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DOES SEABIRD COLONY SIZE DETERMINE THE PHYSIOCHEMICAL PROPERTIES OF ISLAND SOILS?

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Abstract

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Many species of gulls have expanded their range worldwide and massively occupied coastal islands. These colonisations have not only affected the biotic interactions among seabird colonies, but also altered the soil chemistry through excrement accumulation. To test whether the seabird colony size determines nutrient levels of island soil, we carried out a field study during a breeding season on six Mediterranean islands in central North Algeria which harbour different population sizes of the yellow-legged gull (*Larus michahellis*). We sampled the soil and measured a suite of physical (area, floral richness, clay, fine silt, large silt, fine sand and large sand content) and chemical (pH, electric conductivity, limestone, organic matter, N, P, Ca, Mg, K and Na) properties and the colony size and density of the yellow-legged gull. Using principal component analysis, we found that the six islands showed some physicochemical similarities, but island area, colony size and soil N and P levels structured the islands into different groups. Although there was evidence of a positive relationship between colony size and N and P soil levels, this relationship was not linear. Our results suggest that historical rather than punctual data on the colony size of seabirds might give more robust predictions of soil physicochemistry of islands.

Key words: gull, marine bird, nests, excrements, insular ecosystem, Mediterranean.

Introduction

Seabird colonies commonly alter the soil chemistry of islands that they occupy for roosting or nesting through accumulation of droppings (McColl, Burger, 1976; Sánchez-Piñero, Polis, 2000). Such alteration may play a key role in structuring communities of plants and other organisms by facilitating the growth and establishment of some species and excluding other species directly (abiotic tolerance) or indirectly (species competition) (Wootton, 1991; Maron et al., 2006). While the understanding of nutrient–soil interaction is crucial for the conservation and management of insular ecosystems (Maron et al., 2006), we still have little knowledge of whether colony size (number of breeding birds) determines soil chemistry. This information is much important, given the rapid expansion of some seabirds worldwide and need to predict the implication of future invasion scenarios (Vidal et al., 1998a).

Different species of seagulls have expanded their range and colonised coastal areas and islands globally (Mulder et al., 2011). This rapid expansion has been attributed to their ability to disperse, adapt and live in man-modified habitats. The exponential increase in their abundance has caused many ecological, economic and societal impacts, including predation on wildlife (Swennen, 1989; Rgeas et al., 2003), disease transmission (Monaghan et al., 1985), agricultural damage (Blokpoel, Struger, 1988) and pollution of cities (Raven, Coulson, 1997). In the Mediterranean, the yellow-legged gull (*Larus michahellis*) is the most common gull species occurring in most coastal cities and islands (Vidal et al., 1998b). The European population is estimated at 409,000–534,000 pairs (BirdLife International, 2015). It is listed as a superabundant species as it fulfills the main criteria of this category of species, namely, a strong demographic expansion and a population size higher than ever recorded (Blokpoel, Scharf, 1991). Similar to other gull species, studies have shown the ecological and economic nuisance of its high density (Pérez, 1998; Vidal et al., 1998a,b; Matias, Catry, 2010). Its expansion in the Mediterranean has the potential to not only affect the population dynamics of other colonial seabirds of islands (Borg et al., 1992–1994; Keitt et al., 2004; Oro et al., 2005), but also change the soil chemistry, and therefore the invertebrates and vertebrates of the Mediterranean insular ecosystems (Pérez, 1998; Otero et al., 2015).

Here, we test whether the abundance of yellow-legged gull (*L. michahellis*) determines the chemistry of the island soil with recently established colonies in Algerian coasts. Guano is rich in nutrients such as phosphorus, nitrogen and potassium (Hutchinson, 1950; Bosman, Hockey, 1986). Therefore, we predict that soil chemistry is positively correlated with the abun-

