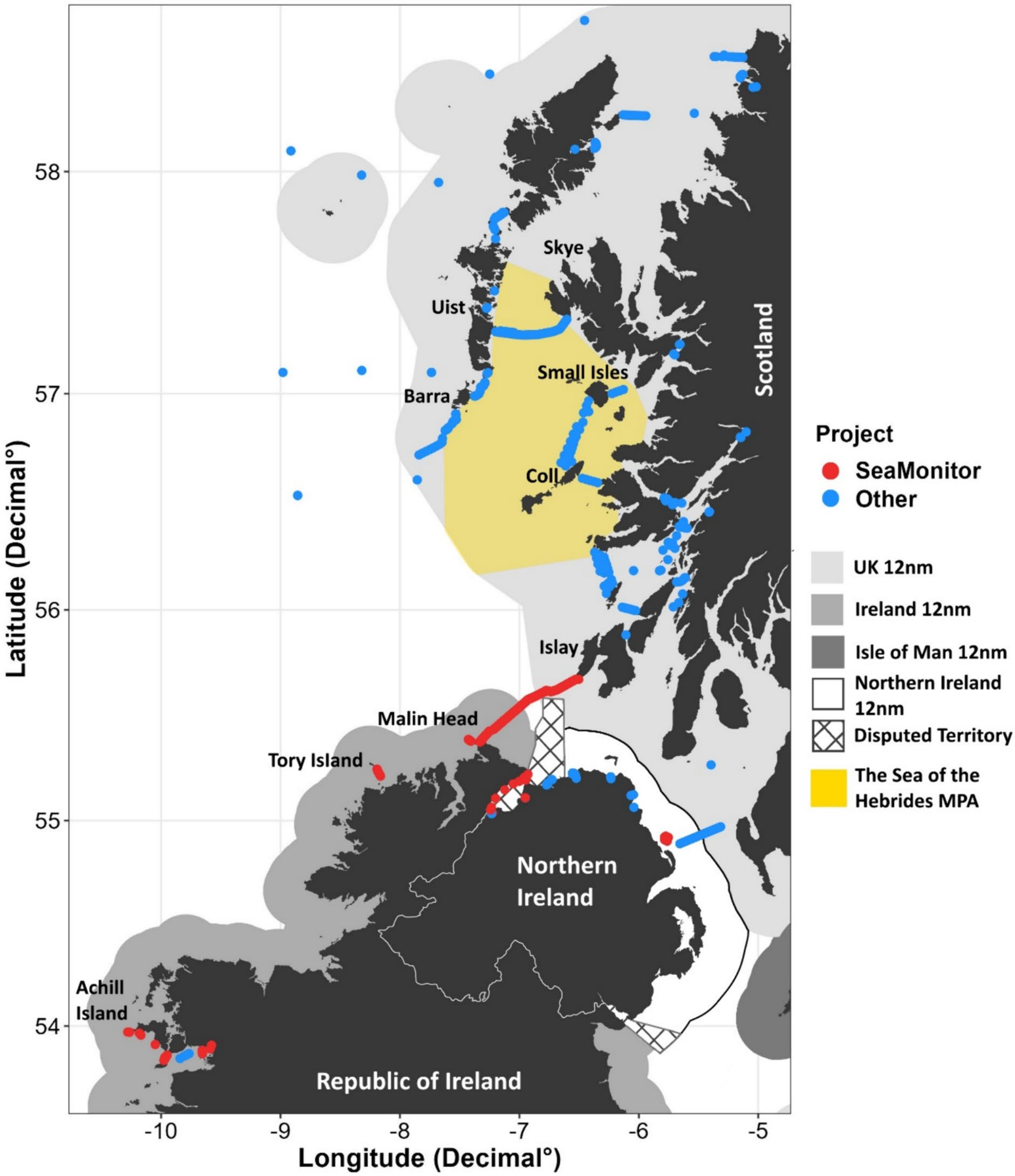

Fig. 1 Map of all compatible acoustic receivers in the water from when the first basking shark was tagged. Red points show receivers deployed as part of SeaMonitor and blue points show receivers deployed as part of other projects. The 12 nm territorial waters of Ireland, Northern Ireland, the UK and the Isle of Man are shown. The Sea of the Hebrides Marine Protected Area (of which basking sharks are one of the protected species) is shown in yellow

arrays throughout the study region also having detections that were removed as possible false detections (mean number of possible false detections per array = 3.61, s.d. 4.17). Of the 2,257 filtered detections, 1462 were from the SeaMonitor receivers, and 795 were from additional arrays. Basking sharks were detected by 96 receivers

