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The Rapid Effects of Yellow-Legged Gull (*Larus michahellis*) Colony on Dune Habitats and Plant Landscape in the Atlantic Islands National Park (NW Spain)

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Abstract: The Atlantic Islands of Galicia Maritime/Terrestrial National Park hosts one of the largest breeding colonies of yellow-legged gull (*Larus michahellis*) in the world. In 2002, a new yellow-legged gull breeding colony was established on the Punta Muxieiro dune complex, which also harbors rare and threatened plant species and habitat types of community interest according to Directive 92/43/EEC. This study assesses the effect of this colony on two habitats of community interest: white dunes and grey dunes. For this purpose, plant cover and soil properties, composition, and nutrient content were monitored in plots with different gull densities. Moreover, historic aerial images were compiled to observe changes in the plant landscape of the dune system. The results showed that, despite the recentness of the occupation of the dune system by yellow-legged gull species, significant changes in acidic–alkaline processes and nutrient availability were already observed in soils. Soils in plots with higher gull density showed more acidic pH values and a higher content of the most labile N and P fractions. Moreover, a decrease in plant cover and number of species was also demonstrated in plots with higher gull densities. Finally, the presence of ruderal and alien species such as *Urtica membranacea* and *Parietaria judaica* was also observed.

Keywords: gull; nitrogen; phosphorus; soil; dune plants

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1. Introduction

The high densities of seabirds that are sometimes reached in areas occupied by breeding colonies can dramatically alter these sites over time. Trampling, plant uprooting for nest building, and soil eutrophication are the main causes for the significant changes in vegetation with respect to the surrounding areas [1–3]. Some studies have shown an increase in plant diversity [4,5]. For instance, Magnusson and Magnusson [4] found an increase in plant diversity in Surtsey (Iceland) from 1990 to 1998. Conversely, others have shown that it virtually disappeared [6,7]. For example, Miller [6] studied the evolution of an island in Colorado after nine breeding seasons of American white pelican (*Pelecanus erythrorhynchos*) and observed the disappearance of 30% of the plant-covered area in the island due to an erosion–deposition imbalance, along with an 85% decrease in the area covered by sandbar willow (*Salix exigua*). Generally, the appearance of ruderal and annual species is observed in most cases, at the expanse of species with a long life cycle, such as camephytes (e.g., *Armeria maritima*) [8–12].

Moreover, studies on colonies that had been abandoned, sometimes for centuries, or whose populations had been substantially reduced showed that changes persist over time, particularly those affecting nutrient content in soils. The impact of seabird colonies is, therefore, irreversible [9,12,13].

This research assesses the effects of the breeding colony of yellow-legged gull (*Larus michahellis*) on plants and soils in a dune system within the Atlantic Islands of Galicia Maritime-Terrestrial National Park (AINP) in the NW Spain), which hosts one of the most important colonies of this species in the world (10,800 breeding pairs in 2015), as well as dune habitats with a high environmental value, such as grey dunes, rare and threatened dune species such as *Corema album* and *Armeria pungens*, or endemic species such as *Iberis procumbens* [14].

The first dune vegetation belt (embrionary and white dunes) is characterized by the dominance of graminoid species (*Elymus farctus, Ammophila arenaria*) capable of withstanding the adverse conditions generated by the proximity to the sea, such as strong winds and mobile sandy substrate. However, as we move away from the area closest to the sea, and environmental conditions improve, biodiversity and vegetation cover increase. The former communities are replaced by cameophyt and bryophyte (brown dunes) [14].

The main aim of our study was to assess the impact of a yellow-legged gull colony, which has recently settled on a dune area of high environmental value within the AINP, on plant cover and seasonal dynamics of nutrients in soils. Therefore, plant abundance and community structure, as well as differences among plots, were studied [15]. An attempt was also made to identify the plant species that are the most dependent on nutrient enrichment by the yellow-legged gull and to describe their response along a fertilization gradient. Finally, the changes in the landscape caused by these seabirds were studied using satellite images from 2004 to 2017.

2. Materials and Methods

2.1. Study Area

The study was performed in the Cíes Islands, within the Atlantic Islands of Galicia Maritime-Terrestrial National Park (AINP), located in the NW Iberian Peninsula (Figure 1). The climate in the Cíes islands is classified as temperate with an average temperature of 13.8 °C and an average annual rainfall of 877 mm. The mean annual rainfall recorded in the Cíes Islands in 2016 was 1175 mm, of which 874 mm corresponded to the period between the beginning of the year and late September; more than 90% concentrated between January and May [16].

In 2002, the yellow-legged gull established a new breeding colony in the Punta Muxieiro dune complex, which can potentially threaten the conservation of dune habitats and some of the rare and threatened species found in this dune system (e.g., *Corema album*, *Armeria pubigera,* and *Iberis procumbens*). In this dune system, several plots were established, for which vegetation and soils were sampled. Plots were placed according to the higher or lower presence of gulls at the beginning of the study. We assumed that dune areas with less than 2–5 nests within an area of 100 m^2 area were weakly influenced by gulls, whereas those with 10–20 nests/100 m^2 were strongly affected by the gulls' presence; observations by natural park rangers were also taken into consideration for this classification.

Additionally, a second dune site located in the Nosa Señora beach was studied. The latter was considered a control site due to the absence of gulls (Figure 1 and Table 1).

2.2. Floristic Inventories and Soil Sampling

A floristic inventory and soil sampling were carried out in 2016. For this purpose, six permanent plots (approximately 7 × 5 m) were previously established in Punta Muxieiro (Figure 1 and Table 1; for more details, see [1]). Plot locations were selected according to gull influence and to the distribution of the main plant communities described by previous studies and reports [14]. The influence of gulls on the dune system was established based on gull censuses previously carried out by the AINP between 2011 and 2015, during which period the Punta Muxieiro colony went from 108 to 217 breeding pairs [17–19].

