Seabird colonies as the main source of nutrients for the coastal ecosystems in the Atlantic Islands of Galicia National Park (NW Spain)

S. De La Peña-Lastra [a], A. Pérez-Alberti [a], X.L. Otero [a, b, *]

[a] CRETUS Institute, Department of Edaphology and Agricultural Chemistry, Faculty of Biology, University of Santiago de Compostela, Galicia. Spain
[b] REBUSC, Red de Estaciones Biológicas de La Universidad de Santiago de Compostela, Estación de Biología Marina A Graña, Casa Do Hórreo, Rúa da Ribeira, N° 1 -4, 15590, A Graña, Ferrol, Spain

HIGHLIGHTS

- The yellow-legged gull is the most important local source of nutrients for AINP.
- Increased bioavailability of N and P can affect fragile habitats and species.
- The yellow-legged gull colony of the AINP emits large amounts of NH_3.

GRAPHICAL ABSTRACT
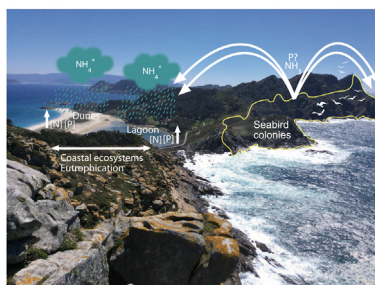
ABSTRACT

Seabirds form large colonies during the reproductive period, producing substantial changes in coastal ecosystems. The present study quantifies the amount of N and P deposited in colonies of yellow-legged gull (*Larus michahellis*) in the Atlantic Islands of Galicia National Park (AINP). Based on the composition of droppings, the amount of total N (TN), total P (TP) and bioavailable P (Pbio) deposited directly on the area occupied by the colony was determined. In addition, the amount of NH_3 released into the atmosphere was also estimated by applying a bioenergetic model. The results indicated that 5.35 t total N, 3.35 t total P and 1.24 t bioavailable P are deposited in the colony annually. The archipelagos that received the greatest amount of nutrients were the Cíes Islands (2.37 t TN y^{-1}, 1.48 t TP y^{-1}, 0.55 t Pbio y^{-1}), Sálvora (1.94 t TN y^{-1}, 1.22 t TP y^{-1}, 0.55 t Pbio y^{-1}) and Ons (1.04 t TN y^{-1}, 0.65 TP y^{-1}, 0.24 t Pbio y^{-1}). Rainwater from the colonies showed higher values of nutrients than in the control plot, possibly also due to gull influence. Therefore, the yellow-legged gull colony seems to be the most important source of nutrients at a local level, exerting a clear influence on the N and P cycles in this National Park. Another aspect worth taking into consideration is that increased N and P bioavailability may have a negative effect on the conservation of rare or threatened habitats and species by promoting the expansion of non-native ruderal species.

© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Seabirds, with more than a billion individuals, are one of the most numerous bird groups in the world (del Hoyo et al., 1996; Otero et al., 2018). Many of these birds gather during the breeding

* Corresponding author. CRETUS Institute, Department of Edaphology and Agricultural Chemistry, Faculty of Biology, University of Santiago de Compostela. Galicia. Spain.
E-mail address: xl.otero@usc.es (X.L. Otero).

season forming large colonies, which have a strong impact on the vegetation established in the surrounding coastal marine environments (Sobey and Kenworthy, 1979; Hahn et al., 2007; Zwolicki et al., 2016).

The Atlantic Islands of Galicia National Park (AINP) is home to one of the world's largest breeding colonies of yellow-legged gull (*Larus michahellis*), with a population of 10,795 pairs in 2015 (Barros, 2015). At the same time, the AINP hosts several habitats included in Annex I of Directive 92/43/CEE (Habitats Directive), some of them considered priority habitats (e.g. fixed coastal dunes with herbaceous vegetation and coastal lagoons), as well as several species of high environmental interest because they are endemic, rare or threatened (i.e., *Armeria pungens*, *Armeria pubigera*, *Corema album*) (Bernárdez et al., 2011).

Plant species present in cliffs and dune systems show specific adaptations in order to tolerate the harsh environmental conditions to which they are subjected, such as strong winds, high salinity, shallow and sandy soils with low availability of nutrients. (Otero and Pérez-Alberti, 2009). These conditions give rise to bands of vegetation that run approximately parallel to the coastline, following a gradient marked by the greater or lesser marine influence (Otero and Pérez-Alberti, 2009). However, in yellow-legged gull colonies, the composition of the flora and plant communities present differ substantially from those in continental cliffs of the NW Iberian Peninsula. Thus, for example, Guitián and Guitián (1990) described new plant communities in the AINP such as *Cochleario-Matricarietum maritimae,* with a marked ornithocoprophilic character and related to the ornitheutrophication effect of yellow-legged gulls (Otero et al., 2018).

The effect of seabird breeding colonies on the flora and plant communities is manifested by an increase in ruderal species, usually to the detriment of those plant species native to marine cliffs (Hogg and Morton, 1983; Vidal et al., 1998; Otero et al., 2015). High bird densities on coastal cliffs generate significant changes in soil composition and properties, which, in turn, may affect plant species composition and vegetation structure. Previous works have evidenced abnormally high nutrient concentrations in soils of seabird colonies. This soil eutrophication is one of the reasons why flora in seabird colonies worldwide is very different from that observed in coastal areas without seabird presence (Sobey and Kenworthy, 1979; Hogg and Morton, 1983; Portnoy, 1990; Bukacinski et al., 1994; Vidal et al., 1998; García et al., 2002). In addition, it is also worth noting that seabird breeding areas shift over time due to different reasons. In the case of yellow-legged gulls, the occupation of new cliffs as breeding grounds was the result of a dramatic increase in their population during the 1980s (Otero et al., 2015).

Conversely, for the last two decades, the population of this species in the AINP has experienced a drastic decrease. This decline appears to be due to the closure of landfills, the ban on fishing discards and/or disease (Oro et al., 1995; Otero et al., 2015). However, despite this population decrease, yellow-legged gull breeding grounds have continued to expand into new areas, particularly dunes and beaches, which are more sheltered from the wind than cliffs. This has been made possible by restrictions in visitor access to these areas either by fences or by enforced limitations or prohibitions (Otero et al., 2015). Likewise, in the Sálvora archipelago, the occupation of the dune system over the last three decades has substantially altered the typical flora and vegetation of the white dune, characterized by the presence of *Ammophila arenaria*, and of the grey dune. Both are habitats of community interest, with the latter being considered a priority habitat (Nat-2000 2260 Grey Dunes, Directive 92/43/CEE). However, no studies have been

carried out so far to determine the causes of the decline in the vegetation of these dunes, which could be due to the physical (e.g. uprooting of plants for nest construction and substrate removal) or chemical (changes in soil properties) pressure exerted by gulls on the vegetation. More recently, yellow-legged gulls have colonised the Punta Muxieiro and Rodas dune system in the Cíes Islands archipelago, which constitutes the most interesting stretch of sandy coast in the whole park. This dune system harbours one of the best-conserved populations of *Corema album* in Galicia and the only population of *Armeria pungens* in the NW Iberian Peninsula, whose conservation could be compromised by the proliferation of the bird colony.

Although other studies have already addressed the impact of yellow-legged gulls on some cliffs within this National Park and have revealed high N and P concentrations both in soils and in runoff water (Otero et al., 2015; Otero and Fernández-Sanjurjo, 2000; Otero and Mouriño, 2002), none of them has quantified the amounts contributed by the nesting yellow-legged gull population on the coastal habitats of the AINP.

