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Testing the boundaries: Seasonal residency and inter-annual site fidelity of basking sharks in a proposed Marine Protected Area

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ABSTRACT

There is a growing need to understand the inter-annual movements of mobile marine species of conservation concern to inform the design and placement of Marine Protected Areas (MPAs) to maximise their conservation potential. We use satellite telemetry data from 36 basking sharks (*Cetorhinus maximus*) tracked in 2012, 2013 and 2014 (cumulative total: 1598 days; median: 44 days; range: 10–87 days) to quantify movements in coastal waters off the west coast of Scotland within the Sea of the Hebrides proposed MPA. Sharks exhibited seasonal residency to the proposed MPA, with a mean of 84% of filtered best daily locations occurring within its boundaries (2012 = 80%, 2013 = 90% and 2014 = 74%). Three long-term tracked basking sharks demonstrated inter-annual site fidelity, returning to the same coastal waters in the year following tag deployment, with two returning to within the boundaries of the proposed MPA. These data likely suggest the area experiences favourable conditions and/or resources for basking sharks across years and, if designated, coupled with appropriate management, could afford protection during summer months.

1. Introduction

With global declines in many marine fish populations and habitats (Watson and Pauly, 2001; Baum et al., 2003; Lotze et al., 2006) the use of Marine Protected Areas (MPAs) has become increasingly popular as a management tool to prevent further population decline, promote recovery and improve biodiversity conservation (Halpern and Warner, 2002; Wood et al., 2008). Studies have suggested that large, mobile species, with wide-ranging movements may benefit from MPAs, e.g. teleost fish (Farmer and Ault, 2011), turtles (Scott et al., 2012), whales (O'Brien and Whitehead, 2013), as well as sharks (Claudet et al., 2009; Barnett et al., 2011), depending on protective measures applied to these areas.

In particular, there is growing concern regarding the rate of decline of global shark populations due to overfishing (Dulvy et al., 2014). The proportion of time individuals spend within MPA boundaries will affect the degree to which these animals could be protected, should adequate management measures also be in place. This protection is likely to vary with species, life stage, sex, size, body condition and food availability (Speed et al., 2010; Escalle et al., 2015). Designing MPA boundaries and management measures to be effective for mobile species require detailed knowledge of the species' biology, movements and habitat use (Grüss et al., 2011; Chin et al., 2016). Establishing MPAs in areas that mobile species use consistently (e.g. areas of key life-history events) may offer some protection at a population level (Heupel and Simpfendorfer, 2005; Meyer et al., 2007), and protection will therefore depend on the degree of overlap between core activity areas and the area of protection (Knip et al., 2012).

Basking sharks were historically exploited in the north-east Atlantic for their meat, fins and large liver containing desired squalene oil; with directed fisheries from Norway, Scotland and Ireland. These fisheries landed 77,204 individuals between 1946 and 1986 (Kunzlik, 1988), leading to depletion in local stocks (Parker and Stott, 1965). Basking sharks are listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), Appendices I and II in the Convention of Migratory Species (CMS; Table S1), and are listed as 'Vulnerable' globally by the International Union for Conservation of Nature (IUCN Red List), and 'Endangered' in the north-east

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Atlantic (Fowler, 2005). The Marine (Scotland) Act (2010) and the UK Marine and Coastal Access Act (2009) include powers for Scottish Ministers to designate MPAs in the seas around Scotland, one of which is the proposed 10,325 km^2 Sea of the Hebrides MPA, between the Isles of Skye, Mull and Outer Hebrides (Scottish Natural Heritage, 2014). This area has been highlighted as a key area for surface sightings of basking sharks (Speedie et al., 2009; Witt et al., 2012) between July and August each year, and for minke whales (*Balaenoptera acutorostrata*) and was thus proposed for designation as a MPA (Scottish Natural Heritage, 2014).

In an attempt to increase protective measures for marine environments and to satisfy international conventions, many MPAs have been implemented opportunistically without prior knowledge of how they may contribute to biodiversity conservation (Roberts, 2000). Assessment of the efficacy of a MPA is important in order to maximise its conservation potential (McNeill, 1994), otherwise there is a possibility of tokenism if placed arbitrarily (Ashe et al., 2010). We used satellite tags in order to (1) describe the seasonal (summer months) space-use of coastal waters off the west coast of Scotland by basking sharks, (2) describe areas of inter- and intra-annual density and (3) evaluate the use of the Sea of the Hebrides proposed MPA and establish the amount of time sharks spent inside the proposed MPA thus quantify the potential importance of this area to basking sharks.

