UNIVERSITY OF CRETE
SCHOOL OF SCIENCES AND ENGINEERING
DEPARTMENT OF BIOLOGY

HELLENIC CENTER FOR MARINE RESEARCH
INSTITUTE OF MARINE BIOLOGICAL RESOURCES AND INLAND WATERS

M.SC Environmental Biology

SPATIAL ANALYSIS OF CETACEAN STRANDINGS IN GREEK SEAS IN RELATION TO FISHING GROUNDS, POTENTIAL FEEDING GROUNDS AND SURFACE CIRCULATION

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M.Sc. in Environmental Biology

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Abstract

Cetacean strandings are a phenomenon that is observed on the coasts and serves as an indicator of cetacean mortality in the sea. Reasons for direct human-induced cetacean mortality include entanglement in fishing gear (by-catch), intentional killing (shooting, wounding), collision with boats/vessels, ingestion of macroplastics, noise pollution from military sonars/seismic surveys. A small percentage of dead cetaceans wash up on beaches and are recorded, which depends on many factors (distance from the coast, marine traffic, morphology and accessibility of the coast) that are often difficult to estimate.

The purpose of this study is to investigate the distribution of cetacean strandings in Greek waters and their relationship with coastal fishing and marine traffic. A total of 1378 strandings of 9 cetacean species were studied, during the period 2010-2021, using the stranding database of the Hellenic Center for Marine Research (HCMR). Kernel density estimate maps were created to identify spatial hotspots of strandings by species and cause of death. Generalized additive models (GAMs) were developed to explore the relationship between strandings and coastal fishing and potential feeding areas. In a stranding hotspot area of particular interest, the possible origin of the dead animal was estimated using the stochastic ensemble trajectory model, Leeway, which estimates the movement of objects on the water surface under the effect of wind and current.

The study showed significantly clustered spatial distributions for both total cetacean strandings and when 4 species of cetaceans were examined separately, revealing the existence of hotspot areas in the study region. Generalized additive models demonstrated a possible positive relationship between stranding events and the extent of fishing grounds, as well as the significant role of the coastline in the recording of stranding events. Finally, possible estimates were made for the potential origin of strandings in the Pagasitikos gulf and surrounding areas using the Leeway model.

Περίληψη

Οι εκβρασμοί κητωδών είναι ένα φαινόμενο που παρατηρείται στις ακτές και αποτελεί δείκτη για την θνησιμότητα των κητωδών στη θάλασσα. Λόγοι για την άμεση ανθρωπογενή θνησιμότητα των κητωδών περιλαμβάνουν: εμπλοκή σε αλιευτικά εργαλεία (by-catch), εκούσια θανάτωση (πυροβολισμός, τραύματα), σύγκρουση με ταχύπλοα σκάφη, κατάποση μακροπλαστικών, ηχορύπανση από στρατιωτικά σόναρ / σεισμικές έρευνες. Ένα μικρό ποσοστό των νεκρών κητωδών εκβράζεται τελικά στις ακτές και καταγράφεται. Το ποσοστό αυτό εξαρτάται από πολλούς παράγοντες (απόσταση από την ακτή, θαλάσσια κυκλοφορία, μορφολογία και επισκεψιμότητα ακτής) που συχνά είναι δύσκολο να εκτιμηθούν.

Σκοπός της παρούσας εργασίας είναι η μελέτη της κατανομής των εκβρασμών κητωδών στις ελληνικές θάλασσες και η σχέση τους με την παράκτια αλιεία και τη θαλάσσια κυκλοφορία. Ειδικότερα μελετήθηκαν 1378 εκβρασμοί 9 ειδών κητωδών που αφορούσαν την περίοδο 2010 - 2021 όπως έχουν καταχωρηθεί στη βάση εκβρασμών του ΕΛΚΕΘΕ. Για τον προσδιορισμό περιοχών αυξημένης πιθανότητας «hotspot» εκβρασμών, δημιουργήθηκαν χάρτες πυκνότητας εκβρασμών ανά είδος και αιτίας θανάτου (Kernel density estimate). Για την διερεύνηση την σχέσης εκβρασμών με την παράκτια αλιεία και πιθανά διατροφικά πεδία εκτιμήθηκαν γενικευμένα προσθετικά μοντέλα (Generalized Additive Models - GAMs). Η μελέτη έδειξε σημαντικά ομαδοποιημένες χωρικές κατανομές για τους συνολικούς εκβρασμούς κητωδών όσο και για 4 είδη κητωδών αποκαλύπτοντας την ύπαρξη περιοχών hotspot στην περιοχή μελέτης. Τα γενικευμένα προσθετικά μοντέλα έδειξαν την ύπαρξη θετικής σχέσης μεταξύ εκβρασμών και της έκτασης των αλιευτικών πεδίων όσο και τον σημαντικό ρόλο της ακτής στην καταγραφή των εκβρασμών. Επίσης, στο πλαίσιο περαιτέρω διερεύνησης των εκβρασμών σε σχέση με τη θαλάσσια κυκλοφορία, εκτιμήθηκε η πιθανή προέλευση ενός νεκρού ζώου στη περιοχή του Παγασητικού κόλπου και του Βόρειου Ευβοϊκού κόλπου μέσω του στοχαστικού μοντέλου Leeway (stochastic ensemble trajectory model). Το τελευταίο εκτιμά την κίνηση αντικειμένων πάνω στην επιφάνεια της θάλασσας, υπό την επίδραση του ανέμου, των επιφανειακών ρευμάτων και της δράσης των κυμάτων.

Λέξεις κλειδιά

Κητώδη, Εκβρασμοί, Hotspot analysis, GAMs, Trajectory models

Contents

1. Introduction

The Mediterranean region, an outstanding hotspot of marine and coastal biodiversity is home to several species of cetaceans, including the regular occurring common dolphin (Bearzi et al., 2016), striped dolphin (Bearzi et al., 2016), bottlenose dolphin (Gaspari et al., 2015), Risso's dolphin (Azzellino et al., 2016), Cuvier's beaked whale (Podestà et al., 2016) and sperm whale (Rendell & Frantzis, 2016) and more species that are rarely observed in the region (Notarbartolo di Sciara, 2016).

Cetaceans are affected by anthropogenic pressure due to their ecological and life history traits (long lifespan, low reproductive potential, small population sizes, late maturity) that make them especially vulnerable (Kiszka et al., 2022; Tavares et al., 2019). Anthropogenic threats can be defined as direct mortality, redistribution caused by short-term habitat degradation and redistribution caused by long-term habitat degradation (Notarbartolo di Sciara, 2016). Many cetacean species rely on fish and other marine animals for food, but overfishing can lead to declines in the abundance of these prey species. This can have a cascading effect on cetacean populations, as individuals become weaker and more vulnerable to other threats (Izquierdo-Serrano et al., 2022). Cetaceans can also be caught accidentally as bycatch in commercial fishing operations, leading to injury or death (Izquierdo-Serrano et al., 2022; Milani et al., 2019). Pollutants, including plastic debris, oil spills, and chemical pollutants can be ingested by cetaceans, leading to blockages in the digestive tract or the release of toxins from the plastic into the animal's tissues (Alexiadou et al., 2019; Fossi et al., 2018). As the world's oceans warm and become more acidic, cetaceans face a variety of challenges. Changes in ocean currents can alter the distribution of prey species, making it harder for cetaceans to feed. Changes in temperature and acidity can also disrupt the balance of plankton and other small organisms that form the base of the ocean food chain, further reducing the availability of food for cetaceans (Simmonds et al., 2012). Cetaceans rely on sound to communicate, find prey and navigate their environment. However, human activities such as shipping, seismic exploration and military exercises can produce high levels of underwater noise, which can interfere with cetacean communication and behavior (Aguilar Soto et al., 2006; Bejder et al., 2006; Campana et al., 2015; Frantzis, 1998; Podestà et al., 2016; Rendell & Frantzis, 2016).

After death a cetacean carcass may float, or sink and later bloat to refloat if ambient temperature and pressure allow sufficient decomposition gas formation and expansion(Moore et al., 2020). Various scenarios are possible: an animal could die at sea remaining there or floating ashore, or strand on a beach alive, where it dies and, if cast high enough, remain beached to be scavenged or decompose (Reisdorf et al., 2012). An animal that rests low on a beach may refloat again, through increased buoyancy from decomposition gas and favorable tides, currents, and wind (Moore et al., 2020). Cetacean most likely strand ashore after death are a relatively small subset of animals that die at sea. These animals tend to be large, robust, positively buoyant and either die

or refloat near shore (Moore et al., 2011; Peltier et al., 2012). The least likely animals to be discovered after death would be sick or naturally lean animals sinking over water deeper than 100 meters. This is the vast majority of offshore odontocetes (Moore et al., 2020).

Strandings can provide important information about species biodiversity in a region (Liu et al., 2022) the health and status of cetacean populations (Azzellino et al., 2017), relative abundance and population trends(Ijsseldijk et al., 2018; Peltier et al., 2012, 2013) and can also help researchers learn more about the factors that lead to cetacean mortality.

This study aimed to investigate the spatial distribution of cetacean strandings in Greek coastal waters, Aegean and Ionian Seas, (a) by identifying cetacean stranding hotspots in the study area, (b) examine the relationship of fishing grounds and potential feeding grounds on strandings through modeling with Generalized Additive Models and (c) investigate the role of surface sea circulation on the drift of cetacean carcasses with Leeway model, in order to assess possible origin locations in an area after a stranding event.

2. Materials and methods

2.1 Study area

The study area is comprised of the entire coastal waters of Greek seas (34°30’ N – 41°00’ N, 19°00’ E – 28°24’ E), located in eastern Mediterranean Sea (Figure *1*a). Oligotrophy is a characteristic feature of the eastern and southern parts of the Aegean Sea as well east Ionian Sea. In contrast, the western and northern parts of the Aegean Sea, are more productive.

For further analysis, the study area was divided into 102 subareas (Figure 1a), based on the high topographic complexity of the region, to assume homogenous coast characteristics and oceanographic conditions within each subarea. The subareas were created with QGIS 3.28.3 software (QGIS Development Team, 2022) from coastline geographic data extracted from European Environment Agency (www.eea.europa.eu) along with a 20km buffer zone.

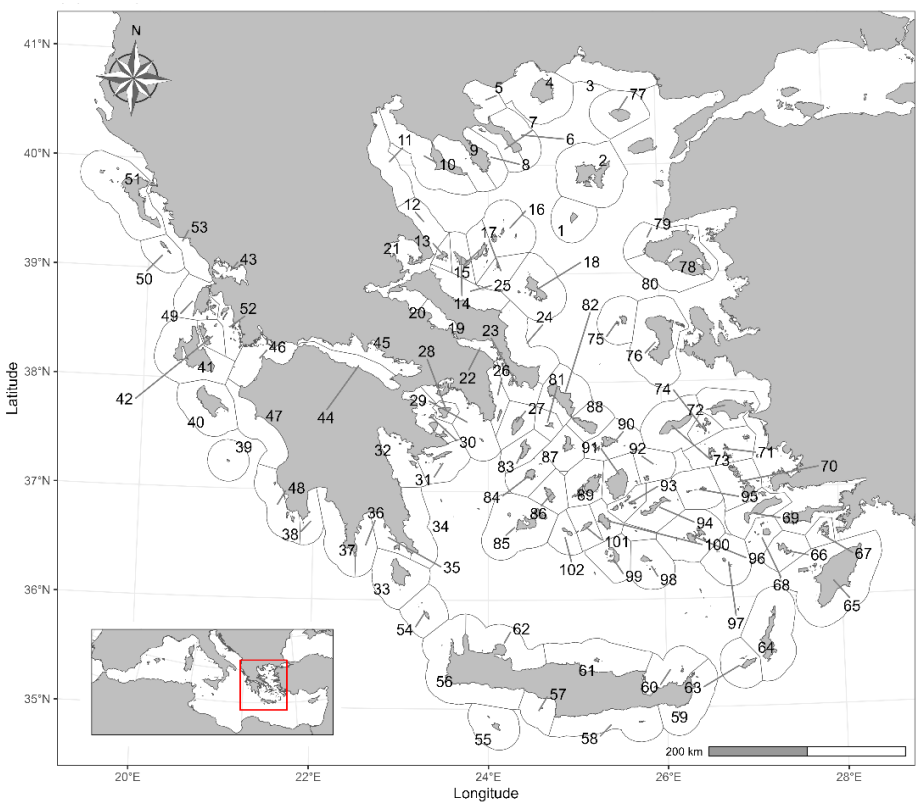

Figure 1a*: Map of the study area with 102 numbered subareas.*

Subareas cover the habitat of the 4 most common cetacean species in the study area, *Tursiops truncatus* (Bottlenose dolphin), *Stenella coeruleoalba* (striped dolphin), *Delphinus delphis (*Short-beaked common dolphin) and *Ziphius cavirostris* (Cuvier's beaked whale). *Tursiops truncatus* is the most common species in coastal waters. It is present in all coastal areas, straits and gulfs, but also between islands in the Ionian Seaand in the Aegean Sea, in depths <200m (Figure 1b top left). *Stenella coeruleoalba* is an offshore species preffering waters with depth >200m (Figure 1b top right). *Dephinus delphis* is absent south of the line that links south Kythira and the Rodos Islands (Figure 1b bottom left). *Ziphius cavirostris* prefers deep-water canyons and continental slopes, as well as areas with steep underwater topography. It is regularly present along the Hellenic Trench, from eastern Rodos Island to northwest Corfu Island (1b bottom right).

