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Environmental variables influencing occurrence and distribution of *Delphinus delphis* in the eastern Aegean Sea (eastern Mediterranean Sea)

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Abstract

1. Cetaceans are considered bioindicators of the health state of marine ecosystems owing to their wide distribution across the different aquatic ecosystems in the world and their significant top-down control role in the food chain, despite their low biomass. At the same time, effective management of wild cetacean populations severely affected by human pressure requires extensive knowledge on species distribution, habitat use, and associated threats. In this context, defining the factors that directly influence the local occurrence and distribution of cetaceans is one of the underlying challenges and is essential for their conservation and long-term survival.
2. *Delphinus delphis* sightings data, collected between 2017 and 2021 during 284 standardized vessel-based surveys, were used to set up a presence–absence distribution model in the eastern Aegean Sea, eastern Mediterranean Sea. Binomial generalized additive models with logit as link function were run using the R package mgcv (restricted maximum likelihood method) and different biogeochemical explanatory variables collected from different sources.
3. Longitude, latitude, salinity, chlorophyll *a*, dissolved ammonium, and dissolved phosphate were selected as non-collinear predictive variables. Through a model validation based on a 10-fold cross-validation approach and a random data splitting procedure of 70%/30% (train/test dataset), a model formula has been selected with an explained deviance of 38.10%, an Akaike information criterion value of 1,661.3, and an area under curve of 0.91.
4. The study confirms that long-term time series of satellite-derived data are useful to assess the occurrence and the spatial distribution of *D. delphis*, suggesting the need for a better understanding of the influence of these environmental factors especially in the framework of climate changes.

5. Outcomes highlight the need to test further variables and further methods in order to provide increasingly reliable results in view of the conservation measures that must be adopted to stop or reduce the degree of pressure to which these species are subjected.

KEYWORDS

Aegean Sea, common dolphin, environmental predictors, environmental variables, GAM, spatial distribution

1 | INTRODUCTION

Cetaceans are considered bioindicators of the health state of marine ecosystems owing to their wide distribution across the different aquatic ecosystems around the world (Gómez de Segura, Hammond & Raga, 2008; Gomez-Salazar, Trujillo & Whitehead, 2012) and their significant top-down control role in the food chain, despite their low biomass (Ricci et al., 2019; Ricci et al., 2020; Carlucci et al., 2021; Ricci et al., 2021a; Ricci et al., 2021b; Ricci et al., 2021c; van Weelden, Towers & Bosker, 2021). Unfortunately, it is often difficult to investigate cetacean ecological traits owing to the significant time they spend underwater, as well as the logistical, political, and legal constraints of researching/working on protected species (Raudino et al., 2019; van Weelden, Towers & Bosker, 2021). At the same time, effective management of human pressures severely affecting wild cetacean populations requires extensive knowledge on species distribution, habitat use, and associated threats (Passadore et al., 2018). In this context, defining which factors directly influence the local occurrence and distribution of cetaceans is one of the underlying challenges and is essential for the successful conservation of cetacean populations (Passadore et al., 2018; Sousa et al., 2019). Indeed, several international instruments, as well as regional and local laws, dedicated to the conservation of nature have stressed the need to investigate such aspects; namely, the Habitats Directive (EC, 1992), the Marine Strategy Framework Directive (MSFD; EC, 2008), the Marine Spatial Planning Directive (MSP; EU, 2014), the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS, Notarbartolo di Sciara & Tonay, 2021), and the United Nations Environment Programme/ Mediterranean Action Plan. In particular, since cetaceans meet most of the criteria defined by the EU MSFD for selecting key species/ groups to develop indicators useful to achieve Good Environmental Status, they need to be the subject of in-depth studies that can highlight which environmental and anthropogenic factors may influence characteristics such as distribution and abundance (Azzellino et al., 2014). In addition, the spatial distribution of cetacean populations and the extension of their habitat are key criteria of Descriptor 1 criteria D1C4 and D1C5 (Palialexis et al., 2021a; Palialexis et al., 2021b) of the MSFD. Currently, studies on the topic have demonstrated the importance of different environmental, ecological and human pressures factors in influencing the distribution and occurrence of cetaceans (e.g., Carlucci et al., 2016; Carlucci et al., 2018a; Carlucci et al., 2018b; Derville et al., 2018; Passadore et al., 2018). The most common variables used to model and/or predict occurrence/distribution of species include characteristics of the habitat, such as bathymetry, distance to coast, slope, salinity, and sea-surface temperature, as well as prey distribution (Giannoulaki et al., 2017) and variables used as proxies of prey availability or of oceanographic processes that enhance local productivity, such as chlorophyll *a* (Chl-*a*), primary productivity, and phytoplankton carbon biomass (Gaskin, 1968; Bush, 2006; Forney, 2006; Parra, Schick & Corkeron, 2006; Cañadas & Hammond, 2008; Di Tullio, Fruet & Secchi, 2015; Hornsby et al., 2017; Zanardo et al., 2017; Passadore et al., 2018; Chavez-Rosales et al., 2019; Giralt Paradell, Díaz López & Methion, 2019; Correia et al., 2021; Milani et al., 2021; Torreblanca et al., 2022; Maglietta et al., 2023) or phosphorus and nitrogen (Muckenhirn, Bas & Richard, 2021). Environmental information can be collected locally during field surveys (uncommon) or retrieved from online databases that provide long-term time series of satellite-derived images, allowing a better assessment of mesoscale, seasonal, and long-term variability of the marine ecosystem (Skliris et al., 2010).