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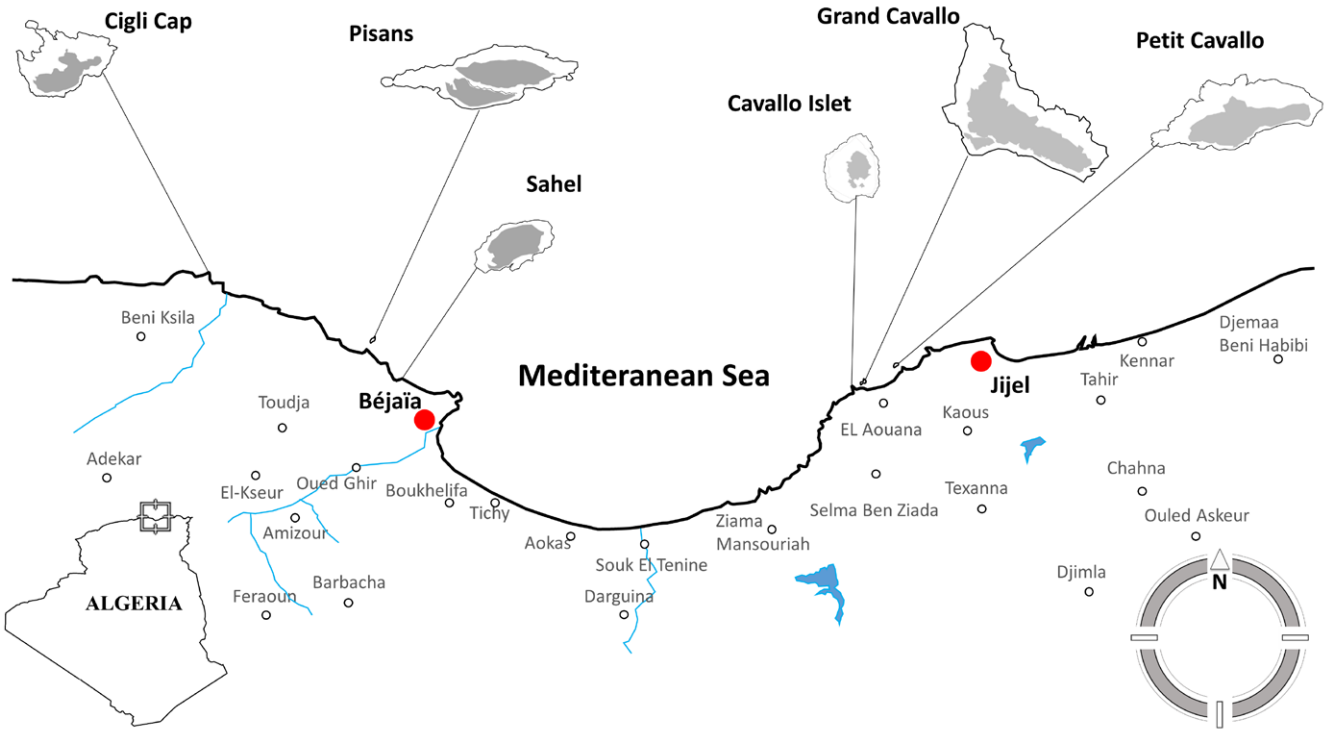


Fig. 1. Geographic location of the six study islands in central North Algeria. The six islands are magnified for visibility. Geographic coordinates and physical features for each island are shown in Table 1.

Table 1. Geographic coordinates and physical characteristics of the studied Mediterranean islands in central North Algeria. Floral richness (total number of species) was obtained from Benhamiche-Hanifi and Moulaï (2012).

Province	Name	Coordinates N	Coordinates E	Area (ha)	Distance to the continent (m)	Height (m)	Colony size	Floral richness
Bejaïa	Pisans	36°49‘30“	4°59‘50“	1.2	1250	30	139	52
	Sahel	36°47‘38“	5°1‘23“	0.2	7	15	15	44
	Cap Cigli	36°53‘34“	4°47‘20“	0.8	120	20	193	60
Jijel	Grand Cavallo	36°47‘7“	5°36‘29“	6	950	50	302	82
	Petit Cavallo	36°48‘5“	5°39‘1“	4	750	10	91	101
	Cavallo Islet	36°46‘42“	5°36‘2“	0.15	50	30	39	23

dance of breeding pairs of the yellow-legged gull. We selected six islands in central North Algeria with different population sizes of yellow-legged gull and sampled the soil to assess its physicochemical characteristics. This allowed us to test whether soil characteristics are dependent on the number of breeding pairs of yellow-legged gulls.