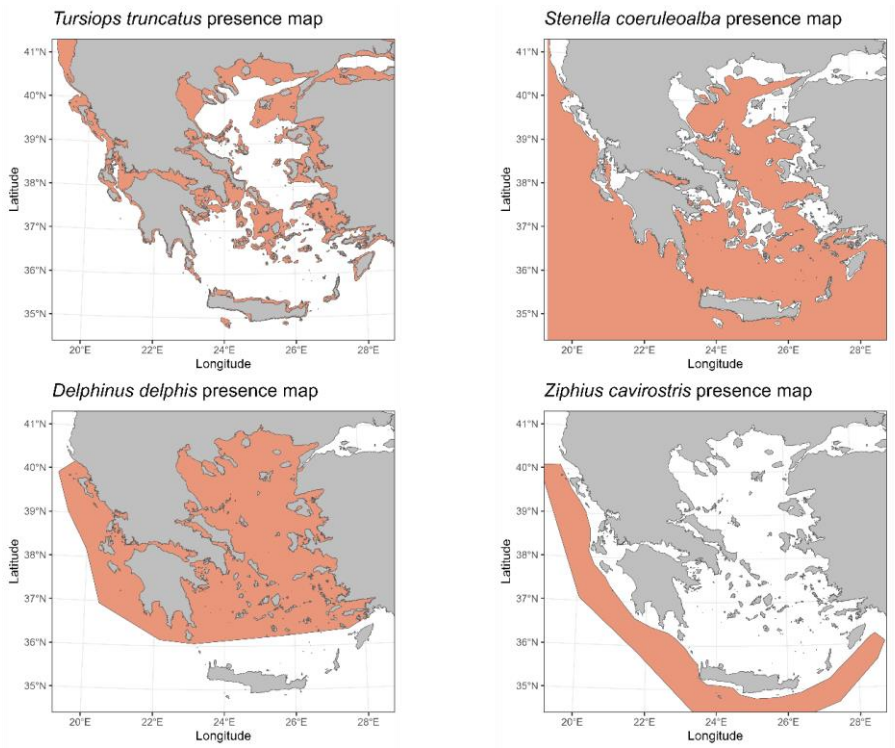

Figure 1b: Presence maps of Tursiops truncatus (top left), Stenella coeruleoalba (top right), Delphinus delphis (bottom left) and Ziphius cavirostris(bottom right).

2.2 Data collection

For this study, "cetacean stranding" refers to any alive or dead cetacean that washed ashore, beached or found afloat in close proximity to the shore. Cetacean stranding records across all Greek territorial coastline are collected by Greek stranding network run by Greek coast guard and respective strandings database is maintained by Hellenic Center for Marine Research (HCMR).

The cetacean strandings database contains information of time/date of the stranding, geo-referenced location of the incident, photos of the stranded animal, species identification, if available post mortem examination findings performed from a designated veterinarian and the cause of death is also reported. Regarding the cause of death, it was assigned into four categories as shown in Table 1.

Table 1: Cetacean strandings cause of death categories.

Cause of death	Category
Unknown	Unknown
Alive	Alive
Disease	Disease
Longlines	Human induced
Fishing nets	
Gun, knife and spearfishing wounds	
Propeller wounds	
Other human related wounds	

2.3 Spatial analysis

2.3.1 Hotspot analysis

To assess whether cetacean strandings have a clustered or random pattern, nearest neighbor analysis was conducted for the total strandings and for each species strandings. The Nearest Neighbor Index (NNI), z-scores and corresponding p-values were calculated.

The kernel density estimation (KDE) (Diggle, 1985) was calculated in order to determine spatial hotspots for a) total strandings b) total strandings of three of the most common small cetacean species in the Greek Seas i.e., *Tursiops truncatus*, *Stenella coeruleoalba* and *Delphinus delphis* and c) human related strandings for the aforementioned species, respectively. The density estimates are calculated at a regular grid of points across the range of the data, corrected for edge effect bias (Jones, 1993). Using rule of thumb, isotropic Gaussian kernel function was selected with fixed 10km smoothing bandwidth at 1x1 km pixel resolution. Each KDE map was normalized (0-1) using Equation 1 and truncated from values <0.1 to allow for better visualization. KDE analysis was conducted using R programming language (R Core Team, 2022) and spatstat package (Baddeley & Turner, 2005).

$$Equation\ 1:\ nd_i = \frac{d_i - \min(d)}{\max(d) - \min\,(d)}$$

Where nd_i: normalized density of pixel I, d_i: density of pixel I, max(d): maximum value density of raster map and min(d): minimum value density of raster map.

2.3.2 Generalized additive models

To model the potential relationships between cetacean strandings and the fishing pressure, potential feeding grounds and coastline, Generalized Additive Models (GAMs) were applied, with the following dependent and independed variables calculated per subarea:

As dependent variables:

i. The number of total strandings
ii. The number of total human induced strandings.
iii. Strandings of *Tursiops truncatus*, *Stenella coeruleoalba* and *Delphinus delphis*, as well the human induced strandings of the same species.

As independent variables:

i. The percentage % of rocky coastline in each subarea using European Marine Observation and Data Network (EMODnet) data of coastal type. Percentage % of rocky coastline was

calculated as the sum % of the following coastal types: A – erosion resistant rock and/or cliffs, loose eroded material in the fronting sea, AC – pocket beaches (<200m long) and B – erodible rock and/or cliffs, with rock waste and sediments at its base.

ii. The coastline length (km) of each subarea, using coastline data from European Environment Agency (www.eea.europa.eu).

iii. The extent (km^2) of the fishing grounds in each subarea, expressed as the upper 50% (2nd quantile) and the upper 25% (3rd quantile) from the modeled based distribution of small-scale fisheries fishing pressure index (SSF FP_c) (Kavadas et al., 2015) (Figure 2a).

iv. The extent (km^2) of the potential feeding grounds in each subarea, expressed as the upper 50% (2nd quantile) and the upper 25% (3rd quantile) of the modeled based distributions of bottom trawl, total undersized discarded catch (Figure 2b), total discarded catch of commercial fish species (Figure 2c) and total discarded catch of cephalopods species (Figure 2d), from the modeled based distribution (Despoti et al., 2016, 2018).

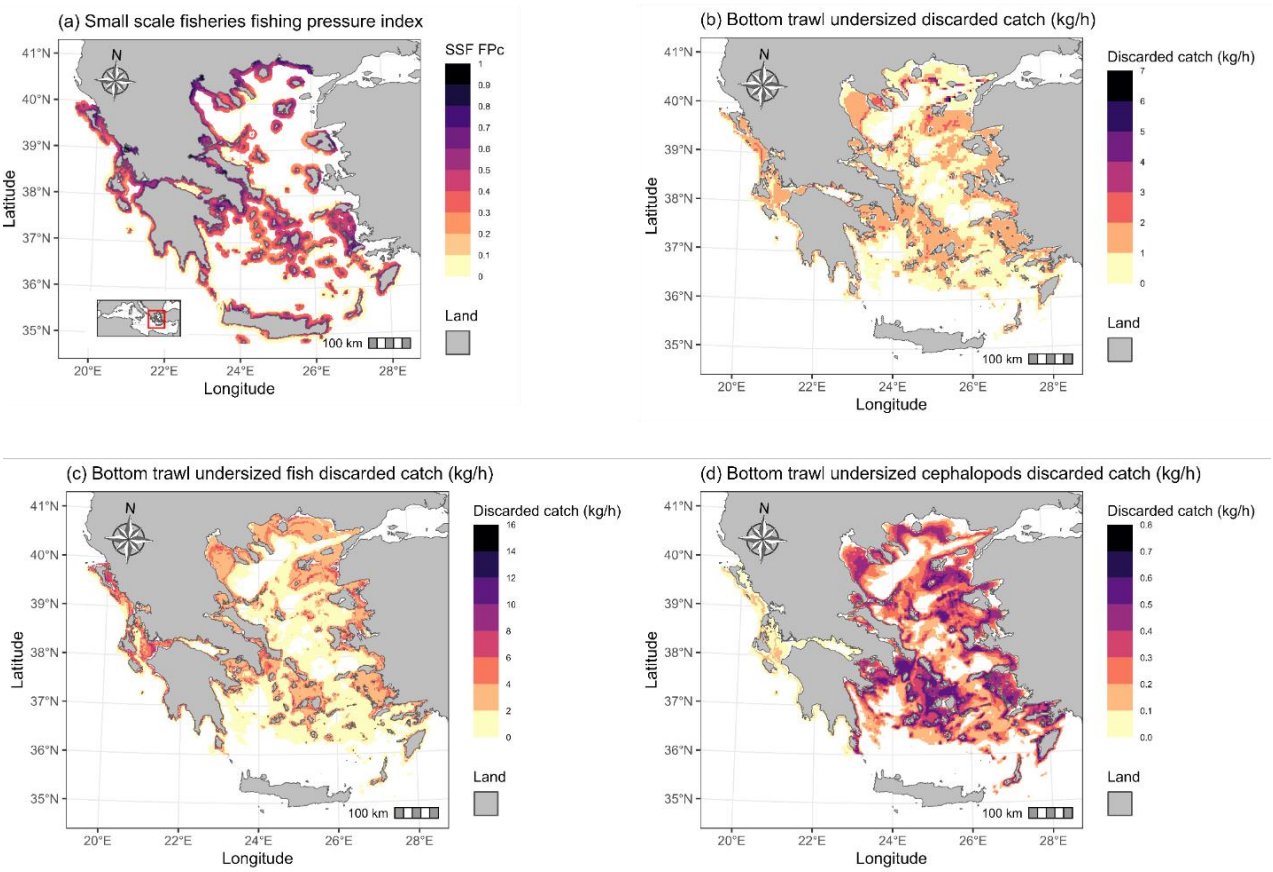

Figure 2: a: The spatial distribution of a. small-scale fisheries fishing pressure index (SSF FP_c) (from Kavadas et al., 2015), *b: bottom trawl total undersized discarded catch, c: bottom trawl total undersized discarded catch of commercial fish species, d: bottom trawl total discarded catch cephalopod species* (from Despoti et al., 2016, 2018).

For each independent variable basic diagnostics were performed (a) normality test through Q-Q plots (Figures S1-S2) and (b) collinearity for each variable pair (Figures S3-S4). All variables were also transformed with using log transformation to assess if the transformation improves normality or decreases collinearity. The independent variables kept were: the percentage % of rocky coastline, log of coastline length, the extent (km^2) of the fishing grounds accounting for the upper 25% (3rd quantile), the extent (km^2) of the upper 50% (2nd quantile) of total discarded catch, total discarded catch of commercial fish species and total discarded catch of cephalopods species.

The selection of the smooth predictor terms in each GAM was done with a forward approach using penalized regression splines and Poisson distribution (link log function). The degree of smoothing was chosen based on the observed data and the restricted maximum likelihood (REML), to avoid over-fitting the smoothing terms the maximum number of k knots used were k=5. The selection of the most appropriate model achieved through the minimization of the Akaike Information Criterion (AIC) in conjunction with deviance explained (%). For each gam validation plots (residual Q-Q plots, residuals vs fitted values, histogram of residuals and response vs fitted) were plotted to check for any pattern in the residuals and assess the model fit (Figures S5-S11). All GAMs were created in R programming language (R Core Team, 2022) and the MGCV package(Simon N. Wood, 2006; Wood, 2011; Wood et al., 2016).

2.3.3 Drifting model

In order to assess the possible origin of a cetacean carcass after a stranding event, an approach of using the search and rescue (SAR) stochastic ensemble trajectory model, “Leeway model” (Breivik & Allen, 2008) was used. The application of the Leeway model as a web application by Hellenic Center for Marine Research (HCMR), was used for this purpose. The approach used in this study was selecting a subarea of the study area, the Pagasitikos gulf – Oreoi strait – Skiathos island, in central west Aegean Sea (Figure 3), based on the complex topography and surface circulation in the area, which gives high uncertainty in a cetacean carcass origin. In the above area 9 positions of possible origin of cetacean carcass were selected. The Leeway model was run with each possible position as the starting positions for 8 days, from 22/10/2022 to 30/10/2022. The object class used for the modelling process was “Person in Water - Deceased” (PIW- 6), with 500 randomized replications in a starting dispersion radius of 0.5 km around each starting point. The output of the model is shown as the average drift path calculated from the positions of the objects during the simulation period and the average ending position at the end of simulation.

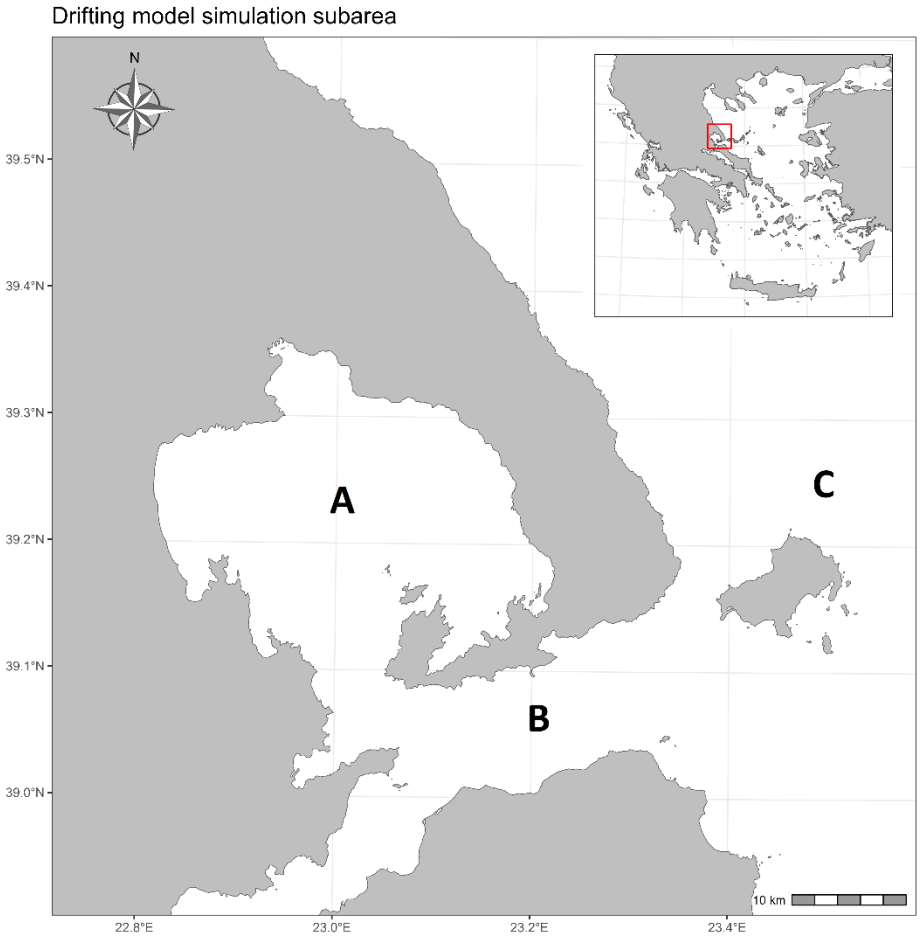

Figure 3: Drifting model simulation subarea (A - Pagasitikos gulf, B - Oreoi strait, C - Skiathos island and adjusted seas)

3. Results

3.1 Cetacean strandings

Cetacean strandings database of the time period 2010 – 2021, showed 1378 reported strandings of 9 identified cetacean species, belonging to 5 families (Table 2). The most common family Delphinidae with 5 species. The most common species was common bottlenose dolphin *Tursiops truncatus* with 437 stranded individuals, followed by the striped dolphin *Stenella coeruleoalba* with 435 individuals and Common dolphin *Delphinus delphis* with 75 individuals (Table 2). The rest of cetacean species were rarer, with < 50 stranded individuals reported, with 2 species only encountered once (*Steno bredanensis* and *Balaenoptera physalus*) (Table 2). Moreover, there were 339 undetermined cetacean strandings, accounting for 24.6% of the total strandings.