Several modelling approaches have already been implemented to assess the occurrence and distribution of cetacean populations (Giralt Paradell, Díaz López & Methion, 2019). Species distribution models are widely recognized as important marine spatial planning tools because they can describe and predict the distribution patterns of highly mobile marine species (Derville et al., 2018; Becker et al., 2020). They have been developed for a wide range of marine predators, such as cetaceans (e.g., Hazen et al., 2017; Abrahms et al., 2019; Becker et al., 2020), and sea turtles (e.g., Benson et al., 2011; Zampollo et al., 2022), as well as used to establish marine conservation areas, guide fisheries management, and assess risks posed by anthropogenic activities (Redfern et al., 2019; Welch et al., 2019).

These models may contribute to disentangling and predicting the outcomes of complex interactions between ecosystem components in a meaningful way by adopting either a presence–absence or a presence-only approach (Waltner-Toews et al., 2003; Evans, Norris & Benton, 2012; Peters & Okin, 2017; Geary et al., 2020). An extensive body of literature confirms the predictive ability of generalized additive models (GAMs) for ecological data related to cetacean species (e.g., Cañadas & Hammond, 2008; Becker et al., 2012; Best et al., 2012; Becker et al., 2014; Becker et al., 2019; Correia et al., 2021).

Therefore, in this study, a GAM approach (Wood, 2017) was implemented, aiming to investigate the environmental driving forces influencing the distribution of the common dolphin, *Delphinus delphis*, occurring in the archipelago of the eastern Aegean Sea, in the eastern Mediterranean Sea.

Delphinus delphis, assessed at the global scale as of 'Least Concern' by the IUCN Red List, is widely distributed throughout the Indian, Pacific, and Atlantic oceans, and is also present in most seas, including the Mediterranean Sea (Braulik, Jefferson & Bearzi, 2021). This species usually lives in groups of 1 to 20 individuals but has often been observed forming larger schools of several hundreds to thousands of individuals (Culik, 2011; Saintignan et al., 2020). In the Mediterranean Sea, the subpopulation of this species is considered 'Endangered' according to the IUCN Red List (Bearzi et al., 2021), because of a continued decline in the population during recent decades in different subregions of the Mediterranean basin, becoming rare or locally absent. In the waters of the eastern Aegean Sea the presence of *D. delphis* has been known since ancient times, as confirmed by the frequent adoption of dolphin motifs by early Greek artists. One of the earliest and best-known ornamentations is the 3,500-year-old dolphin fresco on the wall of the Queen's apartments in the ancient palace of Knossos on the island of Crete (Johnson, 2004). More recently, its occurrence has been confirmed by sightings (Inch, Pietroluongo & Hepburn, 2018; Pietroluongo et al., 2020; Milani et al., 2021) and stranding events (Pietroluongo et al., 2022). In addition, preliminary abundance estimates have been provided (Pietroluongo et al., 2020) and its role as a keystone species in the marine food web of the northern Aegean Sea has been demonstrated (Tsagarakis et al., 2010). However, still little information is available about the distribution and critical habitat of the species throughout the entire area of the eastern Aegean Sea. Although this species occurs in the area together with other cetacean species (e.g., *Tursiops truncatus*, *Stenella coeruleoalba*, *Physeter macrocephalus*, and *Grampus griseus*), information on their biology, ecology, and distribution do not match criteria defined to consider this region as an important marine mammal area (IMMA) for cetaceans. Currently, this area is established as an IMMA for the Mediterranean monk seal (*Monachus monachus*) for criteria A and C1 (IUCN-Marine Mammal Protected Areas Task Force (IUCN-MMPATF), 2017). For this reason, understanding the spatial distribution of the common dolphin represents a baseline to (i) pinpoint the hotspots and the key environmental features influencing their distribution, (ii) forecast its presence–absence and distribution for future studies in the context of climate change, and (iii) inform and support management plans for wildlife conservation in the framework of MSFD and MSP.

2 | MATERIALS AND METHODS

2.1 | Study area

The Aegean Sea is situated in the north-eastern Mediterranean Sea and covers roughly 214,000 km^2. It is surrounded clockwise from the north by the Greek mainland, the Turkish western coast, and the Cretan Arc archipelago. It consists of 60 inhabited islands, more than 1,400 small islands, and more than 2,500 outcrops and rocks (Conides et al., 2020).

The most relevant effects on the salinity, temperature, and productivity of the Aegean Sea seem to be due to the inlet of low salinity cold waters coming from the Black Sea through the Dardanelles and Bosphorus straits. This inlet seems to determine the general cyclonic circulation of the Aegean basin (Lykousis et al., 2002; Olson et al., 2007). The other relevant water masses influencing the biochemical conditions in the Aegean Sea are represented by the highly saline and warm waters of Levantine origin and the very dense deep waters that fill the bottom of the various sub-basins (Skliris et al., 2010).

The study area covers an area of about 7,072 km^2 and is located in the eastern part of the Aegean Sea, between the islands of Samos (37.7548°N, 26.9778°E), Lipsi (37.3011°N, 26.7438°E), and Ikaria (37.6063°N, 26.1524°E), Greece (Figure 1). This area is characterized by extremely oligotrophic conditions (Skliris et al., 2010) and exhibits intense mesoscale variability, including transient and/or recurrent cyclonic and anticyclonic eddies, while the general circulation is strongly influenced by exchange with the adjacent basins (Lykousis et al., 2002).

The area between Samos and Lipsi islands presents relatively shallow waters, not exceeding 200 m in depth. The northernmost portions of Samos and Ikaria are characterized by a steep slope exceeding 1,000 m in depth at a short distance from the shore.