Taking all the aforementioned into account, the main objective of this study was to quantify the amounts of total and bioavailable N and P that are deposited annually throughout the whole AINP as a result from yellow-legged gull droppings and to determine their relevance in the biogeochemical cycle of each of these elements. For this purpose, the total amounts of N (TN) and P (TP), as well as the amount of bioavailable P (Pbio) to plants, have been determined from the concentration of these nutrients in droppings. In addition, the amount of NH_3 released into the atmosphere and its potential effect on the concentration of N in rainwater has been estimated using a bioenergetic model. Furthermore, although other studies have already estimated excreted N and P at the global level (Riddick et al., 2012; Otero et al., 2018) and at the national level (Great Britain, Wilson et al., 2004), none of them have determined in detail the deposition of N, P and its more bioavailable forms at the sub-colony level.

2. Material and methods

2.1. Study area

The present study was carried out in the yellow-legged gull colony of the Atlantic Islands of Galicia National Park (AINP); in addition, the cliffs of Cabo Home (Cangas, Pontevedra), in the NW of the Iberian Peninsula, were selected as a control plot (absence of gulls) (Fig. 1).

The geological substrate is composed of two-mica granite, and the height above sea level varies between 10 and 30 m. Average annual rainfall in the Cíes Islands is 877 mm, with the highest rainfall being concentrated during the period between October and March (Carballeira et al., 1982). However, mean annual rainfall in the Cíes Islands during the study period was slightly lower (798 mm), while mean annual rainfall in Ons Island was 890 mm (METEOGALICIA-Xunta de Galcia, 2015). The average temperature in the months of greatest gull influence (April–August) is 17 °C (METEOGALICIA-Xunta de Galcia, 2015).

It is worth noting that the nesting yellow-legged gull population has undergone remarkable oscillations over the past 35 years due to the influence of human activity on the trophic resources exploited by this species (e.g. urban waste, fishing discards, etc). Thus, for example, the population in the Cíes Islands archipelago went from 4236 pairs in 1976 up to 22,098 pairs in 1991 and back down to 3520 pairs in 2015 (Barros, 2015). This generalised
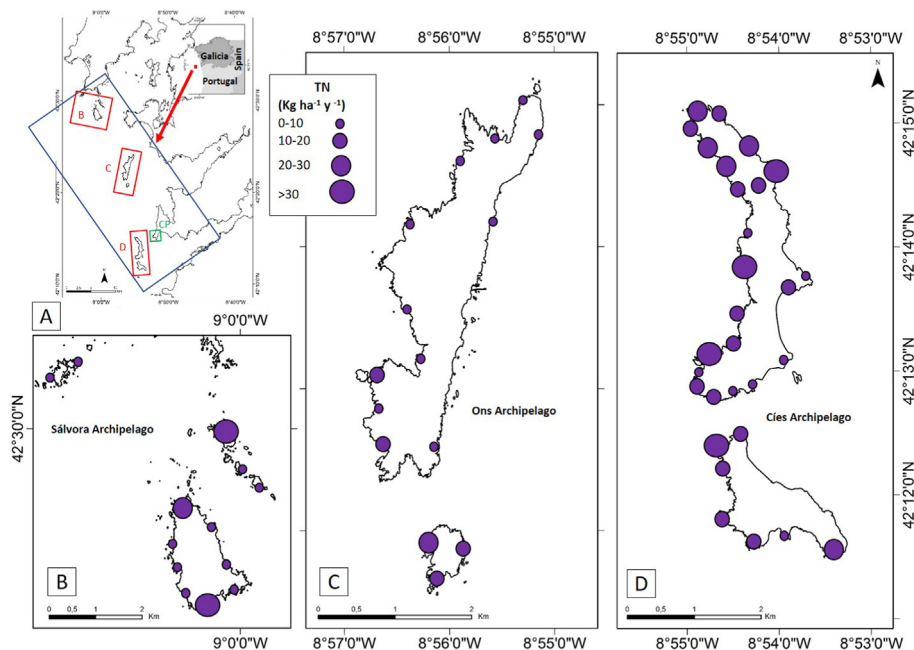
Fig. 1. Location of the Atlantic Islands of Galicia National Park and the Control Plot (CP) (A). In addition, TN (kg ha^{-1} y^{-1}) excreted by seabirds on (B) Sálvora, (C) Ons and (D) Cíes Archipelagos of the AINP is also represented.

decrease in the nesting yellow-legged gull population in the group of archipelagos that compose the AINP seems to be related to the sealing of rubbish dumps and a decrease in fishing discards (Bermejo and Mouriño, 2004).

2.2. Sampling and analysis of excreta

During the breeding season of 2011 and 2012, 40 faeces samples were carefully collected from the colony, paying special attention not to include any substrate material. Each sample consisted of 5−10 fresh droppings. For each sample, the total contents of N, P, N and bioavailable P were analyzed.

The total N (TN) content in gull droppings was determined by analysing a finely ground aliquot of each sample (~0,100 g wt) in a Truspec CHN autoanalyzer. Exchangeable ammonium (NH_4^+) and nitrate (NO_3^-) were extracted from 5 g of fresh droppings in 50 ml of 2 M KCl solution (Mulvaney, 1996). Total phosphorus (TP) was obtained from ground samples after microwave-assisted digestion with concentrated nitric and hydrochloric acid (9:3 v/v), while bioavailable phosphorus (Pbio) was extracted with Mehlich-3 solution (2 M CH_3COOH, 0.25 M NH_4NO_3, 0.015 M NH_4F, 0.013 M HNO_3 and 0.001 M EDTA) (Mehlich, 1984).

2.3. Rainwater sampling and analysis

A total of 11 rain gauges were placed at different distances from the edge of the cliff (one plot in the lower section, 30 m away from the coastline, and another one in the upper section, 350 m away from the coastline) in the main subcolonies of the Cíes and Ons Islands, and an additional rain gauge was placed in a control plot (without gulls) located in Cabo Home. Each rain gauge was 1.5 m tall. Rain samples were taken immediately after the rainy periods of 2011 and 2012, discarding all those samples that presented some type of deposited material inside the rain gauge (mainly excrements or insects). In addition, concentration of dissolved organic carbon (DOC) was determined as a proxy for organic (fecal) contamination, samples that showed a higher content of dissolved

organic carbon (DOC) than control site (DOC <7 mg kg^{-1}; Table 1) were discarded.

Rainwater samples were filtered by 0.45 μm pore size prior to being analyzed. pH of samples was measured, electric conductivity (EC) was determined using specific electrodes, NO_3^- and NH_4^+ were determined by ion chromatography in a Dionex apparatus, phosphate was determined colorimetrically by the molybdenum blue method (Buurman et al., 1996) and DOC was analyzed with a TOC analyzer (Shimadzu, TOC-L Analyzer).

2.4. Estimation of deposited TN, TP and Pbio in the colony

The amounts of TN, TP and Pbio deposited by yellow-legged gulls through faecal material in the colonies of the National Park was estimated based on the content of these elements in excrements collected in the AINP. Furthermore, permanence in the colony was considered to be 122 days (Riddick et al., 2012), each bird was considered to remain in the colony for 18 h d^{-1} (Riddick et al., 2012), defecation rate was considered to be 3.1 droppings h^{-1} (Riddick et al., 2012), and a dry weight of 0.529 g was considered for each dropping (Portnoy, 1990). The latter value has been reported for *Larus argentatus*, since this species is very similar to *L. michahellis* in size and feeding habits and, for this species, no data were found. In fact, during the 1970s and part of the 1980s, the species present in the AINP was first considered to be *L. argentatus*, later *Larus cachinnans*, and currently *L. michahellis* (see e.g. Barcena, 1977; Otero, 1998; Barcena et al., 1984). In addition, according to Cramp and Simmons (1983), three groups can be distinguished within the species *Larus argentatus*: *Larus argentatus argentatus* (nominal group), *Larus argentatus cachinnans* and *Larus argentatus michahellis*, with the AINP population corresponding to the latter. Other authors confer species status to *L. cachinnans*; thus, the AINP population would correspond to the subspecies *Larus cachinnans michahellis* (Haffer, 1982; Munilla, 1997). To calculate the amount of nutrients deposited in each area where the colony of yellow-legged gull is established, the number of breeding individuals obtained in the 2011 census was extrapolated to the whole AINP (Pérez et al.,

Table 1
pH, EC and nutrient mean values ± SD collected in the rain gauges installed in different colonies of the yellow-legged gull of the AINP. The average values of N and P are also shown in kg ha^{-1} y^{-1}. For total AINP and control zone, different lowercase letters mean significant differences (p < 0.05) between AINP - with seabirds vs. control site - without seabirds. n.a. data not available.

