



The impact of anthropogenic pollutants on the distribution of a marine top predator within a coastal estuarine system

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Abstract Due to anthropogenic pressures, estuarine systems are among the most broadly impacted areas for marine top predator species. Given this, it is crucial to study the interaction between the vulnerable marine species that inhabit these regions with environmental and anthropogenic variables. This study aims to determine whether nutrient pollution is related to the presence of bottlenose dolphins in a coastal environment. Using a multi-year dataset and GAMs, we studied the relationship between marine pollutants and the presence of bottlenose dolphins in this highly impacted coastal marine environment. We observed that urban fertilizers were linked to the spatial distribution of bottlenose dolphins. There was a higher presence of bottlenose dolphins in areas with high levels of phosphoric acid. In contrast, at higher concentrations of nitrate, the presence of bottlenose dolphins decreased.

Keywords Phosphorus cycle · Estuarine systems · Conservation · *Tursiops truncatus* · Common bottlenose dolphin · Eutrophication · Nitrates

Introduction

The variability in the global climate in the last half-century has further highlighted the imminent need to consider the marine environment and how it influences marine species (Halpern et al., 2008; Kim et al., 2018). Assessing the health and status of marine mammal populations remains a top priority due to their impacts on their ecosystem (Katona & Whitehead, 1988).

When looking at the interaction between marine mammals and their environment, one must first identify their habitat and factors that contribute to the habitat suitability. Since it is difficult to obtain reliable information on the availability and abundance of prey for cetaceans, environmental and oceanographic factors that influence the availability of their preys are often used as indicators of the distribution of these top predators (Harwood, 2001; Redfern et al., 2006; Pirota et al., 2011; Díaz López & Methion, 2017; Marini et al., 2015; Giralt Paradell et al., 2019; Vassallo et al., 2020). This methodological approach is highly utilized with bottlenose dolphins, and other marine mammal species, which exhibit an incredible degree of flexibility permitting them to occupy a variety of habitat niches (Wells & Scott, 2002).

Coastal dolphin species, in particular, are often at the highest risk of injury and/or mortality due to their greater exposure to human disturbances like fisheries, aquaculture, marine traffic, chemical pollution, and

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habitat degradation (DeMaster et al., 2001; Bejder et al., 2006; Kajiura et al., 2006; Díaz López, 2006, 2012, Methion & Díaz López, 2019; Bachman et al., 2014, Díaz López & Methion, 2017; Díaz López et al., 2018; Giralt Paradell et al., 2019). The common bottlenose dolphin (*Tursiops truncatus*; hereafter bottlenose dolphin) is a marine top predator highly susceptible to environmental changes in shallow and coastal habitats and an ideal candidate species to monitor the impact of human activities on marine top predators in coastal waters (Bejder et al., 2006; Díaz López, 2019; Díaz López et al., 2021). While some of the anthropogenic effects on dolphins impact the individuals directly, such as bycatch, contaminant loading, or vessel-strikes, many of these stressors affect their habitats (e.g., organic pollutants).

The resident population of bottlenose dolphins within Ría de Arousa, Northwestern Spain, comprises of from 56 to 144 individuals (Methion & Díaz López, 2018). The range in population size is likely a result of prey availability, which is highly correlated to a variety of factors including but not limited to: seasonal upwelling events, fisheries presence, and land runoff (Methion & Díaz López 2018; Giralt Paradell et al., 2021; Methion et al., 2023). Different studies carried out in parallel in the study area show evidence of residence site fidelity of certain individuals in the Ría de Arousa and the importance of this ria as a feeding area for the species (Díaz López & Methion, 2017; Methion & Díaz López, 2018, 2019, 2020, 2021). Currently, Atlantic bottlenose dolphin populations are protected under Appendix II of the Convention on the Conservation of 41 Migratory Species of Wild Animals (CMS; www.cms.int 20 June 2022) and in Appendix II (Strictly Protected Fauna Species) of the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention; www.coe.int 20 June 2022). Europe, among other regions, is included in both the aforementioned Bonn and Bern Conventions. According to Article 1 of the Habitats Directive, Site of Community Importance (SCI) and Special Area of Conservation (SAC) sites selected for migratory and wide-ranging species in the EU will correspond to areas both within their natural range and with physical and biological criteria essential to their survival and reproduction (Council Directive 92/43/EEC; www.ec.europa.eu 20 June 2022).

While many of the anthropogenic variables affecting bottlenose dolphins have been studied extensively, there is a paucity of data on the effect of fertilizer-based pollutants on the presence of this species. In coastal systems, anthropogenic pollutants are the most concentrated, particularly phosphorus and nitrogen-based fertilizers (Smith, 2006). Since the Green Revolution, beginning in 1965, the global crop production has seen a 3× increase, an unprecedented growth (Childers et al., 2011). Given phosphorus and nitrogen are essential to modern farming practices, predictions indicate unsustainable surges in fertilizer levels (Smil, 2000). Since phosphorus cannot be recycled in the environment, the effect of increased phosphorus concentration on marine species should be further studied.

