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Seasonal space-use estimates of basking sharks in relation to protection and political–economic zones in the North-east Atlantic

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ABSTRACT

The basking shark *Cetorhinus maximus* is listed as Vulnerable (A1a,d, + 2d) worldwide, and Endangered (EN A1a,d) in the north-east Atlantic in the IUCN Red List. However, protection for this species is limited in European waters and varies spatially. Without information on the amount of time individuals spend in different areas, any potential risks to population levels from incidental capture, possible future exploitation and climate change will be difficult to assess. To quantify the annual space-use patterns within political–economic zones in the north-east Atlantic we used geolocation data from seven transmitter-tagged basking sharks tracked for 964 days (16,754 km). Basking sharks tagged within the UK protection zone off south-west England and north-west Scotland spent subsequently only about 22% (range, 2.4–47.7%) of time at liberty within this zone, and a further 30% in the UK fishing zone. Although only about 6% of time was spent in the territorial waters of Ireland and France, basking sharks remained in UK, Irish and French fishing and EEZ zones for over 71% of track time (range, 51.4–89.2%). Sharks did not occupy International waters away from the European shelf at any time. These results indicate basking sharks move between different economic zones and were not afforded statutory protection for the major part of the time (78%) they spent within preferred habitat on the European shelf. This demonstrates the limited capacity of the British protection zone for encompassing the greater part of shark space utilisation. Tracked basking sharks regularly crossed national zone boundaries suggesting that conservation measures for this species need to be framed on a European, rather than national, basis. This study highlights the need for better information about the movements and habitat use by marine animals if conservation strategies are to be truly effective.

1. Introduction

The populations of many large marine vertebrates are threatened by too high a level of fisheries exploitation, both by targeted fisheries and as bycatch (Jackson et al., 2001; Myers and Worm, 2003). This applies particularly to elasmobranchs (sharks, skates and rays), which have a number of life-history traits that make them particularly vulnerable to levels of harvest mortality that are well above that of natural mortality. Although a recent estimate suggests the populations of some shark species may have declined by as much as 75% in the past 15 years (Baum et al., 2003), there seems little doubt that

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declines, albeit of smaller magnitude, at the scale of the north-west Atlantic and Gulf of Mexico have occurred (Burgess et al., 2005). Many elasmobranch species have a late age at maturity and low fecundity, leading to low rates of reproduction and low potential rates of population growth compared to marine teleosts (Pratt and Casey, 1990). Sharks also have relatively little scope for the compensatory mechanisms that enable teleosts to withstand unnaturally high levels of mortality, such as rapid development, early reproduction and selection for fast growth (Pitcher and Hart, 1982). As a consequence, elasmobranch fisheries not only exhibit rapid declines in catch rates as exploitation increases, but there is a greater potential for the fishery to collapse (Holden, 1973, 1977; Casey and Myers, 1998; Dulvy et al., 2000; Baum et al., 2003; Ward and Myers, 2005).

The basking shark is the world's second largest fish and is widely distributed in coastal waters on the continental shelves of temperate zones in both the northern and southern hemispheres. They show broad site fidelity to productive continental-shelf habitats (e.g., North-east Atlantic) but movements within these regions are extensive both horizontally and vertically, with sharks covering distances of ~2000 km in 2 months and diving to depths of ~800 m, whilst remaining active throughout the year (Sims et al., 2003). In continental shelf and shelf-edge habitats basking sharks often aggregate to forage on dense patches of zooplankton associated with oceanographic features (Sims and Quayle, 1998; Sims et al., 2006).