Archipelago	pH	EC	DOC	NH$_4^+$	NO$_3^-$	HPO$_4^{2-}$	NH$_4^+$	NO$_3^-$	HPO$_4^{2-}$
		μS cm^{-1}	mg l^{-1}				Kg ha^{-1} y^{-1}		
Cíes (n=156)	6.96 ± 1.1	847 ± 1183	2,50 ± 2,40	7.53 ± 19.0	1.07 ± 1.4	9.22 ± 21	66.0	9.38	80.9
Ons (n=8)	7.62 ± 0.8	670 ± 860	n.a	1.79 ± 1.4	0.17 ± 0.2	0.76 ± 1.1	14.3	1.36	6.06
Total AINP	6.99 ± 1.1[a]	840 ± 1171[a]	n.a.	7.31 ± 19[a]	1.02 ± 1.4[a]	8.90 ± 21[a]	61.3[a]	8.55[a]	74.6[a]
Control zone (n=18)	6.44 ± 0.8[a]	1416 ± 921[b]	1,97 ± 1,19	0.56 ± 0.9[a]	0.88 ± 0.9[a]	0.23 ± 0.7[b]	4.91[a]	7.72[a]	2.02[b]

2012). Finally, the area within each sector was calculated and mapped using the ArcGIS software (ESRI 9 inc., 2011).

2.5. Estimation of NH$_3$ emissions

To understand the magnitude and spatial distribution of NH$_3$ emissions by seabirds in the National Park, the model extracted from Riddick et al. (2012) and Wilson et al. (2004) was used (see also Otero et al., 2018).

2.5.1. Adult breeders

Annual emission of NH$_3$ by breeding individuals (Q$_{NH3}$-breeders, g NH$_3$ bird^{-1} y^{-1}) was calculated from adult mass (M, g bird^{-1}), nitrogen content of the diet (F$_{NC}$, g N g^{-1} wet mass), energy content of the diet (F$_{EC}$, kJ g^{-1} wet mass), assimilation efficiency of the ingested food (A$_{eff}$, kJ [energy gained] kj [energy in food]$^{-1}$), proportion of excreted nitrogen volatilized as NH$_3$ (F$_{NV}$), length of the breeding season (brood, days), proportion of time spent in the colony during the breeding season (F$_{TC}$), a habitat correction factor (F$_{hab}$) depending on where the excrements fall (rock, nest or vegetation), and a 17/14 NH$_3$-to-N mass ratio (Equation 1).

$$Q_{NH_3}(breeders) = \frac{9.2 \times M^{0.774}}{F_{EC} \times A_{eff}} \times F_{NC} \times F_{NV} \times t_{breeding} \times F_{tc} \times F_{hab} \times \frac{17}{14}$$

(1)

F$_{NC}$ and F$_{EC}$, estimated at 0.036 g N g^{-1} and 6.5 kJ g^{-1} (both wet mass) (Energy: Nitrogen (E: N) Ratio = 181 kJ g N^{-1}), respectively, were based on the assumption of a high protein content diet composed only of fish (Furness, 1991). A$_{eff}$ was estimated at 0.8 (Furness, 1991). F$_{NV}$ was estimated at 0.3, combining the effect of temperature, humidity, wind speed and solar radiation on volatilization rate for a mid-latitude environment (Wilson et al., 2004). Part of the total excretion of the colony will be washed into the sea by precipitation events or wave action (Blackall et al., 2008).

The value used for adult mass was 1080 g bird^{-1} (Riddick et al., 2012). The term 'brood' is calculated by adding the time of pre-placement (courtship and nest construction) and the incubation and breeding periods and is 152 days (Riddick et al., 2012). The value for F$_{TC}$ takes into account excrement loss while birds are away from the colony, i.e., feeding at sea or during flight, and is 0.6 (Riddick et al., 2012). F$_{hab}$ describes the re-absorption of NH$_3$ by the substrate and overlying vegetation using a value of 0.27 (Riddick et al., 2012).

2.5.2. Non-breeders

Non-breeding individuals were assumed to constitute 33% of the colony and to spend 50% less time in the breeding colony than a breeding individual (Wilson et al., 2004; Riddick, 2012). NH$_3$ emission by non-breeders (Q$_{NH3}$ (non-breeders), g NH$_3$ bird^{-1} y^{-1}) was estimated by equation 2:

$$Q_{NH_3}(non-breeders) = 0.167 \times Q_{NH_3}(breeders)$$

Estimates of the presence of non-breeding birds may have spatial and temporal variation. In general, seabirds spend large amounts of time in the colony before choosing a mate. Variations in the presence of non-breeders have been estimated to range from 35% to 73%; based on these percentages, a value of 0.167 was calculated.

2.5.3. Chicks

The length of the period spent as a chick was estimated as the time between hatching and fledging. Annual emission of NH$_3$ by chicks (Q$_{NH3}$ (chicks), g NH$_3$ bird^{-1} y^{-1}) was estimated based on some of the aforementioned parameters, as well as the mass of the chick (M$_{fledging}$, g) and the offspring productivity (P$_{chicks}$, number of chicks per pair) (Equation 3).

$$Q_{NH_3}(chicks) = \frac{28.43 \times M_{fledging}^{1.06}}{F_{EC} \times A_{eff}} \times F_{NC} \times F_{NV} \times F_{hab} \times \frac{17}{14} \times \frac{P_{chicks}}{2}$$

(3)

For yellow-legged gull, these data were taken from Riddick et al. (2012), using a M$_{fledging}$ value of 900 g and a P$_{chicks}$ value of 0.8 chicks per pair.

2.5.4. Effect of temperature on NH$_3$ emissions

Following the proposal by Riddick et al. (2012), two estimates were made. In scenario 1, NH$_3$ emissions were considered to be independent of temperature, following the method described above. In scenario 2, NH$_3$ emissions were estimated considering the effect of temperature. The correction factor F$_{NV}$ was used, taking into account the average temperature in the National Park during the reproductive period (17 °C; METEOGALICIA-Xunta de Galcia, 2015). The inclusion of factor F$_{NV}$ allows for more realistic NH$_3$ emission estimates (see also Riddick et al., 2017). For this purpose, NH$_3$ emissions were calculated based on the combined Henry and dissociation equilibria for NH$_3$ and ammonium (NH$_4^+$), following the empirical fit by Nemitz et al. (2000) (Equation 4).

$$C_T = \frac{161500}{T} \exp\left(\frac{-10378}{T}\right)$$

(4)

Where C$_T$ is Henry's law constant as a function of temperature and T is mean temperature (K) (Nemitz et al., 2000). Taking 10 °C as a reference, the proportion of excreted nitrogen that is volatilized, F$_{NV}$, at 10 °C is 0.33. In colder climates, where the average temperature during the breeding season is 5 °C, F$_{NV}$ decreases to 0.09. In colonies where the average temperature is higher than 19 °C, it is estimated that all excreted nitrogen is volatilized (F$_{NV}$ = 1) (Riddick et al., 2012). In this case, at 17 °C, factor F$_{NV}$ took a value of 0.8091.

Additionally, according to Riddick et al. (2012), scenario 2 can be considered as the one where NH$_3$ emission is most dependent on

temperature. However, other processes can be expected to offset the temperature effect; for example, in a cold and dry environment, the potential for NH_3 emission may be lower, but as a result of emissions taking place over a longer period of time. Conversely, in hot and dry conditions, the rate of hydrolysis of urea can be very limited, leading to the accumulation of guano.

Given these uncertainties, Riddick et al. (2012, 2017) consider that the average of scenarios 1 and 2 (scenario 3) is the best estimate of NH_3 emissions to the atmosphere from faecal material generated by seabirds.