Marine ecosystem alterations are pronounced with respect to growth-limiting nutrients; therefore, the inadvertent fertilization of shallow estuarine waters can induce several consequences (Smith, 2006). The proximity of estuaries to urban population centers and the shape of many estuarine systems may result in a confluence of high fertilizer inputs and high water retention (Villares et al., 1999). Therefore, although certain studies purport that copious quantities of fertilizer offloading will not significantly impact open ocean systems, where the residence time of nutrients is significantly less, the same result should not be expected in an estuarine or similar coastal oceanographic system (Carpenter et al., 1998; Smil, 2000).

Studies have already been conducted on how certain biota (e.g., mollusks, marine birds) have been impacted by this anthropogenic intrusion in the phosphorus and nitrogen cycle (Chang et al., 2012; Yuan et al., 2018). Recent research conducted on the relationship between marine birds, another secondary consumer, and fertilizer runoff found that an influx of nutrients caused a trophic cascade via modification of the primary producer abundance. However, food-chain alterations are not the only symptom of fertilizer pollution, fertilizer runoff also leads to the creation of dead zones, hypoxia caused by over-eutrophication (Carpenter, 2008). While dead zones are often associated with an increase in primary producer growth, in this region it is predominantly *Ulva* sp., they consequently hinder the viability of the ecosystem as the surface becomes increasingly impenetrable to light (Villares et al., 1999). Decreased light in the water column hinders

predation from upper trophic level organisms, such as fish, as may cause hypoxia via microbial degradation (Diehl, 1988; Lehtiniemi et al., 2005; Turner & Chislock, 2010). This could present a particular stress for bottlenose dolphins as they consume demersal, pelagic, and benthic fish species (Santos et al., 2007). Nitrogen and phosphorous concentrations are observed to negatively impact the presence of demersal fish, an important dolphin prey source (Chang et al., 2012). Unbalanced increases in primary production will undoubtedly exhibit a bottom-up effect to all species along the food web (Giralt Paradell et al., 2020).

However, Mazzoil et al. (2008) discussed within 2002–2005 there was no bottlenose dolphin avoidance of polluted waters with regard to both total nitrogen and total phosphorus. Studies in the Mississippi Sound observed a positive correlation between dolphin presence and nitrate concentration (Pitchford et al., 2015). Similarly, a study recently done with a broader scope, referring to a multitude of marine animals, has found that both nitrate and phosphate have some negative significance to the presence of marine species (Bosch et al., 2018).

Secondary effects of eutrophication also include the spawning of potentially pathogenic bacteria afflicting cetaceans and the increase in populations of planktonic species that are known to excrete toxins that are detrimental to cetaceans among other species (Zaitsev, 1999). Depending upon the severity and location of the eutrophication, a variety of results can be expected. Regarding slightly eutrophicated waters within an oligotrophic region, one study found eco-systemic effects included a moderate augmentation of primary productivity, thus dolphin prey availability (Díaz López et al., 2008). This is because the added nutrients are increasing the carrying capacity of the ecosystem as nitrates and phosphates are often the limiting resource in marine ecosystems. To the same degree, if the anthropogenic eutrophication is excessive, or the original system has an abundance of natural nutrient loading, the contrary would be expected: a decrease of prey availability due to dead zones and constriction of light penetration from overgrowth of those primary producers (Diaz & Rosenberg, 2008). The marine system is very responsive to nitrates and phosphates because they are bio-limiting so it is crucial to monitor the dynamic relationship marine ecosystems have with these species as their

concentrations continue to build (Planavsky et al., 2010).

This study aims to isolate potentially informative relationships between a variety of environmental factors and dolphin presence in the Ría de Arousa. Our study provides information about these inorganic pollutants at extremely high concentrations in a coastal estuarine, high-upwelling system and therefore facilitates bottlenose dolphin conservation by informing future regulation surrounding these pollutants. Using a multi-year dataset, we studied the relationship between organic pollutants (nitrates and phosphoric acid concentration), chlorophyll a concentration, depth, distance to the coastline, sea surface temperature (SST), and monthly seasonality to the presence of bottlenose dolphins in a highly impacted coastal marine environment. We expect the variables most influential to or most representative of primary production (e.g., phosphates, nitrates, seasonality, and chlorophyll a) to have the strongest correlation with dolphin presence.

Methods

Study area

The Ría de Arousa (42.5°N, −8.93°W) is considered a partially mixed ria-type estuary on the NW coast of Spain (Fig. 1). Fresh and salt water mixing is limited for most of the year characterized by estuarine circulation during the wet seasons, or during periods of exceptional runoff from land that rarely lasts more than a week (Evans & Prego, 2003). The average depth of the Ría de Arousa is 19 m, reaching a maximum depth of 70 m (Rosón et al., 1995). This region also has runoff from two rivers the Ulla and Umia, with a mean daily discharge of 14.71 and 11.77 m³ s^{−1}, respectively (Otero et al., 2010). Coriolis circulation and salinity gradients in the wet season (Nov.–Jun.) cause stronger surface current on the east and a stronger bottom current on the west side of the estuary influencing the distribution of riverine inflows (Gong et al., 2021). However, as the dry season approaches (Jul.–Oct.), the salinity gradient and the associated salinity-driven currents are reduced (Alvarez et al., 2005). The described circulation in Ría de Arousa concentrates nutrients in areas with less circulation and carries the sediments and pollutants from the tributaries to various parts of the ria (Rosón et al., 1997).

