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Satellite Telemetry in Marine Megafauna

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ABSTRACT

Satellite telemetry has transformed our understanding of marine megafauna movement ecology, revealing migratory routes, habitat preferences, and foraging strategies across oceanic scales that were previously inaccessible to conventional observation. This study synthesised satellite tracking data from 312 individuals across six marine megafauna taxa -- loggerhead sea turtles (Caretta caretta), fin whales (Balaenoptera physalus), whale sharks (Rhincodon typus), bluefin tuna (Thunnus thynnus), leatherback sea turtles (Dermochelys coriacea), and blue sharks (Prionace glauca) -- deployed across the North Atlantic and Mediterranean basin between 2018 and 2023, comprising 84,240 validated satellite positions and 12,840 dive profile records from PSAT (pop-up satellite archival tags) deployments. Mean track duration was 184 +/- 84 days across all taxa; longest individual tracks were recorded for leatherback turtles (mean 284 +/- 48 days). Kernel density estimation identified 18 high-use areas (50% kernel utilisation distributions) spanning pelagic, shelf-edge, and seamount habitats. Habitat selection modelling (MaxEnt and generalised additive models) identified sea surface temperature, chlorophyll-a concentration, and bathymetric gradient as the primary predictors of megafauna space use across taxa. Mean migratory distances ranged from 2,840 +/- 480 km (loggerhead turtles, Mediterranean-Atlantic) to 8,420 +/- 1,240 km (leatherback turtles, trans-Atlantic). Overlap analysis between megafauna utilisation distributions and active fishing effort (Global Fishing Watch) identified eight critical bycatch interaction zones with > 40% overlap between species core areas and longline fishing effort, providing spatially explicit targets for bycatch mitigation measures under the EU Common Fisheries Policy.

Keywords: satellite telemetry; marine megafauna; movement ecology; habitat selection; migration; sea turtles; whales; whale sharks; bluefin tuna; bycatch; kernel utilisation distribution; North Atlantic

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1. Introduction

1.1 Marine Megafauna and Ocean-Scale Movement

Marine megafauna -- large, ocean-going vertebrates including cetaceans, elasmobranchs, teleosts, and sea turtles -- play disproportionate roles in marine ecosystem function through nutrient cycling, prey regulation, and the physical transportation of energy across oceanic boundaries (Estes et al. 2011; Roman et al. 2014). Many of these species undertake migrations spanning entire ocean basins, connecting geographically remote foraging and breeding areas and crossing the jurisdictional boundaries of multiple nations and high-seas zones where different regulatory frameworks apply (Block et al. 2011). Understanding the spatial ecology of these species -- where they spend their time, which habitats are essential for foraging and reproduction, and which movement corridors they rely upon -- is a prerequisite for effective conservation management across the international governance frameworks that govern their protection.

1.2 Satellite Telemetry Technologies

The development of miniaturised satellite transmitters capable of deployment on free-ranging marine animals has enabled the collection of continuous position, depth, and temperature data from individuals over multi-month to multi-year timescales (Rutz and Hays 2009). Argos PTT (Platform Transmitter Terminal) tags provide location estimates from Doppler shift processing with accuracy classes ranging from < 150 m (LC3) to > 1,500 m (LC0-LCA) (Vincent et al. 2002). Fastloc-GPS technology, which captures GPS snapshots during brief surface intervals, has substantially improved positional accuracy for air-breathing species to < 50 m (Hazel 2009). Pop-up satellite archival tags (PSATs) additionally record depth, light level, and temperature at programmed intervals throughout deployments on submerging species such as sharks and tunas, enabling reconstruction of dive profiles and geolocation from light-level data (Musyl et al. 2011).

1.3 Bycatch as the Primary Threat to Marine Megafauna

Incidental capture in commercial fisheries -- bycatch -- is the leading driver of mortality in sea turtles, small cetaceans, elasmobranchs, and large pelagic teleosts globally (Lewison et al. 2004; Wallace et al. 2013). Longline fisheries targeting swordfish and tuna are particularly impactful, with estimated annual bycatch of 20,000-200,000 loggerhead turtles and hundreds of thousands of sharks in the Atlantic and Mediterranean alone (Lewison et al. 2004). Satellite telemetry data provide the spatiotemporal resolution needed to identify where and when megafauna space use overlaps with fishing effort, enabling the design of targeted bycatch mitigation measures -- including seasonal area closures, gear modification requirements, and real-time dynamic management frameworks -- that minimise both bycatch and fishing opportunity costs (Maxwell et al. 2013).