Owing to its boundaries and geographical position, this area experiences high levels of marine traffic, such as shipping, ferries, and fishing and recreational boats (Inch, Pietroluongo & Hepburn, 2018). Based on local anecdotal knowledge about the fishing fleet working in the area, there are about 100 artisanal fishermen, two purse seines, and three trawlers from Samos and up to five from nearby Turkish waters (Inch, Pietroluongo & Hepburn, 2018). Within this area, several cetacean species coexist. As well as *D. delphis*, the species with high occurrence rates are the common bottlenose dolphin (*T. truncatus*) (Janssen et al., 2022) and the striped dolphin (*S. coeruleoalba*), both considered as of 'Least Concern' in the Mediterranean Sea (Natoli et al., 2021; Lauriano, 2022). In addition, the fin whale (*Balaenoptera physalus*), the sperm whale (*P. macrocephalus*) and the Risso's dolphin (*G. griseus*), all listed as 'Endangered' in the IUCN Red List (Lanfredi et al., 2021; Panigada, Gauffier & Notarbartolo di Sciara, 2021; Pirotta et al., 2021), occur in the area, as well as the Cuvier's beaked whale (*Ziphius cavirostris*), listed as 'Vulnerable' (Cañadas & Notarbartolo di Sciara, 2018).

2.2 | Sighting data

Sightings data of *D. delphis* were collected between 2017 and 2021 during opportunistic vessel-based surveys carried out from different platforms: from 2017 to 2019 from a 16 m sailboat with a sighting position 2.5 m high, a 15.25 m sailboat with a sighting position 2.6 m

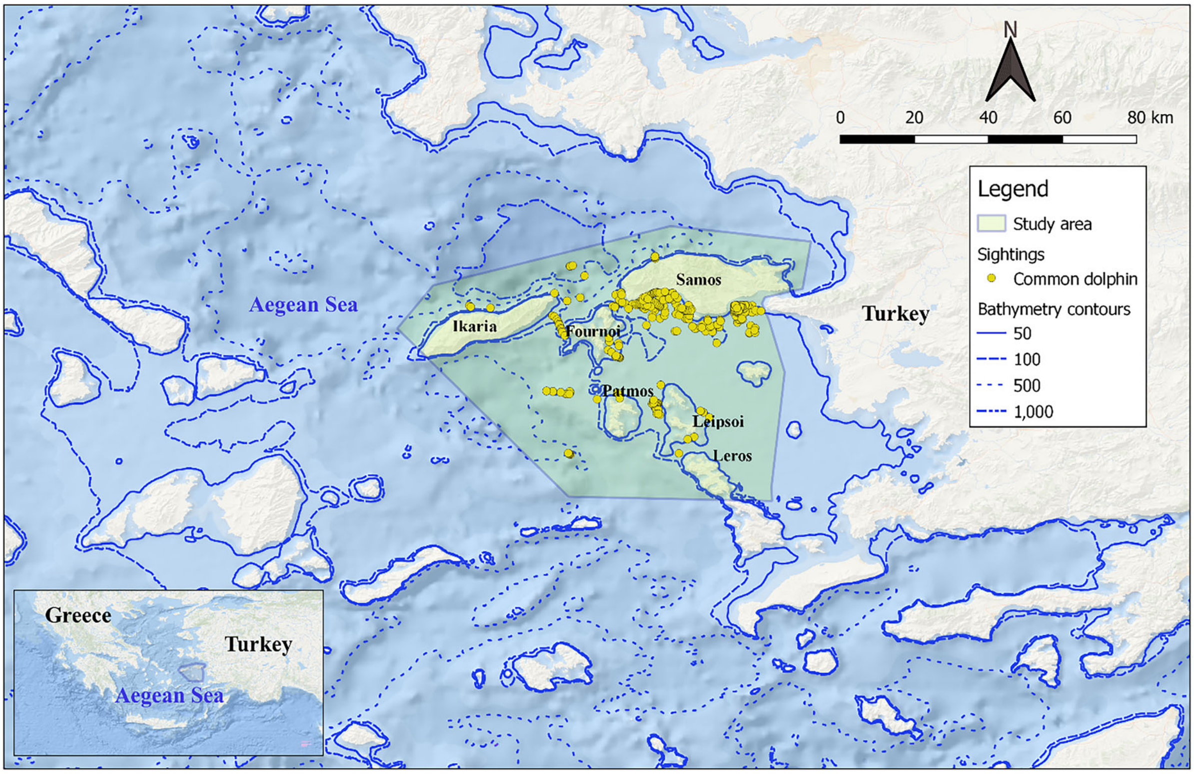

FIGURE 1 Map of the study area (yellow polygon) with indication of the main islands of the archipelago. Yellow dots indicate the location of *Delphinus delphis* sightings.

high, and a 12 m speed boat with a sighting position 2.25 m high. Since 2019, a 21.74 m motorboat with a sighting position 2.9 m high was used in addition to the other vessels.

Surveys were performed on a daily basis only in favourable weather conditions (Douglas scale ≤3 and Beaufort scale ≤4), with a sampling effort set to approximately 5 h per day along transects of different lengths and at a survey speed of about 7.5 kn. The position of the boat was recorded every 30 min using a GPS device.

The surveys mainly took place in the framework of a training programme for young marine researchers promoted by 'Archipelagos Institute of Marine Conservation'. For this reason, the observer team on board changed during the survey period (2017–2021). Nevertheless, each observer, after having successfully completed specific training, took part in the surveys for several months at a time, ensuring the application of a standard protocol for the observation of cetaceans. Surveys were conducted with a minimum of four observers: two at the front of the vessel and two at the back, covering 360° around the vessel. For each survey, the date, name of the boat, geographical coordinates, depth, local environmental conditions (cloud cover and sea state), species name, estimated number of individuals encountered, and time of contact were recorded.

Whenever a group of dolphins was sighted, the position of the research vessel was recorded using a GPS device and the vessel's speed was reduced as the group of dolphins was approached.