Despite maintaining close proximity to productive waters year-round, basking sharks take many years to reach maturity (possibly 12–20 years) due to their relatively slow growth. Females are ovoviviparous and have long gestation periods (1–3 years) at the end of which they give birth to a few, large young (the only recorded litter is of six 2-m long pups) (Kunzlik, 1988). The inherent vulnerability to high levels of exploitation typified by slow growth, late maturity and low fecundity in this species may have resulted in collapses of some stocks (Anderson, 1990). For example, the fishery for basking shark (*Cetorhinus maximus*) near Achill Island off the west coast of Ireland appeared to collapse in the early 1960s after only ten years of peak catches (Kunzlik, 1988). Concern over the strong possibility that populations are depleted as a result of exploitation by fisheries and the lack of scientific knowledge of the species, has led to the basking shark being listed as Vulnerable (A1a,d, + 2d) worldwide, and Endangered (EN A1a,d) in the north-east Atlantic in the IUCN Red List (IUCN, 2004). In 2000, the species was listed in Appendix III of the Convention on International Trade in Endangered Species (CITES). In 2002, on the basis of the UK proposal, the CITES listing was upgraded to Appendix II which requires that International trade in these species is monitored through a licensing system to ensure that trade can be sustained without detriment to wild populations. Although no longer exploited there, they are also protected in British (but not Northern Irish) territorial waters under Schedule 5 of the Wildlife and Countryside Act 1981, and it is a priority species under the UK Biodiversity Action Plan (English Nature, 1999). They are also protected within the territorial waters of the Isle of Man and Guernsey, in the Mediterranean under the Bern Convention on the Conservation of European Wildlife and Natural Habitats (with EU reservation) and Barcelona Convention for the Protection of the Mediterranean Sea against Pollution (unratified).

Despite this vulnerability, the protection for basking shark in Europe is limited and varies spatially. Legal protection against the killing, landing and sale of body parts is afforded to basking sharks only within British, Isle of Man and Guernsey territorial waters. Moreover, the only catch control on fishing for basking sharks in European waters is a total allowable catch (TAC, currently set at zero) for Norwegian vessels fishing in European Community (EC) waters, defined as the combined fishing zones of European Union nations. However, although Norway and all other countries have now ceased to fish for basking sharks in EC waters, there is the possibility that bycatch in trawls and gillnets may be relatively high. Similarly, it has not yet been determined how effective the protection zone of British territorial waters (⩽12 nautical miles, nm) might be in terms of encompassing the major part of basking shark space-use. Thus there is a need to determine what areas within the various European zones are used by basking sharks to provide basic information for assessing potential risks from fishing in specific areas.

There are comprehensive sightings records for basking shark in UK coastal waters dating from 1987 onwards (Doyle et al., 2005). These sightings are often highly variable due to observer bias and due to systematic differences in the surfacing behaviour of basking sharks that occurs with changes in habitat, and which alters the probability of sighting individuals at the surface according to location, season and time of day (Sims et al., 2005a). Therefore, sightings data alone is unlikely to accurately describe the annual patterns of movement and distribution of basking sharks (Southall et al., 2005). In this study, we used geolocations from transmitter-tagged basking sharks and spatial mapping techniques to identify the space-use patterns of individual sharks in relation to European protection and political–economic zones. The two principal questions we addressed were (1) how is basking shark space-use divided among the different protection and political–economic zones on the European shelf and (2) to what extent does space-use change seasonally?

2. Methods

2.1. Satellite tracking

Geolocations of free-ranging basking sharks on the European continental shelf between May 2001 and December 2002 were determined from data retrieved from pop-up archival transmitting (PAT) tags (length: 175 mm; mass in air, 76 g) (Wildlife Computers, Redmond, USA). These tags combine a data-logger that records swimming depth, water temperature and light level with an Argos-certified transmitter with 0.5 W power output. Depth is measured to 1000 m (min. resolution, 0.5 m), temperature from −40 to +60 °C (min. resolution, 0.05 °C), and light level is measured as irradiance (W cm^{-2}) at 550 nm wavelength. Full description of the tags and tagging procedure is given in Sims et al. (2003, 2005b). Briefly, transmitters were attached to 20 individuals at the base of the first dorsal fin during summer foraging within British territorial waters off south-west England and north-west Scotland.