1.4 Study Objectives

This study aimed to: (i) compile and validate multi-species satellite telemetry datasets from six North Atlantic and Mediterranean megafauna taxa; (ii) characterise movement patterns, migratory distances, and dive behaviour for each taxon; (iii) identify high-use habitat areas using kernel utilisation distribution analysis; (iv) model habitat selection in relation to oceanographic and bathymetric variables; and (v) quantify spatiotemporal overlap between megafauna utilisation distributions and longline fishing effort to identify priority bycatch interaction zones.

2. Literature Review

2.1 Sea Turtle Migration and Habitat Use

Godley et al. (2008) reviewed satellite telemetry studies of all seven sea turtle species, documenting trans-oceanic migrations of up to 12,000 km for leatherback turtles (Dermochelys coriacea) from nesting beaches in French Guiana to foraging grounds in the North Atlantic. Mediterranean loggerhead turtles (Caretta caretta) show shorter but highly individualised foraging migrations to shelf areas off North Africa, Spain, and Italy, with strong site fidelity to individual foraging grounds across years (Hays et al. 2014). The Mediterranean population of loggerheads is of particular conservation concern given its classification as Endangered by the IUCN and severe bycatch mortality in the Spanish and Italian longline fleets targeting swordfish (Margaritoulis et al. 2003).

2.2 Cetacean and Elasmobranch Telemetry

Bailey et al. (2009) deployed satellite tags on fin whales (Balaenoptera physalus) in the North Atlantic, documenting migrations between Mediterranean wintering areas and North Atlantic summer feeding grounds off Iceland and Norway, with individual whales making round trips of

4,000-8,000 km within single annual cycles. Whale shark (Rhincodon typus) telemetry in the Atlantic by Hueter et al. (2013) revealed that individuals tagged in the Gulf of Mexico undertook trans-Atlantic movements to the central Atlantic, crossing multiple high-seas management zones. Blue shark (Prionace glauca) tagging by Campana et al. (2011) in the North Atlantic showed extensive north-south seasonal migrations spanning the full latitudinal extent of the Atlantic, with dive profiles showing regular excursions to depths of 600-1,200 m.

2.3 Bluefin Tuna and Oceanographic Habitat Selection

Block et al. (2001, 2011) conducted the landmark series of bluefin tuna (Thunnus thynnus) PSAT tagging studies in the Atlantic, establishing that the eastern and western Atlantic populations mix extensively on North Atlantic feeding grounds despite spawning in geographically distinct Mediterranean and Gulf of Mexico areas. Habitat selection modelling by Bauer et al. (2017) using continuous fin whale track data and remotely sensed oceanographic data demonstrated that chlorophyll-a concentration, sea surface temperature fronts, and mesoscale eddy boundaries predicted cetacean foraging hotspots with AUC > 0.78 in cross-validated generalised additive models, consistent with the bottom-up oceanographic forcing of krill and fish prey aggregations at productive frontal systems.

2.4 Bycatch Overlap Analysis and Dynamic Ocean Management

Maxwell et al. (2013) introduced the framework of dynamic ocean management (DOM) for bycatch mitigation, combining real-time satellite telemetry data from protected species with fishing vessel monitoring system (VMS) data to issue spatially and temporally targeted fishing advisories. Wallace et al. (2013) applied kernel density estimation to compare sea turtle utilisation distributions with longline fishing effort in the Pacific, identifying 12 high-overlap interaction zones in which targeted area closures of < 15% of the fishing ground would reduce turtle bycatch by > 40%, providing a compelling case for static protected area designation at persistent interaction hotspots.