2.5.5. Uncertainty associated with input data

Both NT, PT and Pbio calculations and NH3 estimates were subject to a certain degree of uncertainty due to variations in the parameters used. Therefore, a 10% error for seabird population estimates, a 23% error for variations in diet composition, and a 13% error due to assistance from non-breeding individuals are proposed (Riddick et al., 2012). However, while these uncertainties are of considerable magnitude, the results obtained in this study are not expected to be significantly affected, since the amounts of nutrients mobilized by yellow-legged gull are expected to remain important in relation to those mobilized by other processes, both natural and anthropogenic, present in this national park.

2.6. Statistical analysis

One-way ANOVA was used to test for any differences in N and P concentrations between the control plot (without seabirds) and plots from the colonies. Differences were considered significant at $p < 0.05$. All statistical analyses were carried out using SigmaStat 3.5 software.

3. Results

3.1. Composition of rainwater

Rainwater pH was close to neutral (Table 1), and ionic concentration was not extremely high, as might be expected given its vicinity to the sea, with average electrical conductivity values below $1500\ \mu S\ cm^{-1}$ (Table 1). The concentration of DOC in the rainwater samples considered in this study was low, indicating the absence of organic contamination (e.g. excrements) (Table 1).

The average concentration of N and P forms found in rainwater was much higher in yellow-legged gull colonies than in the control plot. In the colony area, NH_4^+ ranged from $7.53 \pm 19.0\ mg\ l^{-1}$ in Cíes islands to $1.79 \pm 1.4\ mg\ l^{-1}$ in Ons island, while NO_3^- ranged from $1.07 \pm 1.4\ mg\ l^{-1}$ in Cíes to $0.17 \pm 0.2\ mg\ l^{-1}$ in Ons. This means that, for the whole park, deposition was 13 times higher for NH_4^+ and 1.13 for NO_3^- than in the control plot. As for P, its concentration in rainwater ranged from $9.22 \pm 21\ mg\ l^{-1}$ in the Cíes colony to $0.23 \pm 0.7\ mg\ l^{-1}$ in the control plot (Table 2). Therefore, these values were up to 40 times higher in the colonies than in the area without gulls. By unit areas, values for the whole park were $61.3\ kg\ ha^{-1}\ y^{-1}$ for NH_4^+, $8.55\ kg\ ha^{-1}\ y^{-1}$ for NO_3^{-2} and $74.6\ kg\ ha^{-1}\ y^{-1}$ for PO_4^{3-} (Table 1).

3.2. Concentration of TN, TP and Pbio in excreta

Mean concentration of TN in excreta was $44,151 \pm 37,917\ mg\ kg^{-1}$, of which 7.20% was ammonium and only 0.16% was nitrate; meanwhile, TP content was $31,721 \pm 22,270\ mg\ kg^{-1}$, of which 32% corresponded to plant-assimilable P forms (Table 2).

3.3. Spatial distribution and amounts of TN, TP and Pbio excreted in AINP

Overall, the AINP received an average annual contribution of $5.35\ t\ TN\ y^{-1}$, $3.35\ t\ TP\ y^{-1}$ and $1.24\ t\ Pbio\ y^{-1}$ (Table 3). By unit of area, the archipelago that received the most nutrients was Cíes, followed by Sálvora and Ons.

The subcolonies that received the greatest amount of nutrients were found in the Cíes Islands: Portelo, Isla del Faro; Príncipe, Isla de Monte Agudo and Galeira, Isla de San Martiño. High values were also obtained in the subcolonies of Sálvora, Vionta, on the island of Sagres and Gralleiros; and in the Ons archipelago, Onza Oeste and Baxeiral (Figs. 1—3, Table S1).

Overall, six subcolonies received more than $30\ kg\ TN\ ha^{-1}\ y^{-1}$, four of them in the Cíes Islands; seven received between 20 and $30\ kg\ TN\ ha^{-1}\ y^{-1}$; seventeen received $10-20\ kg\ TN\ ha^{-1}\ y^{-1}$ and twenty-seven received less than $10\ kg\ TN\ ha^{-1}\ y^{-1}$. As for TP, there were nine sites that received more than $15\ kg\ TP\ ha^{-1}\ y^{-1}$, seven of them in the Cíes Islands; thirteen received $10-15\ kg\ TP\ ha^{-1}\ y^{-1}$; twelve received $5-10\ kg\ TP\ ha^{-1}\ y^{-1}$ and twenty-three received less than $5\ kg\ TP\ ha^{-1}\ y^{-1}$. Finally, regarding Pbio, nine subcolonies received more than $6\ kg\ Pbio\ ha^{-1}\ y^{-1}$, seven of them in the Cíes Islands; eleven received between 4 and $6\ kg\ Pbio\ ha^{-1}\ y^{-1}$; thirteen received between 2 and $4\ kg\ Pbio\ ha^{-1}\ y^{-1}$ and twenty-four received less than $2\ kg\ Pbio\ ha^{-1}\ y^{-1}$ (Figs. 1—3, Table S1).

3.4. Spatial distribution and total emissions of NH3 in the AINP

The total emissions of the AINP colonies were $9.90\ t\ y^{-1}$, with the highest values corresponding to the Sálvora and Monteagudo

Table 3
Total N (TN), total P (TP) and bioavailable P (Pbio) excreted on each island of the AINP archipelagos.

Archipelago	Island	Breeding individuals	TN	TP	Pbio
			(t y^{-1} in the colony)		
Cíes	Monteagudo	7542	1.20	0.75	0.28
	Faro	2542	0.40	0.25	0.09
	San Martiño	4846	0.77	0.48	0.18
	Total	14930	2.37	1.48	0.55
Ons	Ons	4492	0.32	0.20	0.07
	Onza	2026	0.71	0.45	0.17
	Total	6518	1.04	0.65	0.24
Sálvora	Sálvora	9572	1.52	0.95	0.35
	Sagres	140	0.022	0.014	0.005
	Vionta	2414	0.38	0.24	0.09
	Noro	70	0.011	0.007	0.003
	Herbosa	30	0.005	0.003	0.001
	Total	12226	1.94	1.22	0.55
TOTAL NATIONAL PARK		33674	5.35	3.35	1.24

Table 2
Concentrations of N forms, total P and bioavailable P (mg kg^{-1}) in fresh excrements of the yellow-legged gull in the AINP.

	TN	N-NH$_4^+$	N-NO$_3^-$	TP	Pbio
Mean±SD	$44,151 \pm 37,917$	3183 ± 1196	73.3 ± 203	$27,617 \pm 21,424$	$10,220 \pm 8433$
Median	32,920	2991	5.56	20,480	8740

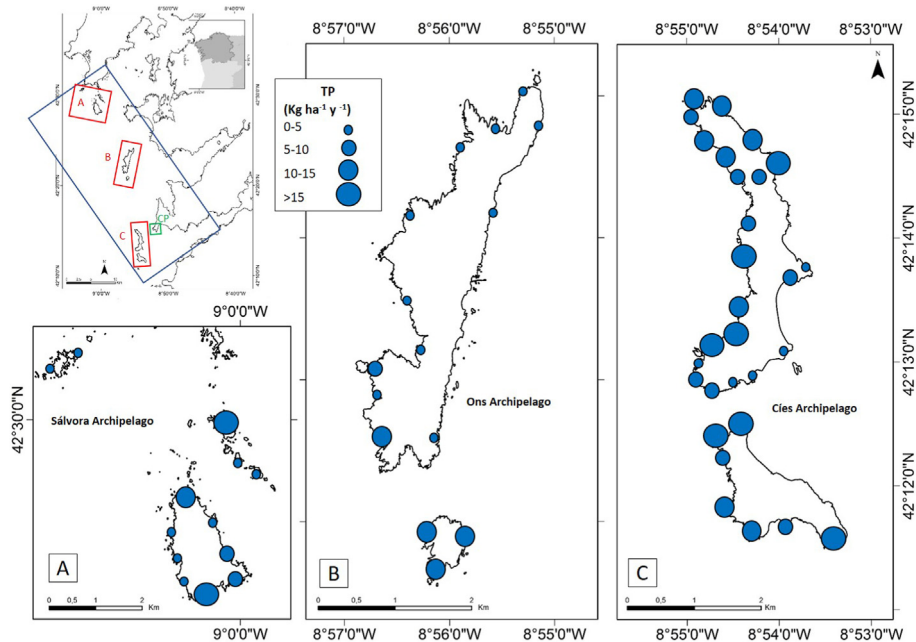**Fig. 2.** Location of the Atlantic Islands of Galicia National Park and the Control Plot (CP) (A). In addition, TP (kg ha^{-1} y^{-1}) excreted by seabirds on (B) Sálvora, (C) Ons and (D) Cíes Archipelagos of the AINP is also represented.