Although basking sharks occur throughout European waters, these areas were chosen because they provide access to higher than usual numbers because they aggregate to feed in productive patches associated with fronts. The number of animals tracked in this study reflects the low abundance of this species, the difficulty of attaching tags for a long enough time period, and the availability of appropriate technology. Each tag remained attached to a shark for a pre-programmed time (between 74 and 217 days) before detaching and floating to the surface where each was geolocated by Argos receivers on NOAA polar-orbiting satellites. Estimated accuracy of the 'pop-up' locations as determined by Argos was between 150–350 m and 350–1000 m (Argos class 1 and 2 locations). Positions of each shark between attachment and tag pop-up were reconstructed using data recovered remotely via satellite (satellite-retrieved) or directly from tags found washed up on beaches (archival data). The data used was daily maximal rate-of-change in light intensity to estimate local time of midnight or midday for longitude calculations (Sims et al., 2003). Latitude along the longitude was fixed by matching tag-recorded sea surface temperature (SST) to SST on night-time advanced very high resolution radiometer (AVHRR) remote-sensing images. Filter routines incorporating SST, water depth and swim-speed parameters were in each case used to fix the most parsimonious geolocation (Sims et al., 2003). Accuracy of light/SST geolocation estimates compared to nearest tagging position (accurate to <5 m; DGPS) and Argos locations were calculated to be between ±0.29 and 1.16° (1° longitude = 71.7 km). The mean number of geolocations per day during tracking was 0.20 ± 0.05 SEM ($n = 7$ sharks, $n = 185$ positions in total). The number of geolocations per tag was dependent on the availability of good-quality light-intensity data from each tag (for discussion see Sims et al., 2006).

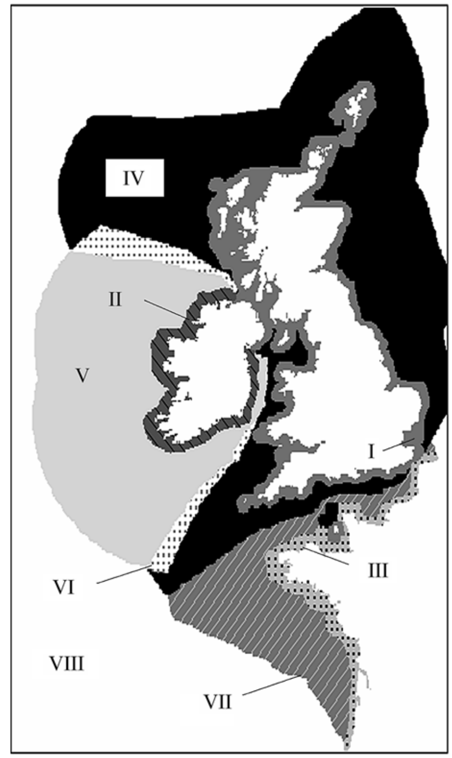

Fig. 1 – The European continental shelf delineated into eight different political–economic zones according to the United Nations Convention on the Law of the Sea 1982. Zones: I, United Kingdom territorial Sea (dark grey infill); II, Ireland territorial Sea (dark grey with black cross-hatch); III, France territorial Sea (light grey with black dots); IV, United Kingdom fishing zone (black infill); V, Ireland fishing zone (light grey); VI, United Kingdom and Ireland unresolved zone (white with grey dots); VII, France: exclusive economic zone (EEZ) and contiguous zone (dark grey with white cross-hatch); and VIII, Unclassified waters (not within 200 nm zone of UK, France or Ireland) (white).

2.2. *Space-use analysis*

The movements of the satellite-tracked sharks were analysed in relation to protection and political–economic zones using MATLAB programming software (MathWorks Inc., MA, USA). A base map of the European continental shelf was demarcated using shape files into eight different political–economic zones (Fig. 1) according to the United Nations Convention on the Law of the Sea 1982. Shape files were obtained from the Global Marine Boundaries Database. The zones relate principally to the territorial sea areas (⩽12 nm) and the fishing zones (>12, ⩽200 nm) of the United Kingdom, Ireland and France. The French fishing zone is also claimed by that nation as an exclusive economic zone (EEZ). The narrow arcs of unresolved sea between the fishing zones of UK and Ireland were also included. The high seas or the unclassified zone were delimited as waters beyond 200 nm of any claimed territory.