Table 2: Cetacean strandings database showing the species identificated, the family name, common name and stranded individuals in the time period of 2010 – 2022.

Species	Family	Common name	Stranded individuals
Tursiops truncatus	Delphinidae	Common bottlenose dolphin	437
Stenella coeruleoalba		Striped dolphin	435
Delphinus delphis		Common dolphin	75
Grampus griseus		Risso's dolphin	17
Steno bredanensis		Rough-toothed dolphin	1
Ziphius cavirostris	Ziphiidae	Cuvier's beaked whale	40
Physeter macrocephalus	Physeteridae	Sperm whale	20
Phocoena phocoena	Phocoenidae	Harbour porpoise	13
Balaenoptera physalus	Balaenopteridae	Fin whale	1

As per cause of death, the majority of the death cause was unknown with 1094 stranding records, accounting for 79.4% of total stranding records. Human induced stranding identified were 265, accounting for 19.2% of total strandings, while disease and alive strandings were the least common with 19 combined strandings and 1.4% of the total strandings.

The above pattern was similar for most of the species (*Tursiops truncatus*, *Stenella coeruleoalba*, *Delphinus delphis*, *Physeter macrocephalus*, *Grampus griseus* and *Phocoena phocoena*) with unknown death cause ranging 65.3% - 78.0% and human induced death cause ranging 19.3% - 30.8% (). Exception to this pattern is *Ziphius cavirostris* with 95.0% unknown death cause and 5.0% human induced death cause observed and the rare species *Steno bredanensis* (n = 1) and *Balaenoptera physalus* (n = 1) due to low number of individuals (Figure 4).

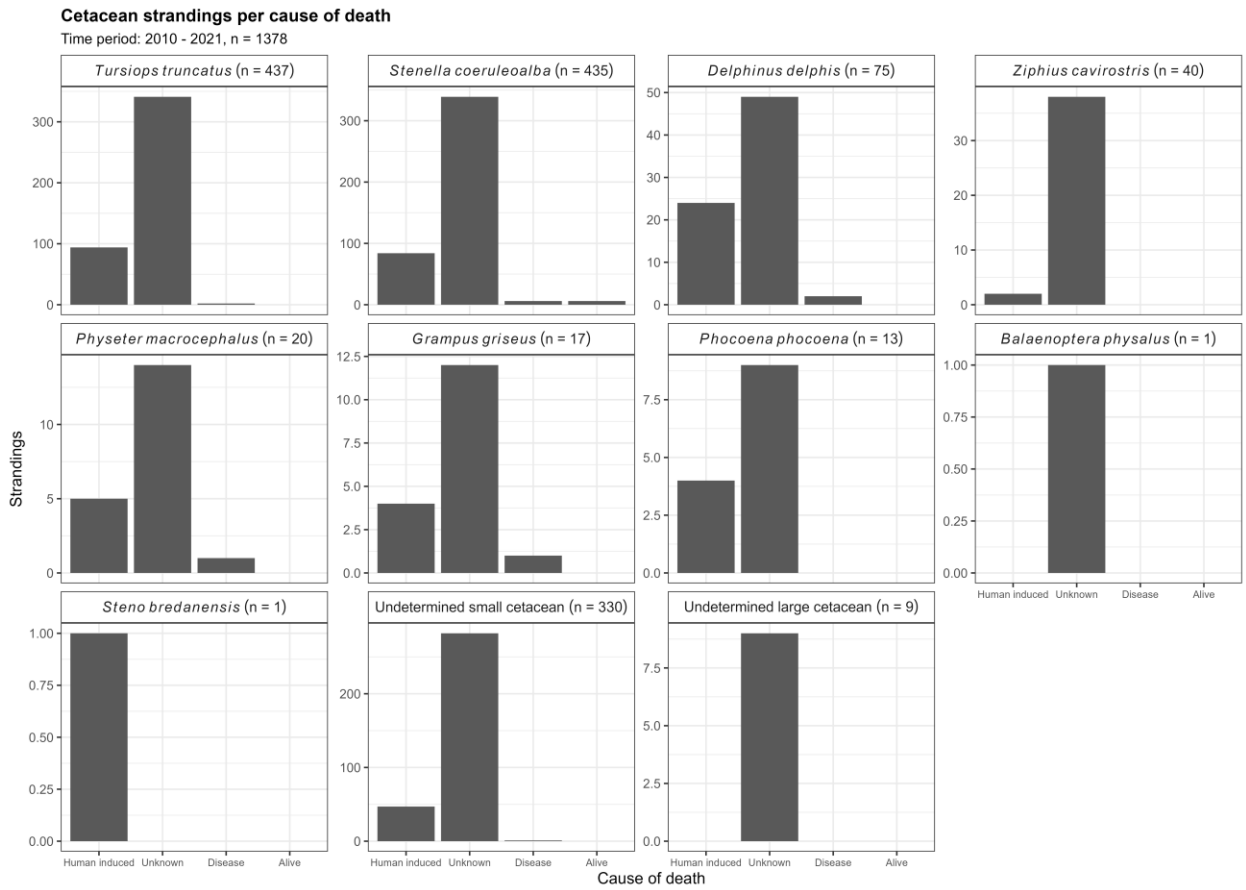

Figure 4: Number of cetacean stranding events per species and death cause.

3.2 Hotspot analysis

Nearest Neighbor Analysis tested if cetacean stranding points observed in the study area have a clustered (NNI < 1) or random pattern (NNI >1). Results showed that total strandings have a significant ($p<0.05$) clustered pattern (z-score = -56.65, $p<0.0001$) (Table 3). Significant clustered patterns are also revealed for the *Tursiops truncatus* (z-score = -28.46, $p<0.0001$), *Stenella coeruleoalba* (z-score = -28.54, $p<0.0001$), *Delphinus delphis* (z-score = -8.69.65, $p<0.0001$) *and Ziphius cavirostris* (z-score = -5.8222, $p<0.0001$) (Table 3). For the species *Physeter macrocephalus, Grampus griseus, Phocoena phocoena, Balaenoptera physalus and Steno bredanensis* there is not enough evidence of having a clustered pattern ($p>0.05$) and therefore cannot proceed to any further spatial analysis (Table 3).

Table 3: Nearest Neighbor Analysis results for total cetacean strandings and strandings per species. $D_{observed}$, mean distance observed between two nearest neighbors, $D_{expected}$: mean distance expected between two nearest neighbors under complete spatial randomness assumption, NNI: Nearest Neighbor Index calculated, n: number of stranding observations, Z-score: Z distribution score value, p: probability. Significant probability values <0.05 are in bold.

Species	$D_{observed}$	$D_{expected}$	NNI	n	Z-score	p
total strandings	1941.7	9597.6	0.2023	1378	-56.65	**<0.0001**
Tursiops truncatus	4820.9	16715.4	0.2884	437	-28.46	**<0.0001**
Stenella coeruleoalba	4839.2	16990.3	0.2848	435	-28.54	**<0.0001**
Delphinus delphis	14184.5	29864.3	0.4749	75	-8.69	**<0.0001**
Ziphius cavirostris	26979.9	52005.3	0.5187	40	-5.8222	**<0.0001**
Physeter macrocephalus	49765.8	57191	0.8701	20	-1.1107	0.1333
Grampus griseus	54603	58740	0.9295	17	-0.5555	0.2893
Phocoena phocoena	48108.8	48377.9	0.9944	13	-0.0383	0.4847
Balaenoptera physalus	-	-	-	1	-	-
Steno bredanensis	-	-	-	1	-	-

Normalized KDE map of the total cetacean strandings show stranding hotspots at the northern coast of Aegean Sea (gulfs of Thermaikos, Kavala and Alexandroupoli), the southern coast of Korinthiakos gulf and gulf of Pagasitikos – Skiathos island area in central - west Aegean Sea and Amvrakikos gulf of Ionian Sea (Figure 5). Minor hotspots were observed in Lesvos, Chios and Samos islands of east Aegean Sea and at Cyclades island complex of Tinos – Mykonos and Naxos – Paros islands in central Aegean Sea (Figure 5).

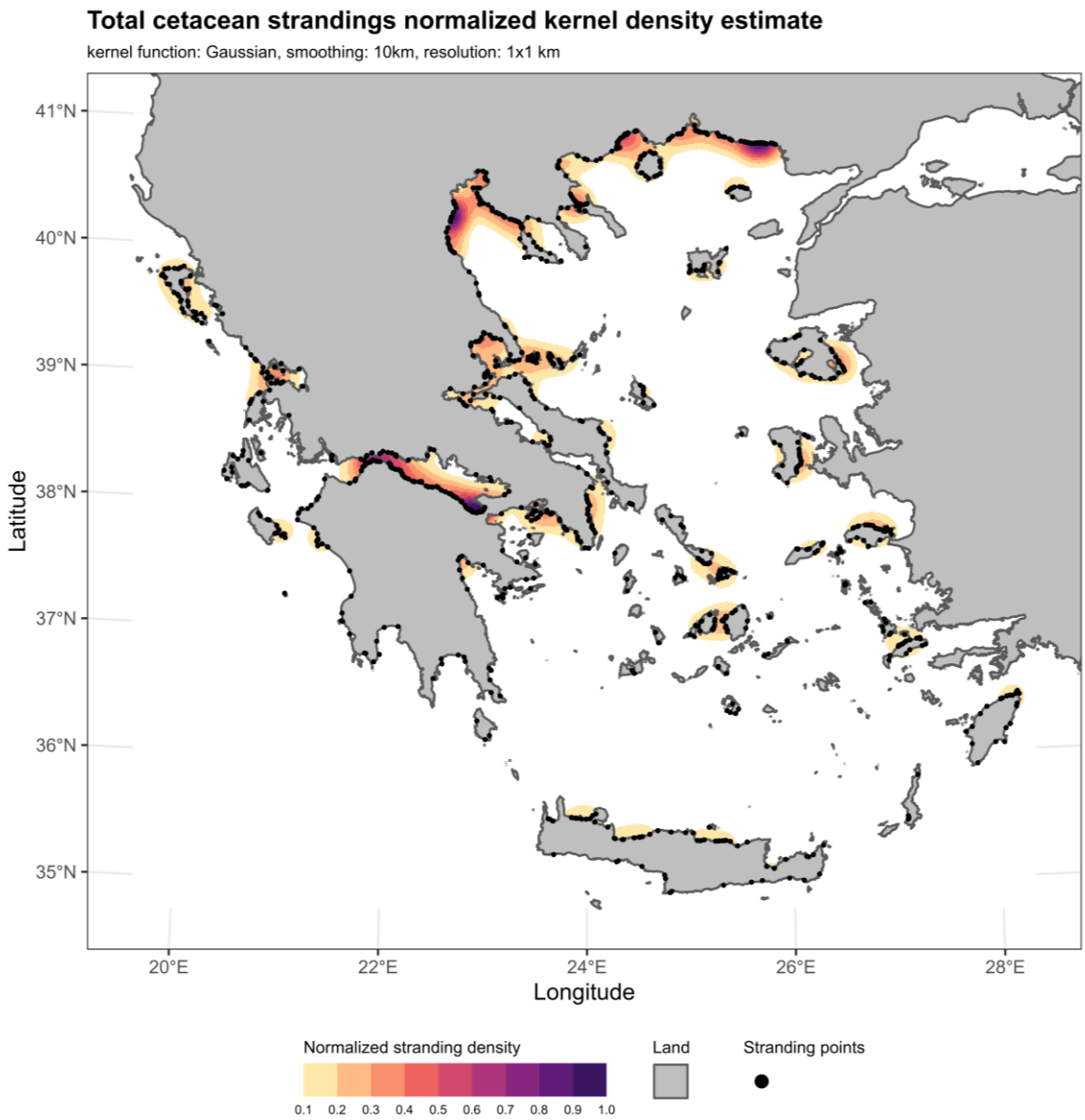

Figure 5: Normalized Kernel Density map of the total cetacean strandings (n=1378). Darker colors indicate higher stranding density. Land is showing as gray and stranding points at black points

Normalized KDE maps of the species *Tursiops truncatus*, *Stenella coeruleoalba*, *Delphinus delphis and Ziphius cavirostris* indicate the presence of several stranding hot spots (Figure 6). *Tursiops truncatus* stranding hotspots appear mostly in northern Aegean Sea, at western part of Thermaikos gulf, the gulf of Alexandroupoli and gulf of Kavala, as well south eastern Korinthiakos gulf and Mytilene strait (Figure 6 top-left). *Stenella coeruleoalba* highest kernel density hotspot was found at the south coast of Korinthiakos gulf, and northern coast of Aegean Sea at the gulfs of Ierissos, Strymonikos, Kavala and Alexandroupoli (Figure 6 top-right). *Delphinus delphis* normalized KDE map shows hotspots at Kos island in south east Aegean Sea, Limnos island in north Aegean Sea, Pagasitikos Gulf, as well as gulfs of Porto Lagos and

Alexandroupoli (Figure 6 bottom-left). Lastly *Ziphius cavirostris* hotspots appear to be around Kerkyra island in Ionian Sea, bay of Ierapetra in Crete and Rhodos islands in southern Aegean Sea (Figure 5 bottom-right).