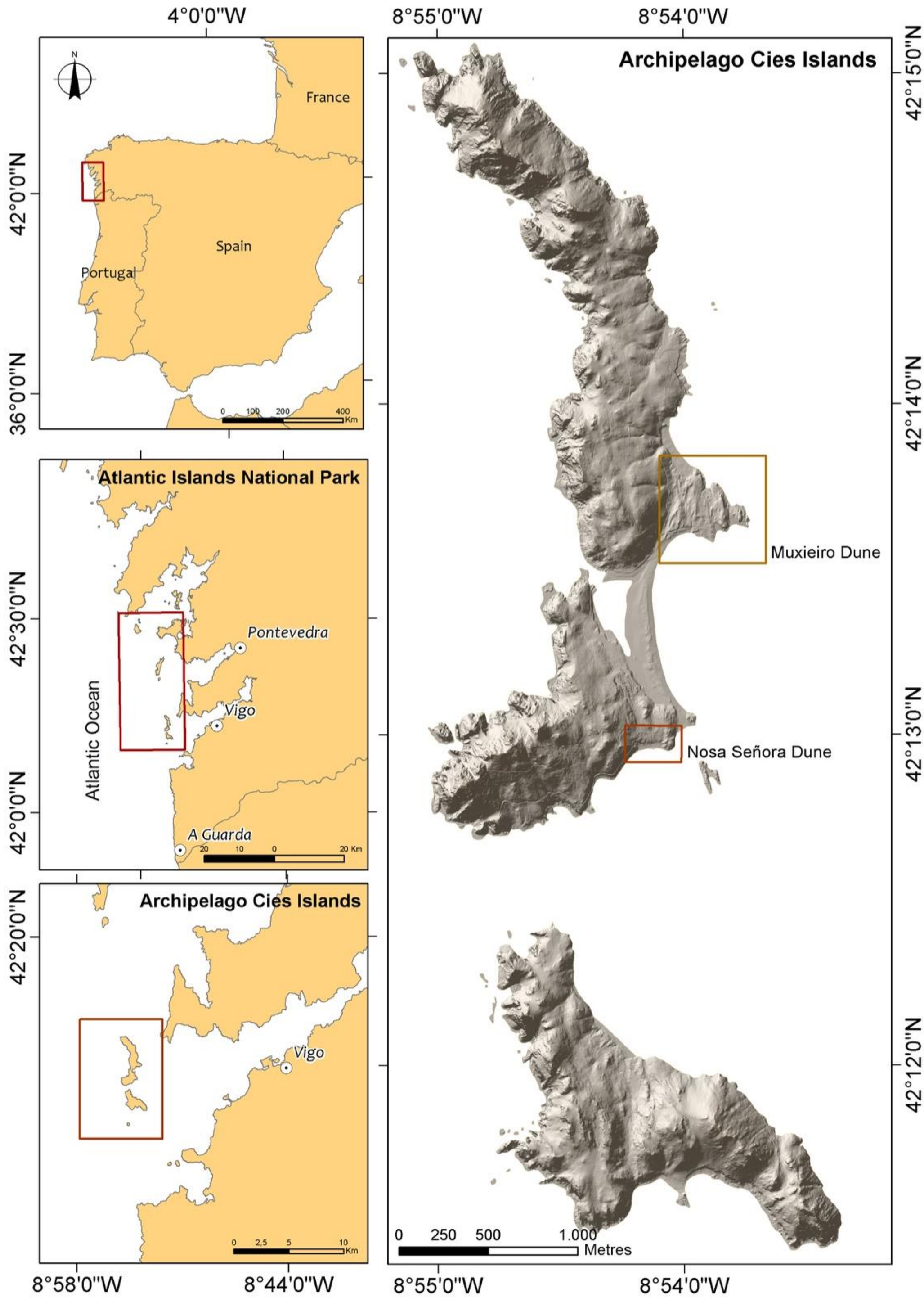

Figure 1. Location of the study area. Muxieiro dune corresponds to the colony of yellow-legged gullsgeoder, whereas Nosa Señora dune is the control plot (CP, without gulls).

Two plots were located within the white dune habitat (Habitat directive 92/43/CEE: 2120 Shifting dunes along the shoreline with *Ammophila arenaria*)—one with low and one with high gull density. Four plots were established in the grey dune area (Habitat directive 92/43/CEE: Fixed coastal dunes with herbaceous vegetation)—two plots with low and two with high gull density. Finally, a single plot was installed in the dunes in Nosa Señora beach (Figure 1 and Table 1), considered a control site (CP; no gulls). The dune in Nosa Señora beach is the only dune system available in the Cíes Islands archipelago that has no gull influence while reproducing similar conditions to those in the Punta Muxieiro dunes.

Table 1. General characteristics of the sampling sites. Huse 29T.