Material and methods

Study sites

The study was conducted in the central North Algerian coast near Bejaïa and Jijel provinces (Fig. 1). We selected six islands (Pisans, Sahel, Cap Cigli [El Euch], Grand Cavallo, Cavallo islet and Petit Cavallo) based on yellow-legged gull breeding and accessibility (Table 1). Yellow-legged gull was the most abundant bird occupying the sites, along with low densities of peregrine falcon (*Falco peregrinus),* domestic pigeons *(Columba livia),* pallid swift *(Apus pallidus),* Sardinian warbler *(Sylvia melanocephala),* common chaffinch *(Fringilla coelebs),* zitting cisticola *(Cisticola juncidis),* common blackbird *(Turdus merula)* and common nightingale (*Luscinia megarhynchos).* The number of breeding pairs varied between 15 and 193. These islands have a surface of 0.2–1.2 ha and do not exceed 30 m in height, except for Grand Cavallo which reaches 50 m. The distance to the shore varies between 7 and 1250 m. Plant richness in each island was obtained from Benhamiche-Hanifi and Moulaï (2012).

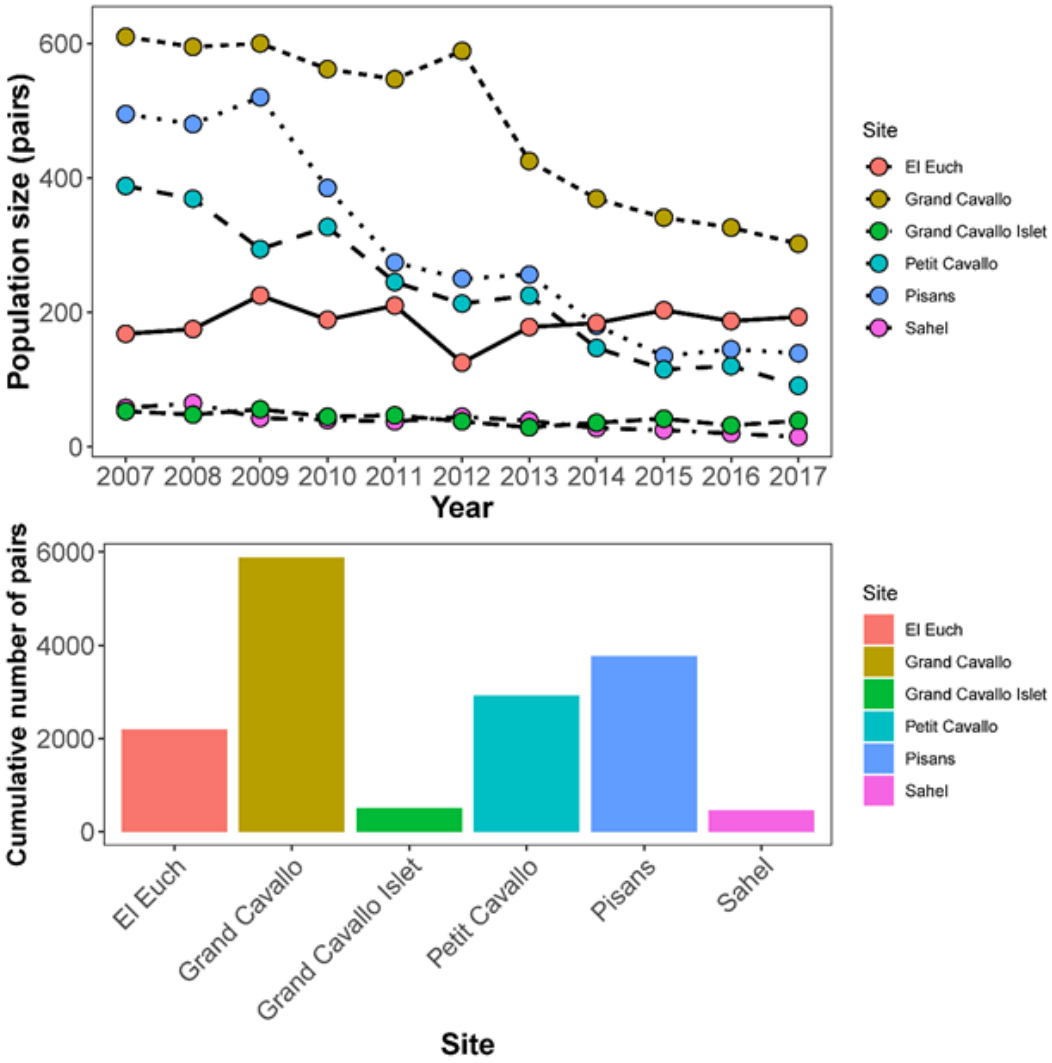


Fig. 2. Population size (number of pairs) of the the yellow-legged gull in six islands in North Algeria between 2007 and 2017 (a) and cumulative number of pairs during the same decade (b).