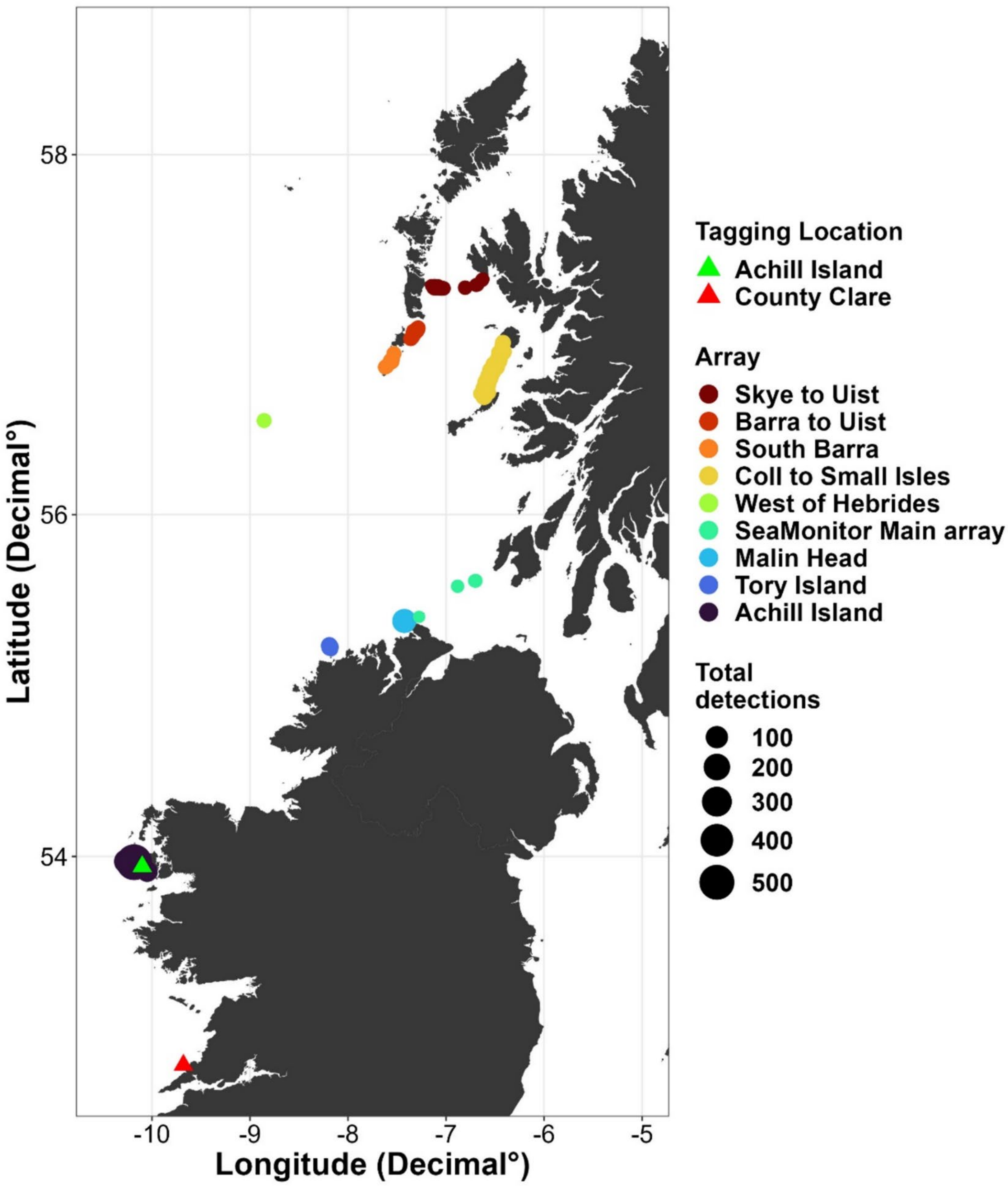

Fig. 2 All basking shark detections per array station. The point size indicates the number of total detections (all sharks) at each receiver station, and the colour of the detection point shows the array this detection was from. The green triangle shows tagging location off Achill Island, and the red triangle shows the tagging location off County Clare

across nine arrays, 15% of the total deployed. The greatest number of detections on a single receiver was 536 (mean = 31.7, s.d. 73.64), deployed at Achill Island on the west coast of Ireland (Fig. 2), and the highest number of detections per individual shark was 216 (mean = 84, s.d. 65) over 12 days (#11).

Overall, 21 (60%) sharks were detected by multiple arrays. For example, eight sharks were detected at more than one location during 2021, two of which were also detected at more than one location during 2022 (Fig. 3), with a further 12 sharks detected at multiple locations during that year (Fig. 3). Of the 23 sharks tagged in 2021, four (#5, #6, #9, and #10) showed inter-annual site fidelity between 2021 and 2022 off Achill Island, Malin Head, the Hebrides (West of the Hebrides, Coll to Small Isles, Barra, Uist, and Skye arrays), and the SeaMonitor main array (e.g., #5 Fig. 4). The location of the detections showed some seasonal patterns, with sharks

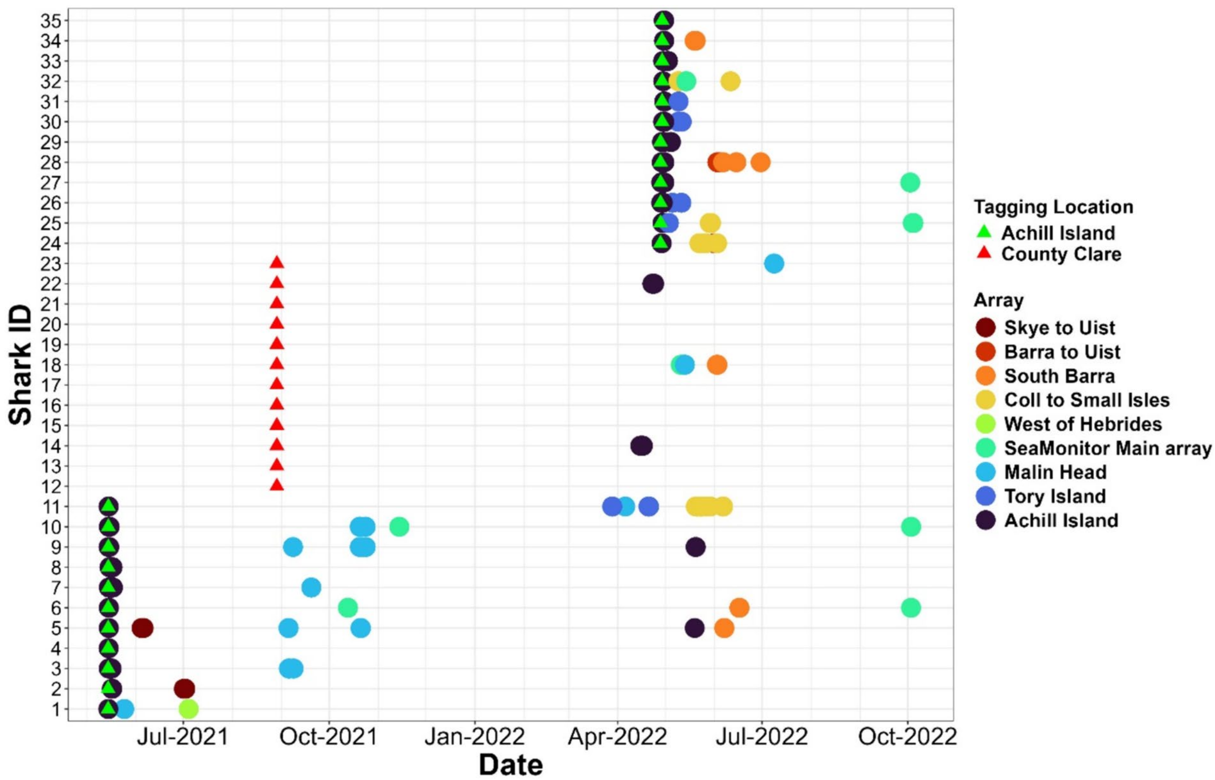

Fig. 3 Detection plot for all basking sharks (Study ID on the y-axis). Detections are colour-coded based on the array that detected the shark (see Fig. 2 for more information). Green triangles denote the date of tagging at Achill Island, and red triangles show the date of tagging at County Clare

being detected around the west of Ireland (Achill Island and Tory Island) in April and early May, north Ireland and Northern Ireland (Malin Head and the SeaMonitor Main Array) mainly in September and October, and off the west coast of Scotland (arrays around the Hebridean islands) in late May and June (Fig. 3). A gap in detections was noticeable in August 2021, between November 2021 and March 2022, and August 2022.

Group detection events occurred at Achill Island, Tory Island and Malin Head in Ireland, the SeaMonitor Main Array, South Barra, and Coll to Small Isles in Scotland (Table 1). Achill Island recorded two large group detection events comprising 11 (May 2021) and 12 (April 2022) sharks (Table 1). Each of these group events comprised different sharks and it is worth noting that the sharks had recently been tagged near Achill in the same month. The Malin Head array recorded several group detection events in 2021 involving six sharks in total. There was evidence of synchronous movements of 10 shark pairs detected within 24 h of each other at two or more arrays over different months. In addition, one pair (#5 and #9) was detected within 24 h of each other four times at three arrays in different months and years (Table 1), with paired detections continuing to occur after nearly a full year at liberty for this pair.