Plot	Coordinates ETRS89	Type of Vegetation	Seagull Influence
White Dune (WDLI)	508439 4675059	*Otantho-Ammophiletum australis*	Low
White Dune (WDHI)	508440 4675073	*Otantho-Ammophiletum australis*	High
Gray Dune (GDLI) (two plots)	508243 4675121; 508249 4675052	*Scrophulario-Vulpietum alopecuroidis;* *Ulici-Coremetum albae*	Low
Gray Dune (GDHI) (two plots)	508248 4675072; 508294 4675120	*Scrophulario-Vulpietum alopecuroidis*	High
Control Plot (CP)	508109 4673837	*Scrophulario-Vulpietum alopecuroidis*	Absence

The floristic inventory and soil sampling were carried out in two different seasons—summer (August), corresponding to the end of the breeding season and coinciding with the moment with the highest possible impact of gulls on soils, and early spring (March), which marks the end of the period without any presence of gulls (which spans from October to February), as well as the end of the rainy season [1]. Both for floral inventory and for soil sampling, a 50 $\times$ 50 cm square was tossed into the air 10 times per plot, which resulted in 70 surveyed subplots. Inside each square, plant species were inventoried, their cover percentage was determined, and a soil sample was collected. For each vegetation plot, species of vascular plants and mosses were recorded using a Braun–Blanquet 7-degree cover-abundance scale [20].

2.3. Study of Vegetation Cover by Image Analysis

A series of eleven images were georeferenced using ArcGIS software version 10.0 (ESRI, Inc. 2010) to assess small-scale changes in plant cover of sand dunes for the period (2004–2017): 2004–2005, 2008, 2010, 2014 PNOA Ortophotographs (CNIG—Ministerio de Fomento, Spanish Government; https://www.cnig.es/); and aerial photographs taken on 8 September 2009, 18 April 2010, 5 May 2010, 20 March 2011 Image © 2018 DigitalGlobe (Google Earth); 30 Agust 2013, 9 July 2016, 16 June 2017 Image Landsat/Copernicus (Google Earth). Georeferencing mean square error was ±5.23 m.

Images of the plots were exported as tagged image file format with 600 dpi resolution and transformed to 8-bit grayscale (256 grayscale levels). Images were then analyzed with the image processing software Image J [21]. Automatic thresholding was performed for both the white and gray dune areas using an iterative procedure based on the IsoData algorithm [22]: threshold = (average background (white dune) + average objects (gray dune))/2. The percentages of vegetation cover from the two gray dune and white dune plots were averaged to obtain a general trend for each soil type.

The three images from the year 2010 of the time series were used to assess the error in the calculation of the white dune and gray dune areas using photographs of different quality and taken within a four-month period.

2.4. Soil Analysis

Soil analysis was performed on the fine earth fraction (<2 mm), and electrical conductivity (EC) was determined by measurement in a soil–water suspension (1:5); pH was determined from a 1:2.5 water solution [23]; granulometry was determined by the Robinson pipette method; total organic C(TOC) and total nitrogen (TN) were determined by a Leco Truspec CHN device after carbonate removal using HCl. Exchangeable ammonium ($N\text{-}NH_4^+$) and nitrate ($N\text{-}NO_3^-$) were extracted from 5 g of wet soil and 50 mL of KCl 2M solution [24]. Total phosphorus (TP) was obtained from ground samples after having subjected them to attack with concentrated nitric and hydrochloric acid (9:3 v/v) in a microwave, while bioassimilable P (P-bio) was extracted using the Mehlich 3 method [25]. Both forms of P were determined on a spectrophotometer at an 880 ηm wavelength.

2.5. Statistical Analysis

Differences in plant cover and soil nutrient content among plots under different influences of gulls and seasonal differences within each plot were established by one-way ANOVA, followed by a nonparametric test (Holm–Sidak and Dunn test). To analyze differences among plant cover based on inventories carried out in the studied dunes, a Mann–Whitney test was performed for some of the most representative species: *Ammophila arenaria australis, Armeria pungens, Artemisia crithmifolia, Calystegia soldanela, Crucianella maritima, Helichrysum picardii virecens, Iberis procumbens, Lagurus ovatus, Pancratium maritimum, Pleurochaete squarrosa, Seseli tortuosum*, bare soil, and plant biodiversity. Trends in the percentage of vegetation cover between the plots were compared using a Pearson´s correlation matrix, and the level of significance was obtained by Student's *t*-test. Statistical analyses were performed using SigmaStat software version 3.5.

Additionally, canonical correspondence analysis (CCA, ref. [26]) was used to determine the links between species assemblages and constraining environmental factors (edaphic parameters, controlled and uncontrolled experimental factors). Partial canonical correspondence analyses (pCCA) and variance partitioning (VP) were used to differentiate the effects of the different explanatory factors. CCA was performed using the package ade4 [27], while pCCA and VP were performed using the package vegan [28].

3. Results

3.1. Floristic Inventories and Plant Cover

The highest species number was observed in the white and gray dunes in Punta Muxieiro (21 species) with low gull densities, as well as in the control site (20 species) (Table S1), while dunes with high presences of gulls showed a substantial decrease in the number of species. In winter, the number of species also decreased in dunes with the presence of gulls, unlike in the control site.

Plant cover was generally lower in dune plots with a high presence of gulls, both in the white dune and in the grey dune. The species with the highest cover values were *Ammophila arenaria australis, Seseli tortuosum, Crucinella maritima*, and *Pleurochaete squarrosa*, in the grey dune, and *Helicrisum picardii* in the white dune (Figure S1). Finally, it is worth noting that the presence of ruderal species such as *Urtica membranacea* and *Parietaria Judaica* was observed in dunes with higher gull influence.

3.2. Study of Plant Cover Using Satellite Images

The evolution of the plant cover percentage on dunes (Figure 2) showed a general trend across all plots, with an increase in 2009, followed by a period of stability until 2011, with the only exception of a sharp decrease in plot WDH. However, the cover percentage during this period was very similar among all plots. The first colonization event known since records are available has led to a marked difference in plant cover between plots, mainly between those on the gray dune and white dune.