Breeding pairs estimation

The yellow-legged gull is a colonial bird that mainly breeds from the month of March on islands on the Algerian coast (Moulaï et al., 2006; Baaloudj et al., 2012, 2014). We visited each island two to three times per week (total of 138 h) from late March to late May during 2017 and 2018. We counted the number of active nests (those including eggs) of the species. Since we checked each portion of the island, we believe that we did not miss any nest. We also obtained the maximum number of nests recorded in each island during 2007–2016 from our previous studies (Moulaï et al., 2006; Bougaham, Moulaï, 2013) (Fig. 2).

Sampling soil

Soil samples were collected from the superficial area of 20-cm depth. For each island, collections were carried out in two 1×1 m^2 patches, wherein three randomly selected samples were obtained from each patch. One patch was near the gull nests and one patch (control) was at least 5 m away from the gull nest. Each sample contained 500 g of soil. Samples were kept separate, brought to the laboratory and left on open air to dry for 3–7 days (depending on the humidity of the sample). We avoided using the oven to maintain the levels of organic matter (OM). The analysis was performed on 2-mm-diameter sieved soil. Soil pH was measured with a pH meter using a mixed solution of 1:2.5 (soil:liquid), where the liquid was CO_2-free distilled water, as described in Thomas (1996). To determine the dissolved salt content in the soil, we measured the electric conductivity (Ce) in the laboratory following Aubert (1978). The total available limestone content in soil was determined using the Bernard calcimeter (Pétard, 1993). OM was estimated using the method described by Walkley and Black (1934) with Van Bemmelen factor of 1.724 (OM = organic carbon × 1.724). The total nitrogen supplying ability of the soil was estimated using the method described in Mathieu et al. (2003), and for phosphorus, the Olsen method was

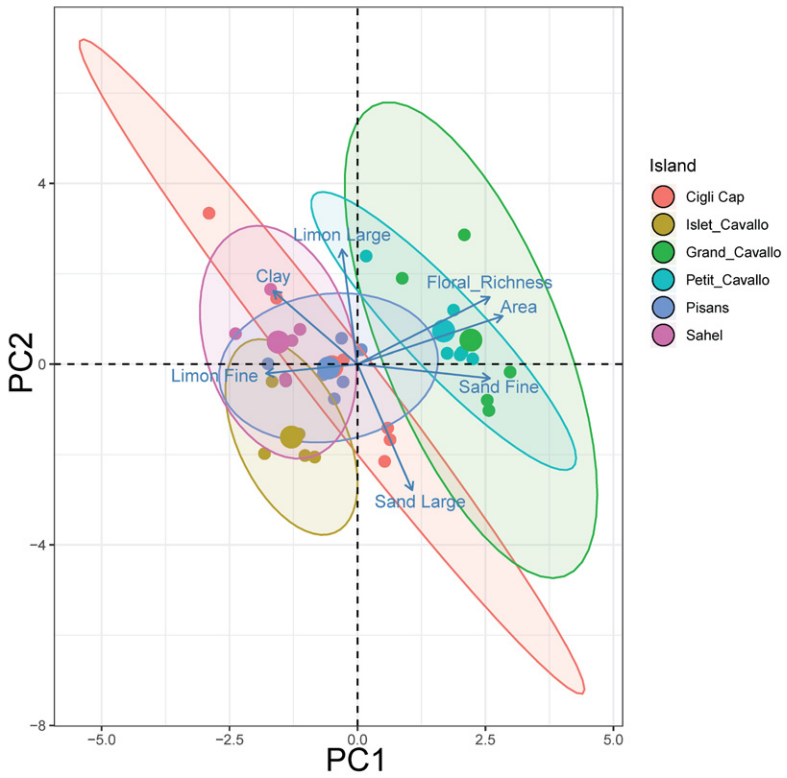


Fig. 3. PCA biplot of the physical characteristics of the six islands hosting yellow-legged gull colonies in central North Algeria. The ellipses encompass the samples of each island. The physical parameters are island area, floral richness, clay, fine silt, large silt, fine sand and large sand content.