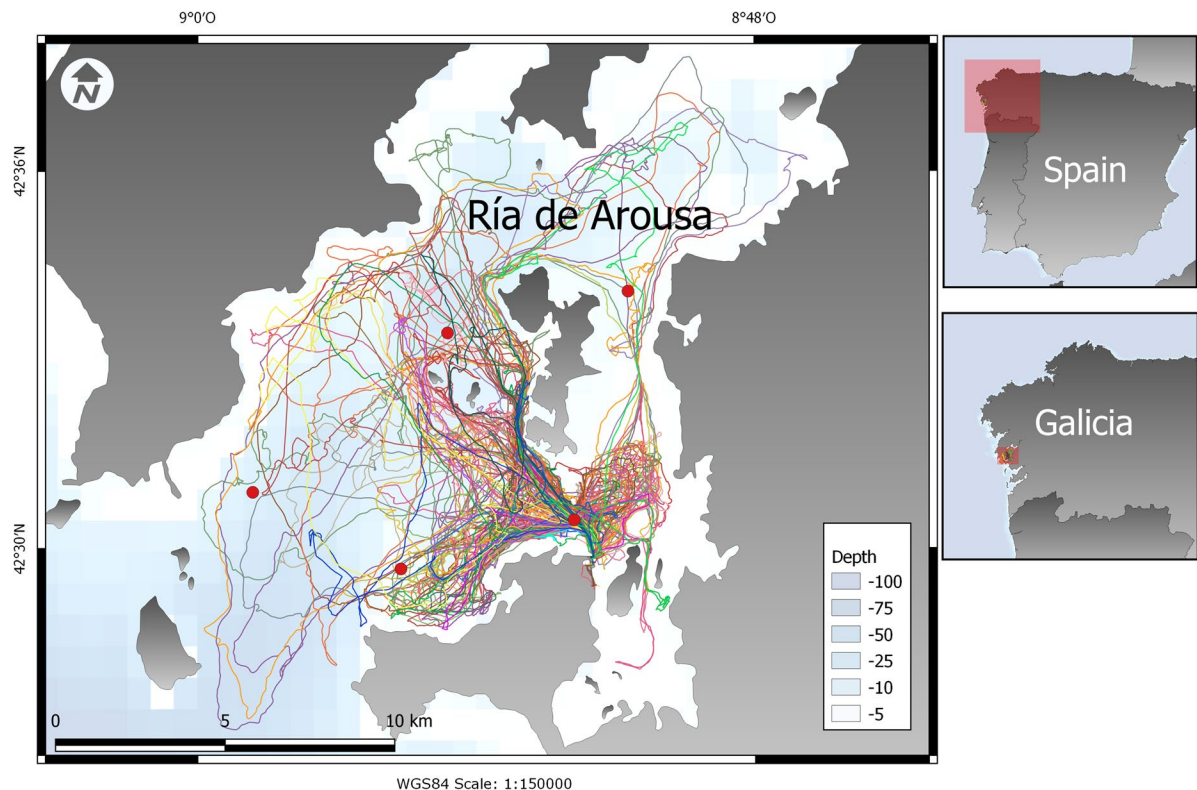


Fig. 1 Study area, Galicia NW Spain. Coloured lines represent the tracks covered during the boat-based surveys. The red hashed box indicates the area of observation. Red dots indicate the survey stations from which environmental data was extracted from

There are 13 main municipalities along the coast of the Ría de Arousa, containing around 180,000 inhabitants (Instituto Español de Estadística 2018, www.ine.es, accessed on 11 August, 2021). Proximal to these urban dwellings are the Ulla and Umia rivers; riverine input was observed by mapping the concentration of both SiO_4 and pollutants, which showed the river mouths were the main input of those species (Real et al., 1993; Álvarez Salgado et al., 1996). The coastline adjacent to the Ría de Arousa is also widely used for agriculture and is a very productive wine-growing area (Lorenzo et al., 2012). Moreover, because the native land type of Galicia is shrubland, extra phosphorus is added to make the area conducive to farming (Piñeiro & González, 2002). All forms of agriculture, however, regardless of supplemental fertilizers, are a significant source of phosphorus, nitrogen, silicates, and other nutrients into the watershed and thus the nearby Ría de Arousa (Álvarez Salgado et al., 1996).