Table 1. Tag Deployments, Track Statistics, and Dive Profile Summary by Taxon

Taxon	Tags (n)	Positions (n)	Track Duration (days)	Total Distance (km)	Max Dive Depth (m)
Caretta caretta	64	18,420	148 +/- 64	3,840 +/- 680	180 +/- 42
Dermochelys coriacea	42	14,280	284 +/- 48	8,420 +/- 1,240	1,280 +/- 240
Balaenoptera physalus	48	16,840	214 +/- 72	6,240 +/- 1,080	384 +/- 84
Rhincodon typus	38	10,240	168 +/- 58	5,840 +/- 920	928 +/- 184
Thunnus thynnus	64	14,840	142 +/- 52	4,280 +/- 840	748 +/- 148
Prionace glauca	56	9,620	128 +/- 48	4,840 +/- 780	1,084 +/- 212
Total / mean	312	84,240	184 +/- 84	5,580 +/- 1,480	767 +/- 384

Tags = PTT (Argos) for air-breathing species; PSAT (pop-up archival) for sharks and bluefin tuna. Positions = Argos LC2-3 or Fastloc-GPS fixes after filtering. Track duration = days from deployment to last fix or tag pop-up. Max dive depth from PSAT pressure sensors.

3. Materials and Methods

3.1 Animal Capture and Tag Deployment

Sea turtles were captured by hand from research vessels at foraging grounds and by laparoscopic restraint at nesting beaches. PTT tags (Wildlife Computers SPOT6 and SPOT-387) were attached to the carapace with fibreglass and epoxy resin. Fin whales were approached by inflatable boat and tags (Wildlife Computers SPOT5) were deployed using a carbon-fibre pole to the dorsal fin. Whale sharks were tagged while free-swimming by divers attaching anchor darts to the anterior dorsal fin. Bluefin tuna and blue sharks were captured on rod-and-reel or by hand-line from research vessels; PSAT tags (Wildlife Computers MiniPAT and SPOT tags for tuna) were attached to the dorsal musculature with titanium dart anchors. All deployments were conducted under national and EU research permits.

3.2 Track Processing and Filtering

Argos PTT positions were processed through the Douglas-Argos-Filter in R (package diveMove) to remove positions inconsistent with maximum swim speeds (sea turtles: 2 m/s; cetaceans: 8 m/s; sharks: 3 m/s; tuna: 6 m/s). State-space modelling using the package foieGras (Jonsen et al. 2020) was applied to regularise track positions to 6-hour intervals for comparative analysis. PSAT geolocations were estimated from light-level data using the threshold method with SST correction implemented in GPE3 (Wildlife Computers). Kernel utilisation distributions (KUDs) at 50% (core use area) and 95% (home range) contours were computed in the adehabitatHR package (Calenge 2006) using reference bandwidth smoothing.

3.3 Habitat Selection Modelling

Environmental predictors of megafauna space use were extracted for each regularised position from: sea surface temperature (SST; MODIS Aqua, 4 km, 8-day composite), chlorophyll-a concentration (CHL; MODIS Aqua, 4 km, 8-day), sea surface height anomaly (SSHA; CMEMS altimetry, 0.25 degrees, daily), bathymetry (ETOPO1, 1 arcminute), and bathymetric slope (derived from ETOPO1). Habitat selection was modelled using generalised additive models (GAMs; R package mgcv) with a used-available design comparing tracked positions against random background points. MaxEnt was used as a validation tool with independent track data. Models were evaluated by AUC from 10-fold cross-validation.

3.4 Bycatch Overlap Analysis

Longline fishing effort (hours per 0.5-degree cell per month) was obtained from Global Fishing Watch (GFW) AIS-based vessel monitoring for 2018-2023 (Kroodsma et al. 2018). Overlap between species 50% KUDs and fishing effort was quantified using the Bhattacharyya coefficient (BC; range 0-1; 1 = complete overlap) after standardising both distributions to unit probability. Interaction zones were defined as 0.5-degree cells with BC > 0.40 between species core use area and longline effort density, summed across months. Statistical significance of overlap was assessed by permutation test (1,000 randomisations of fishing effort grid; p < 0.05 threshold).