The average residency period for sharks at an array was 0.94 days (s.d. 1.64). However, some sharks were detected for more extended periods, up to 9.3 days between 20 May 2022 and 29 May 2022 (detected on May 20th, 21st, 22nd, 23rd, 24th, 27th, and the 29th) at the Coll to Small Isles array off the west coast of Scotland (shark #11, Fig. 5). Other locations with notable individual residency periods included Achill Island (5.6 days), around Tory Island (5.6 days) and off Malin Head (4 days) (Fig. 5). The most extended residency times (>4 days) were all in April and May, with residencies of greater than 1 day recorded frequently in these months. Residency times of approximately three days were also observed during September and October. Sharks displaying residency of over three days (seven occurrences in total by seven different sharks) ranged from relatively small (4–6 m size class; 9.3 days) to very large >8 m (3 and 5.6 days). Two sharks (#5 and #10) were detected 506 days post-tagging off Achill Island, both by the SeaMonitor main array, demonstrating tags can be retained for long periods.

Discussion

This study is the first to demonstrate that acoustic telemetry can reveal multi-year, multi-spatial scale information on space use in coastal waters for basking sharks.

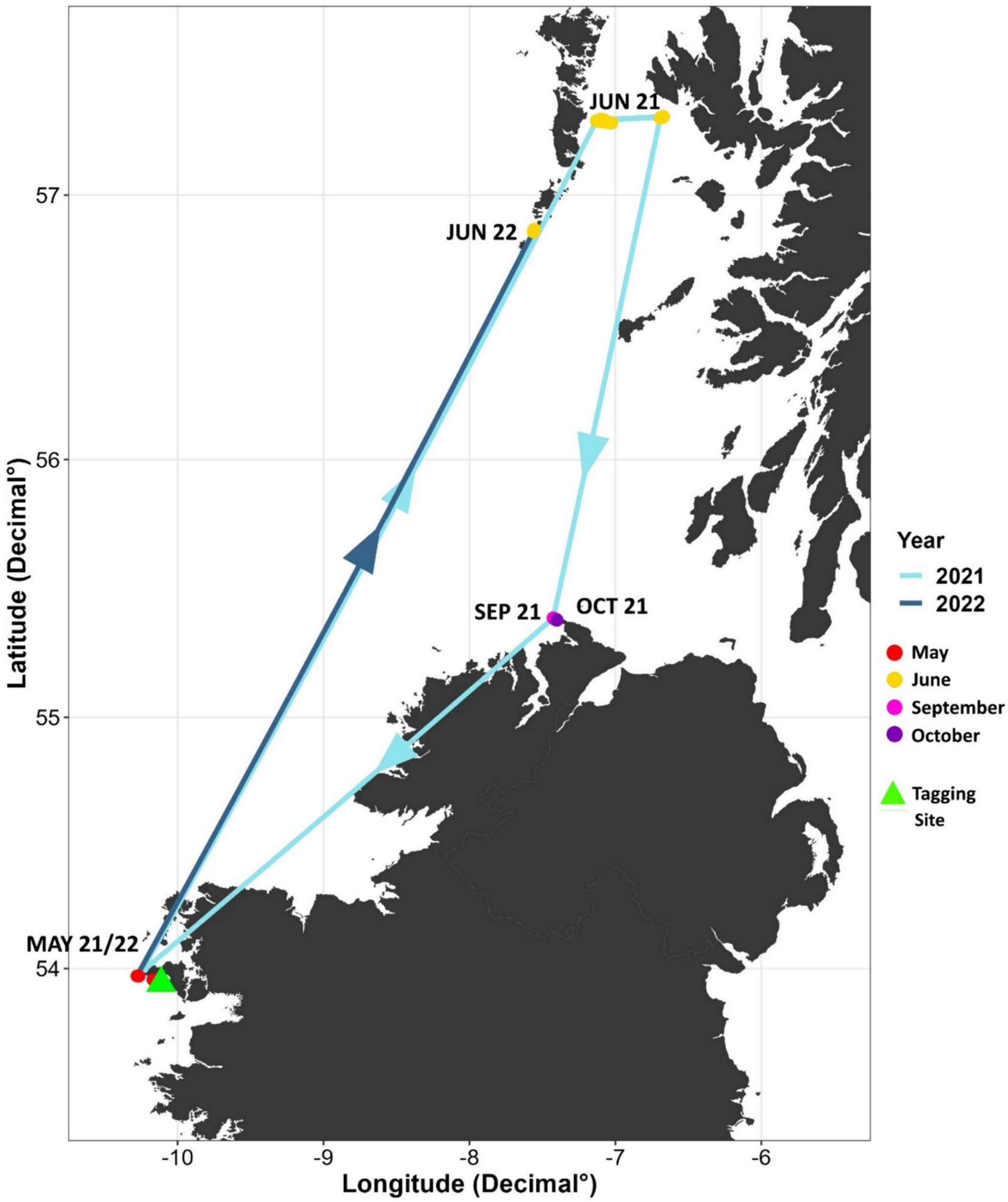

Fig. 4 Detections of basking shark #5 showing annual site fidelity to Achill Island and the Hebrides (Skye to Uist and Barra to Uist arrays). The green triangle shows the tagging location. Coloured points show the receiver stations the shark was detected on. Detections are linked by straight lines with arrows to aid visualisation. These lines are coloured based on the year the detections occurred. Arrows indicate direction of travel

Not only did the data highlight basking shark movements, but also gave valuable insight into residency behaviour and timings, inter-annual fidelity to given sites and trans-boundary connectivity among different political jurisdictions. These data highlight the potential for acoustic telemetry as a monitoring tool for basking sharks in coastal waters, especially where they are subject to statutory conservation/protection requirements. Understanding a species' movement and space use is of particular importance for mobile species as connectivity [3, 7] and time spent within certain areas [7, 13] are highly relevant when designing spatially referenced conservation measures [12].

The ability to undertake relatively straightforward residency analysis with acoustic telemetry data can help identify areas where tagged sharks spend a proportionately

Table 1 Groups of individual sharks (Shark ID) that were detected at the same array within a 24-h period

Array	Shark IDs	Month and year
Achill Island	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	May 2021
Achill Island	24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35	Apr 2022
Achill Island	5, 9	May 2022
South Barra	5, 28	Jun 2022
Malin Head	3, 5/3, 9	Sep 2021
Malin Head	5, 9, 10	Oct 2021
Coll to Small Isles	11, 24/11, 25	May 2022
SeaMonitor main array	18, 32	May 2022
SeaMonitor main array	6, 10, 27	Oct 2022
Tory Island	30, 31/26, 30	May 2022