Data collection

Boat-based observation involved a 12-m research vessel operated by at least 3 experienced observers, whose identity was constant throughout the 5 years of study. All observers had 360° of observation, however in addition, from 6 to 9 additional observers, previously trained to carry out the observations, were onboard (Díaz López & Methion, 2017; Methion & Díaz López, 2019). All observers were equipped with 10× magnification binoculars, and 6 observers were stationed atop a fly-bridge located 4 m above the sea surface (Díaz López & Methion, 2017; Methion & Díaz López, 2019). Boat-based observation was only conducted during the day and in optimal weather conditions, including but not limited to no rain, minimal wind, and swell (≤ 3 on the Beaufort wind force scale), and no fog. The vessel maintained a constant speed of 6–8 knots throughout observation. During monitoring, instantaneous point samples were taken every 20 min, approximately

equivalent to 2 nm, denoting presence and absence of bottlenose dolphins (Díaz López & Methion, 2018). Time, position and speed were extracted from GPS plotter Map Sounder associated with an 83–200 kHz echo sounder transducer in each sampling event. Bottlenose dolphins in this region have also already been established as non-transient during the study period by concurrent studies, so photo identification was not included in this study (Methion & Díaz López, 2018). Data was collected between April 2014 and November 2018.

Sea floor slope was extracted from the General Bathymetric Chart of the Oceans with a spatial resolution of 500×500 m (GEBCO, Weatherall et al., 2015). Additionally, the minimum distance of each sample location to the coast (in meters) was calculated with the NNJoin plugin in QGIS Software 3.6 (Methion & Díaz López, 2018). For the distribution of the observation effort, the study area was divided into 0.85 km^2 hexagonal cells creating a polygon grid using the QGIS software.

Environmental data were obtained from oceanographic data records provided by the INTECMAR and COPERNICUS observation networks from a set of 5 sampling stations distributed in the Ría de Arousa (<http://www.intecmar.gal>, <https://marine.copernicus.eu/>) (Fig. 1). The data obtained included additional environmental data such as chlorophyll a ($\mu\text{g/mL}$), NO_3 ($\mu\text{g/mL}$), H_3PO_4 ($\mu\text{g/mL}$), and SiO ($\mu\text{g/mL}$). These variables were collected throughout the water column, every week, at each station, during the study period, from March 2014 to December 2018. To account for the spatiotemporal variability of each variable and to relate the oceanographic data previously obtained to the bottlenose dolphin presence-absence data, the oceanographic data were transformed to raster format. QGIS 3.6 was used to create the raster files, to extrapolate the spatial variation across the study area, and for each of the oceanographic variables. Thus, a daily raster was created for each variable by interpolating the values for each station using inverse distance weighted interpolation (IDW). IDW is a spatial interpolation method that has been widely used to predict environmental variables (Giralt Paradell et al., 2019). The “point sampling” tool in QGIS was then used to extract raster values (environmental variables) from multiple layers at every instantaneous 20-min sample to link the presence/absence of bottlenose dolphins with environmental variables.

Statistical analysis

To account for seasonal variations in sampling, a randomized selection of 400 sampling points from each season was subset from the total data. The seasonal distribution used was winter: January–March, spring: April–June, summer: July–September, and fall: October–December, following established climate trends in this region.

All statistical analyses were conducted in R Studio version 4.0.3. (R Development Core Team, 2015). Modeling was initiated using a full generalized linear model (GLM) with a binomial distribution and logistic link function, which included all predictor variables that could potentially drive bottlenose dolphin presence and the logarithm of the survey effort as an offset. This GLM included eight covariates (chlorophyll a, SiO_4 , H_3PO_4 , NO_3 , depth, distance to shoreline, SST, and month) that could potentially drive the response variable (presence/absence of bottlenose dolphins). Collinearity between predictor variables was investigated by calculating pairwise Spearman correlation coefficients (r) and variance inflation factors (VIFs). The package “Caret” was employed to obtain the variance inflation factor (VIF) values for each variable (Kuhn, 2008). When variables showed high correlation (above $r=0.75$ or $\text{VIF}>5$), they were not used together in the same model (Dormann et al., 2013). To find a set of explanatory variables that does not contain collinearity, variables were removed one at a time and then the VIF values were recalculated (Naimi et al., 2014). Following this procedure, SiO_4 was excluded before starting the generalized additive model fit. Modeling was continued with generalized additive models (GAMs) with a binomial distribution and logistic link function with the logarithm of the survey effort as an offset using the packages “mgcv” and “gam” (Wood, 2011). The concentration of fertilizers (H_3PO_4 and NO_3) was not directly related to depth ($p>0.05$; $r=-0.06$ and $r=0.02$, respectively). The concentration of H_3PO_4 was highly related to chlorophyll a ($p=0.00001165$; $r=0.13$) while NO_3 was not ($p>0.05$; $r=0.04$). An automatic predictor selection based on cubic splines was utilized ($\text{bs}=\text{cr}$) and to limit relationships to plausible simple forms (Mara & Wood, 2011). Additionally, to limit the risk of overfitting we reduced the number of knots in the smooth functions to 5. Data exploration

protocols described by Zuur et al. (2010) were used to identify outliers, data variability, and relationships between predictor variables and bottlenose dolphin presence. Backwards forwards procedures were then implemented to determine the best model. The best supported model was validated by plotting the distribution of the residuals against the fitted values and was selected based on the lowest Akaike information criterion (AIC) (Akaike, 1973; Zuur et al., 2010).