2.3 | Data processing

The study area was divided into a regular grid of 0.042 × 0.042° using QGIS software (QGIS Development Team, 2022, version 3.2.3). This cell size was chosen to equate to the resolution of the environmental variables selected in this study.

Sixteen different physio-chemical variables were used to investigate the presence–absence and distribution of dolphins in the study area (Table 1). Some of these variables are among the main physio-chemical variables used in other studies on cetaceans, such as geographic coordinates, depth, distance from the coast, sea bottom temperature (BottomT), water column temperature (WCT), salinity, net primary production, Chl-*a* and phytoplankton and pH (Gaskin, 1968; Bush, 2006; Forney, 2006; Parra, Schick & Corkeron, 2006; Cañadas & Hammond, 2008; Di Tullio, Fruet & Secchi, 2015; Hornsby et al., 2017; Zanardo et al., 2017; Passadore et al., 2018; Chavez-Rosales et al., 2019; Giralt Paradell, Díaz López & Methion, 2019; Correia et al., 2021; Milani et al., 2021; Torreblanca et al., 2022; Maglietta et al., 2023), and phosphorus and nitrogen (Muckenhirn, Bas & Richard, 2021). Other variables, such as dissolved oxygen, dissolved carbon, and dissolved ammonium (NH_4) were tested as proxies of local productivity.

In detail, the variables have been derived from the following sources (detailed information is reported in Supporting Information Table S1):

TABLE 1 List of biogeochemical variables selected to model the distribution of common dolphin in the study area.

Variable	Code	Resolution	Source
Longitude	*x*	0.001° × 0.001°	Retrieved from field collection
Latitude	*y*	0.001° × 0.001°	Retrieved from field collection
Sea bottom temperature	BottomT	0.042° × 0.042°	Copernicus Marine Service
Water column temperature	WCT	0.042° × 0.042°	Copernicus Marine Service
Salinity	*S*	0.042° × 0.042°	Copernicus Marine Service
Net primary production	PPN	0.042° × 0.042°	Copernicus Marine Service
Dissolved oxygen	Diss_O_2	0.042° × 0.042°	Copernicus Marine Service
Dissolved carbon	Diss_C	0.042° × 0.042°	Copernicus Marine Service
pH	pH	0.042° × 0.042°	Copernicus Marine Service
Dissolved nitrates	NO_3	0.042° × 0.042°	Copernicus Marine Service
Dissolved ammonium	NH_4	0.042° × 0.042°	Copernicus Marine Service
Dissolved phosphate	PO_4	0.042° × 0.042°	Copernicus Marine Service
Chlorophyll *a*	Chl-*a*	0.042° × 0.042°	Copernicus Marine Service
Phytoplankton	Phyc	0.042° × 0.042°	Copernicus Marine Service
Distance from coast	Dist_c	1 m	Calculated
Depth	Depth	1 m	EMODnet Bathymetry

TABLE 2 Number of daily surveys conducted in the study area between 2017 and 2021, number of sightings of *Delphinus delphis*, frequency of occurrence (no. of sightings/no. of surveys), the median and range values of group size, as well as median and range depth value recorded in each year and over the entire study period.

				Group size (no. of individuals)		Depth (m)	
Year	No. surveys	No. sightings	Frequency of occurrence	Median	Range	Median	Range
2017	56	71	1.27	5	1–18	86	18–1,038
2018	57	26	0.46	6	1–42	80	12–108
2019	81	105	1.30	7	2–50	75	22–496
2020	42	70	1.67	5	1–17	91	36–116
2021	89	114	1.28	6	1–60	55	18–1,071
Total	325	386	1.19	6	1–60	80	12–1,071

TABLE 3 (A) Best model summary. (B) Generalized additive model statistics applied to the explanatory variables with indication of the estimated degrees of freedom (edf), chi squared, and *P*-values obtained from the best model.

(A)			
Formula	**pa ~ *s*(*x*, *y*, *k* = 40) + *s*(Chl-a, PO_4, NH_4) + *s*(*S*)**		
	Estimate	***SE***	***P*-value**
Intercept	**−3.96**	**0.26**	**<2 × 10^{-16}**
R^2	0.32		
Explained deviance (%)	38.10		
REML	888.4		
AIC	1,661.33		
(B)	**edf**	**χ^2**	***P*-value**
s(*x*,*y*)	27.72	165.48	<2 × $^{-16}$
s(Chl-*a*, PO_4, NH_4)	54.17	167.74	<2 × $^{-16}$
s(*S*)	6.78	26.92	0.000506

Abbreviations: AIC: Akaike information criterion; Chl-*a*: chlorophyll *a*; *k*, the number of basis dimension; H_4: ammonium; pa: *Delphinus delphis* presence–absence; PO_4: phosphate; REML: restricted maximum likelihood; *S*: salinity; *x*: longitude; *y*: longitude.

i. Latitude and longitude match geographical coordinates of sightings based on field data collected over the study period.
ii. The depth data were derived from the European Marine Observation and Data Network Bathymetry portal in the form of a raster file (EMODnet, 2022, https://emodnet.ec.europa.eu/).
iii. The distance from the coast was calculated using the osmdata (Padgham & Lovelace, 2021) and geosphere (Karney, 2013) R packages as the Euclidean distance from each centroid of the grid to the shore.
iv. The remaining geochemical variables were derived from the physical reanalysis component of the Mediterranean Monitoring and Forecasting Centre, available on the Copernicus portal (E.U. Copernicus Marine Service information, 2022, http://marine.copernicus.eu/) in the form of NetCDF files.

