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Yellow-legged gull populations (*Larus michahellis*) link the history of landfills to soil eutrophication and time-related vegetation changes on small Mediterranean islands

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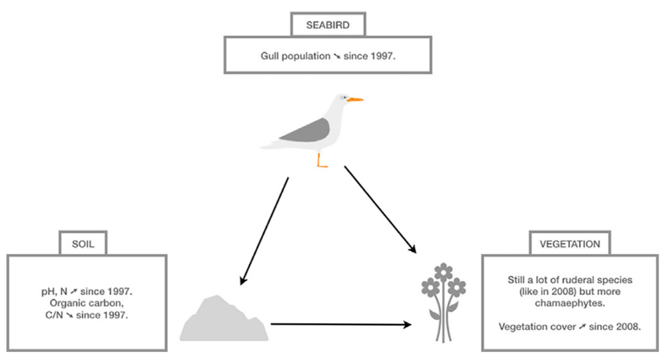
HIGHLIGHTS

- Soil parameters alterations (notably nutrients increase) induced by seagulls persist after the colony declines.
- Ruderal plant species and more chamaephytes still occurred after the gull colony decline.
- Vegetation cover increased with the decline of gull colony.

GRAPHICAL ABSTRACT



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ABSTRACT

Seabird colonies have a strong influence on both the physical and chemical soil parameters and plant communities of the islands where they settle to nest. Scientists have studied the effects of the demographic explosion of seabird populations, but few have explored the long-term effects when the colonies were in decline. The aim of this study was to investigate diachronic changes over a 24 year period of soil parameters, floristic composition and plant functionnal types (Raunkiaer growth forms and Grime life strategies) up to the decrease of the number of nesting yellow-legged gulls (*Larus michahellis* Naumann, 1840) on Mediterranean islands. We used 78 permanent plots to survey the vegetation and the soil parameters on 9 islands and one mainland area within the Calanques National Park (south east of France), for three periods (*i.e.*, 1997, 2008, 2021).
Since 1997, the increase of nesting gulls has caused a nitrogen and pH increase and organic carbon and C/N ratio decrease, although the values were still higher than mainland plots without nesting gulls. This has led to changes in plant species composition *e.g.*, higher values of N favouring the development of ruderal plant species, still present in high frequency in 2021. Furthermore, plant species highly tolerant to disturbances (*i.e.*, R Grime strategy) in harsh environments were still favoured even after the decline of gull abundance. However, both the frequency of the chamaephytes and the vegetation cover has increased with the decline of gull colony. In 2021, measures of trace elements' concentrations and calculation of pollution load index (Cu, Pb and Zn) reveals relatively low multi-contamination levels on the mainland and the archipelagos.

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On naturally oligotrophic and semi-arid Mediterranean islands, gull colonies induce a persistent alteration in soil characteristics that still influences plant communities (composition and functional types), 11 years after the decline in bird abundance.

1. Introduction

Manmade global change has had a profound impact on biodiversity (Vié et al., 2009), especially in the Mediterranean basin which is considered one of the biodiversity hotspots (Cunningham and Beazley, 2018). An important part of Mediterranean plant diversity is linked to the occurrence of 10,000 small islands, islands being refuges for rare and threatened mainland plant species (Médail, 2017). However, the Mediterranean basin has been subjected to an increase in human activity, particularly in coastal and island habitats (UNEP/MAP-Plan Bleu, 2009). Human activities alter ecosystem properties and services (Hooper et al., 2005), especially when they affect biotic factors (Chapin et al., 1997).