The annual percentage increase in the concentration of H_3PO_4 and NO_3 was calculated for illustrative purposes and to visualize the existing trend in the area.

Results

Survey effort and presence of *Tursiops truncatus*

Three hundred fifty-three daily surveys were conducted; in total, 1410 h were spent in satisfactory conditions and 2749 samples were collected (Table 1). Overall, bottlenose dolphins were encountered during 53.9% of the samples. Bottlenose dolphins were found year-round in all monitored months throughout the Ría de Arousa (Table 2, Fig. 2).

Environmental correlates of *Tursiops truncatus*'s presence

Based on AIC scores, the most parsimonious GAM included concentration of chlorophyll a, organic

Table 2 Temporal breakdown of observation effort by month

	Days of observation	Effort (nm)	Number of 20-min samples	% Presence
January	12	220	70	54.28
February	19	350	162	57.41
March	25	417	252	59.13
April	30	506	279	46.95
May	36	655	307	58.31
June	41	690	298	51.01
July	40	800	221	52.94
August	50	982	420	56.90
September	48	1026	378	51.32
October	45	1466	316	46.52
November	7	75	46	58.70
Total	353	7187	2749	Mean: 53.95

min, minutes; *nm*, nautical miles; % *Presence*, percentage of 20-min samples with bottlenose dolphins' presence

pollutants (H_3PO_4 and NO_3), depth, distance to shoreline, and SST as explanatory variables of bottlenose dolphin presence (Table 3, Fig. 3). Bottlenose dolphin presence was measured by counts of groups in a cell. This model explained 27.1% of the variation in the presence of bottlenose dolphins ($n=2358$, $R\text{-sq}=0.068$, $\text{AIC}=3279$). All variables were found to be significantly correlated to bottlenose dolphin presence in this model (Table 4).

As displayed in Fig. 3, there is a linear relationship between NO_3 and presence of the bottlenose dolphins. Bottlenose dolphins are more commonly present in waters with low concentration of NO_3 (Table 4). Chlorophyll a, H_3PO_4 , depth, slope, distance to shoreline, seasonality, and SST showed a non-linear relationship with the bottlenose dolphin presence. Bottlenose dolphins were present in shallow regions and areas 100–1500 m from the coastline with a depth range of 30 cm and 66 m and areas 100–1500 m from the coastline (Table 3, Fig. 3). Peak bottlenose dolphin presence occurred in February, May, July, and November and observed peaks at 13, 16, and 18 °C in SST.

An average annual increase of 21.72% was observed for mean values of H_3PO_4 within the Ria de Arousa. The annual mean values of NO_3 showed a similar trend with an annual average increase of 39.02%. In total, a 175% and 306.8% increase were

Table 1 Temporal breakdown of observation effort by year

	Days of observation	Effort (nm)	Number of 20-min samples	% Presence
2014	67	882	530	60.00
2015	63	894	488	56.97
2016	77	1239	682	59.82
2017	66	2097	632	44.62
2018	80	2075	417	43.41
Total	353	7187	2749	Mean: 53.95

min, minutes; *nm*, nautical miles; % *Presence*, percentage of 20-min samples with bottlenose dolphins' presence

Table 3 Mean and standard deviation of all oceanographic variables included in the best GAM regarding dolphin presence, absence, and total

	Presence		Absence		Overall	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Chlorophyll a ($\mu\text{g/L}$)	3.38	1.99	3.66	2.22	3.51	2.10
NO_3 ($\mu\text{g/L}$)	3.00	2.52	3.07	2.60	3.04	2.56
H_3PO_4 ($\mu\text{g/L}$)	0.35	0.17	0.37	0.19	0.37	0.181
Depth (m)	−14.63	10.70	−17.49	15.47	−15.97	13.22
Distance to coastline (m)	887.39	490.08	949.808	727.43	916.52	613.08
Sea surface temperature ($^{\circ}\text{C}$)	15.42	1.57	15.48	1.37	15.45	1.57