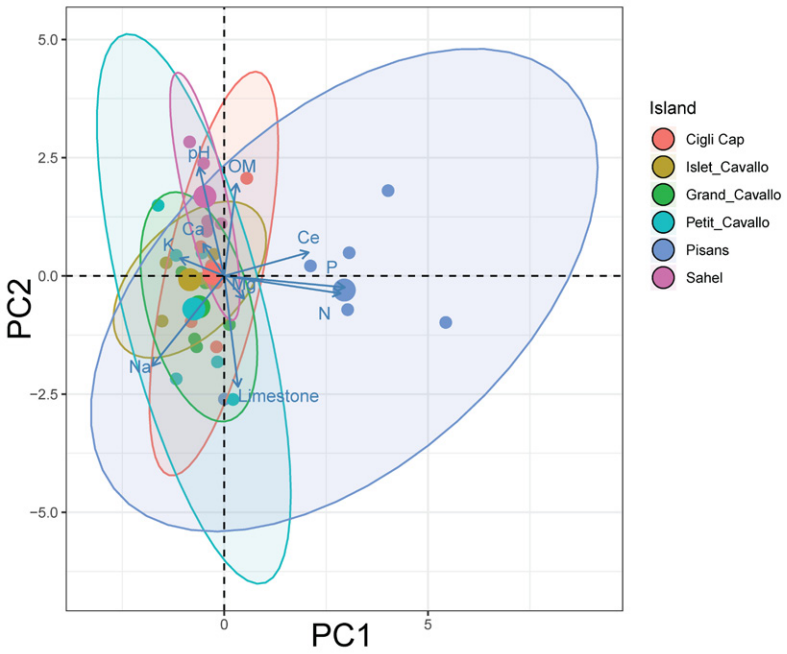


Fig. 4. PCA biplot of the chemical characteristics of the six islands hosting yellow-legged gull colonies in central North Algeria. The ellipses encompass the samples of each island. The chemical parameters are pH, Ce, limestone, OM, N, P, Ca, Mg, K and Na.
Note: Ce, electric conductivity; OM, organic matter.

used (Hafidi et al., 1994). We determined the available Ca, Na, K and Mg in soil using ammonium acetate.

Statistical analysis

Statistical analyses were performed with R 3.5.2 (R Development Core Team, 2020). Principal component analyses (PCAs) were carried out to assess the distribution of the six islands in the physicochemical space by means of the *Factoextra* package (Kassambara, Mundt, 2017). We carried out three distinct PCAs. The first looked at only the physical features of the islands, namely, area, floral richness, clay, fine silt, large silt, fine sand and large sand content. The second analysed the chemical properties of the islands, including pH, Ce, limestone, OM, N, P, Ca, Mg, K and Na. A third PCA was conducted encompassing all physical and chemical parameters as well as the number and density of pairs on the island. Based on the visualisation of the scree plot, we retained two principal components. To determine whether soil chemical properties are correlated with the number of breeding pairs on the island, we tested for potential relationships between the second principal component (PC2) from the physicochemical PCA (correlated with N and P) and the number of breeding pairs of yellow-legged gull during the focal year and the cumulative number of pairs during the preceding decade (2007–2017) with mixed-effects linear regression and a model including site as a random effect. We calculated the R^2 of the fixed effects of the model using the 'r.squaredGLMM' function of the MuMIn package (Barton, 2019). Analysis of variance (ANOVA) was computed to determine potential differences in soil levels of N and P among islands. Tukey tests were carried out to perform pairwise comparison among islands.

Results

Physical analysis

Based on seven physical characteristics of the island (area, floral richness, clay, fine silt, large silt, fine sand and large sand content) and 36 samples, we performed a PCA to determine the physical similarities and differences. The two first principal components (PCs) explained 65.7% of the variance. PC1 (explaining 38.4% of the variance) was strongly influenced by island surface, floral richness and fine sand, whereas PC2 (explaining 27.3% of the variance) was related to fine silt and large sand (Fig. 3, Table 2). The PCA biplot showed that Grand Cavallo and Petit Cavallo were separated from the other islands based on PC1. In fact, these two islands are the largest in terms of surface area; they have higher floral diversity (expect for Cap Cigli) and have soil with higher fine sand content. Cavallo islet and Sahel were relatively separated by PC2 because of the higher content of large sand and lower proportion of fine silt in their soil.

Chemical analysis

To find the differences and similarities in the soil chemistry properties of the six islands, we used 10 parameters and 36 samples. The first two PCs explained 42.9% of the variance, where PC1 accounted for 24.7% and the second explained 18.1% (Fig. 4). PC1 seems to split the Pisans Island from the other five islands, and this PC was positively correlated with nitrogen and phosphorus, indicating that Pisans had higher nitrogen and phosphorus content than the other islands. PC2, which was negatively correlated with limestone and positively correlated with pH, separated Grand Cavallo (more acidic and higher levels of limestone) from Sahel Island (more alkaline and less limestone) (Table 3). The former island harboured more breeding pairs (n = 302) than Sahel Island (n = 15).