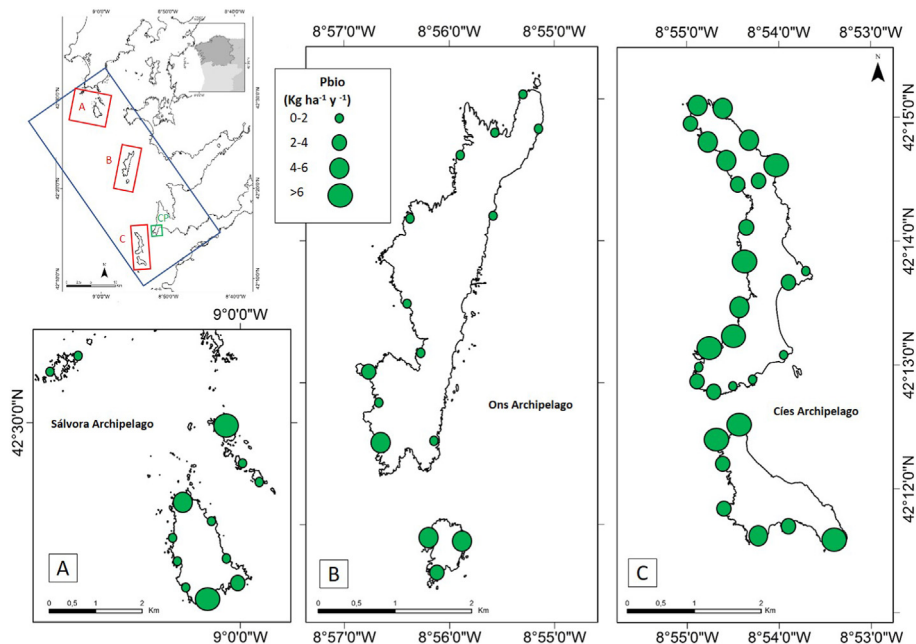**Fig. 3.** Location of the Atlantic Islands of Galicia National Park and the Control Plot (CP) (A). In addition, Pbio (kg ha^{-1} y^{-1}) excreted by seabirds on (B) Sálvora, (C) Ons and (D) Cíes Archipelagos of the AINP is also represented.

islands, in Cíes (Tables 4 and S2).

By unit of area, the most affected sites were the cliffs of Portelo (Faro Island, Cíes), with 78.3 kg NH$_3$ ha^{-1} y^{-1}, Príncipe (Monte Agudo Island, Cíes), with 70.2 kg NH$_3$ ha^{-1} y^{-1}, and Galeira (San Martiño Island, Cíes), with 67.0 kg NH$_3$ ha^{-1} y^{-1}. Table 4 shows the data by islands and archipelagos, with the Cíes, Ons and Sálvora archipelagos listed in decreasing order of emission. However, the island with the highest emissions per unit of surface area was Vionta, followed by Ons and San Martiño. Overall, gulls in the National Park emitted 16.9 kg NH$_3$ ha^{-1} y^{-1} (Tables 4 and S2, Fig. 4).

4. Discussion

4.1. Deposition of N and P forms from rainwater

The primary source of N input to remote ecosystems is rainwater, which represents less than 1 kg ha^{-1} y^{-1} (Phoenix et al., 2006). Nitrogen deposition with rainwater in Galicia ranges from 0 to 68 kg ha^{-1} y^{-1} (Rodríguez-Lado and Macías, 2006; Phoenix et al., 2006), with the lowest values corresponding to areas located far away from sources of pollution and the highest values

Table 4
NH_3 emitted in total and per unit area on each island of the AINP archipelagos.

Archipelago	Island	NH_3 emitted (t y^{-1})	NH_3 emitted (kg ha^{-1} y^{-1})
Cíes	Monteagudo	2.22	34.2
	Faro	0.75	18.2
	San Martiño	1.42	34.4
	Total	**4.39**	**29.8**
Ons	Ons	1.32	7.77
	Onza	0.60	36.0
	Total	**1.92**	**10.3**
Sálvora	Sálvora	2.81	19.6
	Sagres	0.04	0.45
	Vionta	0.71	62.9
	Noro	0.02	5.84
	Herbosa	0.01	4.46
	Total	**3.59**	**14.2**
TOTAL AINP		**9.90**	**16.9**

corresponding to agricultural or industrial areas of Galicia (Rodríguez-Lado and Macías, 2006). In the AINP, the concentration of NH_4^+ in rainwater was 13 times higher than those of the control plot. This difference may be due to emissions of NH_3 and other forms of N produced by yellow-legged gulls.

For P, the results obtained (74.6 kg ha^{-1} y^{-1}) showed an increase of up to 40 times the values found in the control plot. These values of P could be due, on one hand, to the transformation of some of the P compounds present in the excrements, both organic and inorganic, into a volatile form of P such as phosphine (PH_3). Phosphine was already observed in Antarctic soils influenced by penguins (Zhu et al., 2006, 2009, 2014). The possibility that part of the faecal material was carried by the wind, mainly during storms or directly by falling when these birds flew over the samplers, does not seem likely, because by the time the storm season comes, seagulls have already left the colonies. Moreover, as mentioned in the 'Material and methods' section, rainwater samples were always discarded whenever any type of material was observed inside the rain gauge. Nevertheless, the formation of phosphine in seabird colonies warrants further study.

4.2. Incorporation of N and P through excreta

Seabird droppings are characterized by high levels of nutrients, especially N and P, which are deposited mainly in breeding colonies (Smith and Johnson, 1995; Otero et al., 2018).

Different authors set 5−10 kg N ha^{-1} y^{-1} as the critical load that vulnerable ecosystems can support (Krupa, 2003; Bobbink et al., 2010). Our results show an average value of 15.5 kg N ha^{-1} y^{-1}, with 74% of the subcolonies exceeding the 5 kg N ha^{-1} y^{-1} threshold and 53% exceeding 10 kg N ha^{-1} y^{-1}. Extremely high values were obtained for subcolonies such as O Portelo, with a deposition of 42.3 kg N ha^{-1} y^{-1}. These values are consistent with the notion that seabird colonies constitute the main source of soil nutrients in remote areas (Erskine et al., 1998; Otero et al., 2018).

This data is in line with other studies. For example, a study carried out by Smith and Johnson (1995) in Australia compared the amounts produced by colonies of *Anous minutus* and *Puffinus pacificus* (7.8 t N y^{-1} and 1.6 t P y^{-1}; 1.6 t N y^{-1} and 0.3 t P y^{-1}, respectively, with a population of 80,000 breeding pairs) with those produced by human activity in the area (0.29 t N y^{-1} and 0.32 t P y^{-1}; 97,700 people). Erskine et al. (1998) studied how much N was contributed by several species of penguins and elephant seals on Subantarctic Macquarie Island, obtaining relatively greater quantities than in the AINP: for instance, 100,000 pairs of royal penguins produced 154 t N y^{-1}. Penguins and elephant seals in Macquarie Island excrete 240 t N y^{-1} and 24.0 kg N ha^{-1} y^{-1}, respectively (Erskine et al., 1998). Hobara et al. (2005) observed that *Phalacrocorax carbo* not only affects nutrient inputs (N and P) but also their balance, significantly affecting forests in Japan. The variability of contributions by seabirds is due to differences in size, weight or diet among individuals of the same species and among different species, and this is an important factor to take into consideration (Riddick, 2012; De la Peña-Lastra, 2021).