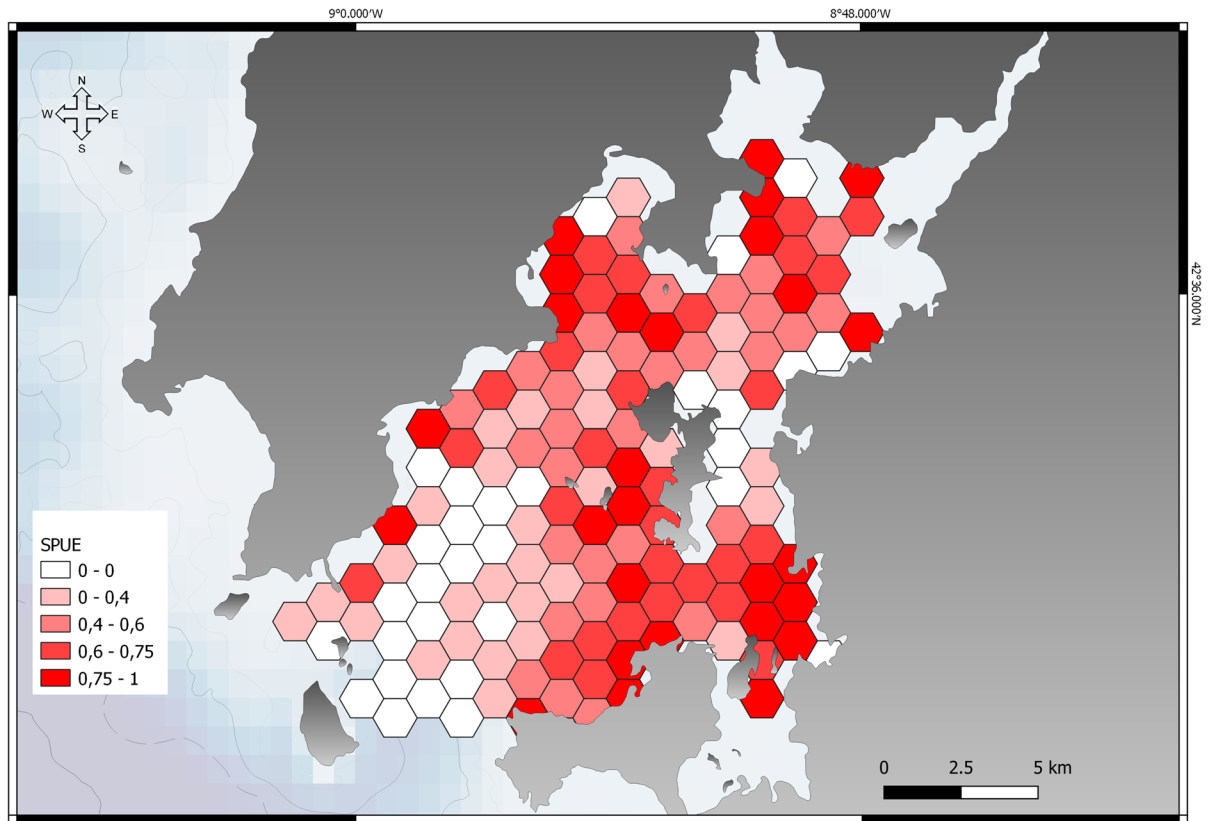


Fig. 2 Spatial distribution of bottlenose dolphins in the Ría de Arousa. The grid corresponds to the distribution of bottlenose dolphins corrected for search effort within each 2.5 km² cell (SPUE)

recorded for H_3PO_4 and NO_3 , respectively, over a 5-year span (Fig. 4).

Discussion

General significance

Estuarine systems and deltas are vital centers for humans, housing around 60% of the world

population; these ecosystems are often highly productive and provide shallow sheltered regions for species not commonly found elsewhere (Halpern et al., 2008; Kennish, 2002; Small & Cohen, 2004). The high concentration of human populations in such regions causes extensive anthropogenic stress on such habitats, and estuaries, rias, and deltas are among the most anthropogenically impacted regions of the ocean (Kennish, 2002; Small & Cohen, 2004).

Table 4 Summary of the best generalized additive model (GAM) selected by a backward-forward stepwise procedure

	edf	Ref.df	Chi sq	p value
Chlorophyll a	4.858	5.708	18.2	0.00505*
NO ₃	1	1	19.82	8.98E-06*
H ₃ PO ₄	6.434	7.372	31.01	7.31E-05*
Depth	8.695	8.96	45.67	<2.00E-16*
Distance to coast-line	6.981	7.846	73.52	<2.00E-16*
Sea surface temperature	7.976	8.641	23.72	0.00371*
Month	6.936	8	31.41	7.21E-06*
R-sq (adj)	0.122		<i>n</i>	1018
Deviance explained	27.1%		AIC	1365.775
UBRE	0.33765			

edf, effective degrees of freedom for the spline smoother; *Ref.df*, reference degrees of freedom; *R-sq (adj)*, adjusted *r*-squared for the model; *Deviance explained*, measure of the “fit” of the model; *UBRE*, UnBiased Risk Estimate, refers to the Poisson GAM equivalent of the Akaike information criterion (AIC) value; it incorporates the number of parameters used to describe the model into the fit. * denotes a *p* value of <0.05

The present study provides novel information on the possible relationship between different levels of inorganic pollutants in an estuarine system and the presence of bottlenose dolphins. Our study shows a higher presence of dolphins in those areas with moderate and high values of H₃PO₄ and chlorophyll

a, which are largely indicative of higher primary production. Unlike previous studies, dolphin presence in our study decreased considerably in areas with high levels of NO₃. Previous studies regarding the distribution of bottlenose dolphins with regard to nitrate and phosphate (Bosch et al., 2018; Mazzoil et al., 2008; Pitchford et al., 2015) suggested either no effect or a positive correlation between dolphin presence and the phosphate/nitrate concentration. However, from the data available, none of these previous studies reflected the high concentrations of nitrate and phosphate observed in this region. This study serves as a warning to those ecosystems and coastal regions across the globe, as similar processes could concentrate nitrates and phosphates in such regions, and lead to the trends we have observed within the Ría de Arousa. Changes in dolphin presence at different concentrations of nitrate and phosphate could be due to bottom-up control (e.g., eutrophication) or through other unstudied effects.