The zone map was created where each zone was represented by a number, with pixel resolution of 1/60th of a degree. For each shark, track intermediate waypoints were created between light/SST-derived track geolocations by using code to interpolate an exact distance of 1/60th degree. This procedure ensured there was no variation in the between-waypoint distance for each part of the reconstructed track and the time stamp for each waypoint remained 'time-accurate', eliminating any potential biases in the route-reconstruction technique due to variable inter-waypoint distances. For each of these interpolated locations the underlying zone number was then determined using nearest–neighbour interpolation. The percentage occupancy for each zone (n locations) was calculated by taking the number of interpolated locations within each zone divided by the total number of interpolated locations multiplied by 100. All distances were calculated using great circle principles, where a great circle is the shortest distance from point to point on the Earth's surface. The track of Shark 2 crossed the peninsula of Brittany because there were too few geolocations to identify the actual route around it. Additional coordinates were interpolated between the two geolocations to prevent the shark crossing land.

Seasonal differences in spatial distribution and the time spent by sharks within the eight political zones was investigated using the same procedures, but by dividing the tracks lengths according to season, which were defined as winter (December–February, inclusive), spring (March–May), summer (June–August) and autumn (September–November).

3. Results

Data were received from 7 of the 20 tagged sharks (35%). We assume the remaining tags malfunctioned because they failed to relay data to satellites at or soon after the pop-up time. Sharks were tracked for a total of 964 days covering an estimated total minimum distance of 16,754 km (Table 1), with geolocations determined during all quarters (seasons) of the year, but with most position fixes occurring in summer and autumn (Table 1).

The distribution of geolocations of sharks tagged off south-west England and north-west Scotland shows high densities in the Celtic and Hebridean Seas, and the Western Approaches to the English Channel (Fig. 2). Two sharks tagged in south-west England moved west around Ireland then north into Scottish waters, whereas two sharks tagged in Scotland travelled south through the Irish Sea to the Celtic Sea. Of the remaining three sharks, one tagged in Scotland remained there, whilst two others tagged off the south-west coast moved into the central Celtic Sea (Fig. 2). Occupancy times of individual basking sharks within each of the eight economic zones demonstrated that all sharks moved between zones during the tracking periods, with each shark using between four and seven of the eight zones (Table 2). The pattern of temporal distribution between zones fell into two main categories: shark geolocations concentrated principally in one zone, and sharks occupying two or three zones more or less equally. Percentage distribution of geolocations was higher in one zone, compared to the other zones for three sharks (1, 2 and 6). For example, shark 2 spent 76% of time in the French fishing zone and between 2.4 and 16% in other zones, while shark 6 occupied the UK fishing zone for 74% of the time and other zones for times between 0.2 and 21% (Table 2). In contrast, the four remaining sharks (3, 4, 5 and 7) occupied two or three different zones nearly equally, such as shark 4, that spent 21, 31 and 37% in the Irish fishing zone, UK fishing zone, and British territorial waters, respectively (Table 2).

The sharks spent 22.4 ± 17.2% (mean ± SD) of time in British territorial waters, but only 3.5 and 2.9% on average in Irish and French territorial waters, respectively (Table 2). Overall, sharks spent only 28.8 ± 14.4% (mean ± SD) of track time in territorial waters of the UK, Ireland and France, which meant for the remaining 71.2 ± 14.4% (mean ± SD) they occupied UK, Irish and French fishing waters. Comparisons between the different national sea areas of the continental shelf showed geolocations of basking sharks most frequently occurred within the territorial and fishing zones of the UK, where they spent 52.9% of the time, which was greater than the amount of time spent in Irish (18.4%) and French waters (24.3%) combined. No time, however, was spent in International waters by the tracked sharks (Table 2).