Considering the world's yellow-legged gull population, the amounts produced by breeding individuals are estimated at 58.3 t N y^{-1}, 36.5 t P y^{-1} and 13.5 t Pbio y^{-1} (Table 5), with the Spanish populations accounting for 68% of the world production
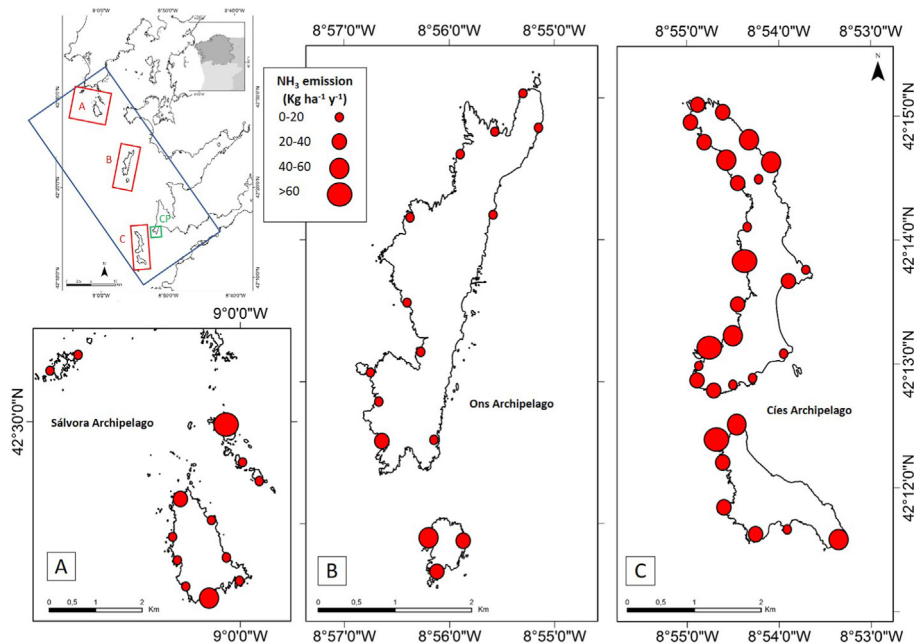
Fig. 4. Location of the Atlantic Islands of Galicia National Park and the Control Plot (CP) (A). In addition, NH_3 (kg ha^{-1} y^{-1}) excreted by seabirds on (B) Sálvora, (C) Ons and (D) Cíes Archipelagos of the AINP is also represented.

Table 5
Nutrient values excreted by Yellow-legged Gulls at different scales.

Location	Breeding individuals	Total N	Total P	Bioavailable P
		(t y^{-1} in the colony)		
AINP	33,674[a]	5.35	3.35	1.24
Galicia	91,802[b]	14.6	9.13	3.38
Spain	250,349[b]	39.8	24.9	9.22
World	366,667[c]	58.3	36.5	13.5

[a] Pérez et al. (2012).
[b] Molina (2009).
[c] Croxall et al. (2012).

and the AINP for almost 10% (Table 5).

N is an important limiting factor for productivity, and an increase in its bioavailability in oligotrophic ecosystems is considered an environmental problem. Thus, for example, Miller (1982) studied the alterations caused by a white pelican colony before and after nesting on nine occasions, observing a change over 85% in the vegetation in the study area. According to the results obtained, these ecosystems should be treated as eutrophic due to the major contributions of nutrients they receive annually.

P, together with N, is one of the main biolimiting factors for primary productivity in terrestrial ecosystems (Bashkin, 2002). However, its atmospheric transport is not clear, since it does not have a stable gas phase (PH$_3$) and is limited to aerosols (Mahowald et al., 2008; Izquierdo et al., 2012). Mahowald et al. (2008) studied the global distribution of P deposition, obtaining a range between 0.5 kg ha^{-1} y^{-1} and 11,000 kg ha^{-1} y^{-1} for TP and between 0.2 and 1100 kg ha^{-1} y^{-1} for Pbio. The highest concentrations were found in the continental part or in places affected by dust in the Sahara desert, while the lowest concentrations were found in remote marine environments.

In the AINP, contributions from the yellow-legged gull colony were 9.72 kg ha^{-1} y^{-1} TP and 2.11 kg ha^{-1} y^{-1} Pbio. These values are higher than expected in these apparently pristine environments (Mahowald et al., 2008). In this regard, Otero et al. (2015) already reported that, due to the contributions of P by the yellow-legged gull colony in the AINP, soils occupied by the colonies of these birds are saturated in P, and Pbio acts as a source of P for surface waters.

4.3. NH$_3$ emissions

Seabird colonies are important localized natural sources of NH$_3$ emissions for several reasons, such as the high nitrogen content of their fish-based diet and their very high metabolic rates (Sutton et al., 2013). In addition, due to overcrowding of seabird colonies (NH$_3$ volatilization increases with the intensity of the emission source; Wilson et al., 2004), they produce large amounts of NH$_3$ that are deposited in nearby areas, normally 4–5 km away from their source (Krupa, 2003). This deposition leads to high exposures to NH$_3$, which can cause visible leaf lesions or other less visible ones in vegetation (intolerance to drought and frost, changes in response to pests, alterations in growth and productivity, changes in competition between species or symbiotic associations, Krupa, 2003; Riddick et al., 2014). In addition, excess NH$_3$ in the environment can lead to acidification, eutrophication, global warming, disruption of plant communities. (Riddick et al., 2014). Another aspect worth taking into account is that seabird colonies are located in remote places, usually fairly inaccessible to humans. Therefore, they are the most important source of this gas and have a significant impact on the N cycle (Wilson et al., 2004).

In the AINP, an emission of 9.90 t NH$_3$ y^{-1} to the atmosphere was estimated for a population of 17,000 breeding pairs of yellow-legged gulls. Emissions were lower than those obtained for other seabird species such as *Morus bassanus* (230 t NH$_3$ y^{-1}; 50,050 pairs), *Uria aalge* (10.3 t NH$_3$ y^{-1}; 9150 pairs) or *Fulmarus glacialis* (57.5 t NH$_3$ y^{-1}; 50,250 pairs) (Wilson et al., 2004).

5. Conclusions

Seabird colonies are the main source of nutrients at the local level and, furthermore, colonies have a clear effect on the cycles of N and P within the National Park. Moreover, N and P can be partially exported outside the colony and deposited by rainwater in nearby ecosystems such as coastal lagoons or dune areas. Eutrophication of these ecosystems is negatively impacting the conservation status both of rare species and of threatened habitats within the AINP (see e.g. Otero et al., 2015).

Authors' contributions

SPL, XLO and APA conceived and designed the study and performed the research; SPL and XLO carried out the statistical analyses; SPL and XLO built the maps; SPL, XLO and APA wrote the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2021.130077.

References

Barcena, F., 1977. Colonias de aves marinas en las islas Cíes. Naturalia Hispania n° 9 Icona, Madrid, p. 24.
Barcena, F., Teixeira, A.M., Bermejo, A., 1984. Breeding seabird population in the atlantic sector of iberian Peninsula. In: Croxall, J.P., Evans, P.G.H., Schreiber, R.W. (Eds.), Status and Conservation of the World's Seabirds. International Council for Bird Preservation. Technical Publication nº 2, Cambridge, pp. 347–362.
Barros, A., 2015. Censo da poboación reprodutora de corvo mariño cristado (*Phalacrocorax aristotelis*), gaivota patiamarela (*Larus michah*ellis), gaivota escura

(*Larus fuscus*) e gaivotón (*Larus marinus*) no Parque Nacional Marítimo-Terrestre das Illas Atlánticas de Galicia: resultados de 2015. Parque Nacional Marítimo-Terrestre das Illas Atlánticas de Galicia. Informe non publicado. Xuño de, 2015.