In this insular context, populations of the yellow-legged gull (*Larus michahellis*, hereinafter refered to as gulls) have greatly increased over the past few decades (Thibault et al., 1996; Bellout et al., 2021). Indeed, the high availability and predictability of food resources (Bosch et al., 1994), provided by open compartments of landfills during their operation on the close mainland, is known to have driven and shaped gull colony distribution and demographic explosion on the studied islands (Duhem et al., 2002, 2003, 2007, 2008). Gulls have therefore been considered as a superabundant bird species in the Mediterranean basin (Vidal et al., 1998b) that conflict with island biodiversity conservation programmes (*e.g.* Médail, 2017; De La Peña-Lastra et al., 2021; Mouga et al., 2021). Gulls, like other seabirds, are chemical and physical ecosystem engineers (Ellis, 2005; Grant et al., 2022). Due to the high spatial heterogeneity of their feeding, nesting and defecation behaviour, seabirds can have contrasting impacts on ecosystems. On the one hand, their presence can lead to an increase of plant biomass and height (Ellis, 2005) and seed dispersal (Nogales et al., 2001; Calvino-Cancela, 2011). On the other hand, high seabird densities can prevent plant growth owing to the uprooting of plants for nest building, trampling and soil compaction (Sobey and Kenworthy, 1979). Many studies have shown that large seabird colonies can alter soil characteristics, increasing the quantity of nitrogen, phosphorus, potassium, magnesium, total salts (Sigurdsson and Magnusson, 2010; Bouyahmed and Moulaï, 2018; Aerts et al., 2020), heavy metals (García et al., 2002; Ziółek et al., 2017; Otero et al., 2018), organic matter (García et al., 2002; Ghermaoui et al., 2016) and soil depth (Ishida, 1997; Mulder and Keall, 2001). They also usually lead to a decrease of soil pH (Mulder and Keall, 2001; Sigurdsson and Magnusson, 2010). Other soil characteristics can also be altered, but the trend can be both upward or downward such as for calcium, carbon content, water retaining capacity and soil moisture (Ellis, 2005). These different alterations may cause changes in plant communities – with high pressure and duration, exotic, ruderal or nitrophilous plant species may develop that may lead to a reduction of the abundance of native plant species (Vidal et al., 1998a, 1998b, 2000; Baumberger et al., 2012; Bou et al., 2020). The reduction of food availability following the closure of open compartments of landfills is indicated as the main driver for a long term reduction on gull population size (Duhem et al., 2007, 2008) and the negative density-dependent breeding investment contributed to population decline (Real et al., 2017).

Few studies (Baumberger et al., 2012; Otero et al., 2015; De La Peña-Lastra et al., 2021) have investigated the long-term patterns of change in plant communities and soil factors after the decrease of gull populations, showing that the environmental effects of the colonies may persist for a long time. For example, high concentrations of phosphorus (P) have been observed 5 (De La Peña-Lastra et al., 2021) and 14 years (Otero et al., 2015) after the decline of gull populations. The amount of P generated by the colony did not decrease and can be considered as an irreversible impact for the plant community (Otero et al., 2015; De La Peña-Lastra et al., 2021). The Mediterranean basin has a particular climate with low precipitation. In these semi-arid ecosystems, alterations linked to trophic shift can lead to a persisting imprint of eutrophication in the soil (Saatkamp et al., 2020) and the impact on plant communities is linked to higher P, C:N and organic matter. The threats to the Mediterranean islands are exacerbated by climate change because of the limited habitat availability and climatic range limitations which may hamper the expansion of the species' range (Vogiatzakis et al., 2016).

Our study focused on nine islands in the two Marseille archipelagos, Frioul and Riou (Calanques National Park, SE France), which are under the influence of breeding gulls (*Larus michahellis*) in comparison with the nearby mainland coastal area without gull colonies. Previous studies have shown that the high pressure of gull colonies leads to a ruderalisation of the floristic community (Vidal et al., 1998a, 1998b, 2000). This pattern has persisted (Baumberger et al., 2012) despite four open landfills having been closed in the Marseille area during the last decade, which has caused a decline in the nesting gull population (Calanques National Park monitoring). We have extended monitoring of the vegetation changes up to 24 years and added information with additional analysis of nutrients and trace elements in the soil according to the fluctuations in the nesting gull density. Because of the strong relationships within the gull/soil/plant system, we expected to demonstrate a resilience in plant communities despite the persistent effect of gull colonies on soil chemistry.