All data recorded during sightings and environmental data were bricked into a multiband regular raster projected in the Coordinate Reference System WGS84. When necessary, data were reshaped according to the characteristics of the study area layer in R Studio environment (v. 1.3.1093) working with R language (v. R-3.6.3), R package raster (version 3.5-2, Hijmans et al., 2023). This approach was adopted to maintain the highest resolution of the data, aiming to reduce the manipulation of the raw data.

In particular, the location of dolphin groups and survey tracks were imported into QGIS to create a binary presence–absence grid of dolphins, considering survey effort.

Though identifying presence data is relatively easy, it is not so simple to assess true absences for highly mobile species such as cetaceans (MacKenzie & Royle, 2005). Thus, since *D. delphis* is a

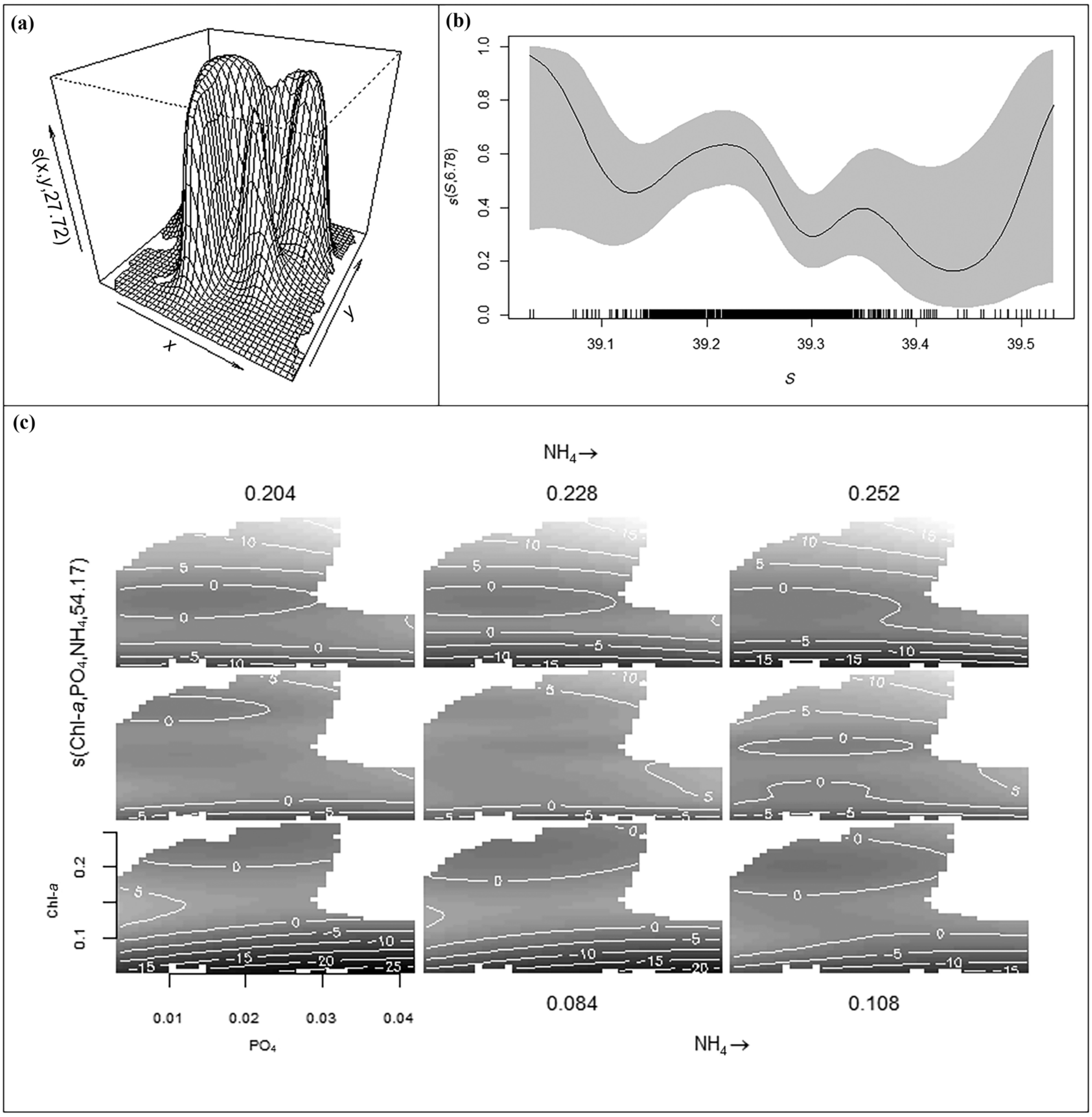

FIGURE 2 Predicted smooth splines of the response variable presence–absence of *Delphinus delphis* as a function of (a) longitude *x* and latitude *y*, (b) salinity *S*, and (c) chlorophyll *a* (Chl-*a*), ammonium (NH_4), and phosphate (PO_4). The degrees of freedom for non-linear fits are shown in parentheses on the *y*-axis. The grey interval represents the 95% confidence interval of the smooth spline functions.

coastal species in this area, rarely diving for more than 10 min (Stewart, 2018), cells where no sighting occurred were treated as cells of pseudo-absence.

Before running the GAM model, collinearity between continuous explanatory variables was investigated using correlation coefficients (threshold: 0.7) (Dormann et al., 2013) and variance inflation factors (VIFs; threshold: 3) (Zuur, Ieno & Elphick, 2010). Highly correlated variables were possibly excluded from the set of variables used for the GAM models using the 'vifcor' and 'vifstep' stepwise procedures with the usdm package (version 1.1-18) in R (Naimi, 2015). The 'vifcor' procedure first finds a pair of variables that has the maximum linear correlation (greater than the threshold), then excludes the one that has the greater VIF. These steps are repeated until there is no variable remaining with a correlation coefficient greater than the threshold. Similarly, 'vifstep' first calculates the VIF for all variables, then excludes the variable with highest VIF (if this is greater than the threshold), and these steps are repeated until no variables with a VIF greater than the threshold remain. Values of VIF before and after the collinearity analysis can be found in Supporting Information Table S2.