Each row shows a group detection event, defined as groups of detections with less than a 24-h break. 'Array' shows the arrays the group detections occurred at. 'Shark IDs' shows which sharks were part of the grouped detection event; a solidus splits discrete group detections that occurred within the same month. 'Month and year' shows when each group event took place

high amount of time. The acoustic telemetry data revealed basking sharks spent periods of up to 9.3 days in the vicinity of arrays within the Sea of the Hebrides Marine Protected Area (MPA) and visited multiple times in one year. In some instances, this repeated site use occurred over multiple years, with four of the sharks tagged in 2021 also detected in 2022, showing inter-annual fidelity to Achill Island, Malin Head, the Hebrides (Coll to Small Isles, Uist, Skye, and Barra), and Malin-Islay front (covered by the SeaMonitor main array), indicating these areas may represent important habitats for the species. While previous research has shown inter-annual fidelity for basking sharks at the Hebrides [15], longer-term acoustic studies will provide an opportunity to demonstrate this over multiple years and should be supported by additional research that could provide information on what these sites are being used for. The consistent use of a particular site is useful for establishing protected areas, for example the Sea of the Hebrides MPA was designated in part for the protection of basking sharks from effort-corrected sightings data [46] and satellite tracking [15]. The present study highlights the potential for acoustic telemetry to provide longer-term data that would complement these other methods, monitoring individuals in relation to MPAs or other effective conservation measures to support effective management in the face of a changing ocean. For instance, the inter-annual connectivity between Achill Island and the Sea of the Hebrides MPA by shark #5 demonstrates current repeated connectivity between the MPA and external arrays, which could contribute to the development of a coherent network of protection for these mobile marine species of high conservation priority [3, 7]. Furthermore, evidence of inter-annual fidelity highlights how acoustic telemetry can contribute valuable insight into basking shark behaviour over protracted timescales.

Prior to this study, our understanding of basking shark movements through marine waters in the UK and Ireland predominantly came from data obtained through a combination of archival and transmitting satellite tags and population genetic studies [14–16, 31, 35, 36, 54, 55, 57, 58, 62, 70]. These highlighted the extensive movements that basking sharks make annually [21, 32]. While data from satellite telemetry provides valuable insight into the movements of a species, the fine-scale movement data that is possible from acoustic telemetry can complement these technologies [40]. If sharks are double tagged with satellite and acoustic tags, acoustic detections can help validate estimated positions from satellite tags. However, acoustic telemetry data are reliant on a network of acoustic receivers to be maintained and the spatial resolution of the data depends on the number of receivers in the network. While mark and recapture data are fundamental for the conservation of many mobile species (e.g., [43, 69]), it has been noted that sightings data for sharks, including basking sharks, has several inherent biases [8, 19], largely related to depth use [31, 58]. In whale sharks (*Rhincodon typus*), for example, seasonal variation in depth use resulted in sightings data incorrectly suggesting the animals only had a seasonal presence, while a concurrent acoustic telemetry project demonstrated year-round residency [8]. The acoustic telemetry data presented here could undoubtedly support mark and recapture studies for basking sharks; collectively helping us to investigate long-standing questions regarding site fidelity, habitat use, and abundance (e.g., [8, 33, 34, 43]).

Currently available acoustic tags have the potential to track animals for up to ten years, but only if the devices stay attached. In this study, the detection of 77% of tagged sharks, and detections up to 506 days after tagging provides confidence that the externally attached acoustic tags could be retained in the long-term, supporting their use as part of a long-term monitoring tool. This capacity to monitor movements over long periods is especially relevant for species' with typically long-life cycles, such as elasmobranchs, as ontogenetic variation in space used has been documented for several species [66, 67].

The acoustic telemetry data not only revealed the movement and space use of individual basking sharks, but provided tentative insights into group behaviour. Our ability to tag sharks within aggregations allowed us to explore the consistency of groups over time. Our data suggested that some sharks tagged in the same location on the same day tended to visit other coastal areas simultaneously. Ten pairs of sharks

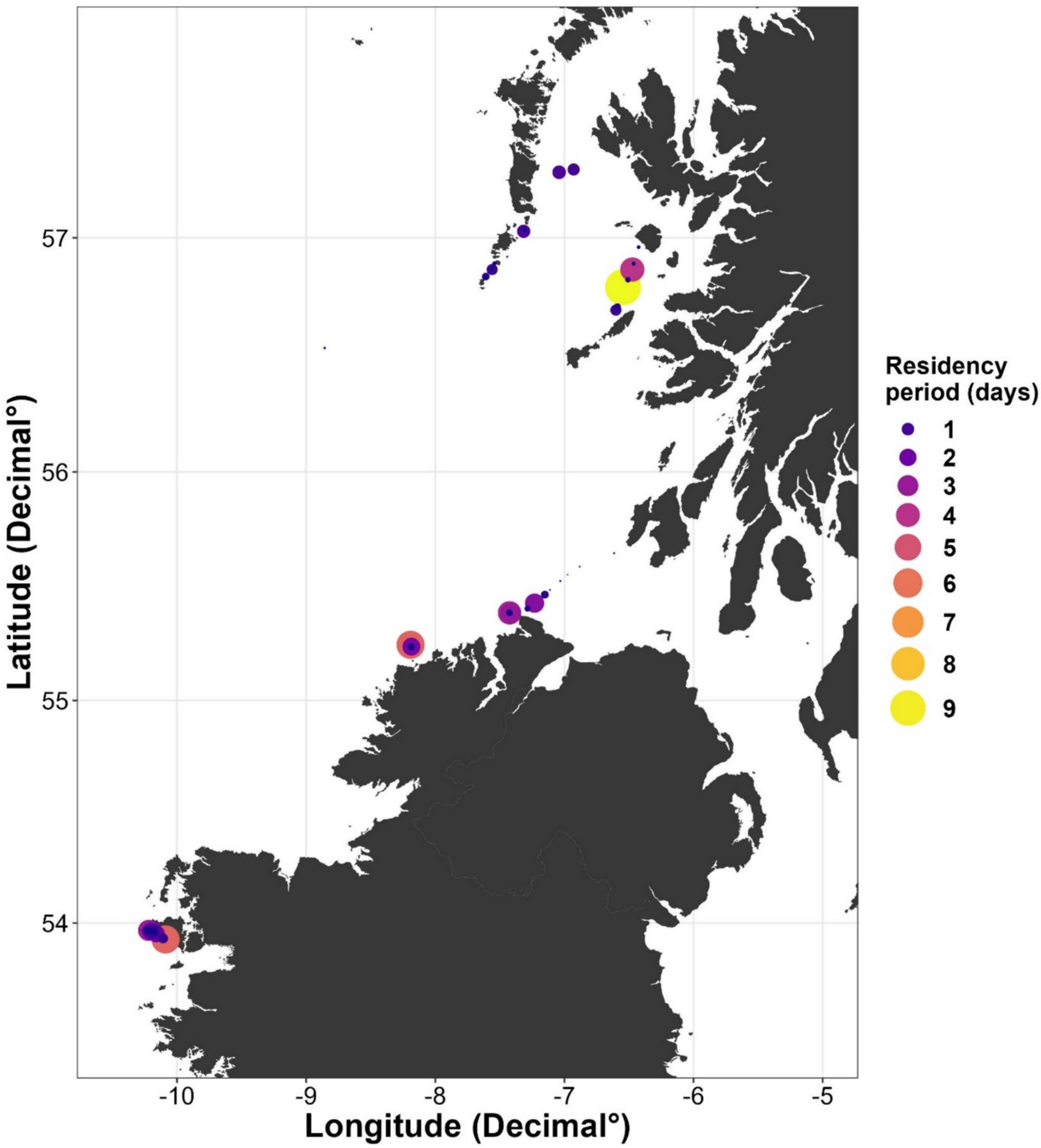

Fig. 5 Residency periods of basking sharks. Residency is estimated per array based on a maximum break of one week between detections. The point is at the mean location of residence within the array, and the size and the colour of the points represent the number of days of residency