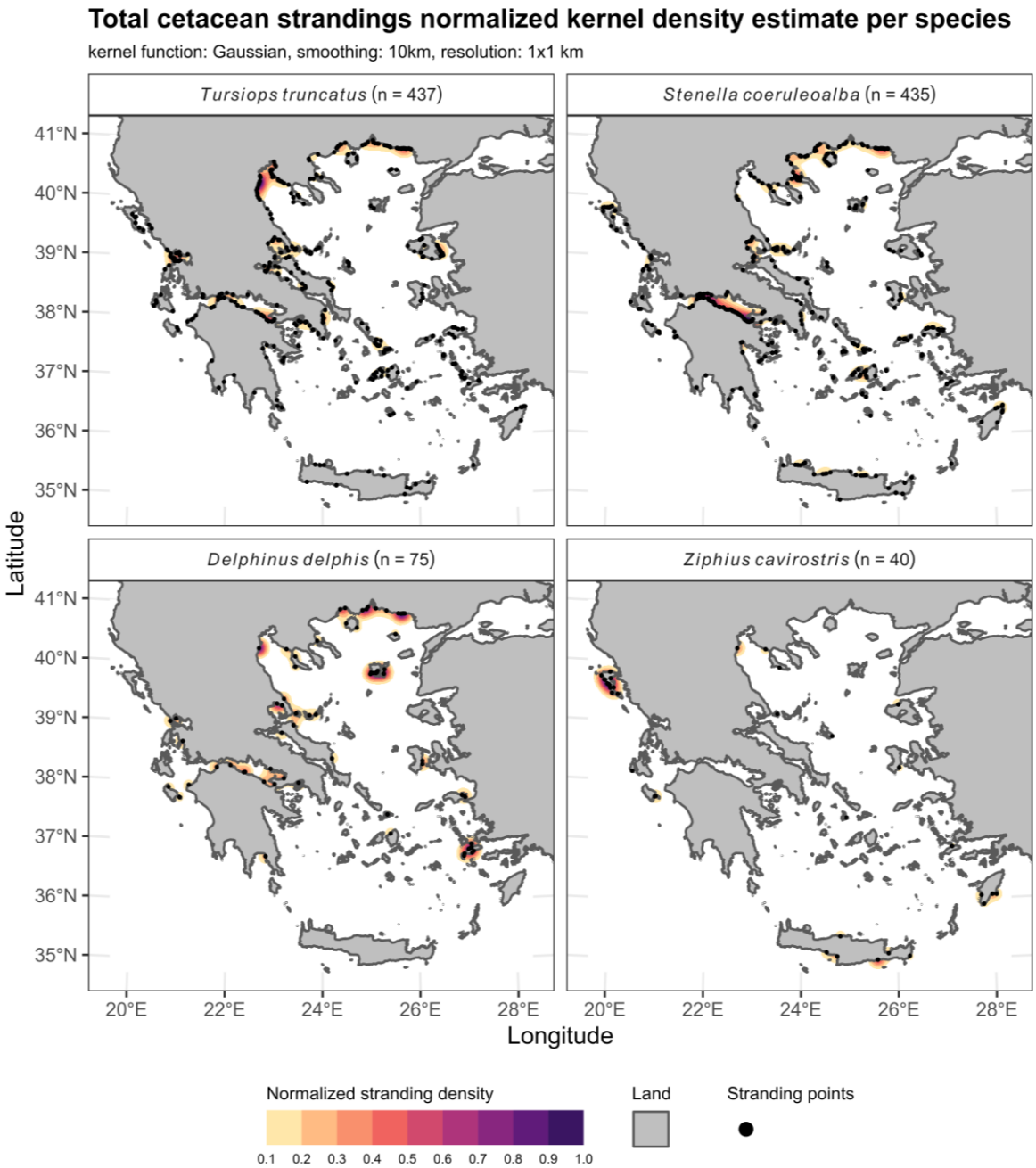

Figure 6: Normalized Kernel Density maps of each cetacean species strandings. Darker colors indicate higher stranding density. Land is showing as gray and stranding points at black points

Results of normalized KDE maps of total human induced strandings and those of unknown death cause are shown in Figure 7. In the case of human induced strandings the highest kernel density found in western and south eastern Korinthiakos gulf, followed by gulf of Alexandroupoli, Porto Lagos, Kavala, Thermaikos and Pagasitikos (Figure 7 left). For the unknown cause of death strandings the highest stranding densities are found in Thermaikos gulf, gulf of Alexandroupoli, south Korinthiakos gulf and Thermaikos gulf – Sporades islands (Figure 7 right).

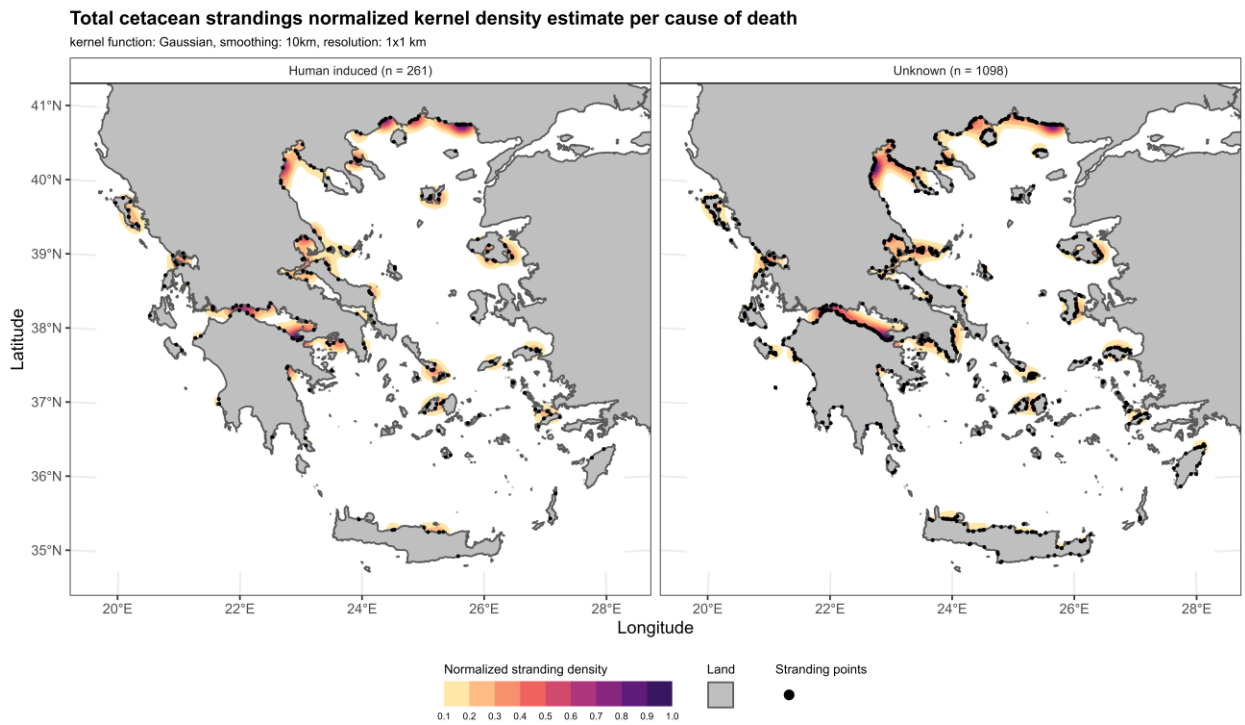

Figure 7: Normalized Kernel Density maps of total cetacean species strandings with human induced death cause (right) and unknown death cause (left). Darker colors indicate higher stranding density. Land is showing as gray and stranding points at black points

3.3 Generalized additive models

The final GAMs selected for each response variable are presented in Table 4, along with the corresponding AIC, Deviance and deviance explained (%).

Table 4: Final selected GAM models of cetacean strandings (response variables) in relationship to coastline characteristics, fishing grounds and potential feeding grounds (explanatory variables). s: smoothing function, ssf 25: the extent (km^2) of the fishing grounds accounting for the upper 25% (3rd quantile), mls total 50: the extent (km^2) of the upper 50% (2nd quantile) of total discarded catch, rocky: percentage % of rocky coastline, log coastline: log of coastline length, AIC: Akaike Information Criteria calculated, Deviance: Deviance of model calculated, Deviance %: percentage % of deviance explained by the model.

Response variable	Best model	AIC	Deviance	Deviance (%)
Total strandings	s(ssf 25) + s(rocky) + s(log coastline)	918.2515	561.0893	61.9
Total human induced strandings	s(ssf 25) + s(rocky) + s(mls total 50)	279.6766	85.54672	57.3
Tursiops truncatus strandings	s(ssf 25) + s(rocky) + s(log coastline)	394.6428	158.4285	64.2
Tursiops truncatus human induced strandings	s(rocky) + s(ssf 25)	119.2116	17.3605	54.6
Stenella coeruleoalba strandings	s(rocky)+ s(ssf 25)	539.2671	306.68	37.1
Stenella coeruleoalba human induced strandings	s(rocky)	135.1533	37.99519	9.81
Delphinus delphis strandings	s(rocky)	106.9657	31.6237	30.3
Delphinus delphis human induced strandings	-	-	-	-

Results for total strandings indicate a positive relation with more extended fishing grounds, a negative relationship with the percentage of rocky shores and an increase with the coastline length (Figure 8, Table 4, model explaining 61.9% of deviance). Regarding the human induced total strandings the best model (Table 4, 57.3% deviance explained) suggests a positive relation with the fishing grounds extent, a negative relationship with rocky shore % and the extent of total discarded catch potential feeding grounds (Figure 9).

For *Tursiops truncatus* strandings, the selected model (Table 4, model explaining 64.2% of deviance) suggests a positive linear relation with the extent of fishing grounds, a negative relation with the percentage of rocky shores and an increase with the coastline length (Figure 10). In the case of *Tursiops truncatus* human related selected model (Table 4, 54.6% deviance explained) indicate a negative relation with the increase in percentage of rocky shore and a weak positive relationship with the increase in the extent of fishing grounds (Figure 11).

Stenella coeruleoalba total strandings model (Table 4, 37.1% deviance explained) shows a negative relationship between strandings and rocky shore % and a generally positive relationship with fishing grounds extent (Figure 12). Human induced *Stenella coeruleoalba* strandings model (Table 4, 9.81% deviance explained) have a linear negative relation only with the rocky shore % (Figure 13).

The best model for the *Delphinus delphis* total strandings (Table 4, 30.3% deviance explained) showed only a linear negative relation with the rocky shore % (Figure 14). Lastly, no explanatory variables showed any significant relationship with the *Delphinus delphis* human induced strandings in any of the models.

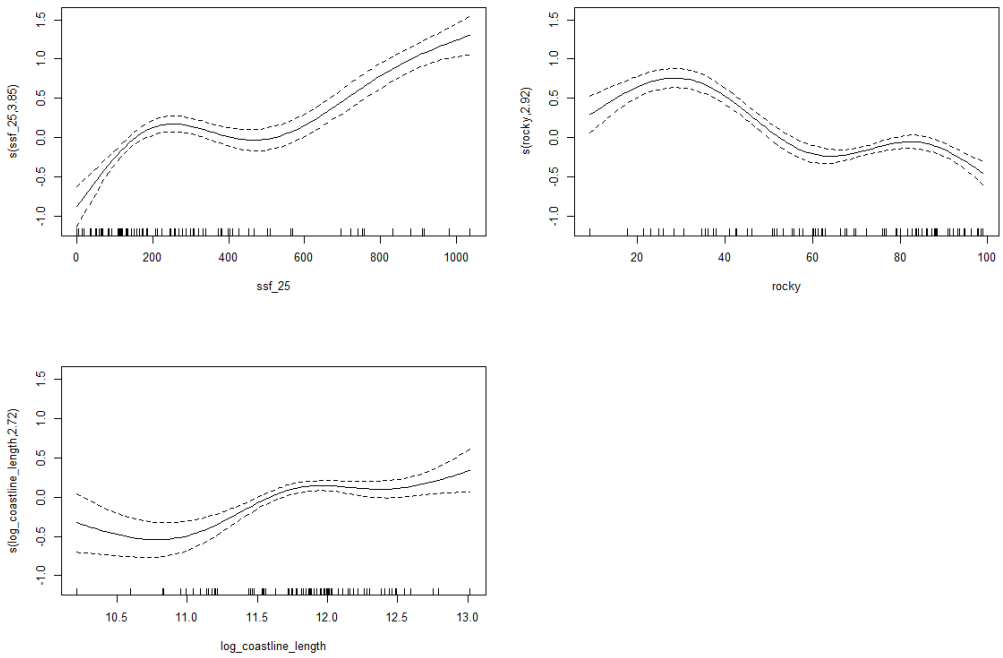

Figure 8: Total cetacean strandings GAM predictors plots showing the smoothed function of each predictor. ssf_25: the extent of the upper 25% (>3rd quantile) extent of fishing grounds (km²), rocky: percentage of rocky coast, log_coastline_length: log transformed coastline length.

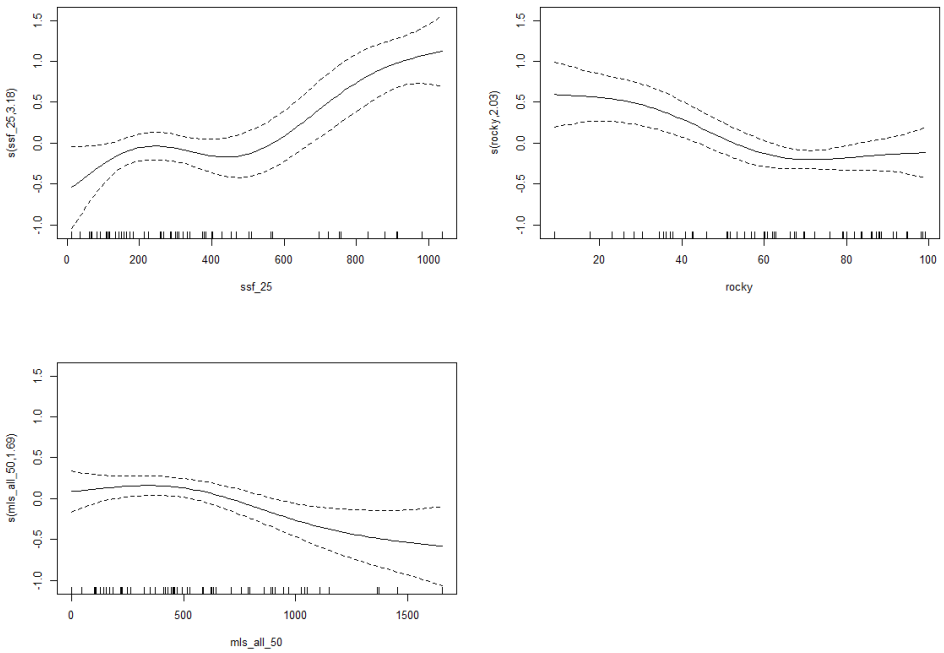

Figure 9 Total human induced cetacean strandings GAM predictors plots showing the smoothed function of each predictor. ssf_25: the extent of the upper 25% (>3rd quantile) extent of fishing grounds (km²), rocky: percentage of rocky coast, mls_all_50: the extent of the upper 50% (>2nd quantile) extent of total discarded catch (km²).