Then, a second correlation analysis was performed through the R package corrplot (Supporting Information Figure S1), aiming to analyse the pairwise correlation between variables and support the choice of including or excluding collinear variables from the modelling procedure.

The multivariate analysis was performed through GAMs (Hastie & Tibshirani, 1990; Ruppert et al., 2003; Wood, 2017), using the mgcv R package (v. 1.8-34) (Hastie & Tibshirani, 1990; Pedersen et al., 2019). In these models, λ was selected using restricted maximum likelihood (REML) to give a good fit to the data.

A stepwise procedure was adopted in order to explore all the meaningful possible combinations. In particular, models were run starting from a binary model to a polynomial expression. Models were built using a binomial error distribution with 'logit' as the link function. A 10-fold cross-validation method was implemented for each model with a random data splitting procedure of 70%/30% for model calibration and testing respectively using the R packages gamclass and CVgam (Maindonald, 2020). This percentage split of the training/testing dataset has previously been adopted in other studies aimed at modelling species distribution (e.g., Hijmans, 2012; Bucklin et al., 2015; Watling et al., 2015; Zanardo et al., 2017; Passadore et al., 2018). Models were also checked for concurvity through the 'concurvity' function of the mgcv package.

The receiver operating characteristic curve and the area under curve (AUC) were calculated with the sigr (Mount, Zumel & Win-Vector, 2021) and cdata R packages, aiming to define the prediction power of the single model. Only models that proved to have AUC > 0.75 were considered. The coefficient of determination R^2, the deviance explained, the REML, and the Akaike information criterion (AIC) values were the parameters used to determine the best model fitting the data and later to select the best-performing models. Then, the best model was used to predict areas of presence for *D. delphis* through the 'predict' function of the mgcv package.

3 | RESULTS

3.1 | Sighting data

During the time period 2017–2021, a total of 284 days were spent at sea, resulting in 386 sightings of *D. delphis* (Table 2). Survey effort and number of dolphin groups sighted varied between the years. The lowest number of *D. delphis* sightings was made during 2018 (26 sightings), which was also the year with the lowest frequency of occurrence (0.46). The highest number of sightings was made during 2021 (114 sightings), with a frequency of occurrence of 1.28. The year with the highest frequency of occurrence (1.67) was 2020. The frequency of occurrence over the entire time period was equal to 1.19 (Table 2).

During the study period, the common dolphin was sighted in groups ranging from 1 to 60 individuals with a median value of 6 (Table 2). Sightings occurred in waters with depths between 12 and 1,071 m, with a median value of 80 m over the entire time period.

3.2 | Data analysis

Collinearity was detected for 6 of the 16 input variables: BottomT, WCT, Diss_O_2, NO_3, pH, and Phyc (Supporting Information Table S2). Therefore, only non-collinear variables were taken into account by proceeding with a stepwise approach. The best model selected showed that the presence of common dolphin is mainly affected by geographical coordinates, the combined effects of Chl-*a*, dissolved NH_4, and phosphate (PO_4) as well as salinity (Table 3, Figure 2, Supporting Information Figures S2, S3). The smoothing interaction between longitude and latitude shows a high probability of presence in the centre of the study area, in the area in the south of Samos and

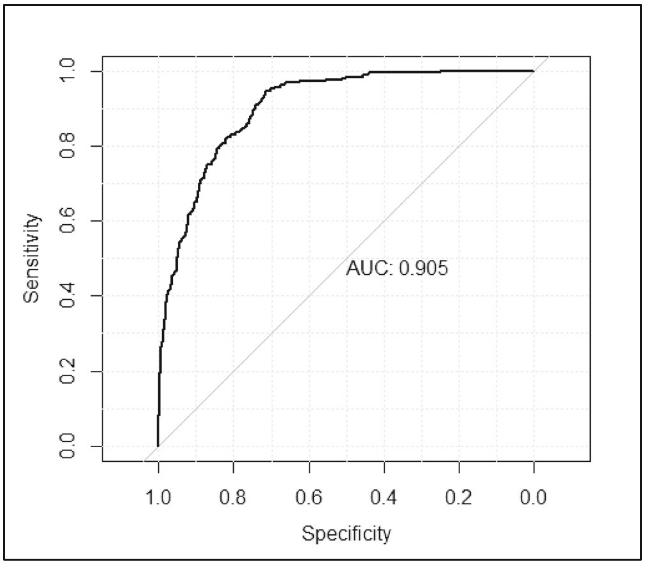

FIGURE 3 The receiver operating characteristic curve (black line) and the area under curve (AUC) value for the best model.

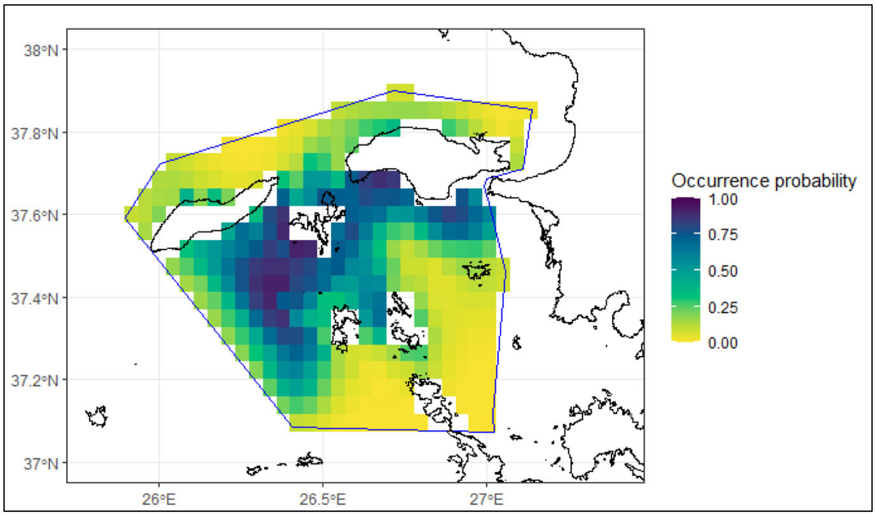

FIGURE 4 Map showing the generalized additive model of *Delphinus delphis* occurrence probability throughout the study area. Colours as shown in the legend indicate the probability of occurrence of dolphins.