Table 2. Eigenvalue, proportion of variance explained by the PCs, cumulative proportion and correlation coefficients between PC1 and PC2 with the physical parameters of the islands where the yellow-legged gull breeds.

	PC1	PC2
Eigenvalue	1.64	1.38
Proportion of variance	0.38	0.27
Cumulative proportion	0.38	0.66
Area	0.53	0.24
Floral richness	0.48	0.33
Clay	−0.31	0.36
Limon fine	−0.33	−0.05
Limon large	−0.06	0.56
Sand fine	0.48	−0.07
Sand large	0.20	−0.62

Note: PCs, principal components.

Table 3. Eigenvalue, proportion of variance explained by the PCs, cumulative proportion and correlation coefficients between PC1 and PC2 with the chemical parameters of the islands where the yellow-legged gull breeds.

	PC1	PC2
Eigenvalue	1.57	1.35
Proportion of variance	0.25	0.18
Cumulative proportion	0.25	0.43
pH	−0.12	0.52
Ce	0.40	0.11
Limestone	0.07	−0.53
OM	0.06	0.44
N	0.55	−0.08
P	0.57	−0.05
Ca	−0.10	0.15
Mg	0.09	−0.11
K	−0.21	0.09
Na	−0.34	−0.43

Note: Ce, electric conductivity; OM, organic matter; PCs, principal components.

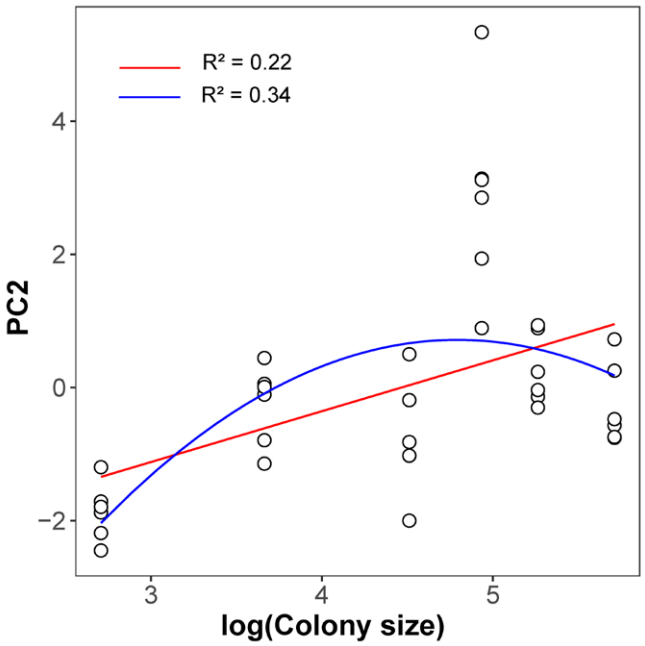


Fig. 5. Relationship between PC2 (correlated with phosphorus and nitrogen) and colony size (log-transformed). The red line is a simple linear regression explaining 22% of the variance. The blue line is a quadratic non-linear relationship explaining 34% of the variance.

Table 4. Eigenvalue, proportion of variance explained by the PCs, cumulative proportion and correlation coefficients between PC1 and PC2 with the physicochemical parameters of the islands where the yellow-legged gull breeds.

	PC1	PC2
Eigenvalue	2.05	1.65
Proportion of variance	0.22	0.14
Cumulative proportion	0.22	0.37
Floral richness	0.40	−0.05
Clay	−0.18	0.17
Limon fine	−0.26	−0.28
Limon large	0.04	−0.17
Sand fine	0.34	−0.05
Sand large	0.07	0.18
Area	0.45	−0.04
Breeding density	−0.28	0.11
Breeding pairs	0.35	0.17
pH	−0.19	−0.26
Ce	−0.18	0.32
Limestone	0.14	0.17
OM	−0.17	−0.11
N	−0.08	0.49
P	−0.08	0.51
Ca	−0.22	−0.09
Mg	0.03	0.06
K	−0.11	−0.19
Na	0.15	−0.17

Note: Ce, electric conductivity; OM, organic matter; PCs, principal components.