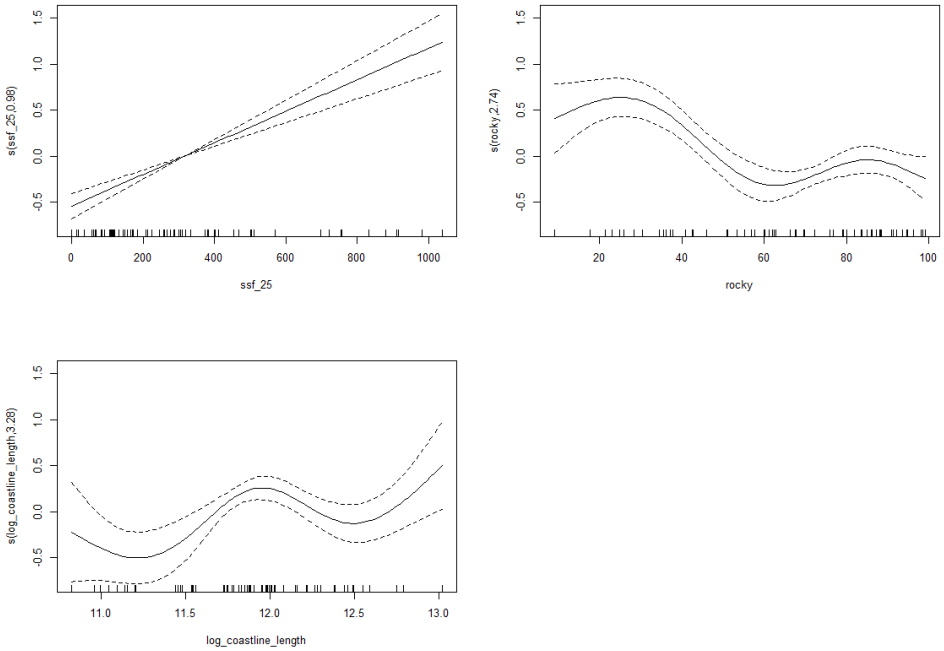

Figure 10 Total Tursiops truncatus strandings GAM predictors plots showing the smoothed function of each predictor. ssf_25: the extent of the upper 25% (>3rd quantile) extent of fishing grounds (km²), rocky: percentage of rocky coast, log_coastline_length: log transformed coastline length.

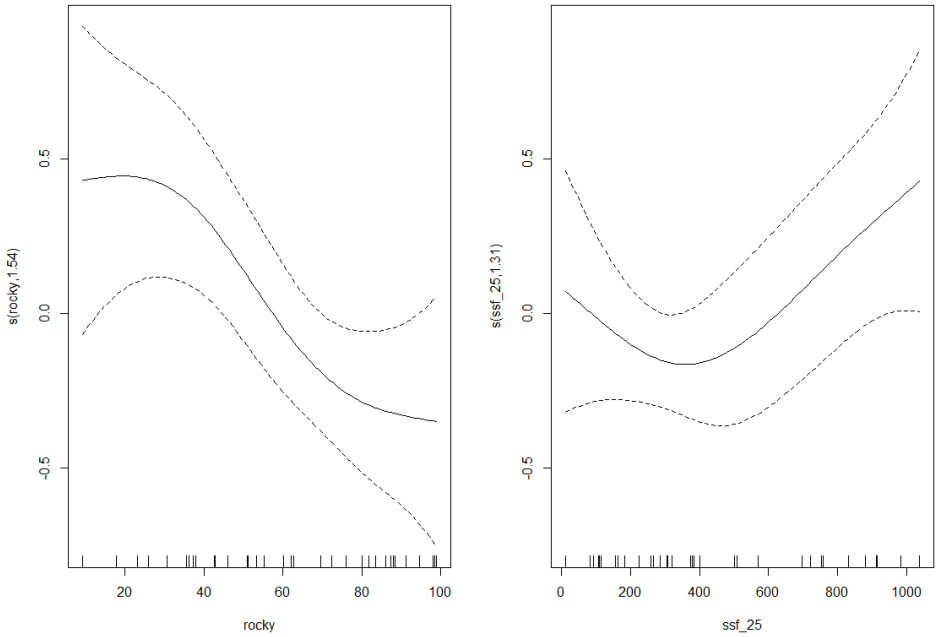

Figure 11: Total Tursiops truncatus human induced strandings GAM predictors plots showing the smoothed function of each predictor. ssf_25: the extent of the upper 25% (>3rd quantile) extent of fishing grounds (km²), rocky: percentage of rocky coast

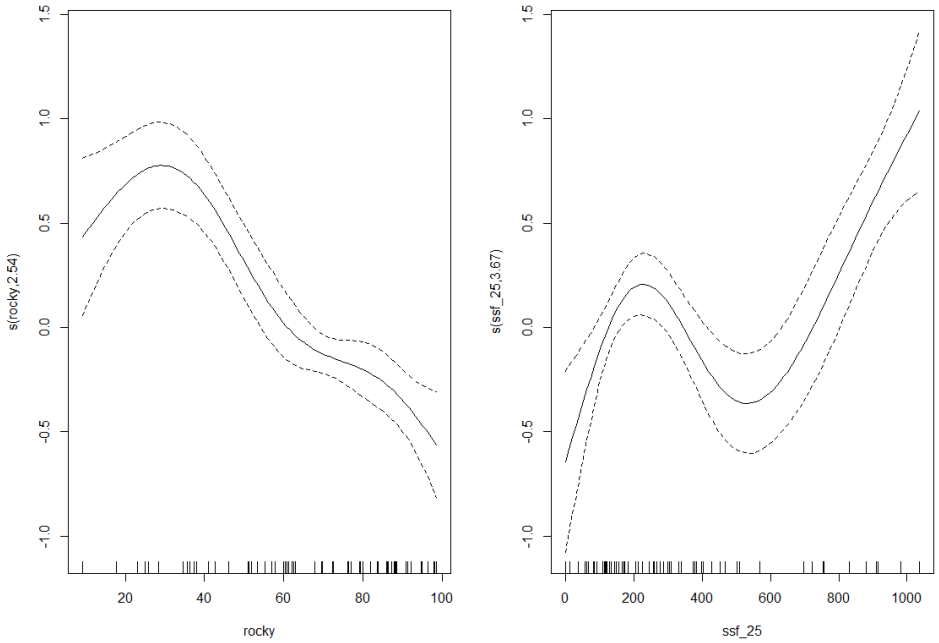

Figure 12: Total Stenella coeruleoalba strandings GAM predictors plots showing the smoothed function of each predictor. ssf_25: the extent of the upper 25% (>3rd quantile) extent of fishing grounds (km²), rocky: percentage of rocky coast.

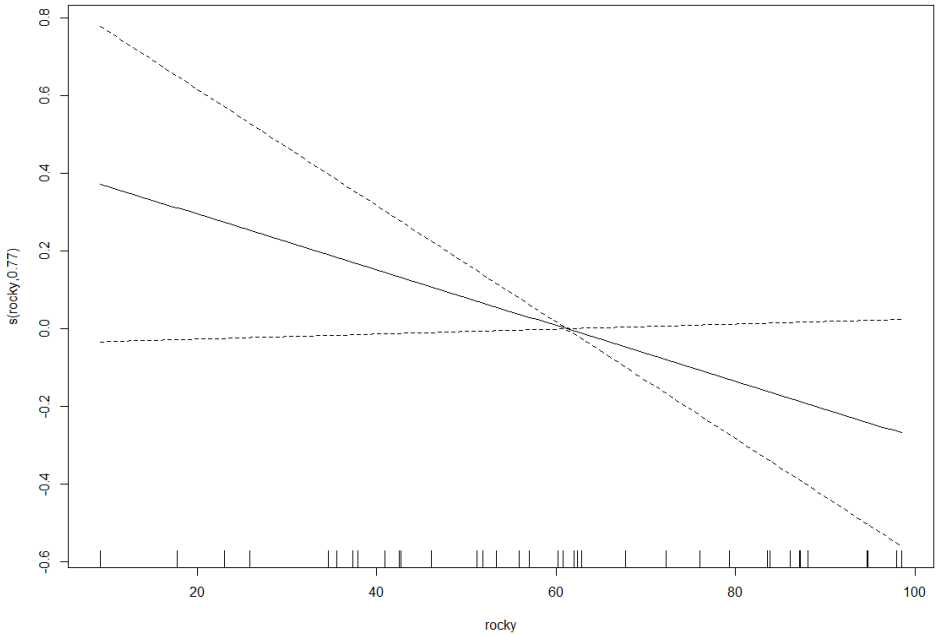

Figure 13: Total Stenella coeruleoalba human induced strandings GAM predictors plots showing the smoothed function of each predictor, rocky: percentage of rocky coast.

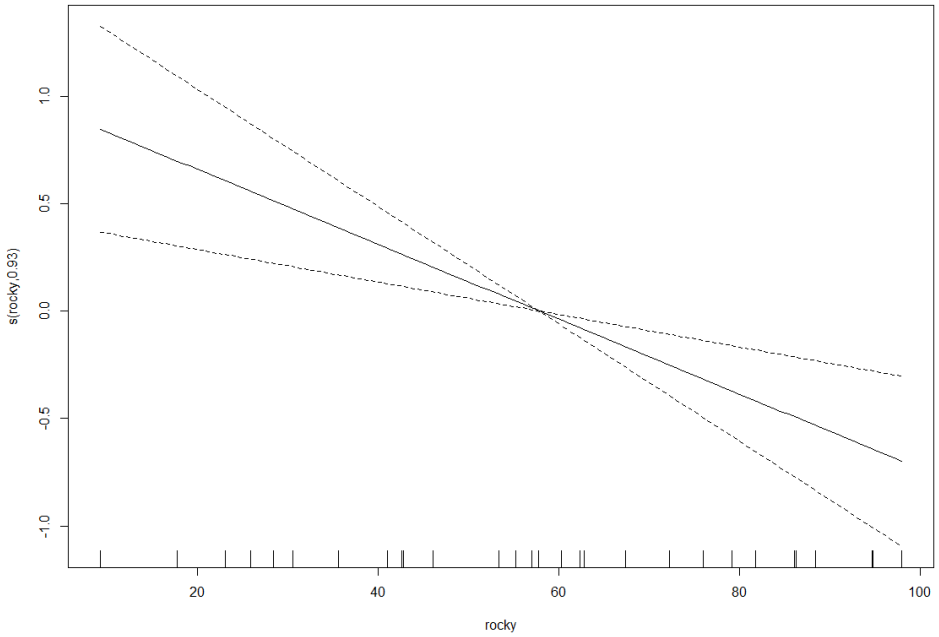

Figure 14 Total Delphinus delphis strandings GAM predictors plots showing the smoothed function of each predictor, rocky: percentage of rocky coast.

3.4 Drifting model

Leeway model results shows the mean drift position of objects during the 8-day simulation from 8 hypothetical origin positions of cetacean carcasses around the area of Pagasitikos gulf, Oreoi strait and Skiathos island (Figure 15). The object class used for the modelling process was "Person in Water - Deceased" (PIW- 6), with 500 randomized replications in a starting dispersion radius of 0.5 km around each starting point

Carcasses starting inside the Pagasitikos gulf shows a cyclonic circular drift inside the gulf. Inside the Oreoi strait object shows an irregular drifting motion, while near Skiathos island there is a clear outward drifting motion to the north and south of the island (Figure 14).

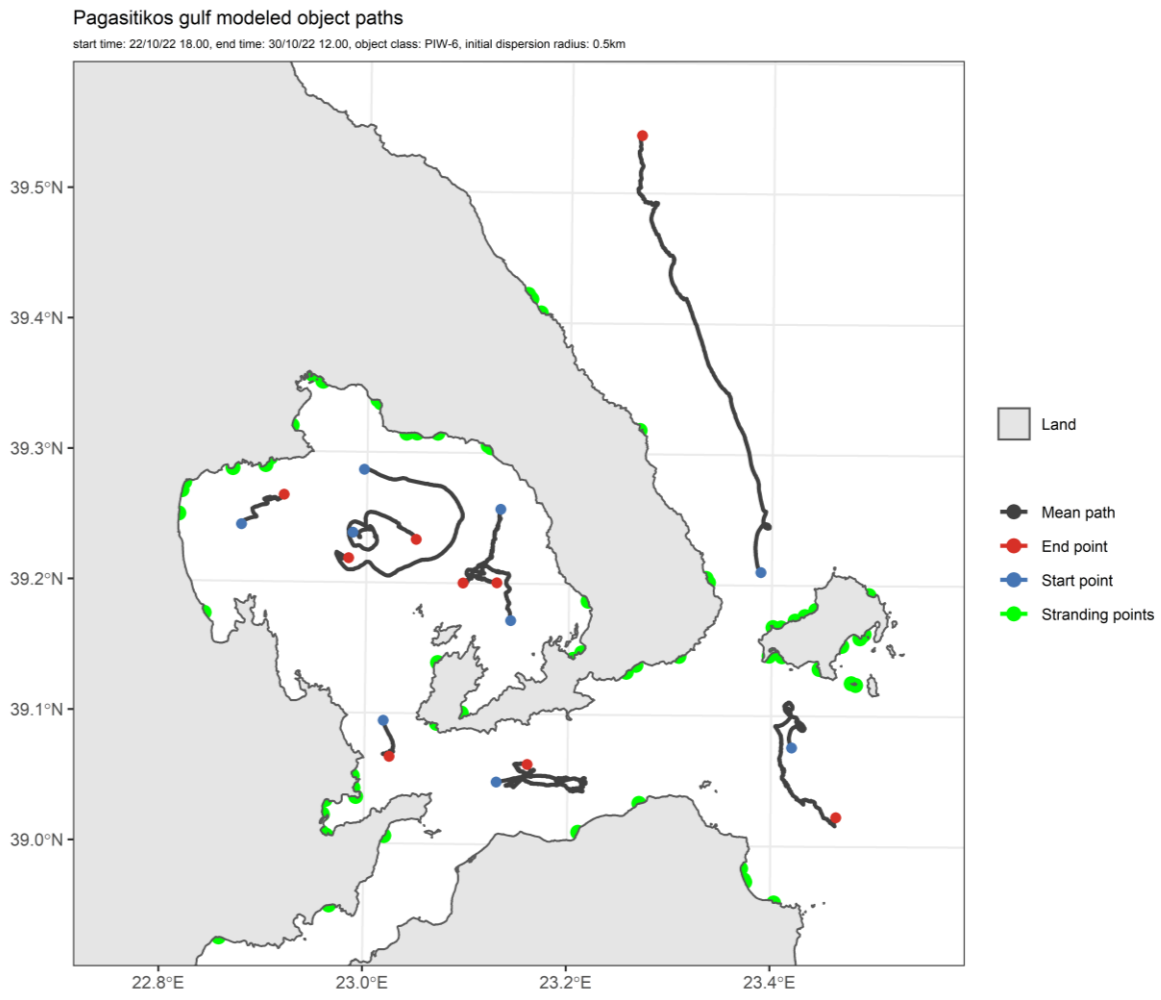

Figure 15: Mean object drifting paths results from Leeway model. Simulation duration: 8-days from 22/10/2022 to 30/10/22, object class: "Person in Water – Deceased", mean drifting path shows in black lines, end points with red color, starting points with blue color, observed cetacean stranding points with green color and land in gray color.