Ikaria (Figure 2). Moreover, salinity seems to favour dolphin presence in areas with lower salinity values. It is not easy to interpret the combined response of Chl-*a*, NH_4 and PO_4 because, although the occurrence of the species seems to increase at higher values of Chl-*a*, there seems to be no specific trend for the other two variables, whose response curves oscillate (Figure 2, Supporting Information Figure S2). The explained R^2 and deviance were equal to 0.32% and 38.10% respectively. The AIC value was equal to 1,661.33, whereas the REML value was equal to 888.4. The model fully converged and had an acceptable level of concurvity ($x \leq 0.85$). The 10-fold cross-validation showed values of 0.08. The AUC for the best model was equal to 0.91, with a precision of 0.77 and an accuracy of 0.91 (Figure 3).

Delphinus delphis occurrence probability predicted throughout the study area is shown in Figure 4. Sightings mostly occurred where water depth was shallower than 125 m, with a peak in waters between 75 m and 100 m in depth.

4 | DISCUSSION AND CONCLUSIONS

This study represents the first attempt to predict the occurrence of the *D. delphis* in the eastern Aegean Sea considering some environmental variables known to influence the species' distribution. This information contributes to corroborating the scientific baseline for the common dolphin in this area, which is one of the least surveyed portions of the Mediterranean Sea (Notarbartolo di Sciara, 2016). This study represents a temporal snapshot of what has been observed and requires further sampling effort to corroborate the knowledge gained. However, there are peculiarities that need careful consideration. During 2020, owing to restrictions related to the Covid-19 pandemic outbreak, fewer surveys were possible, resulting in the year with the lowest number of surveys. At the same time, 2020 was the year with the highest frequency of occurrence of this species; this could be related to a relative reduced human pressure reflecting the global trend, and the more local trend as was demonstrated for the Mediterranean monk seal (*M. monachus*) in the Gulf of Corinth (Azzolin et al., 2020).

In this study, a GAM approach was adopted owing to the fact that these models are useful for fitting highly variable data and are generally used when there is no a priori reason for choosing a particular response function (Spedicato et al., 2019). Furthermore, GAMs are used to estimate smooth functional relationships between multiple predictor variables and the response (Pedersen et al., 2019); in fact, through the smoothing parameter λ, it has been possible to investigate the smoothing relationship between several variables, as in this case with Chl-*a*, NH_4, and PO_4. More generally, comparing the GAM approach with other common presence–absence (random forest) or presence-only (MaxEnt) methods, it has been shown to be less efficient when the predictor variables interact with each other, especially when their number is large. Conversely, the major benefit lies in its flexibility in assessing non-linear cetacean–habitat relationships without imposing limitations on their form (Blasi & Boitani, 2012). Those advantages motivate the adoption of GAMs for this study. Moreover, the adoption of a GAM approach has been reinforced by the fact that it is often assumed that binary predictions make prediction maps easier for managers and planners to understand and use than continuous maps (Bryn et al., 2021) for conservation purposes.

Concerning the quality of data used for the study, according to Bryn et al. (2021), data from citizen science projects could be affected by considerable variability in the quality of data collection or the equipment used. For these reasons, this study focused first on identifying which variables contribute more to determining dolphin distribution rather than performing wider or more complex models that could reduce the overall understanding of the phenomenon. This choice was made in order to start from a common baseline for any other attempt aiming to analyse other variables interfering with dolphin presence, such as human impacts and climate change effects.

Finally, the adoption of two approaches for the selection of variables aimed to ensure greater reliability in the choice of variables to be included in the final model. In fact, the VIF approach was adopted to identify the correlation of one independent variable with a group of other variables, whereas the correlation analysis performed with the Pearson matrix was adopted to identify the correlation or bivariate relationship between two independent variables.

4.1 | Influence of environmental variables on occurrence and distribution of common dolphin

The best model chosen confirms that the occurrence probability of *D. delphis* is higher in areas near to the coastline and generally in water depths less than 150 m.

Although depth and distance from the coast are not included in the selected model owing to their high correlation and collinearity, they are represented by the geographical coordinates in the prediction model. In particular, the higher occurrence of this species is predicted in the waters south of Samos Island and around Fourni Island, as already reported in other studies carried out in the same area (Inch, Pietroluongo & Hepburn, 2018; Pietroluongo et al., 2020). In the same way, this confirms that these physiographic variables directly or indirectly influence dolphin distribution by acting upon other biotic factors, such as prey availability, predator avoidance, or the facilitation of social interaction (Wells, Irvine & Scott, 1980; Scott, Wells & Irvine, 1990; Wells & Scott, 2002).

In the study area, although salinity varied over a limited range of values, it affected common dolphin occurrence. This is in line with what has been observed in the North Aegean Sea, where a positive relationship between common dolphin occurrence and higher values of salinity has been shown (Milani et al., 2021). Similarly, salinity has also proved to be an important predictor variable to assess habitat suitability for common dolphin in north-west Spain (Giralt Paradell, Díaz López & Methion, 2019) and *T. truncatus* in Barataria Bay, Gulf of Mexico (Atlantic Ocean) (Hornsby et al., 2017).