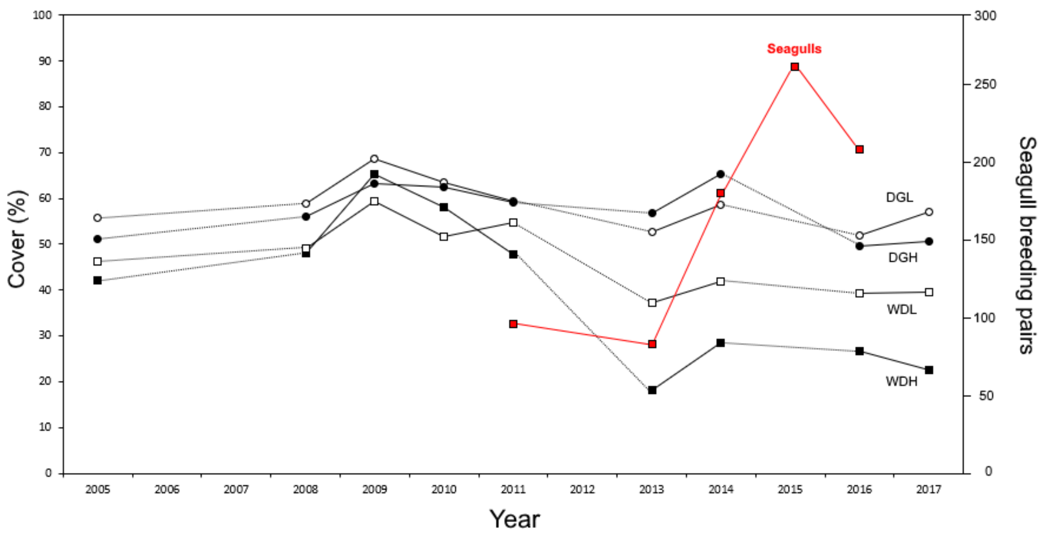

Figure 2. Evolution of plant cover in each plot against the number of breeding gull pairs for the 2005–2007 period.

Plant cover in all the plots fell during the years 2011–2013, after the first colonization event by seagulls. The decrease in cover was more pronounced in the white dune, with WDL (−29.76%) and WDH (−17.65%), and more attenuated in the gray dune, with GDL (−6.54%) and GDH (−2.30%). The threshold value to delimit a change in trend was a mean percentage of intra-annual error of 2.5 (0.47–6.13) obtained from three images with different characteristics from the year 2010 and with the same plant cover percentage values. In the 2013–2014 period, plant cover grew in all plots, as the number of gull breeding pairs increased (+98), especially in high-occupancy plots (GDH (+8.44%) and WDH (+10.00%)) and only slightly in those with low occupancy (GDL (+5.90%) and WDL (+4.68%)). The number of gull breeding pairs grew during the 2014–2015 period (+78) and decreased in the 2016–2017 period (−41); however, the number of gulls during the 2016–2017 period (260−219) stabilized at twice the number of existing ones in the 2011–2013 period (108–84). Plant cover values in the 2016–2017 period remained stable below the threshold value (0.47–6.13), while the number of gulls increased in the white dune plots, with WDL (−1.67%) and WDH (−2.64%). Conversely, plant cover decreased in gray dune plots, with GDL (−6.85%) and GDH (−15.60%). In 2017, changes in plant coverage remained stable in all plots, compared with the previous year (<6%). The plots with the lower influence of breeding pairs showed lower variability in plant cover, while those with greater numbers of breeding pairs showed higher plant cover percentages. Only plot WDH did not show a final recovery due to its greater fragility and its high gull influence (Table 2).

There was no statistical linear correlation between the trends in the number of gull breeding pairs and plant coverage in the plots. However, a statistical correlation was found between the trends in plant cover in plot GDL and those in plots WDL and WDH (p-value < 0.05) (Table S2).

In addition, Figure 3 shows annual changes in plant landscape at a smaller scale. As mentioned above, plant landscape showed greater plant cover values during the first years after colonization of the Punta Muxieiro dunes by gulls (2004–2008), later decreasing in 2014 due to the cumulative effect of pressure over time and due to the increase in colony size.

3.3. Soil Properties and Nutrient Concentration

In all plots, soils were Arenosol (sand fraction > 90%; data not shown) according to the IUSS Working Group WRB (2015), showing low TOC contents (generally < 1%), slightly alkaline reaction (pH 8.1–9.2), and very low electrical conductivity (<0.12 dS m^{-1})

(Tables S2 and S3). As for nutrient concentration, generally nitrogen ($N\text{-}NH_4^{+}$, $N\text{-}NO_3^{-}$) and phosphorus (P-bio, TP) forms, the lowest values were found in the control plot, while the highest ones corresponded to dunes with seabird influence. The spatiotemporal variations found in the content of N and P forms are discussed in more detail below.

Table 2. Statistical linear correlation between the trends in the number of gull breeding pairs and the vegetation coverage in the plots. White dune with low gull influence (WDLI), white dune with high gull influence (WDHI) and, with the highest values, grey dune with low (GDLI) and high (GDHI) in-fluence of yellow-legged gull.

Pearson Correlation	GDLI	GDHI	WDLI	WDHI
Seagull influence	−0.220	−0.521	−0.361	−0.224
GDLI		0.698	0.861	0.855
GDHI			0.521	0.482
WDLI				0.958
WDHI				
***p*-value**	**GDLI**	**GDHI**	**WDLI**	**WDHI**
seagulls	0.723	0.368	0.551	0.717
GDLI		0.036	0.003	0.003
GDHI			0.151	0.189
WDLI				<0.0001
WDHI				

3.3.1. Total Nitrogen (TN) and Inorganic Nitrogen ($N\text{-}NH_4^{+}$, $N\text{-}NO_3^{-}$)

The control plot (CP) showed the lowest values for both N forms, followed by the white dune with low gull influence (WDLI) and white dune with high gull influence (WDHI), and then the highest values in grey dune with low (GDLI) and high (GDHI) influence of yellow-legged gull, with significant differences observed between the latter and all other plots (Figure 4).