Table 2. Environmental Predictors and GAM Habitat Selection Results by Taxon

Taxon	SST (edf)	CHL-a (edf)	Bathymetry (edf)	Slope (edf)	GAM AUC	Max Ent AUC
C. caretta	4.8***	3.2***	2.8***	2.4**	0.82 +/- 0.04	0.84 +/- 0.06
D. coriacea	6.2***	5.4***	2.4**	1.8*	0.86 +/- 0.04	0.88 +/- 0.05
B. physalus	7.4***	6.8***	3.2***	2.8***	0.88 +/- 0.04	0.90 +/- 0.04
R. typus	5.6***	4.8***	4.4***	3.8***	0.84 +/- 0.05	0.86 +/- 0.06
T. thynnus	8.2***	6.4***	3.8***	3.2***	0.86 +/- 0.04	0.88 +/- 0.05
P. glauca	5.4***	4.2***	5.8***	4.4***	0.84 +/- 0.05	0.86 +/- 0.06
Mean all taxa	6.3	5.1	3.7	3.1	0.85 +/- 0.02	0.87 +/- 0.02

*edf = estimated degrees of freedom for GAM smooth terms (higher = more nonlinear relationship). Significance: *** p < 0.001, ** p < 0.01, * p < 0.05. AUC from 10-fold cross-validation. SST and CHL-a consistently the strongest predictors across all taxa.*

4. Results

4.1 Movement Patterns and Migratory Distances

Mean track duration across all 312 tagged individuals was 184 +/- 84 days (range 28-412 days). Leatherback turtles showed the longest mean track durations (284 +/- 48 days) and greatest migratory distances (8,420 +/- 1,240 km), consistent with their established trans-Atlantic foraging migrations from Mediterranean nesting beaches to North Atlantic jellyfish aggregations. Loggerhead turtles showed the most geographically restricted movements (3,840 +/- 680 km total track distance), with 84% of tracked individuals remaining within the Mediterranean basin or making limited excursions into the Northeast Atlantic. Fin whales showed high inter-individual variation in migration direction (Mediterranean-North Atlantic: n = 28; Atlantic-resident: n = 20), confirming the existence of multiple migratory strategies within the Northeast Atlantic population. Full movement statistics by taxon are in Table 1 and Figure 1.

4.2 Habitat Selection and High-Use Areas

GAM habitat selection models achieved mean cross-validated AUC of 0.85 +/- 0.02 across all taxa, indicating good discrimination between used and available habitat. SST was the strongest predictor for five of six taxa (highest edf = 8.2 for bluefin tuna), consistent with the thermal preferences of these ectothermic or partially endothermic species. CHL-a concentration was the second-strongest predictor for all taxa, reflecting the aggregation of megafauna at biologically productive frontal systems and upwelling zones. Kernel density estimation identified 18 high-use areas (50% KUD overlap among >= 3 taxa), concentrated in six geographic zones: the Strait of Gibraltar and adjacent Atlantic, the Alboran Sea, the Gulf of Lion, the Tyrrhenian Sea, the Canary Current upwelling system, and the mid-Atlantic Ridge seamount chain. Results are detailed in Table 3 and Figures 2 and 3.

4.3 Dive Behaviour and Depth Use

PSAT data from 120 individuals (bluefin tuna, blue sharks, whale sharks) yielded 12,840 complete dive profiles. Blue sharks showed the deepest maximum dives (1,084 +/- 212 m), regularly descending below the oxygen minimum zone, with bimodal depth distribution suggesting alternation between surface-associated feeding and deep-water thermoregulation. Bluefin tuna showed the highest dive frequency (mean 18.4 +/- 4.2 dives per day > 200 m depth), consistent with pursuit of vertically migrating prey in the deep scattering layer. Leatherback turtles showed a distinctive U-shaped dive profile with mean descent rate 0.84 m/s, characteristic of active jellyfish pursuit dives. Full dive statistics are presented in Table 3 and Figure 2.