Bashkin, V.N., 2002. Modern Biogeochemistry: Environmental Risk Assessment. Springer, New York, p. 444.

Bermejo, A., Mouriño, J., 2004. Gaviota patiamarilla (*Larus cachinnans*). In: Martí, R., del Moral, J.C. (Eds.), Atlas de aves reproductoras de España. Dirección General de Conservación de la Naturaleza, Sociedad Española de Ornitología. Organismo Autónomo Parques Nacionales, Madrid, pp. 272–273.

Bernárdez, J.G., Blanco-Dios, J.B., Mouriño, J., Rigueiro-Rodríguez, A., 2011. Flora y vegetación del Archipiélago de Cortegada (Parque Nacional Marítimo-Terrestre de las Islas Atlánticas de Galicia). Naturaleza y Parques Nacionales, Serie técnica. Organismo Autónomo de Parques Nacionales, Guadalajara, p. 434.

Blackall, T.D., Wilson, L.J., Bull, J., Theobald, M.R., Bacon, P.J., Hamer, K.C., Wanless, S., Sutton, M.A., 2008. Temporal variation in atmospheric ammonia concentrations above seabird colonies. Atmos. Environ. 42, 6942–6950. https://doi.org/10.1016/j.atmosenv.2008.04.059.

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidso, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., De Vries, W., 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecol. Appl. 20, 30–59. https://doi.org/10.1890/08-1140.1.

Bukacinski, D., Rutkowska, A., Bukacinska, M., 1994. The effect of nesting black-headed gulls (Larus ridibundus L.) on the soil and vegetation of a Vistula River island, Poland. Ann. Bot. Fenn. 31 (4), 233–243. https://www.jstor.org/stable/43922218.

Buurman, P., Van Lagen, B., Velthorst, E.J., 1996. Manual for Soil and Water Analysis. Backhuys publishers, Leiden, p. 314.

Carballeira, A., Devesa, C., Retuerto, R., Santillán, E., Ucieda, F., 1982. Bioclimatología de Galicia. Fundación Barrié de la Maza, A Coruña, p. 391.

Cramp, S., Simmons, K.E.L., 1983. Handbook of Birds of Europe, the Middle East and North Africa: the Birds of the Western Palearctic, vol. 3. Oxford University Press, Oxford, p. 906. Waders to gulls.

Croxall, J.P., Butchart, S.H.M., Lascelles, B., Stattersfield, A.J., Sullivan, B., Symes, A., Taylor, P., 2012. Seabird conservation status, threats and priority actions: a global assessment. Bird. Conserv. Int. 22, 1–34. https://doi.org/10.1017/S0959270912000020, 01.

De la Peña-Lastra, S., 2021. Seabird droppings: effects on a global and local level. Sci. Total Environ. 754, 142148. https://doi.org/10.1016/j.scitotenv.2020.142148.

del Hoyo, J., Elliott, A., Sargatal, J., 1996. Handbook of the Birds of the World, vol. 3. Hoatzin to Auks. Lynx editions, Barcelona, 821pp.

Erskine, P.D., Bergstrom, D.M., Schmidt, S., Stewart, G.R., Tweedie, C.E., Shaw, J.D., 1998. Subantarctic Macquarie Island - a model ecosystem for studying animal-derived nitrogen sources using 15 N natural abundance. Oecologia 117 (1–2), 187–193. https://doi.org/10.1007/s004420050647.

Furness, R.W., 1991. The occurrence of burrow-nesting among birds and its influence on soil fertility and stability. Symp. Zool. Soc. Lond. 63, 53–67.

García, L.V., Marañón, T., Ojeda, F., Clemente, L., Redondo, R., 2002. Seagull influence on soil properties, chenopod shrub distribution, and leaf nutrient status in semi-arid Mediterranean islands. Oikos 98, 75–86. https://doi.org/10.1034/j.1600-0706.2002.980108.x.

Guitián, J., Guitián, P., 1990. A paisaxe vexetal das illas Cíes. Santiago de Compostela: Xunta de Galicia, p. 600.

Haffer, J., 1982. Systematik und Taxonomie der *Larus argentatus* − Artengruppe. In: Glutz, U.N., Bauer, K.M. (Eds.), Handbuch der Vögel Mitteleuropas, vol. 8. Wiesbaden Akademisches Verlagsgesellschat, Wiesbaden, pp. 502–515.

Hahn, S., Bauer, S., Klaassen, M., 2007. Estimating the contribution of carnivorous waterbirds to nutrient loading in freshwater habitats. Freshw. Biol. 52, 2421–2433. https://doi.org/10.1111/j.1365-2427.2007.01838.x.

Hobara, S., Koba, K., Osono, T., Tokuchi, N., Ishida, A., Kameda, K., 2005. Nitrogen and phosphorus enrichment and balance in forests colonized by cormorants: implications of the influence of soil adsorption. Plant Soil 268 (1), 89–101. https://doi.org/10.1007/s11104-004-0231-6.

Hogg, E.H., Morton, J.K., 1983. The effects of nesting gulls on the vegetation and soil of islands in the Great Lakes. Can. J. Bot. 61, 3240–3254. https://doi.org/10.1139/b83-361.

Izquierdo, R., Benítez-Nelson, C.R., Masqué, P., Castillo, S., Alastuey, A., Àvila, A., 2012. Atmospheric phosphorus deposition in a near-coastal rural site in the NE Iberian Peninsula and its role in marine productivity. Atmos. Environ. 49, 361–370. https://doi.org/10.1016/j.atmosenv.2011.11.007.

Krupa, S.V., 2003. Effects of atmospheric ammonia (NH_3) on terrestrial vegetation: a review. Environ. Pollut. 124, 179–221. https://doi.org/10.1016/S0269-7491(02)00434-7.

Mahowald, N., Jickells, T.D., Baker, A.R., Artaxo, P., BenitezNelson, C.R., Bergametti, G., Bond, T.C., Chen, Y., Cohen, D.D., Herut, B., Kubilay, N., Losno, R., Luo, C., Maenhaut, W., McGee, K.A., Okin, G.S., Siefert, R.L., Tsukuda, S., 2008. Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts. Global Biogeochem. Cycles 22, GB4026. https://doi.org/10.1029/2008GB003240.

Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of the mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15, 1409–1416. https://doi.org/10.1080/00103628409367568.

METEOGALICIA-Xunta de Galcia, 2015. Consellería de Medio Ambiente, Territorio e Infraestruturas - Xunta de Galicia Santiago de Compostela. A Coruña. Disponible en. http://www.meteogalicia.es/galego/observacion/estacions/Consulta:Marzo_de_2015.

Miller, G.C., 1982. Changes in plant distribution and island size accompanying white pelican nesting. Colon. Waterbirds 5, 73–78. https://www.jstor.org/stable/1521037.

Molina, B. (Ed.), 2009. Gaviota reidora, sombría y patiamarilla en España. Población en 2007-2009 y método de censo. SEO/BirdLife, Madrid, p. 166.

Mulvaney, R.L., 1996. Nitrogen-Inorganic forms. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H. (Eds.), Methods of Soil Analysis. Part 3. Chemical Methods. USA: SSSA Book Ser. 5.3. SSSA. ASA, Madison, WI, pp. 1123–1184.

Munilla, I., 1997. Estudio de la población y la ecología trófica de la gaviota patiamarilla, Larus cachinnans Pallas, en Galicia. PhD Dissertation, Facultad de Biología, Universidad de Santiago de Compostela).

Nemitz, E., Sutton, M.A., Schjoerring, J.K., Husted, S., Wyers, G.P., 2000. Resistance modelling of ammonia exchange over oilseed rape. Agric. For. Meteorol. 105, 405–425. https://doi.org/10.1016/S0168-1923(00)00206-9.