Whilst the length of time each shark was tracked varied, the overall movement data indicated that the basking sharks occupied territorial waters for only approximately 20% of the time they were tracked in winter, spring and autumn. The remaining time was spent in national fishing zones and

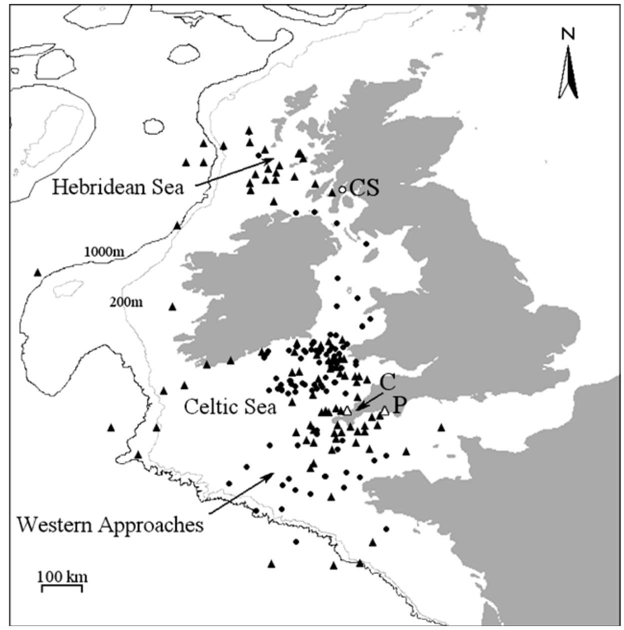

Fig. 2 – Geolocations of seven satellite-tracked basking sharks (filled symbols) in relation to the UK and the European continental shelf edge. Tagging locations are indicated by open symbols (P, Plymouth, England; C, Cornwall, England; CS, Clyde Sea, Scotland). Symbol shape of each geolocation denotes original tagging location (triangles, P and C; circles, CS).

Table 1 – Summary of the seven basking sharks tracked for a total of 964 days in 2001 and 2002 on the European Continental shelf, covering a minimum distance of 16,754 km

Shark #	Sex, if known	Length (m)	Location tagged	Date tagged	Pop-up date	No. of track days	Pop-up latitude (°N)	Pop-up longitude (°W)	Minimum distance moved (km)	Track time span (Sp, spring; S, summer; A, autumn; W, winter)
1	F	4.5	Plymouth	24/05/01	07/08/01	77	56.42	7.26	1878	Sp, S
2	–	6.0	Plymouth	24/05/01	07/12/01	197	49.87	2.42	1616	Sp, S, A, W
3	F	7.0	Clyde sea	28/07/01	05/01/02	162	50.79	5.35	3421	S, A, W
4	–	2.5	Clyde sea	28/07/01	14/03/02	229	51.67	6.64	3201	S, A, W, Sp
5	–	5.0	Cornwall	18/07/02	31/10/02	105	57.31	8.17	3034	S, A
6	–	6.0	Cornwall	18/07/02	30/09/02	74	51.55	5.72	1937	S, A
7	F	6.0	Plymouth	18/06/02	15/10/02	120	51.77	7.79	1667	S, A

Table 2 – Summary of the proportion of time that seven sharks (numbered 1–7 as in Table 1) spent within each of the eight political–economic zones

Zones	Shark							
	1	2	3	4	5	6	7	Mean
United Kingdom: territorial sea	3.8	2.4	7.9	37.2	20.4	21.1	47.7	22.4
Ireland: territorial sea	11.1	0.0	0.0	5.7	10.1	0.0	0.9	3.5
France: territorial sea	0.1	16.0	2.9	0.0	0.0	0.0	0.0	2.9
All territorial waters	14.9	18.5	10.9	42.9	30.4	21.1	48.6	28.8
United Kingdom: fishing zone	15.2	5.9	31.6	30.6	23.7	74.0	35.0	30.5
Ireland: fishing zone	49.2	0.0	6.4	21.1	34.0	0.2	8.4	14.9
United Kingdom and Ireland: unresolved zone	3.7	0.0	2.9	5.4	11.9	4.8	5.0	4.2
France: EEZ and contiguous zone	17.1	75.7	48.3	0.0	0.0	0.0	3.0	21.6
All fishing and EEZ zones	85.1	81.6	89.2	57.1	69.6	79.0	51.4	71.2
Unclassified waters (not within 200 nm zone of UK, France or Ireland)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