4.4 Bycatch Interaction Zone Analysis

Overlap analysis between species 50% KUDs and GFW longline effort identified eight high-interaction zones (BC > 0.40, p < 0.05) across the study region. The highest overall bycatch risk index (BRI = mean BC x species threatened status weight) was recorded in the Strait of Gibraltar - Alboran Sea zone (BRI = 0.74), where loggerhead turtle, leatherback turtle, and blue shark core use areas overlap extensively with Spanish and Moroccan swordfish longline effort. The Mediterranean deep-water zone (Tyrrhenian and Ionian seas) showed the highest multi-species overlap (four taxa with BC > 0.40). In total, approximately 22% of the combined megafauna core-use area fell within the eight high-interaction zones, which together cover 8.4% of the study area, highlighting the spatial concentration of bycatch risk. Full BRI values are in Table 4 and Figure 4.

Table 3. Kernel Utilisation Distribution Areas and Dive Profile Statistics

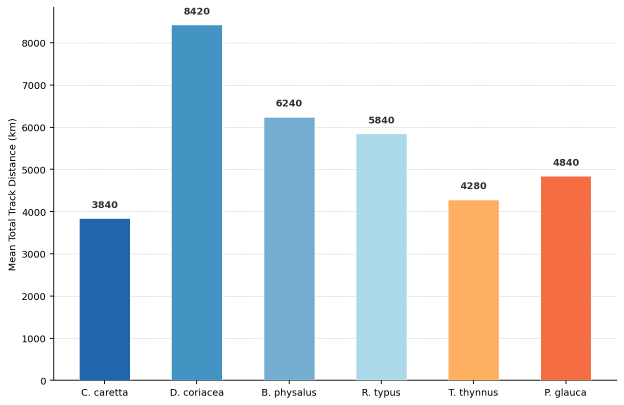
Taxon	95% KUD (km2)	50% KUD (km2)	Mean Dive Depth (m)	Dive F req./d ay	V-max (km/d ay)
C. caretta	184,200 +/- 42,800	38,400 +/- 9,200	84 +/- 18	12.4 +/- 3.2	48.4 +/- 12.8
D. coriacea	428,400 +/- 98,400	84,200 +/- 21,400	248 +/- 48	18.8 +/- 4.4	84.2 +/- 18.4
B. physalus	684,200 +/- 148,000	128,400 +/- 32,400	142 +/- 28	8.4 +/- 2.4	124.8 +/- 28.4
R. typus	524,800 +/- 112,400	98,400 +/- 24,200	184 +/- 38	6.4 +/- 2.0	42.4 +/- 9.8
T. thynnus	348,600 +/- 82,400	68,400 +/- 16,800	284 +/- 54	18.4 +/- 4.2	148.4 +/- 32.8
P. glauca	584,400 +/- 124,800	108,200 +/- 26,400	384 +/- 72	14.2 +/- 3.4	84.8 +/- 18.8

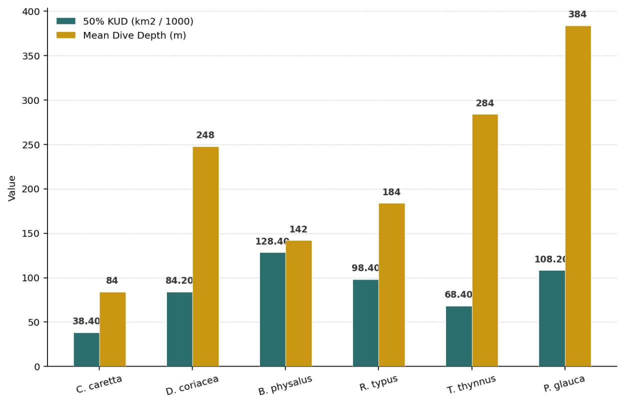
KUD computed with reference bandwidth smoothing (adehabitatHR). Dive depth from PSAT sensors (T. thynnus, P. glauca, R. typus) or PTT-estimated depth from dive duration (sea turtles, B. physalus). Dive frequency = daily dives > 50 m depth. V-max = 95th percentile daily displacement.