More specifically, the lowest TN concentrations were recorded during the spring in WDHI and WDLI D (102 ± 96 and 107 ± 154 mg Kg^{-1}, respectively). Conversely, the highest values were obtained in the summer in soils from plots GDHI and GDLI (1083 ± 689 and 624 ± 467 mg Kg^{-1}, respectively). The remaining cases showed intermediate values.

As for inorganic nitrogen forms, the lowest $N\text{-}NH_4^{+}$ concentrations were found in winter in soils from the control plot, with a mean value of 3.14 ± 0.2 mg kg^{-1}, while the highest corresponded to GDHI (10.8 ± 4.9 mg kg^{-1}). For $N\text{-}NO_3^{-}$, the lowest value was recorded in winter in WDLI (3.77 ± 2.0 mg kg^{-1}), while the highest was obtained in the summer in GDHI (19.6 ± 12 mg kg^{-1}). The remaining plots showed intermediate values (Figure 4).

3.3.2. Total Phosphorus (TP) and Bioassimilable Phosphorus (P-Bio)

The lowest TP concentrations were found in soils from the control plot, with negligible seasonal changes (spring: 72.6 ± 14; summer: 71.2 ± 41 mg kg^{-1}), while the highest corresponded to WDHI in the summer (435 ± 131 mg kg^{-1}) (Figure 5). Seasonally, both in summer and in winter, the lowest values were found in the control plot, which were significantly different from those obtained in the remaining plots except for GDLI in spring. Seasonal changes within the same plot were negligible.

As for P-bio, the lowest values corresponded to plot CP (both in winter and in summer) and to winter samples from plots GDLI and WDLI (7.09 ± 4.2 and 13.1 ± 5.6 mg kg^{-1}); in turn, the highest value was observed in WDHI (96.1 ± 59 mg kg^{-1}) (Figure 5).

3.4. Interaction between Soil Conditions and Vegetation

Canonical correspondence analysis showed a clear effect of soil variables on the distribution of plant species (Figure 6). Differentiation between dune types was related to a combination of directions CCA1 and CCA2 (33% and 27%, respectively), characterized by

TP, P-bio, and EC. From bottom left to top right, following the increase in values of these parameters, the grey dune was followed by the white dune with low seagull density, which, in turn, was followed by high seagull density. Ellipses spread mostly along a perpendicular direction characterized by TOC and pH. The CP area was relatively small and exhibited homogeneity of samples across seasons and years. In addition, CP showed the lowest values for all the soil parameters studied except for pH, which had the highest values.