Physicochemical analysis

We performed a PCA using seven physical characteristics of the island, 10 chemical parameters, colony size, breeding pair density and 36 samples. The two first PCs explained 36.5% of the variance, with PC1 and PC2 accounting for 22.1% and 14.4%, respectively. PC1 was positively correlated with island area, floral richness and colony size, whereas PC2 was positively correlated with N and P (Table 4). The biplot shows that PC1 splits Grand Cavallo from Sahel and Cavallo islet (other populations overlap greatly), whereas PC2 splits Sahel, which is less rich in N and P, from Cavallo islet, Cigli cap and, to some extent, Pisans (Fig. 5).

Relationship between soil chemistry and population size

We used PC2 from the physicochemical analysis as an organic pollution response variable because it was correlated with N and P. Although PC2 was positively correlated with the population size (log-transformed) of the yellow-legged gull (linear model: slope = 0.76, $P = 0.003$, $R^2 = 0.22$), the relationship was better explained by the quadratic relationship of population size ($R^2 = 0.34$) (Table 5, Fig. 5). This non-linear relationship was mostly driven by the high values of P (ANOVA: $F_{5,30} = 16.2$, $P < 0.0001$) and N (ANOVA: $F_{5,30} = 23.8$, $P < 0.0001$) in Pisans Island, which was 12 times higher than the average of the five other populations (Tukey test: $P < 0.0001$; Tables 6, 7). The Pisans colony had an intermediate number of breeding pairs (n = 139 pairs) during the studied years (Table 1).

Discussion

Our study investigated the correlation between physicochemical properties and the number of breeding pairs of the yellow-legged gulls in recently colonised islands on the Algerian coast. Our hypothesis was: the number of yellow-legged gulls determines the physicochemical characteristics of the island because more birds generate more guano, and thus more nutrients in the soil (Sánchez-Piñero, Polis, 2000). Our results give some evidence of a positive correlation, suggesting that the nutrient inputs are mediated by the colony size of the yellow-legged gull.

Physical characteristics

The six islands were different in area, floral richness and soil structure. There is overwhelming evidence of the positive relationship between surface and floral richness in islands (Nilsson et al., 1988; Kohn, Walsh, 1994), and the islands of our study showed a similar pattern (Benhamiche-Hanifi, Moulaï, 2012). Given the similarity in climate and proximity of the islands to each other, the higher floral richness is probably due to island area as well as the soil structure and heterogeneity which differed among islands. The area of the island and the interaction of soil and plant community have probably played a key role in the establishment of colonies of the yellow-legged gull and in determining their abundance (Burger, Shisler, 1978; Fasola, Canova, 1992; Bosch, Sol, 1998). In the same way, there is probably a feedback effect from the bird colony on the plant community structure of the island which typically promotes alien species colonisation and establishment through increased levels of soil nutrients coming from the

Table 5. Summary statistics of the linear model testing for quadratic effects of the colony size of the yellow-legged gull on the principal component correlated with nitrogen and phosphorus levels in the soil. $R^2 = 0.34$.

	Estimate	Std. error	*t* value	*P* value
Intercept	−13.825	4.435	−3.117	0.004
Log(colony size)	6.069	2.208	2.749	0.010
Log(colony size²)	−0.633	0.262	−2.416	0.021

Table 6. Tukey test for the model testing of differences in phosphorus levels among the six islands.

Site pair	Difference	Lower confidence interval	Upper confidence interval	*P* value
Islet Cavallo | Cigli Cap	−3.241	−15.174	8.692	0.960
Grand Cavallo | Cigli Cap	−3.447	−15.380	8.487	0.949
Grand Cavallo | G islet Cavallo	−0.206	−12.139	11.727	1.000
Petit Cavallo | Cigli Cap	−2.028	−13.961	9.905	0.995
Petit Cavallo | G islet Cavallo	1.213	−10.721	13.146	1.000
Petit Cavallo | Grand Cavallo	1.419	−10.515	13.352	0.999
Pisans | Cigli Cap	24.659	12.726	36.592	**<0.0001**
Pisans | G islet Cavallo	27.900	15.967	39.833	**<0.0001**
Pisans | Grand Cavallo	28.106	16.173	40.039	**<0.0001**
Pisans | Petit Cavallo	26.687	14.754	38.621	**<0.0001**
Sahel | Cigli Cap	−3.846	−15.779	8.088	0.921
Sahel | G islet Cavallo	−0.605	−12.538	11.328	1.000
Sahel | Grand Cavallo	−0.399	−12.332	11.534	1.000
Sahel | Petit Cavallo	−1.818	−13.751	10.116	0.997
Sahel | Pisans	−28.505	-40.438	−16.572	**<0.0001**

Note: Pisans had 12 times more P than the other islands.