Regarding the variables implemented in our GAMs, the marine environment is a complex and dynamic entity that comprises far more variables than we can account for. However, in determined regions which are characterized by unique circulation and concentrations of species, we can track specific variables. Due to the large number of farms in such coastal regions, the present study provides us with a better understanding of the possible

Fig. 3 Graphical representation of significant variables. From left to right: chlorophyll a (chl_a), nitrates (NO₃), phosphoric acid (H₃PO₄), depth, season, distance to shoreline (distance0), sea surface temperature (SST), and month from the best GAM (family = binomial, function = logistic) on the presence of bottlenose dolphins

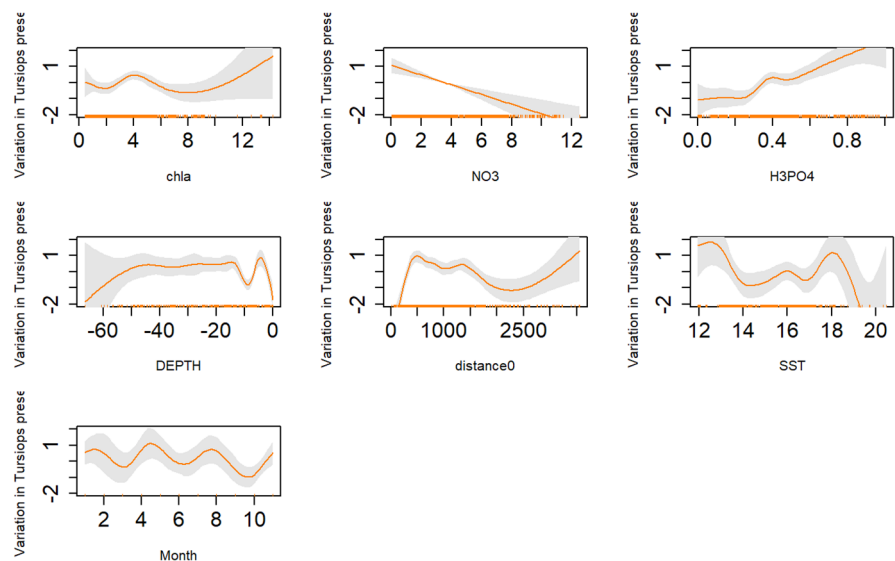
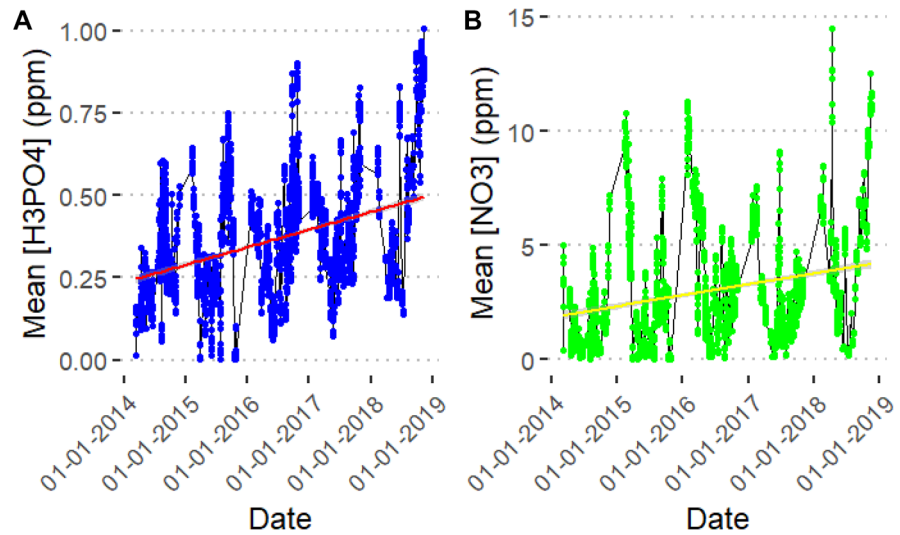


Fig. 4 Temporal change in H_3PO_4 (A) and NO_3 (B). Data ranges from 2014 to 2018. Trendline was created using a Spearman's correlation test



relationship between fertilizer runoff and top marine predators. Phosphoric acid in the environment is primarily derived from anthropogenic sources. Natural sources minimally contribute as a particularly intensive process is necessary to extract significant amounts phosphoric acid from phosphate rock (Ge et al., 2017). Therefore, any substantial concentration of phosphoric acid in the ria is likely a consequence of agriculture, entering the estuary from the rivers Ulla and Umia. Furthermore, although nitrate is a non-conservative element and there are numerous processes that impact its concentration in the marine geosphere (Romanelli et al., 2020), the concentrations of nitrate distal to the rivers Ulla and Umia are negligible compared to the values proximal to the river entrances. Additionally, because Galicia is naturally a shrubland, denoting a low phosphorus concentration in soils, extra phosphorus in the form of fertilizer is added to the soil to account for this dearth (Mombiela et al., 1986; Piñeiro & González, 2002).