2. Materials & methods

2.1. Tag attachment and specification

Sixty-two satellite tags, communicating with the Argos System, were attached to basking sharks off the west coast of Scotland during July and August in 2012, 2013 and 2014. Basking sharks were approached by boat from behind to avoid the line of sight of the shark and to minimise disturbance. On approach to the shark, the individual was, where possible, sexed using a pole mounted camera and total body length was estimated based on comparison to the total length of the boat (10 m). Satellite tags were deployed using a titanium M-style dart (Wildlife Computers, Redmond, California, USA) inserted into the sub-dermal layer at the base of the first dorsal fin with a modified pole spear and attached via a tether consisting of heat-shrink covered stainless steel flexible cable, a swivel and monofilament line attached to the tag. Four models of satellite tags were deployed to gather a variety of information on the movements and distribution of tagged animals. Thirty-six satellite tags were used in this analysis; Smart Position or Temperature tags (SPOT; $n = 23$, Wildlife Computers, Redmond, California, USA) and SPLASH-F tags ($n = 13$, Wildlife Computers, Redmond, California, USA) and transmitted data in real-time while attached to study animals. Both tag models provided Argos Doppler-based estimates of location (termed Argos locations) during shark surfacing events. SPLASH-F tags also contained Fastloc™ GPS technology, providing GPS locations in addition to collecting light, temperature and depth data. Both, Argos and GPS locations were used for analysis of summer movement patterns and seasonal site fidelity. Remaining tags that transmitted data ($n = 24$) were Pop-up Archival tags fitted with Fastloc™ GPS technology (PAT-F; $n = 12$) and MiniPAT ($n = 12$; Wildlife Computers, Redmond, California, USA). These tags were used to gather information on longer-range movements of basking sharks away from the west coast of Scotland using the principles of light geolocation (Doherty et al., 2017).

2.2. Location data processing

Analysis focused on coastal movement within the summer months; therefore, data were confined to 90 days (approx. mid July–mid October) following tag deployment and prior to the departure of sharks from the region. Data from satellite tags transmitting in the year following tag attachment were examined to ascertain inter-annual site fidelity. Argos location data from SPOT tags were subject to filtering, retaining location classes 1 (accurate to 500–1500 m), 2 (accurate to 250–500 m), 3 (accurate to <250 m), 'A' (three messages received but no accuracy estimation) and 'B' (one or two messages received but no accuracy estimation) (Witt et al., 2010). GPS location data from SPLASH-F tags deployed in 2014 were filtered to include only positions with a residual error value of <30 and where five or more satellites were visible to estimate the location (Shimada et al., 2012). GPS locations from SPLASH-F tags in 2014 were favoured over Argos locations from the same tags as the number of GPS locations was more numerous (662 vs. 463 Argos locations; post-filtering) and GPS locations have a greater spatial accuracy (Table S2). A maximum plausible speed filter was applied to both datasets removing locations if speed between two locations exceeded 10 km h^{-1}. These data were later reduced to a single, most accurate best daily location (highest location class as described above for Argos locations and maximum number of visible satellites for GPS locations) to minimise spatial and temporal autocorrelation. All tag data were downloaded from CLS-Argos and archived using the Satellite Tracking and Analysis Tool (STAT) (Coyne and Godley, 2005).

2.3. Data analysis

We used four techniques to identify core activity areas of residency, these techniques were; Minimum Convex Polygons (MCPs), polygon sampling grid, Time Local Convex Hulls (T-LoCoH) and Kernel Density Estimation (KDE). MCPs create the smallest convex polygon that incorporates all filtered best daily locations. To determine areas of high relative importance, a polygon sampling grid (hexagonal cells; 2 km from each grid cell centroid to its perimeter; cell area 14 km^2) was spatially intersected with filtered best daily locations. The proportion of locations within each grid cell was calculated for each tracked shark; a mean proportion for each cell was then calculated. We used T-LoCoH to construct utilisation distributions by aggregating local MCPs around each point, which were then sorted and progressively merged to form isopleths. Local Convex Hull (LoCoH) methods have been shown to outperform traditional kernel-smoothing techniques in excluding areas known not to be used (Getz et al., 2007). These attributes make LoCoH methods applicable to analyse collective area use of multiple individuals. T-LoCoH offers an advantage over traditional approaches because it further improves the ability to partition area use and study patterns through time (Lyons et al., 2013). We applied the k-based method with no time-based weighting, constructing hulls for defined numbers of neighbouring points due to the absence of areas with high density of clustering as well as areas of sparsely distributed points (Lyons et al., 2013). We also applied KDE interpolation with barriers as described by Macleod (2014). KDE with barriers uses the shortest distance between points without intersecting a defined barrier, in this case land, allowing the contour of the kernel to change at the edge of the barrier (Sprogis et al., 2016). Output cell size was 250 m side length and the bandwidth (search radius) was 5000 m. The bandwidth is a smoothing value that determines the width of the kernel. Choice of bandwidth method may vary depending on the study goals, sample size and patterns of space use by the study species (Gitzen et al., 2006), therefore the bandwidth value was selected by iterative visual inspection of outputs and evaluating the results based on extant ecological knowledge of the species.

Individual trajectories of tracked basking sharks were separated into groups based on movements relative to the boundaries of the proposed MPA using k-means cluster analysis (Hartigan and Wong, 1979). Individual tracks were initially separated into *High-use* ($n = 29$) and *Low-use* ($n = 7$) groups based on time spent within the boundaries of the proposed MPA. To ascertain the use of the proposed MPA, movements of tracked basking sharks the *High-use* group was further split into *Near* ($n = 23$) and *Far* ($n = 6$) groups based on their maximum displacement distances from tagging location.