2. Material and methods

2.1. Study area

The study was conducted on two archipelagos and on the mainland area near Marseille (SE France) (Fig. 1). The sampling took place on two archipelagos of Marseille: the Riou archipelago (43°11′N, 5°21′E; five islands and two islets), and the Frioul archipelago (43°16′N, 103 5°18′E; four islands) (Fig. 1). The Riou archipelago islands studied are from 50 to 3525 m distant from the mainland (Table 1). Concerning the Frioul archipelago, the two islands studied are 1800 and 2800 m away from the mainland. The mainland area was considered as a habitat not subjected to gull pressure (no gulls nesting on the studied mainland area). These islands and the mainland area are included in natural protected areas managed by the Calanques National Park (CNP). Situated within the thermo-Mediterranean bioclimatic belt (Quézel and Médail, 2003), these islands and the mainland area have semi-arid climatic conditions, with lower precipitations on the islands (*e.g.*, Planier, an island located 9 km from Marseille: 342 mm) compared to the mainland (Marseille 524 mm), however little reliable data exists (Météo France, 2023). The studied sites are composed of compact limestone on the surface of which soils are limited to thin proto-rendzina patches, and are calcareous, skeletal and oligotrophic (Vidal, 1998).

The plants on the islands and the mainland coastal area are subjected to stresses both hydric (low precipitation and frequent strong wind episodes) and haline (with salt input from the sea and the toxicity of the salt within the tissues). The islands are mainly covered by low vegetation from halophyte plants to matorral shrub species (Baumberger et al., 2012). Vegetation on the mainland shows a similar composition, with however higher species richness compared to islands of similar size (Martín-Queller et al., 2017).

Yellow-legged gull status is considered as Least Concern in the IUCN European Red List, it is a protected specie in France and a determining specie of natural areas of ecological, faunistic and floristic interest (INPN MNHN, 2023). Gull colonies are nesting in the Mediterranean basin and