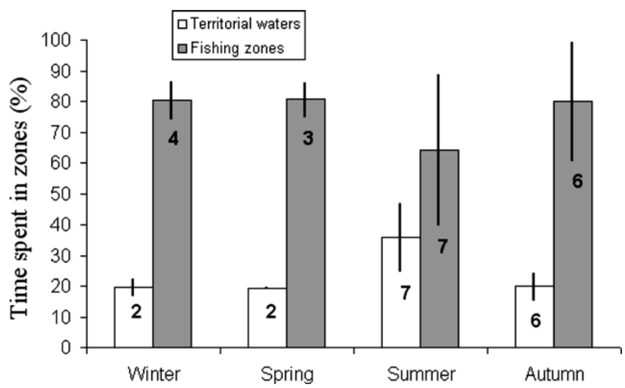

Fig. 3 – Changes in the mean percentage time (±1 SD) basking sharks spent within the Territorial and Fishing EEZ zones in different seasons. Duration: winter, December–February; spring, March–May; summer, June–August; autumn, March–May. Number of individual sharks in each season for which there were data is given on corresponding histogram bars.

the EEZ (Fig. 3). However, during summer, the number of geolocations in territorial waters increased to about 40%.

4. Discussion

Aerial, ship-borne and land-based sightings data of basking sharks in coastal waters provide useful information on surface occurrence and distribution (Cotton et al., 2005; Doyle et al., 2005). However, recent work comparing these data with satellite tag-derived geolocations indicated sightings data do not adequately describe the areas used by basking sharks when they are below the surface (Southall et al., 2005). Significant differences in density distributions were apparent (Southall et al., 2005), which highlights the importance of tracking technology for the routine study of basking shark spatial distribution patterns. This is because geolocations fixed using electronic tags provide an independent measure of habitat utilisation that is free from the constraints of observer and effort biases associated with surface sightings. Nevertheless, in estimating the time spent by sharks in different political–economic zones in this study, it was important to minimise potential biases that may arise from adopting an indirect geolocation method for reconstructing positions of individual sharks through time.

4.1. *Potential biases*

The amount of time spent by satellite-tracked basking sharks in different political–economic zones in this study was estimated from geolocations fixed using light intensity, SST measurements and depth and swim-speed filters (Sims et al., 2003). This track reconstruction technique has been used in various recent studies with pelagic fish (e.g., Block et al., 2001; Block et al., 2005), but it is not without error (Teo et al., 2004). First, the accuracy with which geolocations are derived depends on several factors, including weather conditions affecting light intensity measurements aboard the tag, and the behaviour of the tagged animal. The error distances associated with geolocations in this study were calculated to be between 0.29 and 1.16°, which was similar to the geolocation error range reported in a recent validation study with bluefin tuna and blue sharks (Teo et al., 2004). This suggests any potential errors arising from the geolocation methodology were similar here to previous estimates. Furthermore, the geolocation errors we calculated were very small relative to the areas of the political–economic zones themselves, indicating that large errors in space-use estimates between zones was less likely. Another potential source of error is associated with the presence of significant time gaps in an individual track. Because of the indirect method of determining horizontal trajectories we used, the time between successive geolocations for each individual may not be constant, but may vary due to some of the factors noted above. For example, changes in fish swimming depth around the time of sunrise and sunset resulting in large errors in longitude estimates, precludes their use in track reconstruction. This may result in gaps in the track reconstruction due to 'missing' data. Significant gaps in the track due to a paucity of accurate geolocation estimates reduces the resolution of the ground track such that an animal's position may not be known for long periods of time. In the context of the current study, this would be a source of error resulting in over- or under-estimating occupation time in a zone if a shark spent a significant proportion of time near a zone boundary. In our study this potential error was limited because geolocations were obtained approximately every 5 days (see Section 2).

Overall, we attempted to limit potential sources of error associated with track reconstruction that might affect significantly estimates of occupancy times in the different zones. Despite this, the occupancy times calculated in this study are the best estimates available using an indirect track reconstruction method.