4. Discussion

In this study of stranding records in Greek coastal waters, out of 1378 total strandings, 1039 (75.4%) were identified to the species level and 339 undetermined cetacean strandings were recorded, accounting for 24.6% of the total strandings. Based on the stranding reports, these strandings was not possible to be identified to species level, due to the carcass decomposition or even the difficulty in approaching the stranding location (cliffs, rocks, bad weather conditions). For the majority of strandings, the cause of death remains unknown (79.4%), as for the determination of the most probable cause of death during the post mortem examination, requires a "fresh" carcass with little to no decomposition. Human induced stranding identified, accounted for 19.2% of total strandings showing a wide range anthropogenic pressures on cetaceans.

Monitoring marine mammal populations through live survey methods is often logistically challenging, due to the temporal heterogeneity of the marine environment and the range and mobility of cetacean species. Despite the number of biases, data on stranded animals when interpreted appropriately can yield valuable information which can be used in addition to live animal abundance surveys for population monitoring purposes (Peltier et al., 2012, 2013)

Results of NNA analysis suggests that there are significant clustered patterns of strandings both regarding total strandings as well the 4 most common species in the area (*Tursiops truncatus*, *Stenella coeruleoalba*, *Delphinus delphis* and *Ziphius cavirostris*). Hotspot KDE analysis revealed several stranding hot spots differentiating per species (Figures 5-6). Common bottlenose dolphin *Tursiops truncatus* stranding events were reported in every coastal area in this study, as it is reported to be the most common cetacean in the region (Frantzis et al., 2003; Notarbartolo di Sciara, 2016). *Tursiops truncatus* stranding hotspots appear mostly in Thracian Sea, Thermaikos gulf, Korinthiakos gulf and Pagasitikos gulf in the Aegean Sea and in Amvrakikos gulf in Ionian Sea. Thracian Sea and Thermaikos gulf have extended continental shelf waters, whereas Pagasitikos and Amvrakikos gulfs are enclosed seas. These areas are reported to be highly preferential habitat of *Tursiops truncatus* as per (Frantzis et al., 2003; Giannoulaki et al., 2017). This study suggest *Tursiops truncatus* strandings are positively related to small scale fisheries fishing pressure. In the recent study of Milani et al. (2019), *Tursiops truncatus* use of resources showed high overlap with trawls and static nets (30%). Also, in the study of Tsagarakis et al., (2021) it was found that there was almost negligible interaction with purse seines, whereas there was strong negative interaction with fishing nets, mainly due to entanglement, as well as in Crosti et al., (2017) where it is also suggested that there is a relation between *Tursiops truncatus* and fisheries.

Common dolphin *Delphinus delphis* strandings, showed a much narrower spatial distribution, matching the species predicted abundance in ACCOBAMS, (2021) aerial surveys as well the distribution reported in (Frantzis et al., 2003; C. Milani et al., 2021). *Delphinus delphis*

strandings hotspots reported in this study largely overlap with those of *Tursiops truncatus* in north Aegean Sea. Spatial isolated hotspot areas occur around Limnos island in Thracian Sea, where there is a recorded population (Frantzis et al., 2003; C. Milani et al., 2021; C. B. Milani et al., 2019) and Kos island in southeast Aegean Sea, where there isn't any dedicated survey assessing common dolphin population, although there is a confirmed population in the nearby island of Samos (Pietroluongo et al., 2020). This study didn't provide any evidence of common dolphin strandings relation to fishing activities as they were not significant in any model. This is probably due to the low number of stranded individuals reported (n=75) and the low number of subareas that this species was reported (n=29). The striped dolphin *Stenella coeruleoalba* is the most common offshore cetacean in the region (ACCOBAMS, 2021), which is depicted here as the second most abundant in reported strandings. Two main stranding hotspots were found in this study, Thracian Sea and Korinthiakos gulf with a weak positive relation with fishing pressure. This can be attributed to this species ecological characteristics, as it's an offshore species it showed a weak resource overlap (<10%) with fisheries as suggested by Milani et al., (2019), in Thracian Sea. In the case of Korinthiakos gulf the stranding hotspots of *Tursiops truncatus*, *Stenella coeruleoalba* and *Delphinus delphis* overlap in the eastern and western parts of the gulf, with those of *Stenella coeruleoalba* being the most extensive in the south coast of the gulf. Korinthiakos gulf is an enclosed gulf with a narrow continental shelf, very steep slope and up to 500-900m depth. In this gulf there are mixed species groups of *Stenella coeruleoalba* and *Delphinus delphis*, as well groups of *Tursiops truncatus* as presented by various studies in the area (Bearzi et al., 2016; Frantzis et al., 2003). Cuvier's beaked whale *Ziphius cavirostris* strandings hotspots (Kerkyra island, south Crete island and Rhode island) reflect the species habitat (Hellenic trench arch), which is offshore waters over steep continental edge (Podestà et al., 2016). Strandings in this study reveal only a portion of the mortality at sea, as not all cetacean carcasses float and drift or strand ashore, in addition to not all carcasses being reported to authorities (Moore et al., 2020; Peltier et al., 2012; Reisdorf et al., 2012).

Results of the Leeway model on the 8 starting points of potential cetacean carcass origin locations, shows the mean path of each object from each starting position during the simulation period (22/10/2022 – 30/10/22) (Figure 14 black lines). From these mean paths of the drifting objects and starting and ending position of each object, the simulation was applied separately into 3 distinct subareas based on the drifting results. Inside the Pagasitikos gulf area, objects are shown to have a clear cyclonic drifting motion, therefore based on this evidence, the most possible origin of cetacean carcasses stranding on the northern part of Pagasitikos gulf, are animals that died inside the gulf area. Simulated objects inside the area of Oreoi strait exhibited an unclear, irregular back and forth motion in the strait, making impossible to identify a possible area of origin for the cetacean stranding in the Oreoi strait, as it is possible to originate from Maliakos gulf, Pagasitikos gulf or the outer Aegean Sea open waters. Near Skiathos island there is clear drift motion to the outward of the island toward north and south.

Drift models have been used with success in predicting likely tracks of sea turtle carcasses to assess possible origin of death locations (Nero et al., 2013) and possible mortality hotspots (Santos et al., 2018), as well as in predicting cetacean carcass drift in north European waters (Hélène et al., 2020; Peltier et al., 2012), though there are no occurrences of using drift models to predict cetacean drifts after a stranding event to determine the location where the animal died. Cetaceans show a wide range of size between species and age groups (Notarbartolo di Sciara, 2016), therefore it is difficult assess the parameters affecting buoyancy, volume, wind coefficients and other parameters that a drift model uses to simulate a drifting path over time, therefore the object parameters available and used for this study are for a deceased human. It is clear that more research is needed before the use of drifting modeling tool in management use for the assessment of the origin of a carcass after a stranding event.

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APPENDIX

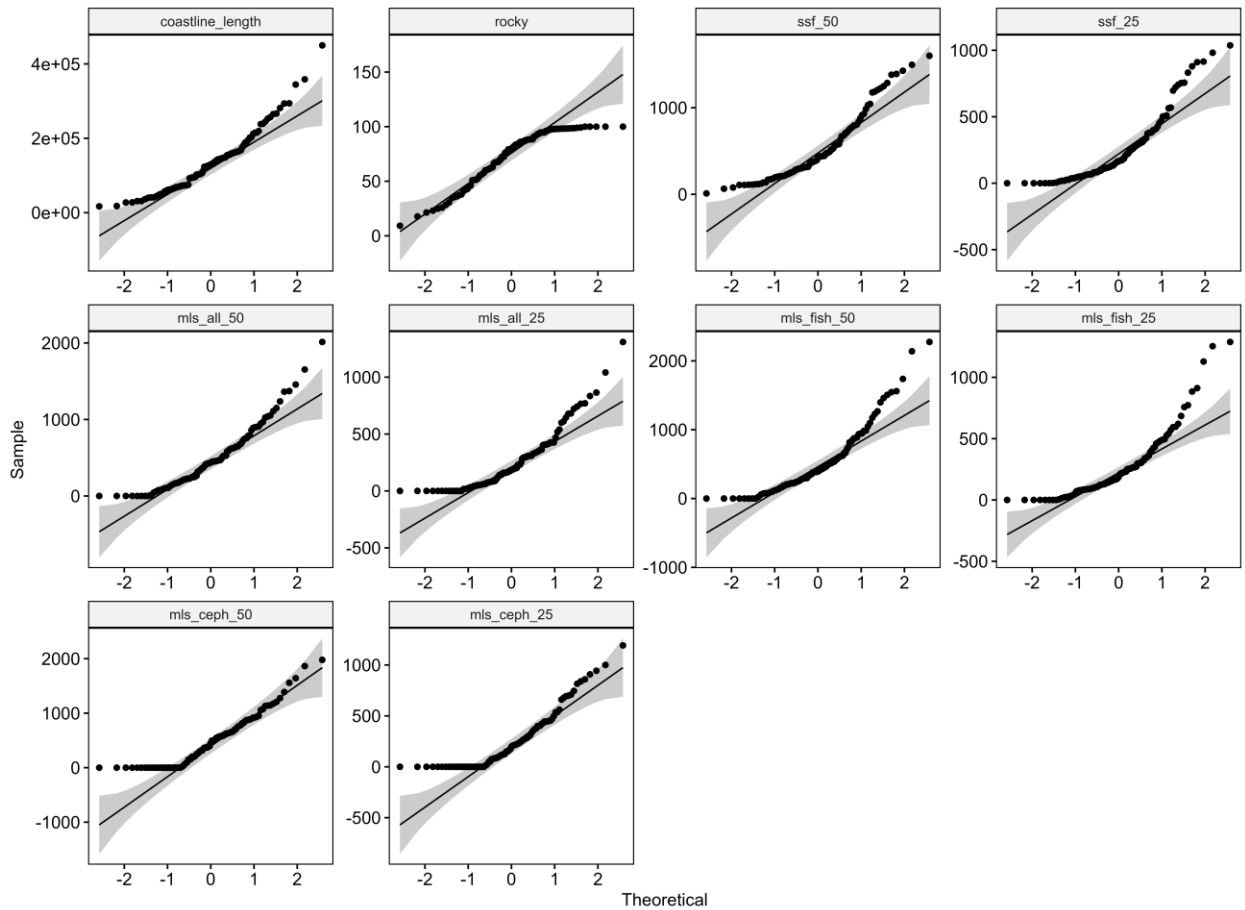

Figure S1: Q-Q plots of each subarea variable calculated, to assess normality. Coastline_length: the length (km) of the coastline, rocky: percentage % of rocky coastline, ssf_50: extent (km^2) of small-scale fishing pressure index accounting for upper 50%, ssf_25: extent (km^2) of small-scale fishing pressure index accounting for upper 25%, mls_all_50: extent (km^2) of accounting for upper 50% of bottom trawl total undersized discarded catch, mls_all_25: extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, mls_fish_50: extent (km^2) of accounting for upper 50% of bottom trawl total undersized fish discarded catch, mls_fish_25: extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, mls_ceph_50: extent (km^2) of accounting for upper 50% of bottom trawl total cephalopods discarded catch, mls_cephl_25: extent (km^2) of accounting for upper 25% of bottom trawl total cephalopods discarded catch.