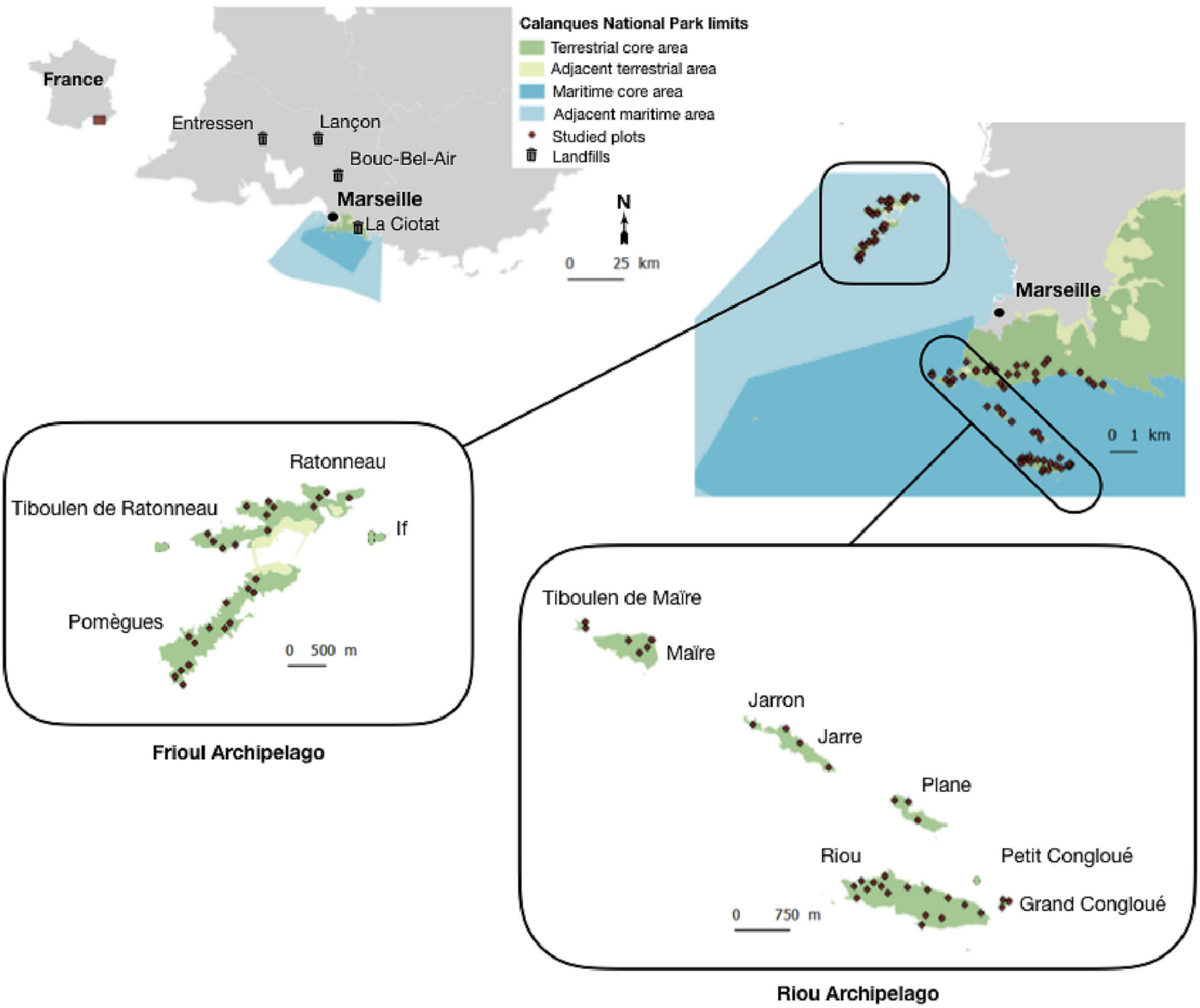

Fig. 1. Location of the islands in the Frioul archipelago and the Riou Archipelago (Marseille, south-eastern France). The dark squares show the localisation of the plots on the islands studied (56) and the nearby mainland areas (22).

Table 1
Data of studied islands and the coastal part of the Calanques National Park (CNP), and number of plots surveyed in 1997, 2008 and 2021.

	Islands	Area (ha)	Distance to mainland sea shore (m)	Maximum altitude (m)	Number of plots
Frioul Archipelago	Pomègues	89	2800	86	13
	Ratonneau	95	1800	74	13
Riou Archipelago	Riou	90.3	3100	190	16
	Maïre	27.6	50	141	4
	Plane	15	2100	22	3
	Jarre	18	800	57	3
	Jarron	3	800	33	1
	Grand Congloué	2	3525	50	1
	Tiboulen de Maïre	2.3	525	47	2
Mainland part of CNP		8157.8		645	22

the Atlantic coast from Morocco to the southern Brittany (Duhem, 2004). Gull colonies can be found on all the islands close to Marseille. However, nesting gull abundance and densities are not homogenous between the archipelagos, and depend on local habitats. The gull population increased in the Riou and Frioul archipelagoes between 1997 and 2005, with a growth rate ranging from 6 % for the Riou archipelago to 177 % for the Frioul archipelago (Duhem et al., 2008). The fluctuations of gull population size in the two archipelagos are presented in Fig. 2, between 1923 and 2021. Data were compiled by the CNP. Gulls' census on the islands of Marseille is part of a CNP program taking place every five years as well as the national census every ten years. Gull estimation was carried out by counting the number of nests (empty and with eggs) exhaustively on each island until 2021.

In 2021, exhaustive counting was done on only Grand Congloué and Tiboulen de Maïre. For the rest of the islands, estimation was done by distance sampling, an effective method for many gull species (Barbraud et al., 2014).

The main available anthropogenic food resources, four landfills (with open compatments during their operation) located within a radius of 60 kms, were closed in 2008, 2010 and 2013 and led to a decline in gull population size (Calanques National Park monitoring). The