detected within 24 h of each other at two or three arrays throughout the study area up to one-year post-tagging, suggesting shared routes and/or the possibility of social behaviour. While basking sharks have been observed in groups [19, 52, 55, 56], the long-term, multi-site nature of these groups has not been explored with tracking technology. Acoustic telemetry data have been previously used to explore the social interactions within other shark species [30, 45] and using long-term acoustics telemetry would allow further investigation of the social interactions in basking sharks populations by tracking pairs or groups of sharks across multiple locations over successive years. Further understanding of drivers behind grouping behaviours is crucial for effective conservation management [30, 41]; evidence from molecular studies suggests that basking sharks may have some form of social cohesion, moving throughout the NE Atlantic in genetically discrete kin groups [37] which has implications for management when considering preserving genetic diversity [65]. However, the capacity of acoustic telemetry to study this behaviour more extensively relies on the continued deployment of large-scale, regionally coherent receiver arrays.

The detections of sharks across 96 receiver stations with a maximum straight-line travel distance of 1,236 km between detections reinforces the value of coordinating monitoring efforts and data sharing across organisations and national boundaries from projects dedicated to different target species to maximise array coverage. Innovative partnerships such as the Ocean Tracking Network [11] and the European Tracking Networks [50] are advancing the use of acoustic telemetry to facilitate global-scale studies, investigating a wealth of pressing questions about aquatic animals the answers to which help inform management and policy decisions [1, 2, 11, 24, 29, 40]. Future acoustic telemetry approaches for basking sharks could involve the use of real-time acoustic telemetry data collection systems [71] which would underpin rapid response adaptive management decisions. For example, tools that that notify marine users of time and areas where due care and attention needs to be paid (e.g., proximate to shark aggregations). Such approaches have been adopted with great success for other marine species, including real-time fisheries closures for salmon species (*Oncorhynchus tshawytscha*) [38], spurdog (*Squalus acanthias*) [25], bluefin tuna (*Thunnus thynnus*) [4, 26], and cod (*Gadus morhua*) [28].

In conclusion, this study demonstrated that acoustic telemetry offers a cost-effective, and adaptive tool that has strategic benefit in the study of highly mobile species, such as basking sharks. Acoustic telemetry can provide complementary data to augment mark and recapture and satellite tagging studies, providing information on space use, residency behaviour, inter-annual fidelity, connectivity among political jurisdictions, and may, over time, provide insight into group dynamics. Although the current study only considered results comprising detections across two years, these data indicate that acoustic telemetry may provide long-term value for monitoring basking sharks. The initial evidence of residency, connectivity, and inter-annual site fidelity that the acoustic data showed in relation to the Sea of the Hebrides MPA suggests that acoustic telemetry could form part of the monitoring toolbox for this site, and any future areas of spatial management for basking sharks. As demonstrated in this study, the use of acoustic telemetry as a monitoring tool requires wide-scale acoustic telemetry infrastructure to be in place. The continued growth and networking of acoustic telemetry capabilities in the NE Atlantic is providing an increased capability to track the movements of basking sharks and other species. Yet, in order to fully exploit acoustic telemetry as a tool, there needs to be a trans-boundary collaborative effort [2] to support long-term deployments of acoustic telemetry array networks. However, aside from an obvious funding requirement, such aspirations rely on dialogue, collaboration, and planning among researchers, jurisdictions, government agencies and departments to ensure access to long-term infrastructure and investment.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-024-00370-5.

Supplementary material 1.

Acknowledgements

We want to thank the two anonymous reviewers for taking the time and effort to review the manuscript. Their valuable comments and suggestions helped us to improve the quality of the manuscript. As part of the SeaMonitor project, acoustic receivers were loaned by the Ocean Tracking Network and University of California Davis Agricultural Experiment Station (#2098-H and #2467-H). Acoustic detection data were contributed from multiple projects throughout the study region. The West Coast Tracking Project, the COMPASS project (funded by the EU's INTERREG VA Programme managed by the Special EU Programmes Body (SEUPB)), and the SAMOSAS project funded by the Scottish Government all contributed data, and we would like to thank them for making the data available. SeaMonitor was funded via the EU's INTERREG VA Programmes (Environment Theme).

Author contributions

JT undertook data collection, the main analysis, prepared the figures and led the writing of the main manuscript. PC: substantial contributions to project conception, funding procurement, data collection, and substantial contributions to paper writing. AG: substantial contributions to data collection and paper writing. HW: substantial contributions to data collection. NP: substantial contributions to data collection and paper revisions. AD: substantial contributions to data collection and paper revisions. JC: substantial contributions to data collection and paper revisions. CW: substantial contributions to data collection and paper revisions. NÓM: substantial contributions to project conception, data collection and paper revisions. EJ: substantial contributions to data collection and paper revisions. HD: substantial contributions to data collection and paper revisions. SB: substantial contributions to data collection and paper revisions. GH substantial contributions to data collection. JH: substantial contributions to data collection. DD: substantial contributions to data collection and paper revisions. RM: SeaMonitor lead. Led overall funding procurement. Substantial contributions to paper revisions. FW: OTN Project lead. Provided project capital. Substantial contributions to paper revisions. NF: Provided project capital. Substantial contributions to data paper revisions. AM: substantial contributions to data collection and paper revisions. AR: Provided project capital. Substantial contributions to paper revisions. RK: substantial contributions to data collection and paper revisions. JL: substantial contributions to data collection and paper revisions. JR: substantial contributions to data collection and paper revisions. CA: PI on SeaMontior Salmon work. Substantial contributions to data collection and paper revisions. NVG: Substantial contributions to data collection and paper revisions. DR: Substantial contributions to data collection and paper revisions. LW: Substantial contributions to data collection and paper revisions. SH: Substantial contributions to paper revisions. PAM: Substantial contributions to data collection and paper revisions. PM: Substantial contributions to data analysis and paper revisions. MW: Substantial contributions to paper revisions. LH: Substantial contributions to paper revisions. APK: Helped conceive the study and loan of acoustic equipment. JH: PI on the project. Led funding procurement and project conception, substantial contributions to data collection and analysis and co-led paper writing.

Funding

SeaMonitor was funded via the EU's INTERREG VA Programmes (Environment Theme). University of California Davis Agricultural Experiment Station (#2098-H and #2467-H).

Availability of data and materials

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at Queens University Belfast. Data are also stored with the Ocean Tracking Network: https://oceantrackingnetwork.org/

Declarations

Ethics approval and consent to participate
The project was reviewed by the Queen's University Belfast AWERB committee. Tagging work was carried out under a HPRA project license (Number: AE /19121/P003) held at the Marine Institute, Ireland.