4.2. Space-use

The results show that basking sharks tagged in the UK protection zone off south-west England and north-west Scotland spent a significant proportion of time (53%) in the UK territorial and fishing zones, with the remainder spent in Irish and French territorial, fishing and EEZs. With the observation that no sharks occupied International waters, this demonstrates that the European continental shelf encompassed the movements of tagged basking sharks, which were each tracked for significant periods ranging between 74 and 217 days. Movement patterns in this study, although based on seven individuals, were broadly consistent with the limited data available in other studies on this species to date (Priede, 1984; Skomal et al., 2004). Persistent occupation of the shelf suggests this region comprises the preferred habitat of basking sharks. For example, they are known to exploit thermal fronts for foraging and courtship opportunities (Sims and Quayle, 1998; Sims et al., 2000), which are common features of the shelf seas (Pingree, 1978). The increase in occupancy of territorial waters during summer months (June–August) was consistent with inshore movements linked to foraging activity, presumably to take advantage of seasonal increases in zooplankton abundance that occur in coastal front areas during summer (Sims and Quayle, 1998).

The most striking finding of the present study was that basking sharks occupied British territorial waters for only 22% of the time they were tracked. Intentional capture, landing and sale of basking shark is prohibited in British territorial waters, however, this cannot prevent incidental capture. Even within the zone, mortality of basking shark may still be significant despite no current targeted fishing. Mortalities in UK territorial waters have been documented as being caused by boat collision, accidental entanglement in fishing gear, including trawls, gill-nets and buoyed creel ropes (Doyle et al., 2005). Although a realistic estimate for the total number of mortalities is unknown in this zone, 45% of the total number of dead basking sharks reported were close inshore off south-west England (Doyle et al., 2005). This is a region characterised by a relatively high level of fishing activity (Southward et al., 2004). Our study shows that it is also an area with a high density of tag geolocations. The presence of high-use habitat of basking sharks overlapping with intensive fishing activity, may explain why incidental mortality rate off south-west England appears disproportionately high even within a protection zone.

We found tracked sharks spent the majority of the time (78%) outside the UK protection zone, thus, in areas without statutory protection. In these zones, together termed the European Exclusion Zone there is a zero total allowable catch (TAC) for basking sharks by Norwegian vessels, but no other controls are presently in place. There is no directed fishing for basking shark in Europe, but incidental captures may be significant when you consider high habitat use of basking sharks overlapping with trawl fleets as it appears to in the Celtic Sea (Robin et al., 2002; Rochet et al., 2002; Verdoit et al., 2003). In the same way that incidental captures appear high in inshore areas off south-west England, fishing activity in the Celtic Sea and Western Approaches to the English Channel may be impacting populations. A comprehensive study on catches of basking sharks by commercial trawls in New Zealand showed catch rates reached a level of 58 sharks per 1000 trawls (Francis and Duffy, 2002). The majority of trawls that captured basking shark usually caught a single shark, however, sometimes between 2 and 14 sharks in a single trawl were also recorded (Francis and Duffy, 2002). Clearly, the lack of the requirement to report incidental captures of basking sharks in European fishing zones, despite their high use by basking sharks, results in a lack of data without which potential risks cannot be assessed.

In summary, the current study describes the occupancy times of tracked basking sharks in different political–economic zones. It draws attention to the relatively short time sharks originally tagged in British territorial waters subsequently spend in this statutory protection zone. The greater part of basking shark space-use found in this study occurred in national fishing zones that also represent important foraging and overwintering habitat for basking sharks (Sims et al., 2003). Because incidental capture of basking shark in fishing gear in other parts of the world have been shown to be high in important shark habitat, catches off south-west England in the Celtic Sea, Western Approaches and off Scotland may be significant, but which at present go unreported. This may be exerting a 'hidden' effect on the population. This study found basking sharks cross national boundaries between different political–economic zones, which strongly supports the listing of *C. maximus* on the Convention of Migratory Species of Wild Animals (Bonn Convention), a status that should facilitate wider protection and better reporting of incidental captures. Therefore, we recommend protection of the basking shark be extended throughout EU waters coupled with the requirement to report incidental bycatch of this species so fishing mortality can be quantified.

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