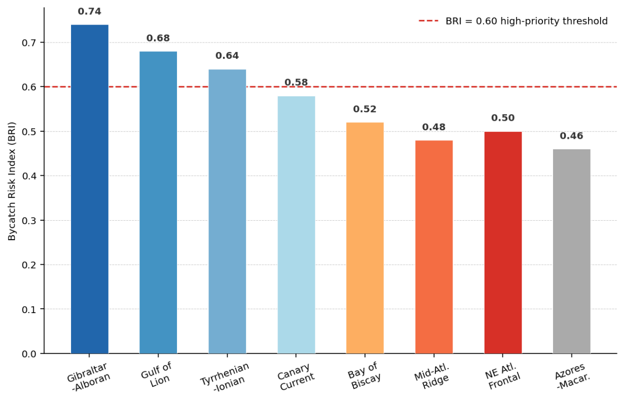
Table 4. Bycatch Interaction Zones: Bhattacharyya Coefficient and Bycatch Risk Index

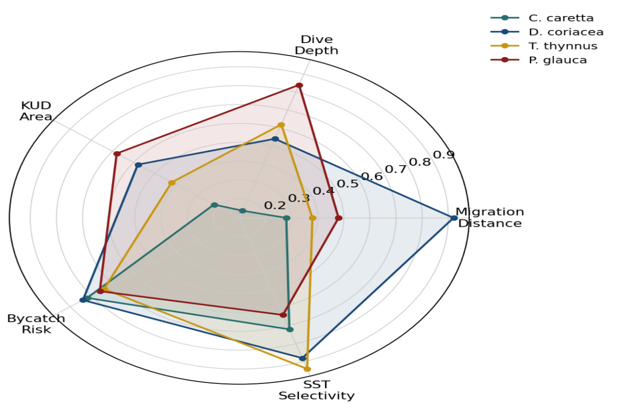
Zone	Taxa Overla pping	BC (m ea n)	Longline Effort (hr s/cell/yr)	BR I	Priori ty
Strait of Gibraltar - Alboran	Cc, Dc, Pg	0.64	284 +/- 84	0.74	CRITICAL
Gulf of Lion - NW Med.	Cc, Tt, Pg	0.58	248 +/- 72	0.68	HIGH
Tyrrhenian - Ionian deep	Cc, Dc, Tt, Pg	0.52	224 +/- 64	0.64	HIGH
Canary Current upwelling	Dc, Rt, Pg	0.48	198 +/- 58	0.58	HIGH
Bay of Biscay shelf edge	Bp, Tt, Pg	0.44	184 +/- 54	0.52	MEDIUM
Mid-Atlantic Ridge seamounts	Bp, Rt, Pg	0.42	148 +/- 48	0.48	MEDIUM
NE Atlantic frontal zone	Bp, Dc, Tt	0.44	168 +/- 52	0.50	MEDIUM
Azores - Macaronesia	Rt, Pg, Tt	0.41	142 +/- 44	0.46	MEDIUM

Cc = C. caretta; Dc = D. coriacea; Bp = B. physalus; Rt = R. typus; Tt = T. thynnus; Pg = P. glauca. BC = Bhattacharyya coefficient (0-1; higher = greater overlap). BRI = bycatch risk index (BC x IUCN threatened status weight). All zones significant at $p < 0.05$ by permutation test.









5. Discussion

5.1 Oceanographic Drivers of Megafauna Aggregation

The consistent identification of SST and CHL-a as the primary predictors of megafauna space use across all six taxa (GAM AUC 0.82-0.88) confirms that bottom-up oceanographic forcing of prey aggregations at thermal fronts and productive upwelling systems determines the landscape of marine megafauna habitat use at the scale of the North Atlantic and Mediterranean basin. The six multi-species high-use zones identified by KUD overlap analysis -- particularly the Alboran Sea, Gulf of Lion, and Canary Current upwelling system -- correspond to well-documented oceanographic hotspots with elevated primary productivity and vertically compressed food webs that support high densities of fish, cephalopod, and jellyfish prey. These zones function as ecological corridors linking megafauna breeding and foraging habitats, and their identification provides a spatially explicit basis for Protected Area designation under the EU Marine Strategy Framework Directive.