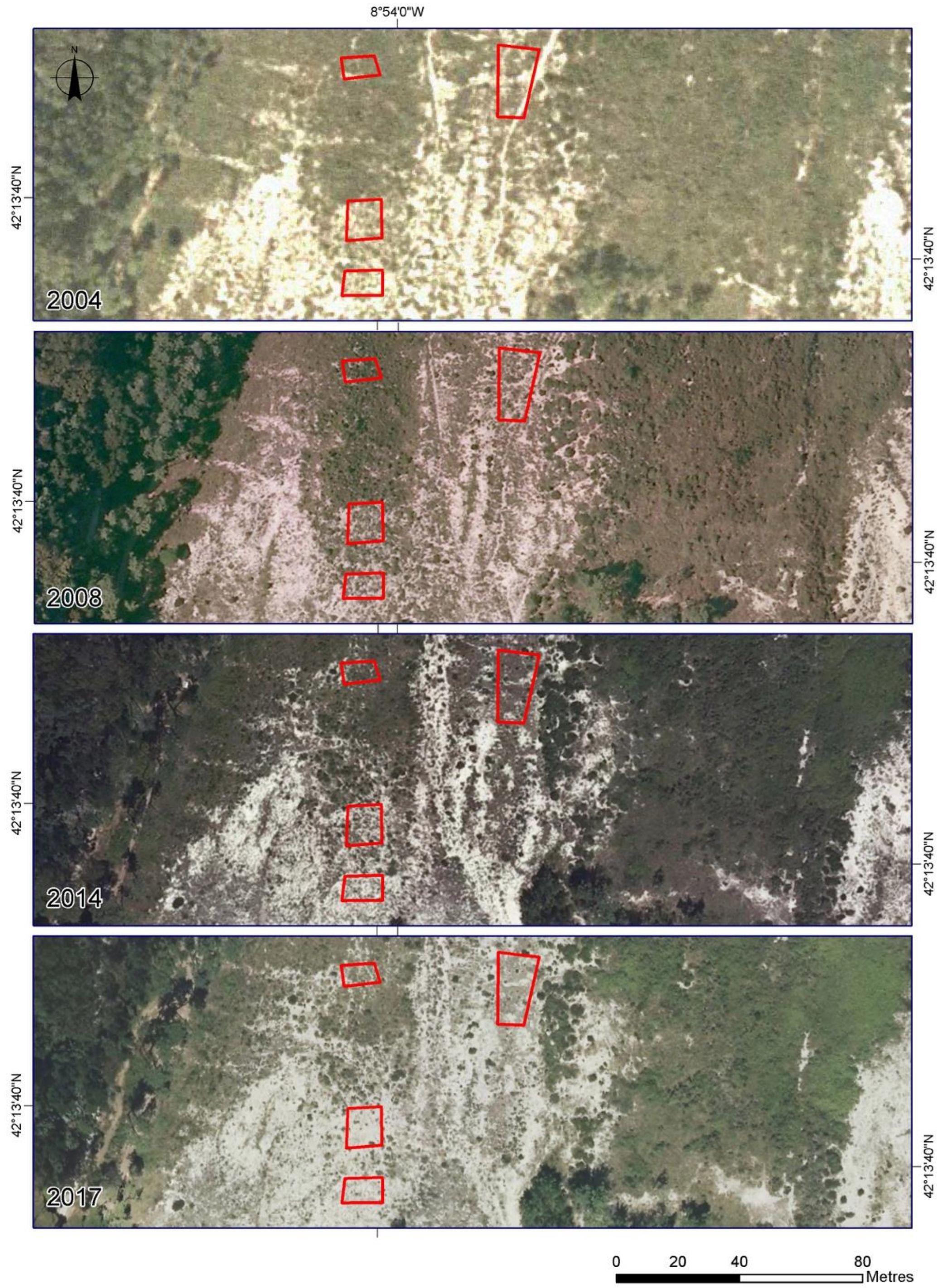

Figure 3. Changes in dune plant landscape for the 2004–2017 period. The locations of the different plots on the Punta Muxieiro dune system are shown in red.

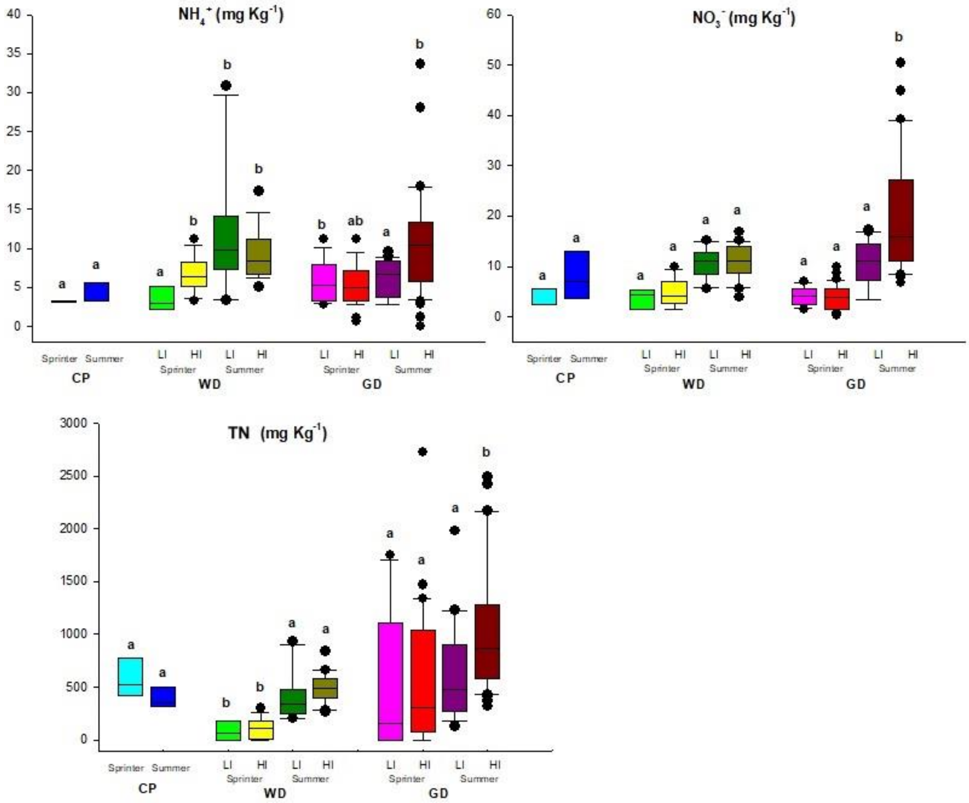

Figure 4. Spatiotemporal variation in the concentrations of total nitrogen (TN) and inorganic N forms ($N\text{-}NH_4^+$, $N\text{-}NO_3^-$) in soils from the control site and from the yellow-legged gull colony. Different letters (a, ab, b) above the boxes indicate significant differences among sites and seasons at the $p < 0.05$ level. CP, control plot; WD, white dune; GD, grey dune; LI, low influence; HI, high influence.

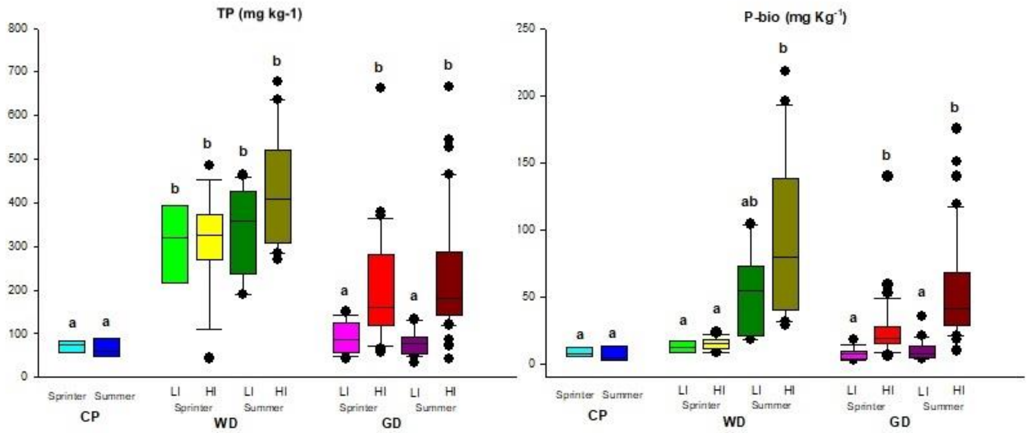

Figure 5. Spatiotemporal variation in the concentrations of total phosphorus (TP) and bioavailable phosphorus (P-bio) in soils from the control site and from the yellow-legged gull colony. Different letters above the boxes indicate significant differences among sites and seasons at the $p < 0.05$ level. CP, control plot; WD, white dune; GD, grey dune; LI, low influence; HI, high influence.