Consent for publication
Not applicable.

Competing interests
We declare that the authors have no competing interests as defined by BMC, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Author details
[1]School of Biological Sciences, Queen's University Belfast, Belfast, Co. Antrim, UK. [2]Queen's University Marine Laboratory, Portaferry, Co. Down, UK. [3]School of Applied Sciences, Edinburgh Napier University, Edinburgh, UK. [4]Centre for Conservation and Restoration Science, Edinburgh Napier University, Edinburgh, UK. [5]Marine Institute, Furnace, County Mayo, Newport, Ireland. [6]Department of Zoology, School of Natural Sciences, Trinity College Dublin, Dublin, Ireland. [7]Irish Whale and Dolphin Group, Merchants Quay, Co. Clare, Kilrush, Ireland. [8]Manx Basking Shark Watch, Manx Wildlife Trust, Isle of Man, UK. [9]Loughs Agency, Derry/Londonderry, Ireland. [10]Ocean Tracking Network, Dalhousie University, Halifax, NS, Canada. [11]Department of Wildlife, Fish and Conservation Biology, University of California, Davis, USA. [12]Coastal Oregon Marine Experiment Station, Oregon State University, Newport, OR, USA. [13]Department of Fisheries, Wildlife and Conservation Sciences, Oregon State University, Corvallis, OR, USA. [14]Agri-Food & Biosciences Institute, River Bush Salmon Station, Bushmills, Co. Antrim, UK. [15]Fisheries and Oceans Canada, St. Johns, NF, Canada. [16]Scottish Centre for Ecology and the Natural Environment, School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow, Rowardennan, Glasgow, UK. [17]Scottish Association for Marine Science, Oban, Argyll, UK. [18]Atlantic Salmon Trust, Redgorton, Perth, UK. [19]NatureScot, Inverness, UK. [20]Marine & Fisheries Division, Department of Agriculture, Environment & Rural Affairs, Belfast, Co. Antrim., UK. [21]Department of Biology, Biological & Geological Sciences Building, Western University, London, Canada. [22]School of Biosciences, University of Exeter, Hatherly Building, Exeter, UK. [23]Marine and Freshwater Research Centre, Atlantic Technological University, Old Dublin Road, Galway, Ireland. [24]National Parks and Wildlife Service, North King Street, Dublin, Ireland.

Received: 9 February 2024 Accepted: 29 April 2024
Published online: 12 July 2024

References

1. Abecasis D, Steckenreuter A, Reubens J, Aarestrup K, Alós J, Badalamenti F, Bajona L, Boylan P, Deneudt K, Greenberg L. A review of acoustic telemetry in Europe and the need for a regional aquatic telemetry network. Animal Biotelemetry. 2018;6:1–7.
2. Alós J, Aarestrup K, Abecasis D, Afonso P, Alonso-Fernandez A, Aspillaga E, Barcelo-Serra M, Bolland J, Cabanellas-Reboredo M, Lennox R. Toward a decade of ocean science for sustainable development through acoustic animal tracking. Glob Change Biol. 2022;28:5630–53.
3. Anadón JD, D'Agrosa C, Gondor A, Gerber LR. Quantifying the spatial ecology of wide-ranging marine species in the Gulf of California: implications for marine conservation planning. PLoS ONE. 2011;6: e28400.
4. Armsworth PR, Block BA, Eagle J, Roughgarden JE. The economic efficiency of a time–area closure to protect spawning bluefin tuna. J Appl Ecol. 2010;47:36–46.
5. Block BA, Jonsen ID, Jorgensen SJ, Winship AJ, Shaffer SA, Bograd SJ, Hazen EL, Foley DG, Breed GA, Harrison A-L, Ganong JE, Swithenbank A, Castleton M, Dewar H, Mate BR, Shillinger GL, Schaefer KM, Benson SR, Weise MJ, Henry RW, Costa DP. Tracking apex marine predator movements in a dynamic ocean. Nature. 2011;475:86–90. https://doi.org/10.1038/nature10082.
6. Bloomfield A, Solandt J-L. The marine conservation society basking shark watch 20-year report (1987–2006). Ross on Wye: Marine Conservation Society; 2008.
7. Breen P, Posen P, Righton D. Temperate marine protected areas and highly mobile fish: a review. Ocean Coast Manag. 2015;105:75–83.
8. Cagua EF, Cochran JE, Rohner CA, Prebble CE, Sinclair-Taylor TH, Pierce SJ, Berumen ML. Acoustic telemetry reveals cryptic residency of whale sharks. Biol Let. 2015;11:20150092.
9. Chevis MG, Godley BJ, Lewis JP, Lewis JJ, Scales KL, Graham RT. Movement patterns of juvenile hawksbill turtles *Eretmochelys* imbricata at a Caribbean coral atoll: long-term tracking using passive acoustic telemetry. Endangered Species Res. 2017;32:309–19.
10. COMPASS. Collaborative Oceanography and Monitoring for Protected Areas and Species. 2023. https://compass-oceanscience.eu/. Accessed Dec 2023
11. Cooke SJ, Iverson SJ, Stokesbury MJ, Hinch SG, Fisk AT, VanderZwaag DL, Apostle R, Whoriskey F. Ocean Tracking Network Canada: a network approach to addressing critical issues in fisheries and resource management with implications for ocean governance. Fisheries. 2011;36:583–92.
12. Davies TE, Carneiro APB, Campos B, Hazin C, Dunn DC, Gjerde KM, Johnson DE, Dias MP. Tracking data and the conservation of the high seas: opportunities and challenges. J Appl Ecol. 2021;58:2703–10. https://doi.org/10.1111/1365-2664.14032.
13. Diamond SL, Kleisner KM, Duursma DE, Wang Y. Designing marine reserves to reduce bycatch of mobile species: a case study using juvenile red snapper (*Lutjanus campechanus*). Can J Fish Aquat Sci. 2010;67:1335–49.
14. Doherty PD, Baxter JM, Gell FR, Godley BJ, Graham RT, Hall G, Hall J, Hawkes LA, Henderson SM, Johnson L. Long-term satellite tracking reveals variable seasonal migration strategies of basking sharks in the north-east Atlantic. Sci Rep. 2017;7:42837.
15. Doherty PD, Baxter JM, Godley BJ, Graham RT, Hall G, Hall J, Hawkes LA, Henderson SM, Johnson L, Speedie C. Testing the boundaries: seasonal residency and inter-annual site fidelity of basking sharks in a proposed marine protected area. Biol Cons. 2017;209:68–75.
16. Dolton HR, Gell FR, Hall J, Hall G, Hawkes LA, Witt MJ. Assessing the importance of Isle of Man waters for the basking shark *Cetorhinus maximus*. Endangered Species Res. 2020;41:209–23.
17. Donaldson MR, Hinch SG, Suski CD, Fisk AT, Heupel MR, Cooke SJ. Making connections in aquatic ecosystems with acoustic telemetry monitoring. Front Ecol Environ. 2014;12:565–73.
18. Gennari E, Irion DT, Cowley PD. Active acoustic telemetry reveals ontogenetic habitat-related variations in the coastal movement ecology of the white shark. Animal Biotel. 2022;10:1–14.
19. Gore M, Abels L, Wasik S, Saddler L, Ormond R. Are close-following and breaching behaviours by basking sharks at aggregation sites related to courtship? J Mar Biol Assoc UK. 2019;99:681–93.
20. Gore MA, Frey PH, Ormond RF, Allan H, Gilkes G. Use of photo-identification and mark-recapture methodology to assess basking shark (*Cetorhinus maximus*) populations. PLoS ONE. 2016;11: e0150160.
21. Gore MA, Rowat D, Hall J, Gell FR, Ormond RF. Transatlantic migration and deep mid-ocean diving by basking shark. Biol Let. 2008;4:395–8.
22. Hammerschlag N, Gallagher AJ, Lazarre DM. A review of shark satellite tagging studies. J Exp Mar Biol Ecol. 2011;398:1–8. https://doi.org/10.1016/j.jembe.2010.12.012.
23. Hart KM, Hyrenbach KD. Satellite telemetry of marine megavertebrates: the coming of age of an experimental science. Endangered Species Res. 2009;10:9–20.
24. Hays GC, Bailey H, Bograd SJ, Bowen WD, Campagna C, Carmichael RH, Casale P, Chiaradia A, Costa DP, Cuevas E. Translating marine animal tracking data into conservation policy and management. Trends Ecol Evol. 2019;34:459–73.
25. Hetherington SJ, Bendall VA. People, sharks and science. Collaborative Res Fish Co-creating Knowledge Fish Governance Eur. 2020;22:263.
26. Hobday AJ, Hartog JR, Spillman CM, Alves O. Seasonal forecasting of tuna habitat for dynamic spatial management. Can J Fish Aquat Sci. 2011;68:898–911.