Marine pollution is especially concerning because the geographical characteristics of the Rías Baixas, of which includes Ría de Arousa, cause less new water input from the ocean, which further fueling eutrophication (Villares et al., 1999). In fact, similar coastal plain estuaries, namely, the Ems, exhibited retention of 40% of phosphorus contributed from agriculture or other anthropogenic sources (van Beusekom & de Jonge,

1998). A known consequence of inorganic matter pollution in the marine ecosystem includes the generation of algal blooms. In relation to algal growth of *Ulva* sp. within the Ría de Arousa, it was observed that phosphorus was the most significant nutrient in growth determination (Villares et al., 1999). However, with regard to algal communities within the ria, a study found that nitrate concentration was the most impactful variable to beta diversity and that this effect is exacerbated in regions of high nitrate concentration that occur in regions with minimal wave action in the ria (Vale et al., 2021).

Great care should be taken to monitor the increasing phosphoric acid and nitrates concentration in the ria given that both phosphoric acid and nitrates are increasing over time within the ria far beyond the extent of seasonal cycles of precipitation. There are no indications that these compounds will cease aggregating. The persistent increase in inorganic pollutants in coastal embayments, combined with the lack of information surrounding how these species impact top predators, makes it a key issue to study. In such instances of environmental degradation or stress, we would expect a healthy population of bottlenose dolphins to leave the area unless the area was extremely significant to the population or they were unable to migrate (Gill et al., 2001; Beale & Monaghan, 2004; Beijder et al., 2006; Pirotta et al., 2013).

Conclusion

The patterns observed in this study are not merely a concern for the Ría de Arousa, but for highly impacted coastal embayments. Phosphorus and nitrogen are the most utilized minerals (Carpenter, 2008) and following the increasing trend of phosphoric acid and nitrates increase in this region, it is likely other coastal regions are experiencing similar effects from nutrient loading. While we are looking at its implications for bottlenose dolphins, it is entirely possible that other marine top predator species can be affected in an equivalent manner (Díaz & Rosenberg, 2008). In related estuary systems, such as the Sado estuary in Portugal, the resident bottlenose dolphins are exhibiting signs of depressed immune systems due to habitat degradation, which includes eutrophication in this region (Harzen et al., 1997). All these concerns are compounded by the abundance of global nitrate and phosphate usage in fertilizer application which has reached 150 million and 14 million tons per year, respectively, and this number is only increasing (Randive et al., 2021). It has become abundantly clear that there is no present alternative for these nutrients in modern agriculture and there are no present methods of adequately preventing such nutrients from escaping into the watershed and ocean. Currently, phosphorus and nitrate are exported to oceanic systems by surface runoff and soil erosion, with secondary transport via subsurface flow (Gächter et al., 1998; Ballantine et al., 2008). Again, as is shown by our results, there is reduced presence of bottlenose dolphins in zones with high levels of nitrates. If these areas become unsuitable for the preys of bottlenose dolphins, then dolphins will be forced to move into potentially more high-risk regions, namely, those with more marine traffic and fishing effort. This habitat exclusion could lead to increased overlap with humans and thus more dangerous encounters between bottlenose dolphins and human activities. Implications of this study extend far beyond the scope of bottlenose dolphins, and even other marine mammals, as marine top predators are considered to be indicators for overall ecosystem wellness (Furness et al., 1997; Zacharias & Roff, 2001; Wells et al., 2004). We recommend additional research be conducted in similar estuarine regions as well as the consideration of shallow topographies within the Ría de Arousa when making protected

areas. The amounts of phosphoric acid and nitrates being utilized in this region, or methods of reducing the entrance of such compounds into the watershed, should also be researched and regulated. The potential for excessive eutrophication is apparent and this could cause significant impacts onto the *Tursiops truncatus* species and likely many more.

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Author contribution Cheyenne Bridge: conceptualization, writing—original draft, formal analysis, review and editing. Séverine Methion: conceptualization, investigation, data curation, writing—review and editing, project administration, funding acquisition. Bruno Díaz López: conceptualization, investigation, data curation, methodology, software, formal analysis, writing—review and editing, supervision, funding acquisition.

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

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Data/code availability Data/code will be provided under request.

Declarations

Ethics approval This research was exclusively observational and adhered to ASAB/ABS guidelines, the legal requirements of Spain (the country in which it was conducted), and all institutional guidelines.

Consent to participate All authors gave final approval to participate.

Consent for publication All authors gave final approval for publication.

Conflict of interest The authors declare no competing interests.

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