As for vegetation, species seemed to respond well to the environment. Thus, soil parameters were found to explain 51% of plant variability. Therefore, plant species seemed to grow in areas where soil parameters were favorable or not limiting. For example, plant species in the GDLI area were closely related to pH. When this parameter increased, the species *Crucianella maritima* (Crumar), *Calystegia soldanella* (Calsol), and *Artemisia crithmifolia* (Artcri) were present. However, when this parameter decreased, these species were replaced by *Seseli tortuosum* (Sestor), *Daphne gnidium* (Dapni), and *Lagurus ovatus* (Lagova).

Malcolmia littorea (Mallit) and *Sedum album* (Sedalb) were more common in the white dune. It is worth noting the greater coverage of bryophyte *Pleurochaete squarrosa* (Plesqu) in CP, compared with the other plots.

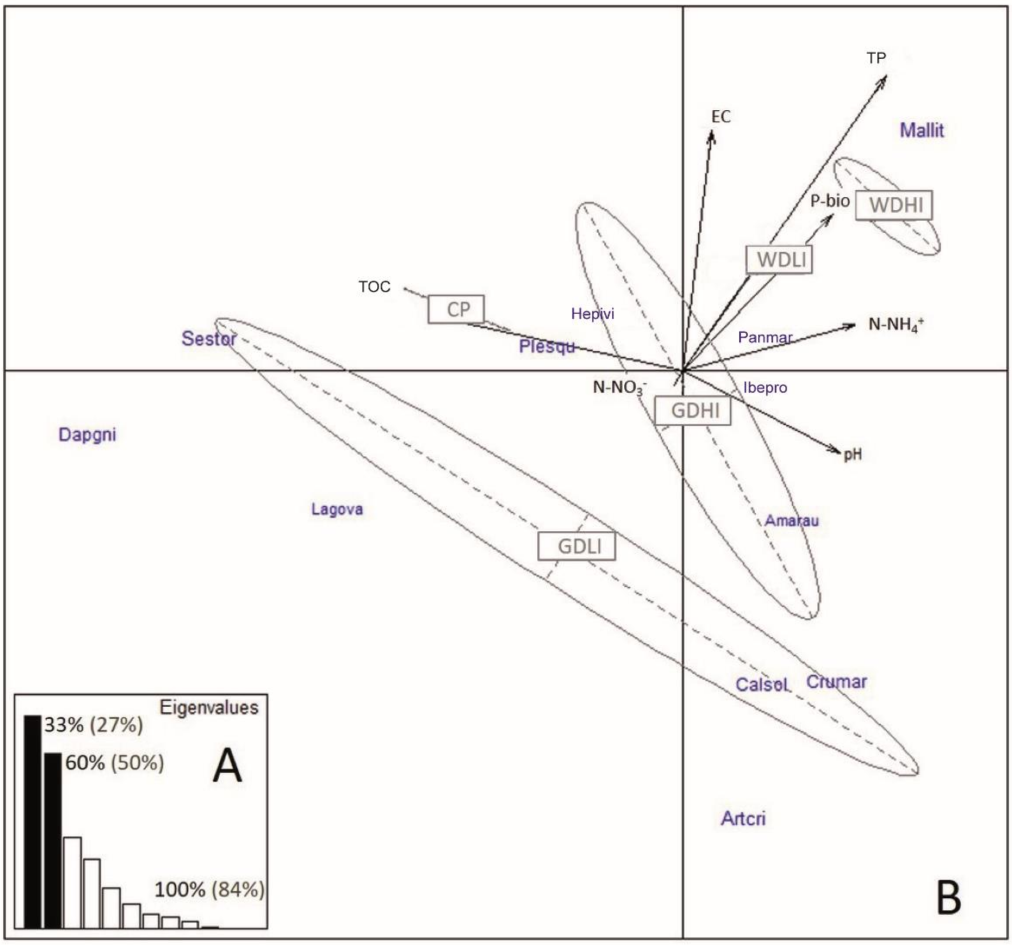

Figure 6. Canonical correspondence analysis on a table with 20 samples × 13 species as explained by 8 soil parameters + dune type: (**A**) cumulative variability decomposition according to successive CCA principal directions showing strong rupture between CCA2 and CCA3. The percentage indicates the cumulative part of the variability explained relative to the total constrained variability of species (dark font) and total unconstrained variability of species (grey); (**B**) CCA triplot representation of samples, species, and explanatory parameters. The mean position and dispersion of each set of samples originating from the same dune type is summed up through an ellipse. Site acronyms: control site, CP (control plot, no gulls); subcolonies with low gull influence: white dune (WDLI) and grey dune (GDLI); subcolonies with high gull influence: white dunes (WDHI) and grey dune (GDHI). In order to determine the influence of gulls on dune vegetation within the AINP, a group of 12 species was selected, corresponding to those identified by previous studies as the most characteristic species of plant communities on dunes in the NW Iberian Peninsula [14]. The selected characteristic and accompanying species in plant communities of dunes in the NW Iberian Peninsula were *Pleurochaete squarrosa* (bryophyte; Plesqu); *Ammophila arenaria australis* (Amarau); *Artemisia crithmifolia* (Artcri); *Calystegia soldanella* (Calsol); *Crucinella maritima* (Crumar); *Helichrysum picardii virescens* (Hepivi); *Daphne gnidium* (Dapgni); *Iberis procumbes* (Ibepro); *Lagurus ovatus* (Lagova); *Malcomia littorea* (Mallit); *Pancratium maritimum* (Panmar); *Sesili tortuosum* (Sestor). Species font size is proportional to their contribution. TP, total phosphorous; TOC, total organic C; EC, electric conductivity. Parameters with relatively high contributions to CCA1 and CCA2 are TP, TOC, NNH4, EC, PBA, GDL, and WDH.