27. Holbrook C, Hayden T, Binder T, Pye J, Nunes A. glatos: A package for the great lakes acoustic telemetry observation system R package version. Can J Fish Aquat Sci. 2017;75(10):1755.
28. Holmes SJ, Bailey N, Campbell N, Catarino R, Barratt K, Gibb A, Fernandes PG. Using fishery-dependent data to inform the development and operation of a co-management initiative to reduce cod mortality and cut discards. ICES J Mar Sci. 2011;68:1679–88.
29. Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT, Harcourt RG, Holland KN, Iverson SJ, Kocik JF. Aquatic animal telemetry: a panoramic window into the underwater world. Science. 2015;348:1255642.
30. Jacoby DMP, Croft DP, Sims DW. Social behaviour in sharks and rays: analysis, patterns and implications for conservation. Fish Fish. 2012;13:399–417. https://doi.org/10.1111/j.1467-2979.2011.00436.x.
31. Johnston EM, Houghton JDR, Mayo PA, Hatten GKF, Klimley AP, Mensink PJ. Cool runnings: behavioural plasticity and the realised thermal niche of basking sharks. Environ Biol Fishes. 2022;12:1–15.
32. Johnston EM, Mayo PA, Mensink PJ, Savetsky E, Houghton JD. Serendipitous re-sighting of a basking shark *Cetorhinus maximus* reveals interannual connectivity between American and European coastal hotspots. J Fish Biol. 2019;95:1530–4.
33. Kohler NE, Turner PA. Shark tagging: a review of conventional methods and studies. Environ Biol Fishes. 2001;60:191–224.
34. Lavender E, Aleynik D, Dodd J, Illian J, James M, Wright PJ, Smout S, Thorburn J. Movement patterns of a critically endangered elasmobranch (*Dipturus intermedius*) in a marine protected area. Aquat Conserv Mar Freshwat Ecosyst. 2021;32:348–65.
35. Lavender et al. Movement patterns of a Critically Endangered elasmobranch (Dipturus intermedius) in a MarineProtected Area. Aquat Conserv Mar Freshwat Ecosyst. 2022;32(2):348–65.
36. Lieber L, Dawson DA, Horsburgh GJ, Noble LR, Jones CS. Microsatellite loci for basking shark (*Cetorhinus maximus*) monitoring and conservation. Conserv Genet Resour. 2015;7:917–44.
37. Lieber L, Hall G, Hall J, Berrow S, Johnston E, Gubili C, Sarginson J, Francis M, Duffy C, Wintner SP. Spatio-temporal genetic tagging of a cosmopolitan planktivorous shark provides insight to gene flow, temporal variation and site-specific re-encounters. Sci Rep. 2020;10:1–17.
38. Little AS, Needle CL, Hilborn R, Holland DS, Marshall CT. Real-time spatial management approaches to reduce bycatch and discards: experiences from Europe and the United States. Fish Fish. 2015;16:576–602.
39. Lowerre-Barbieri SK, Kays R, Thorson JT, Wikelski M. The ocean's movescape: fisheries management in the bio-logging decade (2018–2028). ICES J Mar Sci. 2019;76:477–88. https://doi.org/10.1093/icesjms/fsy211.
40. Matley JK, Klinard NV, Martins APB, Aarestrup K, Aspillaga E, Cooke SJ, Cowley PD, Heupel MR, Lowe CG, Lowerre-Barbieri SK. Global trends in aquatic animal tracking with acoustic telemetry. Trends Ecol Evol. 2022;37:79–94.
41. McInturf AG, Bowman J, Schulte JM, Newton KC, Vigil B, Honig M, Pelletier S, Cox N, Lester O, Cantor M. A unified paradigm for defining elasmobranch aggregations. ICES J Mar Sci. 2023;80:1551–66.
42. Merrifield M, Gleason M, Bellquist L, Kauer K, Oberhoff D, Burt C, Reinecke S, Bell M. eCatch: enabling collaborative fisheries management with technology. Eco Inform. 2019;52:82–93.
43. Neat F, Pinto C, Burrett I, Cowie L, Travis J, Thorburn J, Gibb F, Wright PJ. Site fidelity, survival and conservation options for the threatened flapper skate (*Dipturus cf. intermedia*). Aquatic Conserv Mar Freshw Ecosyst. 2014;25:6–20. https://doi.org/10.1002/aqc.2472.
44. Nosal AP, Cartamil DP, Ammann AJ, Bellquist LF, Ben-Aderet NJ, Blincow KM, Burns ES, Chapman ED, Freedman RM, Klimley AP. Triennial migration and philopatry in the critically endangered soupfin shark Galeorhinus galeus. J Appl Ecol. 2021;58:1570–82.
45. Papastamatiou YP, Bodey TW, Caselle JE, Bradley D, Freeman R, Friedlander AM, Jacoby DMP. Multiyear social stability and social information use in reef sharks with diel fission–fusion dynamics. Proc Royal Soc B Biol Sci. 2020;287:20201063. https://doi.org/10.1098/rspb.2020.1063.
46. Paxton, C.G., Scott-Hayward, L.A.S., Rexstad, E.A., 2014. Statistical approaches to aid the identification of Marine Protected Areas for minke whale, Risso's dolphin, white-beaked dolphin and basking shark. Scottish Natural Heritage, Policy and Advice Directorate.
47. Queiroz N, Humphries NE, Couto A, Vedor M, Da Costa I, Sequeira AM, Mucientes G, Santos AM, Abascal FJ, Abercrombie DL. Global spatial risk assessment of sharks under the footprint of fisheries. Nature. 2019;572:461–6.
48. Queiroz N, Humphries NE, Mucientes G, Hammerschlag N, Lima FP, Scales KL, Miller PI, Sousa LL, Seabra R, Sims DW. Ocean-wide tracking of pelagic sharks reveals extent of overlap with longline fishing hotspots. Proc Natl Acad Sci. 2016;113:1582–7.
49. Renshaw S, Hammerschlag N, Gallagher AJ, Lubitz N, Sims DW. Global tracking of shark movements, behaviour and ecology: a review of the renaissance years of satellite tagging studies, 2010–2020. J Exp Mar Biol Ecol. 2023;560: 151841.
50. Reubens J, Verhelst P, Van Der Knaap I, Wydooghe B, Milotic T, Deneudt K, Hernandez F, Pauwels I. The need for aquatic tracking networks: the permanent Belgian acoustic receiver network. Anim Biotelemetry. 2019;7:2. https://doi.org/10.1186/s40317-019-0164-8.
51. Rodger et al. Inshore and offshore marine migration pathways of Atlantic salmon post-smolts from multiple rivers in Scotland, England, Northern Ireland, and Ireland. J Fish Biol. 2024. https://doi.org/10.1111/jfb.15760
52. Rudd JL, Bartolomeu T, Dolton HR, Exeter OM, Kerry C, Hawkes LA, Henderson SM, Shirley M, Witt MJ. Basking shark sub-surface behaviour revealed by animal-towed cameras. PLoS ONE. 2021;16: e0253388.
53. Schaber M, Gastauer S, Cisewski B, Hielscher N, Peña M, Sakinan S, Thorburn J. Extensive oceanic mesopelagic habitat use of a migratory coastal and continental shark species. Sci Rep. 2022;12:2047–2047.
54. Sims DW. Tracking and analysis techniques for understanding free-ranging sharkl movements and behaviour. In: Carrier J, Heithaus M, Musick J, editors. Biology of sharks and their relatives biodiversity adaptive physiology and conservation. Boca Raton: CRC Press; 2010.
55. Sims DW. Sieving a living: a review of the biology, ecology and conservation status of the plankton-feeding basking shark Cetorhinus maximus. Adv Mar Biol. 2008;54:171–220.
56. Sims DW, Berrow SD, O'Sullivan KM, Pfeiffer NJ, Collins R, Smith KL, Pfeiffer BM, Connery P, Wasik S, Flounders L. Circles in the sea: annual courtship "torus" behaviour of basking sharks Cetorhinus maximus identified in the eastern North Atlantic Ocean. J Fish Biol. 2022;101:1160–81.
57. Sims DW, Southall EJ, Quayle VA, Fox AM. Annual social behaviour of basking sharks associated with coastal front areas. Proc Royal Soc London Series B Biol Sci. 2000;267:1897–904.
58. Sims DW, Southall EJ, Richardson AJ, Reid PC, Metcalfe JD. Seasonal movements and behaviour of basking sharks from archival tagging: no evidence of winter hibernation. Mar Ecol Prog Ser. 2003;248:187–96.
59. Sims DW, Witt MJ, Richardson AJ, Southall EJ, Metcalfe JD. Encounter success of free-ranging marine predator movements across a dynamic prey landscape. Proc Royal Soc London B Biol Sci. 2006;273:1195–201. https://doi.org/10.1098/rspb.2005.3444.
60. Southall EJ, Sims DW, Metcalfe JD, Doyle JI, Fanshawe S, Lacey C, Shrimpton J, Solandt JL, Speedie CD. Spatial distribution patterns of basking sharks on the European shelf: preliminary comparison of satellite-tag geolocation, survey and public sightings data Marine biological association of the United Kingdom. J Marine Biol Assoc United Kingdom. 2005;85:1083.
61. Southall EJ, Sims DW, Witt MJ, Metcalfe JD. Seasonal space-use estimates of basking sharks in relation to protection and political–economic zones in the North-east Atlantic. Biol Cons. 2006;132:33–9.
62. Southwood L. Assessment of the reliability of photo identification using skin patterns for the basking shark, Cetorhinus maximus in the Irish Sea. 2008.
63. The Atlantic Salmon Trust. West Coast Tracking Project. 2023. https://atlanticsalmontrust.org/our-work/west-coast-trackingproject/. Accessed Dec 2023.
64. Thorburn J, Dodd J, Neat F. Spatial ecology of flapper skate (Dipturus intermedius) and spurdog (Squalus acanthias) in relation to the Loch Sunart to the Sound of Jura Marine Protected Area and Loch Etive. Scottish Nat Herit Res. 2018. Report No.1011.
65. Thorburn J, Jones R, Neat F, Pinto C, Bendall V, Hetherington S, Bailey DM, Leslie N, Jones C. Spatial versus temporal structure: Implications of interhaul variation and relatedness in the North-east Atlantic spurdog Squalus acanthias. Aquat Conserv Mar Freshwat Ecosyst. 2018;28:1167–80.
66. Thorburn J, Neat F, Burrett I, Henry L-A, Bailey D, Jones C, Noble L. Ontogenetic and seasonal variation in movements and depth use, and evidence of partial migration in a benthopelagic elasmobranch. Front Ecol Evol. 2019;7:353.