Chl-*a* is related to the primary productivity of the water column and can be used to estimate the quantity and distribution of productivity (Baumgartner et al., 2000). NH_4 and PO_4 were retained in the smoothing interaction with the aim of assessing nutrient availability. The smoothing relationship between Chl-*a*, NH_4, and PO_4 constitutes an innovative attempt to represent the productivity of the investigation area and to include it in the modelling approach. Thus, the use of this interaction in the model formula made it possible to dispense with the use of net primary production, resulting in high concurvity within the set of variables. Similarly, WCT was excluded because it was highly collinear and concurve within the set of variables. Moreover, this choice is supported by the fact that, when this approach was adopted, the model performance parameters and the concurvity analysis improved (Supporting Information Figure S1). Specifically, the presence cells was characterized by higher values of PO_4. This condition is similar to the one highlighted by Muckenhirn, Bas & Richard (2021) and may suggest the need to investigate the role of nutrients in top-predator distribution in the area. The availability of phosphorus can strongly affect the marine carbon cycle, as it is a limiting factor for primary production (Paytan & Mclaughlin, 2007), and thus likely linking cetaceans and prey distribution (Muckenhirn, Bas & Richard, 2021).

In this framework, to achieve holistic and effective protection of the endangered Mediterranean *D. delphis*, special attention should be given to both the latest research findings and current knowledge in a fast-changing marine environment due to climate change effects. In fact, as experienced by Cañadas & Vázquez (2017) in the Alboran Sea, a two-decade-long dataset of environmental changes investigating the potential effect of climate change on common dolphins at the local level revealed an inverse relationship between animal density and sea-surface temperature. It is likely that climate change effects will increasingly challenge the species resilience and test the effectiveness of conservation management provisions, including the designation of conservation areas (Vella et al., 2021).

Obviously, further analysis should be performed by testing other modelling approaches and/or different oceanographic variables (e.g., the euphotic depth, sea-level anomaly, or sea-surface current speed) and spatio-temporal variable aggregations (Cañadas & Hammond, 2008; Moura et al., 2012; Cañadas & Vázquez, 2017; Giannoulaki et al., 2017; Giménez et al., 2017; Giménez et al., 2018; Karamitros et al., 2020; Bonizzoni, Furey & Bearzi, 2021; Gannier, 2021; Maglietta et al., 2023).

Moreover, since cetacean species coexist in the area with several anthropogenic pressures, such as fisheries, marine traffic, naval activity, and the occurrence of marine litter (Janssen et al., 2022; Pietroluongo et al., 2022), interaction between dolphins and anthropogenic pressures should be investigated to assess the effects exerted by human pressures on the ecological traits of dolphins.

4.2 | Implications for conservation

According to ACCOBAMS/MOP8 (2022), determining the spatial distribution of cetacean species and their preferred habitats represents a key step in the development of efficient management strategies and conservation measures. This study identifies the key environmental features influencing *D. delphis* distribution and the hotspots occurring in the study area, in particular in the shallow waters south of Samos Island and around Fourni Island.

These outcomes corroborate the knowledge about the distribution patterns of this species in the eastern Aegean Sea supporting the implementation of the ACCOBAMS common dolphin conservation plan (Bearzi et al., 2004) and responding to the requirements of the Habitats Directive and MSFD. Moreover, these findings expand the knowledge base of common dolphin distribution within the area, which is particularly relevant for future maritime spatial planning programmes and meeting the criteria A, C1, and C2 as defined by the IUCN-MMPATF (2017) and the potential of this region as an IMMA for cetaceans.

Until now, only 5 years of monitoring have been considered; thus, according with the Habitats Directive (Article 1), to avoid (i) a long-term decline in dolphin population (maintaining a stable or increasing population) and (ii) a long-term reduction in the areas used by the population, the monitoring plan should cover a longer time-range and a wider region. In fact, as suggested by Cañadas & Hammond (2006), those improvements may pick up shifts in distribution and may also lead to a greater understanding of the causes of any change in abundance within managed sites. Moreover, improving knowledge on the suitable habitat of the common dolphin over extended areas can improve our ability to monitor, detect, and respond to shifts in species distribution (Vella et al., 2021) and abundance.

In addition to this, knowledge of the preferred habitats for common dolphin, especially with respect to its different needs, such as feeding or reproduction, is essential for effective conservation. Identifying the areas most used by dolphins with calves or for feeding could lead to specific management measures for those areas, which may need special or different treatment from other areas (Cañadas & Hammond, 2008). Thus, monitoring and conservation plans must take into account those aspects. In fact, models that use environmental information to assess the distribution of a species have been gaining increasing importance in the different steps of spatial and conservation planning (Margules & Pressey, 2000; Rodríguez et al., 2007; Guisan et al., 2013; Giralt Paradell, Díaz López & Methion, 2019).

AUTHOR CONTRIBUTIONS

Maurizio Ingrosso: Conceptualization; software; formal analysis; investigation; writing—original draft; data curation; methodology. **Beatriz Tintoré:** Data curation; investigation; writing—review and editing; validation. **Giulia Cipriano:** Formal analysis; writing—original draft; writing—review and editing; validation. **Pasquale Ricci:** Writing—review and editing. **Tim Grandjean:** Investigation; formal analysis; visualization. **Thodoris Tsimpidis:** Supervision; investigation; project administration. **Paraskevi Nomikou:** Supervision. **Roberto Carlucci:** Conceptualization; supervision; project administration; funding acquisition; resources. **Anastasia Miliou:** Conceptualization; investigation; validation; supervision; project administration.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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