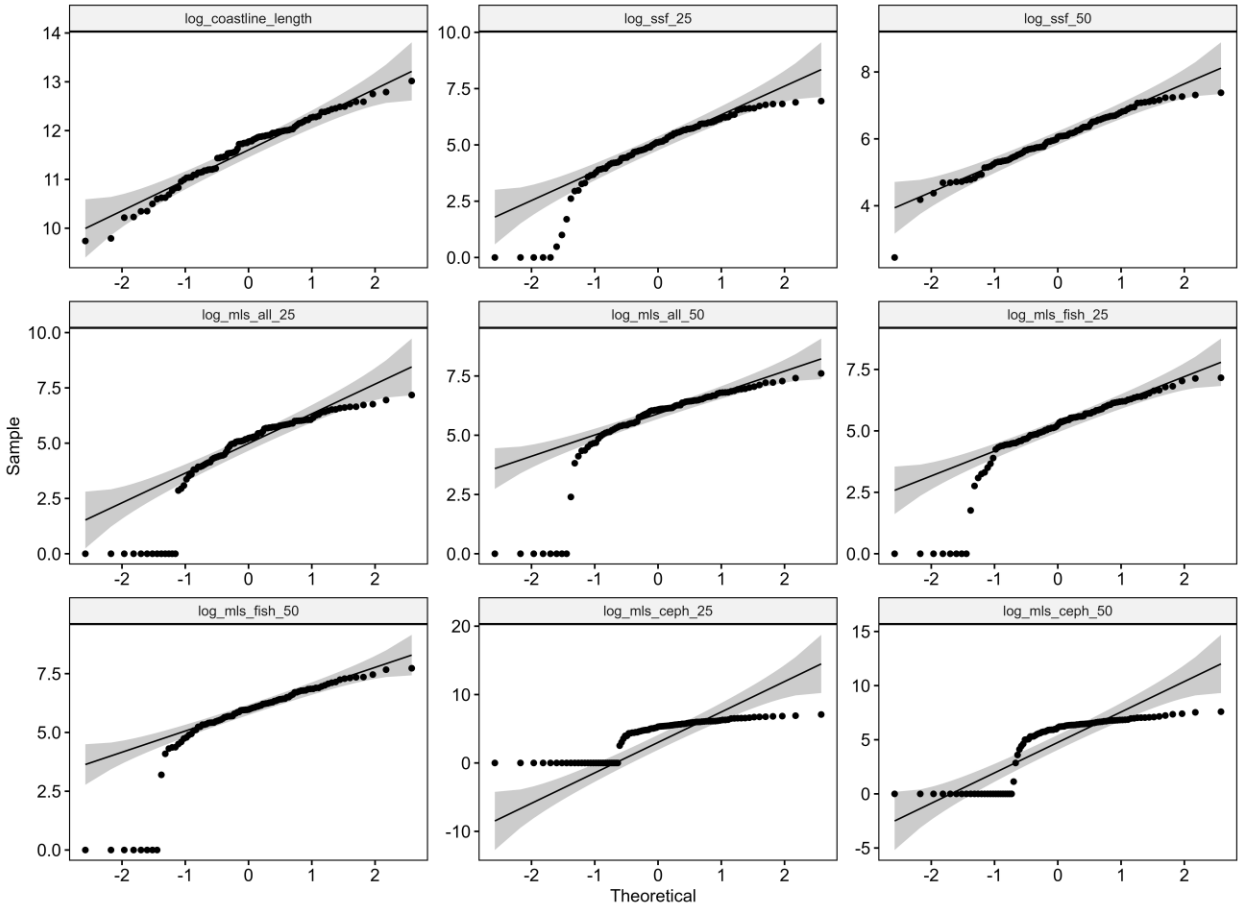

Figure S2: Q-Q plots of each variable calculated, after log transformation to assess normality. log_coastline_length: the log length (km) of the coastline, log_ssf_50: log extent (km^2) of small-scale fishing pressure index accounting for upper 50%, log_ssf_25: log extent (km^2) of small-scale fishing pressure index accounting for upper 25%, log_mls_all_50: log extent (km^2) of accounting for upper 50% of bottom trawl total undersized discarded catch, log_mls_all_25: log extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, log_mls_fish_50: log extent (km^2) of accounting for upper 50% of bottom trawl total undersized fish discarded catch, log_mls_fish_25: log extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, log_mls_ceph_50: log extent (km^2) of accounting for upper 50% of bottom trawl total cephalopods discarded catch, log_mls_cephl_25: log extent (km^2) of accounting for upper 25% of bottom trawl total cephalopods discarded catch.

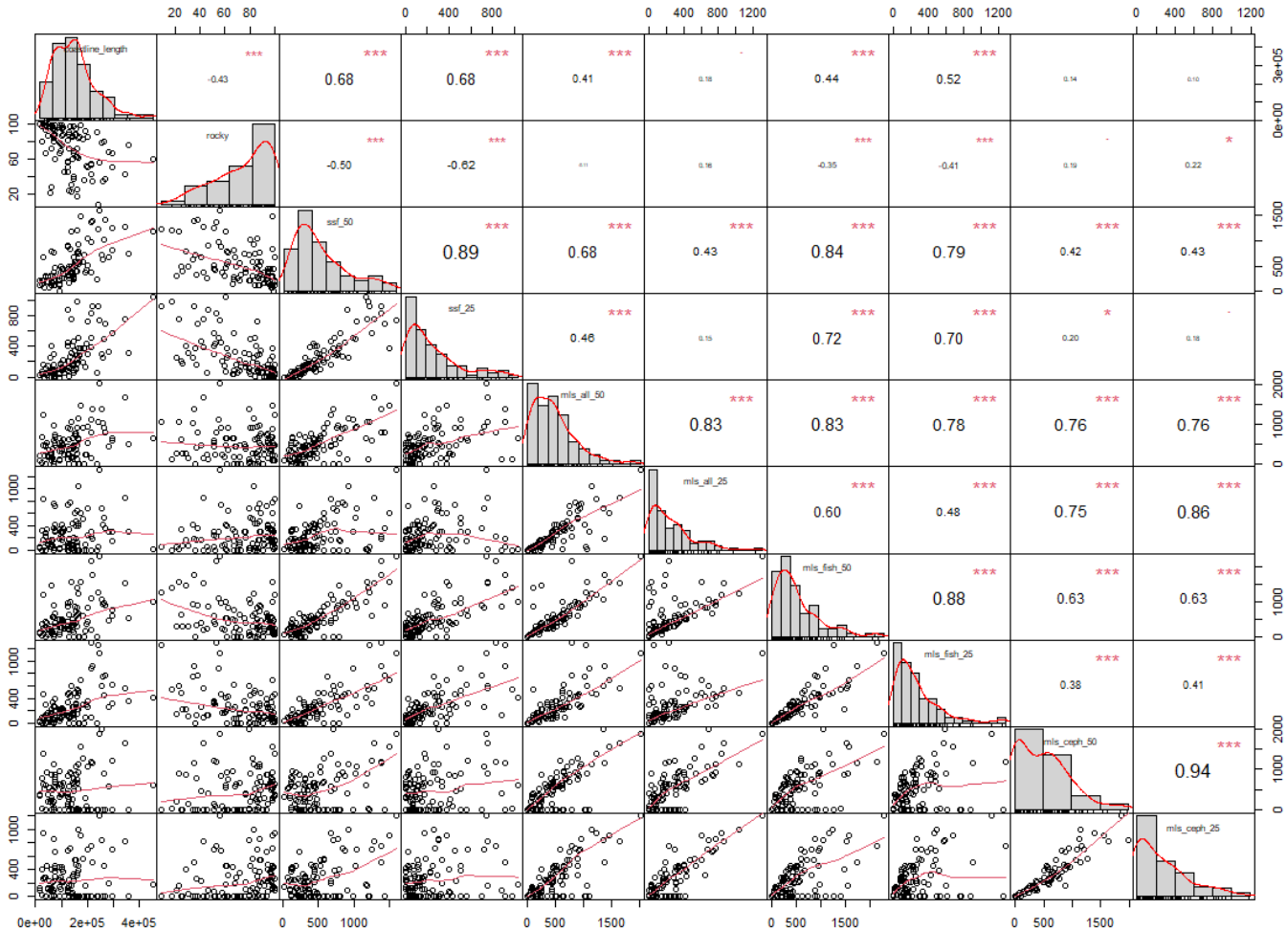

Figure S3: Top: Pearson correlation coefficient for each variable pair, bottom: scatterplot of each variable pair, diagonal: variable name and histogram. Coastline_length: the length (km) of the coastline, rocky: percentage % of rocky coastline, ssf_50: extent (km^2) of small-scale fishing pressure index accounting for upper 50%, ssf_25: extent (km^2) of small-scale fishing pressure index accounting for upper 25%, mls_all_50: extent (km^2) of accounting for upper 50% of bottom trawl total undersized discarded catch, mls_all_25: extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, mls_fish_50: extent (km^2) of accounting for upper 50% of bottom trawl total undersized fish discarded catch, mls_fish_25: extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, mls_ceph_50: extent (km^2) of accounting for upper 50% of bottom trawl total cephalopods discarded catch, mls_cephl_25: extent (km^2) of accounting for upper 25% of bottom trawl total cephalopods discarded catch.

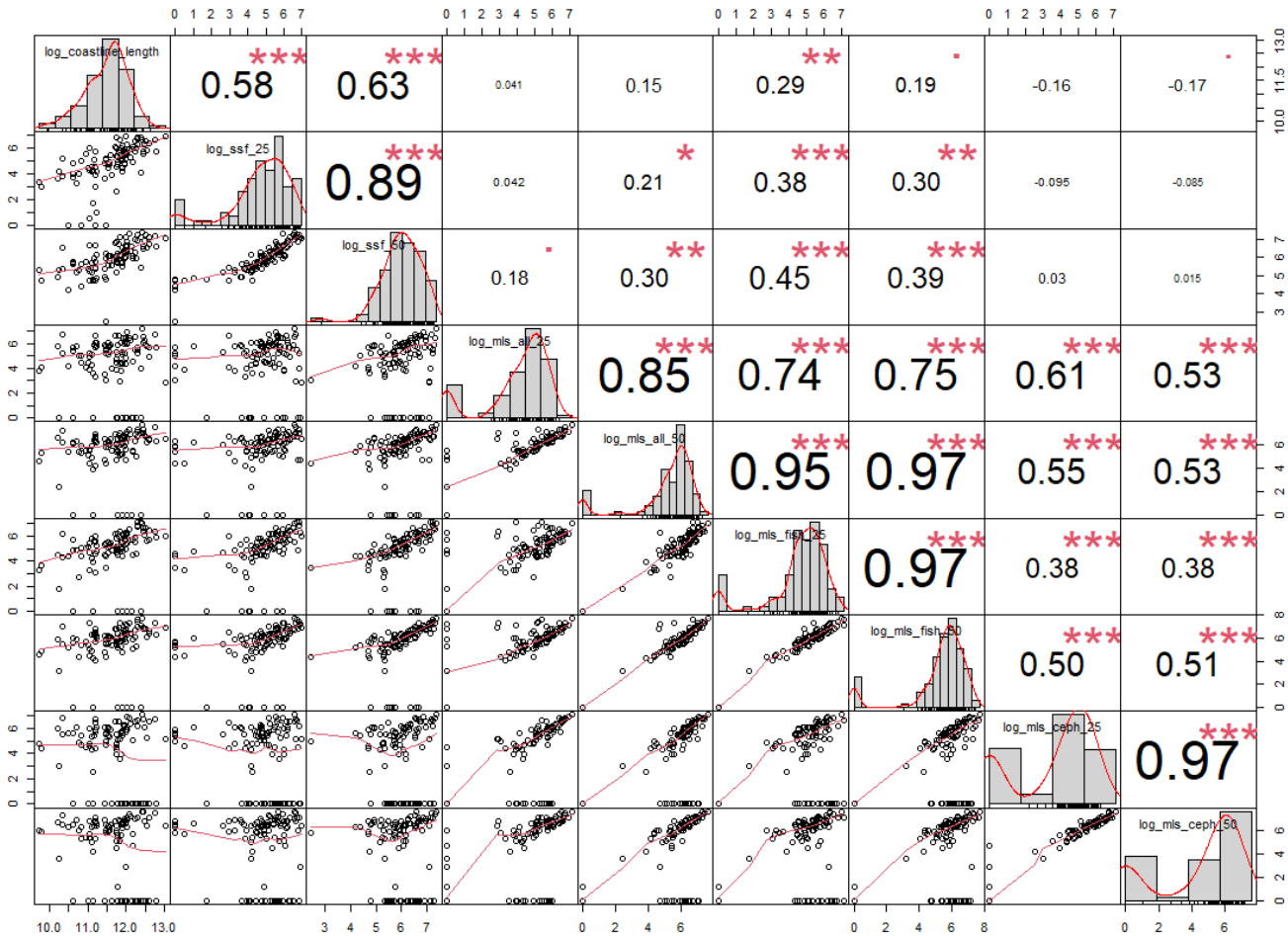

Figure S4: Top: Pearson correlation coefficient for each variable pair after log transformation, bottom: scatterplot of each variable pair, diagonal: variable name and histogram. log_coastline_length: the log length (km) of the coastline, log_ssf_50: log extent (km^2) of small-scale fishing pressure index accounting for upper 50%, log_ssf_25: log extent (km^2) of small-scale fishing pressure index accounting for upper 25%, log_mls_all_50: log extent (km^2) of accounting for upper 50% of bottom trawl total undersized discarded catch, log_mls_all_25: log extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, log_mls_fish_50: log extent (km^2) of accounting for upper 50% of bottom trawl total undersized fish discarded catch, log_mls_fish_25: log extent (km^2) of accounting for upper 25% of bottom trawl total undersized discarded catch, log_mls_ceph_50: log extent (km^2) of accounting for upper 50% of bottom trawl total cephalopods discarded catch, log_mls_cephl_25: log extent (km^2) of accounting for upper 25% of bottom trawl total cephalopods discarded catch.