Oro, D., Jover, L., Ruiz, X., 1995. Influence of trawling activity on the breeding ecology of a threatened seabird, Audouin's gull Larus audouinii. Mar. Ecol. Prog. Ser. 139, 19–29.

Otero, X.L., 1998. Effects of nesting yellow-legged gulls (*Larus cachinnans* Pallas) on the heavy metals content of soils in Cíes Islands (Galicia-NW Spain). Mar. Pollut. Bull. 36, 267–272. https://doi.org/10.1016/S0025-326X(98)80010-6.

Otero, X.L., Fernández-Sanjurjo, M.J., 2000. Seasonal variation in inorganic nitrogen content of soils from breeding sites of yellow-legged gulls (Larus Cachinnans) in the Cies Islands Natural Park (NW Iberian Peninsula). Fresenius Envion 8, 685–692.

Otero, X.L., Mouriño, J., 2002. Nitrogeno (NH_4^+, NO_3^-), Fosforo asimilable y Metales traza (Hg, Cd, Pb, Zn, Ni y Cu) en suelos de la colonia de la gaviota patiamarilla (*Larus cachinnans*) en el Parque Natural de las Islas. Cuad. Soc. Esp. Cien. For. 14, 143–149.

Otero, X.L., Pérez-Alberti, A., 2009. Parque Nacional de Marítimo Terrestre de las Islas Atlánticas de Galicia. Lunwerg, Barcelona, p. 310.

Otero, X.L., Tejada, O., Martín-Pastor, M., De la Peña, S., Ferreira, T.O., Pérez-Alberti, A., 2015. Phosphorus in seagull colonies and the effect on the habitats. The case of yellow-legged gulls (*Larus michahellis*) in the Atlantic Islands National Park (Galicia-NW Spain). Sci. Total Environ. 532, 383–397. https://doi.org/10.1016/j.scitotenv.2015.06.013.

Otero, X.L., De La Peña-Lastra, S., Pérez-Alberti, A., Ferreira, T.O., Huerta-Díaz, M.A., 2018. Seabird colonies as new global drivers in the nitrogen and phosphorus cycles. Nat. Commun. 9, 246. https://doi.org/10.1038/s41467-017-02446-8.

Pérez, C., Baros, Á., Velando, A., Munilla, I., 2012. Seguimento das poboacións reproductoras de corvo mariño (*Phalacrocorax aristotelis*) e gaivota patimarela (*Larus michahellis*) do Parque Nacional das Illas Atlánticas de Galicia (Unpublished report).

Phoenix, G.K., Hicks, W.K., Cinderby, S., Kuylenstierna, J.C.I., Stock, W.D., Dentener, F.J., Giller, K.E., Austin, A.T., Lefroy, R.D.B., Gimeno, B.S., Ashmore, M.R., Ineson, P., 2006. Atmospheric nitrogen deposition in world biodiversity hotspots: the need for a greater global perspective in assessing N deposition impacts. Global Change Biol. 12, 470–476. https://doi.org/10.1111/j.1365-2486.2006.01104.x.

Portnoy, J.W., 1990. Gull contribution of phosphorus and nitrogen to a Cape Cod Kettle pond. Hydrobiologia 202, 61–69. https://doi.org/10.1007/BF00027092.

Riddick, S., 2012. Global Ammonia Emissions from Seabird Colonies. PhD Dissertation. King's College, London, 2012.

Riddick, S.N., Dragosits, U., Blackall, T.D., Daunt, F., Wanless, S., Sutton, M.A., 2012. The global distribution of ammonia emissions from seabird colonies. Atmos. Environ. 55, 319–327. https://doi.org/10.1016/j.atmosenv.2012.02.052.

Riddick, S.N., Dragosits, U., Blackall, T.D., Daunt, F., Braban, C.F., Tang, Y.S., MacFarlane, W., Taylor, S., Wanless, S., Sutton, M.A., 2014. Measurement of ammonia emissions from tropical seabird colonies. Atmos. Environ. 89, 35–42. https://doi.org/10.1016/j.atmosenv.2014.02.012.

Riddick, S.N., Blackall, T.D., Dragosits, U., Tang, Y.S., Moring, A., Daunt, F., Wanless, S., Hamer, K.C., Sutton, M.A., 2017. High temporal resolution modelling of environmentally-dependent seabird ammonia emissions: description and testing of the GUANO model. Atmos. Environ. 161, 48–60. https://doi.org/10.1016/j.atmosenv.2017.04.020.

Rodríguez-Lado, L., Macías, F., 2006. Eutrophication trends in forest soils in Galicia (NW Spain) caused by the atmospheric deposition of nitrogen compounds. Chemosphere 63 (9), 1598–1609. https://doi.org/10.1016/j.chemosphere.2005.08.072.

Smith, J.S., Johnson, C.R., 1995. Nutrient inputs from seabirds and humans on a populated coral cay. Mar. Ecol. Prog. Ser. 124, 189–200. https://doi.org/10.3354/meps124189.

Sobey, G.G., Kenworthy, J.B., 1979. The relationship between herring gulls and the vegetation of their breeding colonies. J. Ecol. 67, 469–496. https://www.jstor.org/stable/2259108.

Sutton, M.A., Reis, S., Riddick, S.N., Dragosits, U., Nemitz, E., Theobald, M.R., Tang, Y.S., Braban, C.F., Vieno, M., Dore, A.J., Mitchell, R.F., Wanless, S., Daunt, F., Fowler, D., Blackall, T.D., Milford, C., Flechard, C.R., Loubet, B., Massad, R., Cellier, P., Personne, E., Coheur, P.F., Clarisse, L., Van Damme, M., Ngadi, Y., Clerbaux, C., Skjoth, C.A., Geels, C., Hertel, O., Kruit, R.J.W., Pinder, R.W., Bash, J.O., Walker, J.T., Simpson, D., Horvath, L., Misselbrook, T.H., Bleeker, A., Dentener, F., de Vries, W., 2013. Towards a climate-dependent paradigm of ammonia emission and deposition. Philosophical Trans. R. Soc. B-Biological Sci. 368, 20130166. https://doi.org/10.1098/rstb.2013.0166.

Vidal, E., Medail, F., Tatoni, T., 1998. Is the yellow-legged gull a superabundant bird

species in the Mediterranean? Impact on fauna and flora, conservation measures and research priorities. Biodivers. Conserv. 7 (8), 1013–1026. https://doi.org/10.1023/A:1008805030578.

Wilson, L.J., Bacon, P.J., Bull, J., Dragosits, U., Blackall, T.D., Dunn, T.E., Hamer, K.C., Sutton, M.A., Wanless, S., 2004. Modelling the spatial distribution of ammonia emissions from seabirds in the UK. Environ. Pollut. 131, 173–185. https://doi.org/10.1016/j.envpol.2004.02.008.

Zhu, R.B., Kong, D.M., Sun, L.G., Geng, J.J., Wang, X.R., Glindemann, D., 2006. Tropospheric phosphine and its sources in coastal Antarctica. Environ. Sci. Technol. 40, 7656–7661. https://doi.org/10.1021/es061601e.

Zhu, R., Liu, Y., Sun, J., Sun, L., Geng, J., 2009. Stimulation of gaseous phosphine production from Antarctic seabird guanos and ornithogenic soils. J. Environ. Sci. 21 (2), 150–154. https://doi.org/10.1016/S1001-0742(08)62243-3.

Zhu, R., Wang, Q., Ding, W., Wang, C., Hou, L., Ma, D., 2014. Penguins significantly increased phosphine formation and phosphorus contribution in maritime Antarctic soils. Sci. Rep. 4, 7055. https://doi.org/10.1038/srep07055.

Zwolicki, A., Zmudczyńska-Skarbek, K., Richard, P., Stempniewicz, L., 2016. Importance of marine-derived nutrients supplied by planktivorous seabirds to high arctic tundra plant communities. PloS One 11 (5), e0154950. https://doi.org/10.1371/journal.pone.0154950.