Table 7. Tukey test for the model testing of differences in nitrogen levels among the six islands.

Site pair	Difference	Lower confidence interval	Upper confidence interval	*P* value
Islet Cavallo | Cigli Cap	0.082	-44.640	44.803	1.000
Grand Cavallo | Cigli Cap	−2.270	-46.991	42.452	1.000
Grand Cavallo | Islet Cavallo	−2.351	-47.073	42.370	1.000
Petit Cavallo | Cigli Cap	−0.939	-45.660	43.782	1.000
Petit Cavallo | Islet Cavallo	−1.021	-45.742	43.700	1.000
Petit Cavallo | Grand Cavallo	1.331	-43.391	46.052	1.000
Pisans | Cigli Cap	123.359	78.638	168.080	**<0.0001**
Pisans | Islet Cavallo	123.278	78.556	167.999	**<0.0001**
Pisans | Grand Cavallo	125.629	80.908	170.350	**<0.0001**
Pisans | Petit Cavallo	124.298	79.577	169.020	**<0.0001**
Sahel | Cigli Cap	−1.272	-45.993	43.450	1.000
Sahel | Islet Cavallo	−1.353	-46.075	43.368	1.000
Sahel | Grand Cavallo	0.998	-43.723	45.719	1.000
Sahel | Petit Cavallo	−0.333	-45.054	44.389	1.000
Sahel | Pisans	−124.631	−169.352	-79.910	**0.000**

Note: Pisans had 12 times more N than the other islands.

bird guano (Hogg, Morton, 1983; Vidal et al., 1998a,b). The flora of the six islands is relatively diverse hosting endemic species at the North African level (*Chrysanthemum fontanesii*, *Pancratium foetidum* and *Sedum multiceps*), at the regional Algero-Tunisian level (*Cynosurus polybrateatus* and *Sedum pubescens*) and at the Algerian level (*Genista numidica*). Therefore, the monitoring of seabird colonies, especially the superabundant ones, is key for the conservation of native rare plants and invertebrates (Vidal et al., 1998a,b). In the Algerian coasts, the yellow-legged gull has relatively recently established different populations in most of the islands (Moulaï et al., 2006; Hussein et al., 2021); thus, such seabird–plant impacts could be assessed in the long term.

Chemical characteristics

The studied islands showed some differences in the chemical properties of the soil. Phosphorus and nitrogen seemed to be the two important nutrients that showed considerable differences among sites – Pisans had 12 times more P and N than the other islands. P and N are the important components of seabird guano (Otero et al., 2015) and the latter represented the main source of these nutrients in our studied islands. However, if guano is the main input of nutrients on the island, we should perceive a clear positive relationship between colony size and P and N nutrient levels. Although we found an evidence of positive relationship, Pisans Island showed excessively higher levels of P and N, even though the colony size was not the highest. The historical abundance of the yellow-legged gull prior to our study might explain the high levels of nutrients in Pisans. The colony size of Pisans was 96 pairs in 1978 (Jacob, Courbet, 1980) and this number increased to 510 in 2002 due to the opening of a nearby refuse dump which sustained large numbers of yellow-legged gulls and probably the colony size of Pisans (Moulaï, 2007). After closing the refuse dump in 2015, Pisans colony declined by nearly four times, but the nutrients that had accumulated over the years and dramatically increased the P and N levels in the soil seem to remain on the island. This finding goes in line with that of Otero et al. (2015) who suggested that the increase in nutrients such as P in soil colonies is an irreversible process. This highlights the importance of monitoring superabundant species to overcome major environmental perturbations that might affect the abundance and distribution of native threatened species.

Conclusion

Our results show that colony size of the yellow-legged gull in the focal year might account for the soil chemical properties. However, historical monitoring should give better estimates of the nutrient levels in the soil because of the accumulation of guano from previous years and the potential fluctuation of the colony size across the years. Similar to other studies (Hogg, Morton, 1983; Otero et al., 2015), our study suggests that seabird guano accumulation might persist in islands and has long-lasting effects on soil chemistry, which will determine the community composition and dynamics of the island (Vidal et al., 1998a,b). Therefore, long-term monitoring of superabundant seabirds is key for better management of their impacts on the biodiversity of insular ecosystems.

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