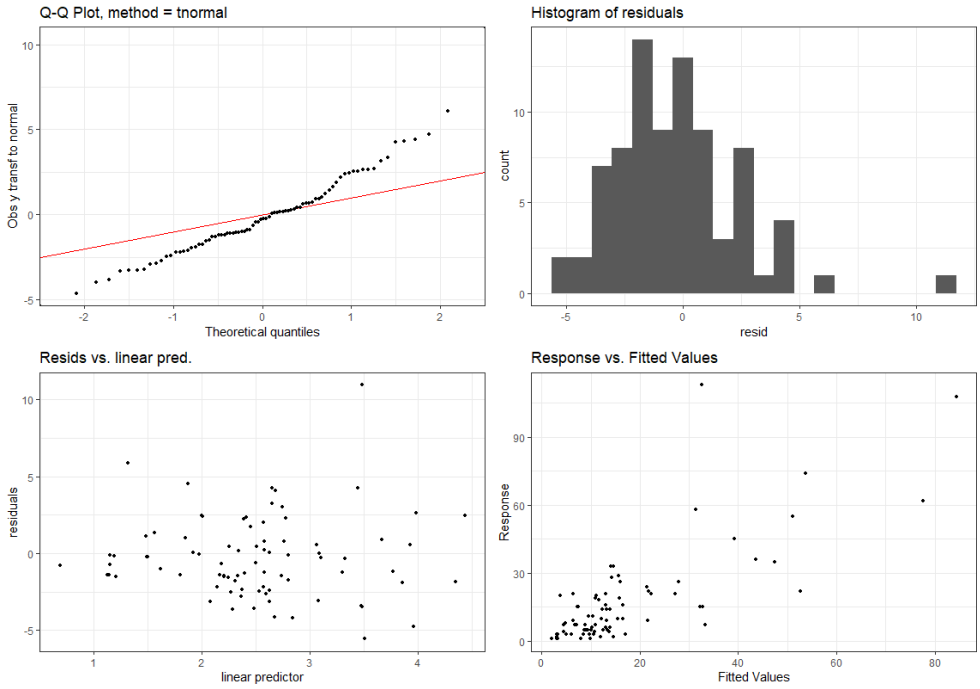

Figure S 5: Total cetacean strandings model residual plots

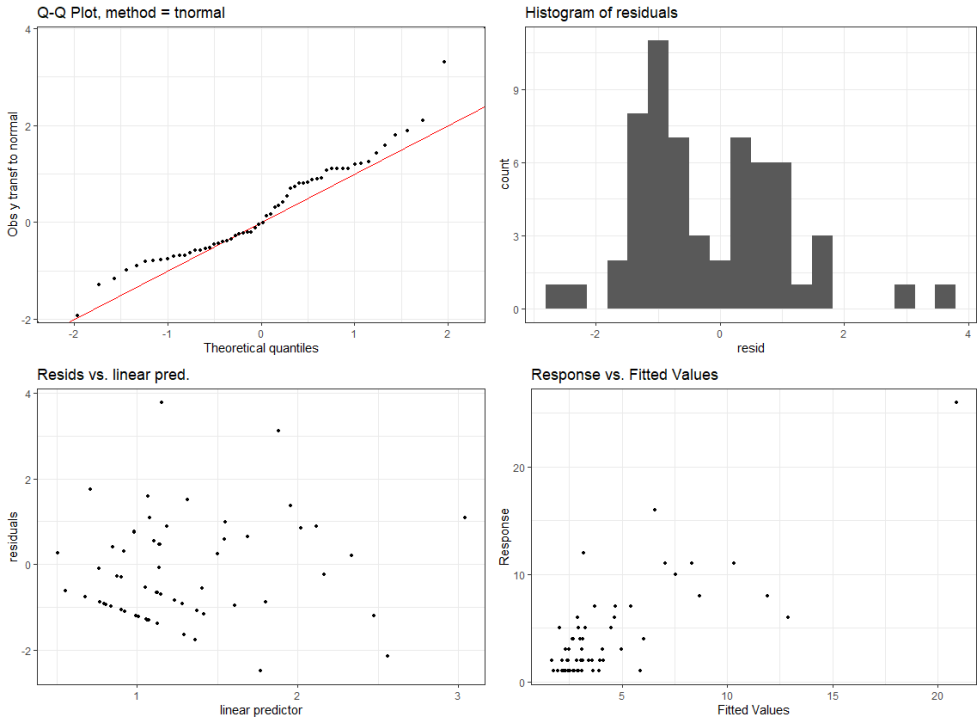

Figure S 6: Total human related cetacean strandings model residual plots

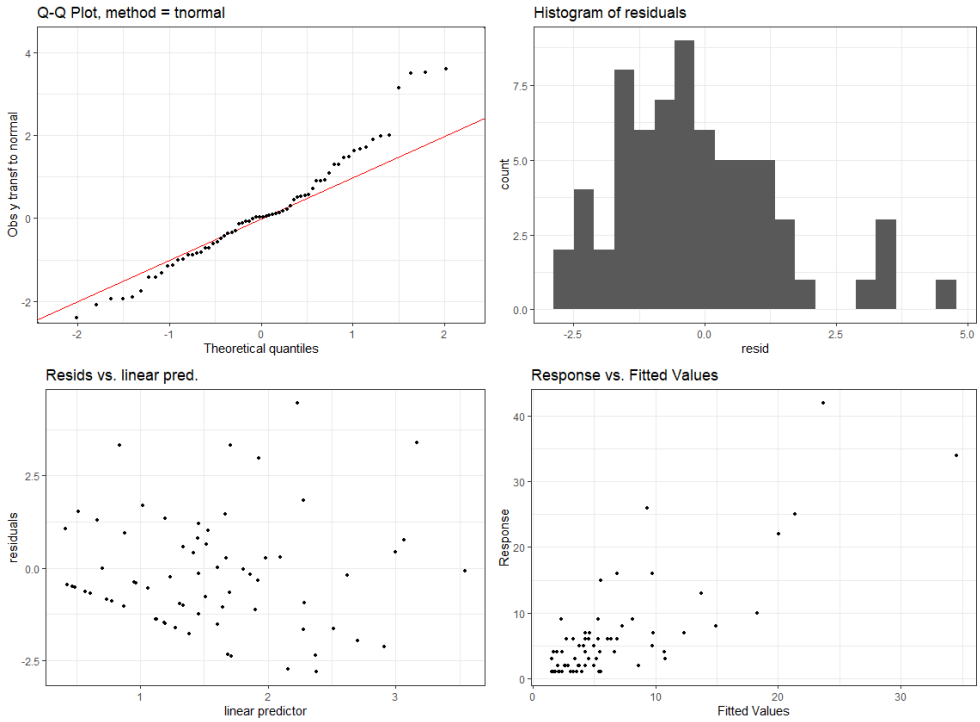

Figure S 7: Tursiops truncatus strandings model residual plots

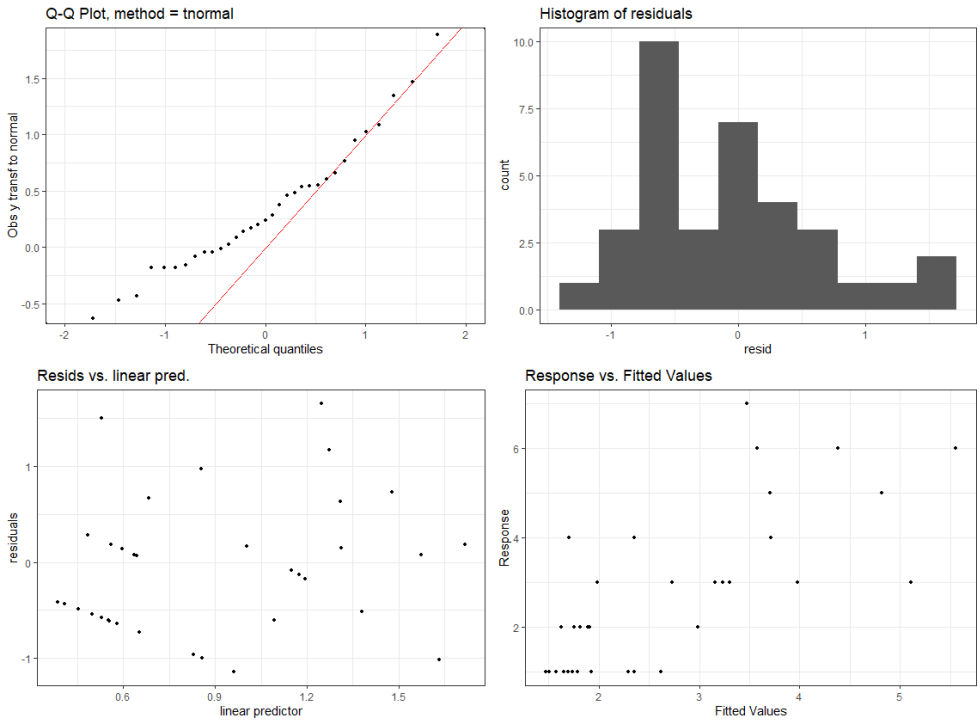

Figure S 8: Tursiops truncatus human related strandings model residual plots

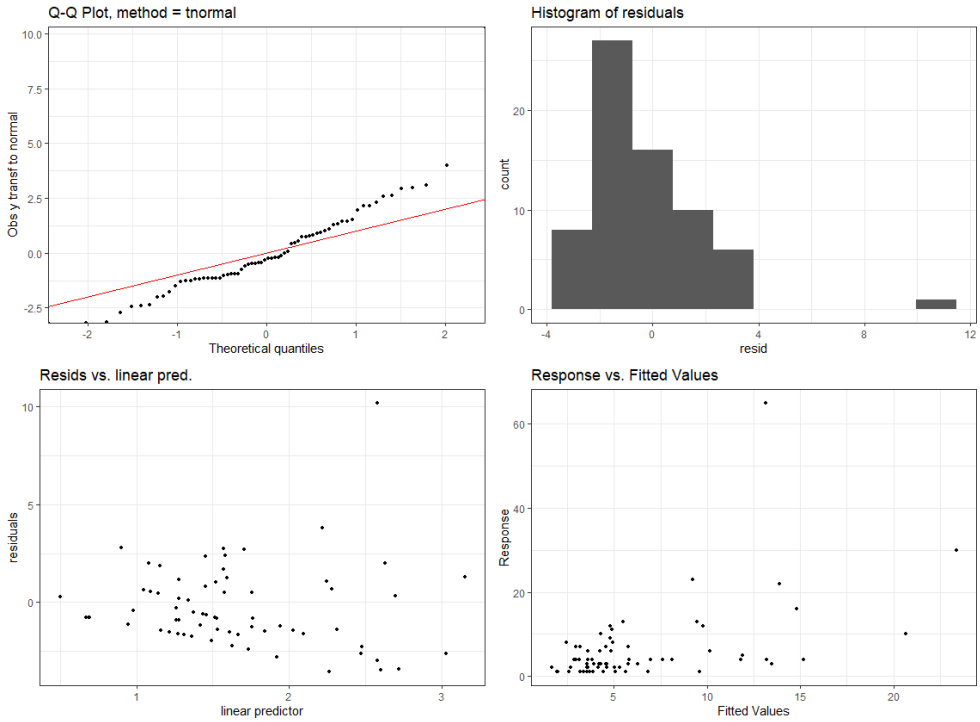

Figure S 9: Stenella coeruleoalba strandings model residual plots

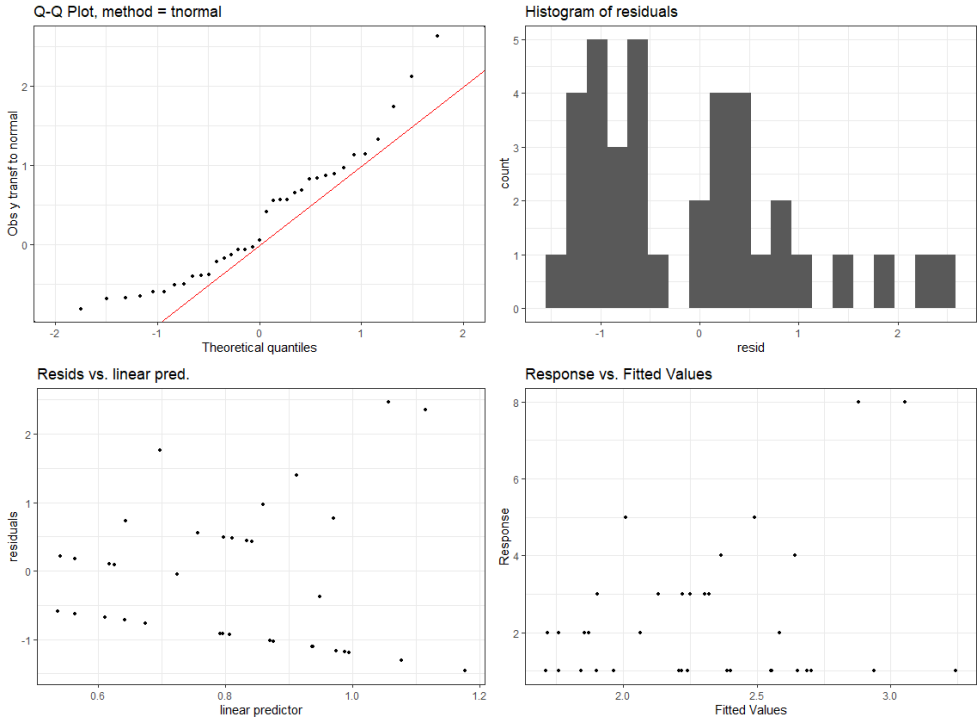

Figure S 10: Stenella coeruleoalba human related strandings model residual plots

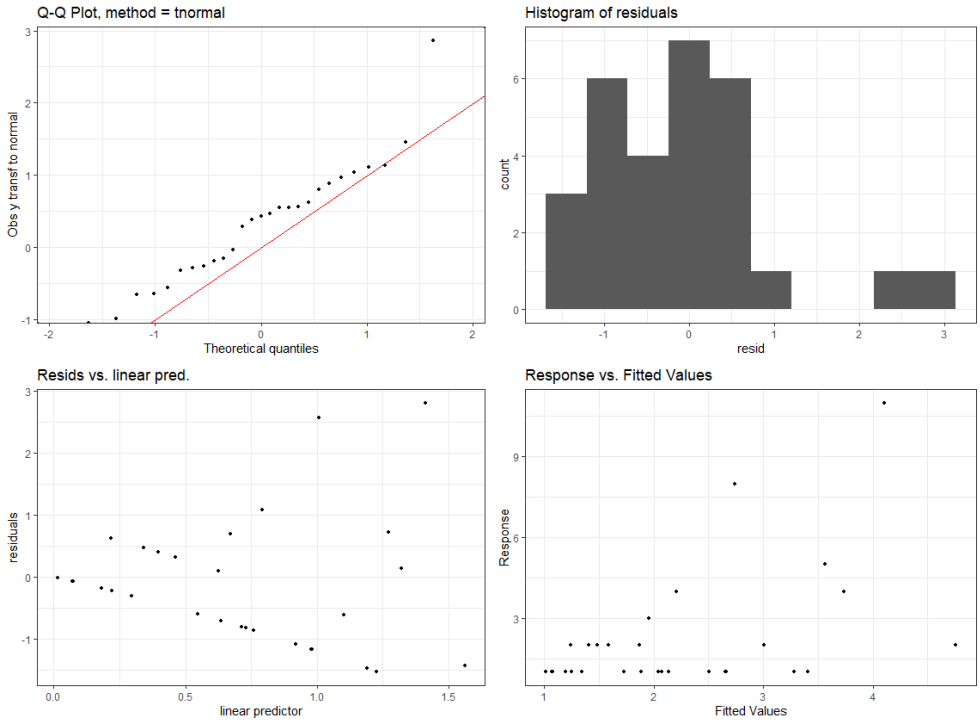

Figure S 11: Delphinus delphis strandings model residual plots