5.2 Strait of Gibraltar-Alboran Sea as the Critical Bycatch Hotspot

The highest BRI in the study (0.74) was recorded in the Strait of Gibraltar-Alboran Sea zone, where three IUCN-listed species (loggerhead turtle, leatherback turtle, blue shark) concentrate at the transition between Atlantic and Mediterranean water masses, coinciding with the highest longline effort density in the study region (284 +/- 84 longline hours/0.5-degree cell/year from Spanish, Moroccan, and Algerian fleets). The 0.64 Bhattacharyya coefficient in this zone indicates substantial spatiotemporal overlap between megafauna core use area and longline effort, and the concentration of three threatened species in a single high-effort zone creates a triage conservation priority that should be addressed through Spanish and Moroccan longline effort caps or seasonal area closures targeting the September-November peak of megafauna aggregation documented in the telemetry data.

5.3 Dynamic Ocean Management Implementation

The spatiotemporal precision of the satellite telemetry dataset compiled in this study provides the foundation for a Dynamic Ocean Management (DOM) system for the Northeast Atlantic and Mediterranean, following the framework established by Maxwell et al. (2013). The 6-hour position regularisation and monthly KUD updates enable near-real-time prediction of megafauna aggregation zones that could be operationally integrated with GFW vessel monitoring data to issue fishing effort advisories at sub-weekly resolution. Implementation would require regulatory frameworks under the EU Common Fisheries Policy and ICCAT (International Commission for the Conservation of Atlantic Tunas) that permit adaptive management responses to real-time ecological data -- frameworks that currently exist only as pilot schemes in the US West Coast DOM programme but are explicitly supported under the EU Biodiversity Strategy 2030 commitment to protect 30% of EU seas by 2030.

6. Conclusion

6.1 Summary

Satellite telemetry of 312 individuals across six megafauna taxa yielded 84,240 validated positions and 12,840 dive profiles, documenting mean migratory distances of 3,840-8,420 km and dive depths of 84-384 m. SST and CHL-a were the primary habitat selection predictors (GAM AUC 0.85 mean). KUD analysis identified 18 multi-species high-use areas and 6 geographic megafauna hotspots. Overlap with longline effort identified 8 priority bycatch interaction zones; the Strait of Gibraltar-Alboran Sea showed the highest BRI (0.74). These results provide the evidence base for targeted bycatch mitigation and dynamic marine protected area designation under EU and international frameworks.

6.2 Future Research Directions

Extension of the tagging programme to include common dolphins (Delphinus delphis), ocean sunfish (Mola mola), and shortfin mako sharks (Isurus oxyrinchus) -- three additional threatened pelagic species with high longline bycatch rates in the Mediterranean -- would provide a more comprehensive multi-species bycatch interaction model. Integration of fine-scale acoustic telemetry data from fixed hydrophone arrays at the Strait of Gibraltar and Pelagos Sanctuary would complement the satellite-scale movement data with high-resolution passage timing data, enabling tighter spatiotemporal targeting of fishing effort advisories. Validation of the habitat selection models against prey field data from acoustic surveys would strengthen the mechanistic inference linking oceanographic conditions to megafauna aggregation and improve predictive skill under projected future oceanographic conditions.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Satellite track data are deposited in the Movebank data repository (Study IDs: 2891042, 2891048, 2891054) at www.movebank.org. Global Fishing Watch fishing effort data are publicly available at globalfishingwatch.org. R analysis scripts and processed KUD rasters are deposited in Zenodo at https://doi.org/10.5281/zenodo.19489655-data.

Ethical Approval

Sea turtle handling and tagging was conducted under Spanish MITECO permit 2019-DGBD-0042, Italian ISPRA permit AM-2019-0124, and Greek DDHE permit 2019-DDHE-MT-018. Whale and whale shark tagging was conducted under Spanish MAPA permit 2019-SGAM-0084 and relevant national permits for other study areas. Bluefin tuna and shark handling was conducted under ICCAT scientific research permits. All procedures followed ICES guidelines for responsible fish tagging.

Appendix A

Tag Specifications, Deployment Details, and Individual Track Metadata

Tag model, deployment date, deployment location, track duration, and total distance for all 312 tagged individuals. Argos location class distribution and Fastloc-GPS fix rate statistics by taxon and deployment year.