4. Discussion

4.1. Influence of the Yellow-Legged Gull Colony on Dune Vegetation and Habitats

Previous studies had already observed that seabird colonies exert strong pressure on flora, leading to dramatic changes in plant communities [29–31] on cliffs and beaches occupied by colonies. However, the effect that seabird colonies can have on floristic diversity and plant cover is still widely unknown.

Dune environments are essentially averse to plant growth due to their extreme environmental conditions, such as low concentration of water and nutrients, salt spray, episodic overwash, highly permeable substrate, substrate mobility, high irradiation and temperatures, and strong winds [32–34]. In addition, plant communities are extremely fragile to variations such as rising sea levels, changes in marine current dynamics, wind direction, and substrate erosion and compaction [35,36].

The inventories carried out showed that as seabird influence increases, plant cover and number of species decrease, and the area occupied by bare substrate grows. However, not all species displayed the same behavior, as plant cover increased for some species such as *Pancratium maritimum*, while it significantly decreased for others (e.g., *Ammophila arenaria australis*). This may be due to changes in nutrient availability affecting interspecific competition. Therefore, those species with a higher capacity to quickly respond to increases in nutrients have a competitive advantage over those adapted to low levels of these elements [37,38]. For example, as evinced by previous studies, the species *Ammophila arenaria australis* is highly sensitive to variations in nutrient contribution. Thus, this species tends to disappear as a response to increasing nutrient availability [39,40]. Moreover, the presence of ruderal species such as *Urtica membranacea* and *Parietaria Judaica* seems to suggest that alterations caused by the gull colony promote the entry of new species to the dune area, which can act as new competitors against the native flora.

On the other hand, at a larger working scale, analyzing satellite images taken in different years showed that plant cover increased during the first years after the colony settled and under pressure from gulls (years 2004 and 2008), only to later undergo a substantial decrease after 15 years of breeding seasons in some of the plots located in the areas with the highest pressure (2017). As mentioned above, the modification of plant landscape in the dunes is promoted by the intrinsic fragility of the dune environment due to substrate instability and low plant cover (Figure 3) [35].

4.2. The Effect of Seabird Colony on Nutrient Availability

Dune soils, with a sandy texture and alkaline pH, generally show low nutrient concentrations [13,41,42]. Nevertheless, the concentrations of bioassimilable forms of both N and P observed in this study were significantly higher than those in the control site, although differences among dune types were not as clear. Moreover, the highest values were found in the summer and in the plots under the highest gull influence. These results suggest a significant seasonal influence of seabirds on nutrient content in dune soils since, in the winter, a large proportion of the nutrients contributed by gulls are lixiviated from soils. This process is promoted by the sandy texture of the soils [1,30,43–45].

In the case of $N\text{-}NH_4^+$, up to 60% of the initial N present in bird excrement can be lost by volatilization as NH_3, a process that is promoted by the alkaline pH of dune soils (see, e.g., [46–48]). Moreover, nitrification of $N\text{-}NH_4^+$ to $N\text{-}NO_3^-$ also favors its loss by lixiviation during the rainy season since this anion is scarcely adsorbed by the soil's colloidal system [49].

The results found for P seem to suggest an influence of gull colonies on soil over time [1,13]. Phosphate ions are more strongly adsorbed by the soil's colloidal fraction than N forms; in addition, they can precipitate as calcium phosphate in alkaline environments such as dune soils [1,50,51]. For this reason, in the winter, despite the abandonment of the colony by gulls and the increase in rainfall, their lixiviation is not as apparent as that of N forms, and significant differences with the control site persist across seasons.

4.3. Interaction between Soil Conditions and Vegetation

Previous studies have shown that seabird colonies significantly affect plant cover and diversity due to their effect on soils (eutrophication) and to their direct effect on plants (trampling, uprooting of aerial portion, etc.) [4–6,9,11,12]. In our case, changes in soil parameters were found to explain 51% of plant variability. This clear influence is mainly determined by marine influence, which gives white dunes a higher salinity and substrate instability, while the action of gulls leads to increased heterogeneity in soil properties (i.e., higher variability), and the results seem to suggest that some species (e.g., *Malcomia littorea*) are favored by the increase in nutrient availability. In this sense, Baumberger et al. [12] observed that gull colonies lead to changes in plant diversity, promoting ruderal species (e.g., gramineous species, *Urtica membranacea.*, *Parietaria judaica* [52,53]). Moreover, these changes in plant diversity persist after the disappearance of the colony; therefore, changes that occurred both in the substrate and in plant diversity in the Punta Muxieiro dune complex must be considered irreversible [1,12,52,53].

5. Conclusions

Despite the short period of time elapsed, the settlement of a yellow-legged gull breeding colony on the Punta Muxieiro dune system has induced significant changes in soil composition (mainly an increase in nutrient bioavailability) and on plant cover and diversity. These results suggest that, in the medium term, irreversible damage may be caused to the conservation of habitats of community interest (grey and white dunes) and associated plant species. Special attention should be paid to its impact on bryophyte species. Moreover, the enriched nutrient availability in soils can promote colonization by alien ruderal species that can compete with native species.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land11020258/s1, Figure S1: Seasonal inventories, Table S1: plant species, Table S2: interannual changes, Table S3: soil reaction.

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