67. Thorburn J, Wright PJ, Lavender E, Dodd J, Neat F, Martin JG, Lynam C, James M. Seasonal and ontogenetic variation in depth use by a Critically Endangered benthic elasmobranch and its implications for spatial management. Front Marine Sci. 2021;8:829.
68. Van Geel NC, Risch D, Benjamins S, Brook T, Culloch RM, Edwards EW, Stevens C, Wilson B. Monitoring cetacean occurrence and variability in ambient sound in Scottish offshore waters. Frontiers in Remote Sensing. 2022;3: 934681.
69. Vermeulen, E., Cammareri, A., Failla, M., 2008. A photo-identification catalogue of bottlenose dolphins (Tursiops truncatus) in Northeast Patagonia, Argentina: A tool for the conservation of the species. Report-International Whaling Commission.
70. Witt MJ, Hardy T, Johnson L, McClellan CM, Pikesley SK, Ranger S, Richardson PB, Solandt J-L, Speedie C, Williams R. Basking sharks in the northeast Atlantic: spatio-temporal trends from sightings in UK waters. Mar Ecol Prog Ser. 2012;459:121–34.
71. Yang Y, Elsinghorst R, Martinez JJ, Hou H, Lu J, Deng ZD. A real-time underwater acoustic telemetry receiver with edge computing for studying fish behavior and environmental sensing. IEEE Internet Things J. 2022;9:17821–31.

Publisher's Note