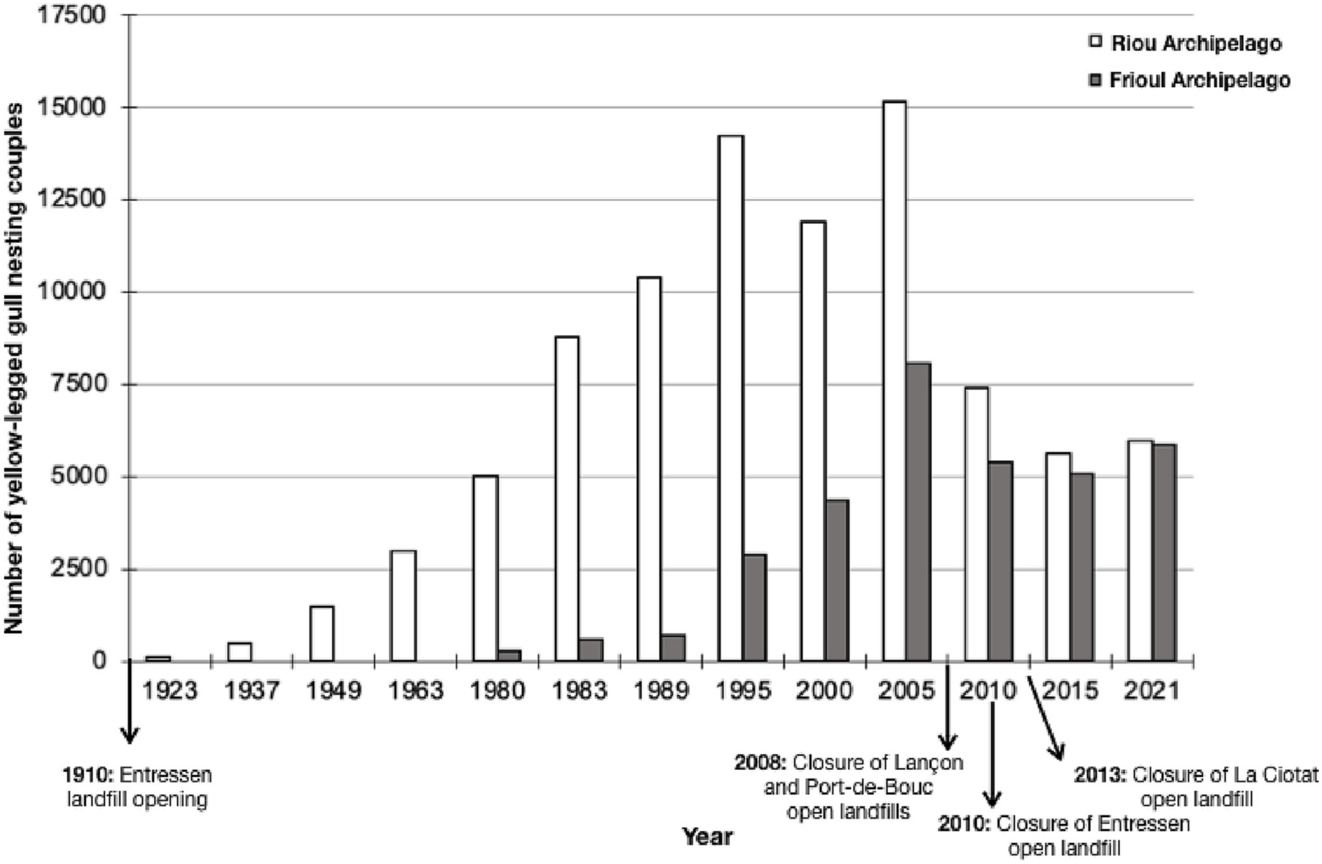

Fig. 2. Gull (*Larus michahellis*) population dynamics in the Riou and Frioul archipelagos from 1923 to 2021, and indications of the opening and closing of the landfills in the vincinity of Marseille.

decrease of easily accessible food resources led to the decline of the nesting population by 63 % in the Riou archipelago and 37 % in the Frioul archipelago between 2005 and 2015 (Fig. 2). However, an increase was recorded in 2021 with the difference being about 1100 nesting couples.

2.2. Sampling design

The vegetation was surveyed on the 56 island plots and on the 22 mainland plots in 1997, 2008 and in 2021 (Table 1). The number of plots was proportional to the size of the island in order to take into account the heterogeneity of the zones studied and the different vegetation types. A plot consisted of two concentric circles, a first one of 500m^2 where environmental variables and gull density were measured, and, a second of 100m^2 where floristic inventories and soil sampling took place (Vidal, 1998).

2.3. Mesological parameters

Environmental variables were measured in the 500 m^2 circles for each plot to better qualify and quantify the environmental effects (see Table 2 for further details). Measures and estimations were made during the floristic inventories from April to May in 1997, 2008 and 2021. The environmental variables measured were the elevation above sea level, the distance from the coastline, the slope, the exposure, and the cover rate of each substrate type: rock, block, stone, bare ground, the vegetation cover of the different layers.

Gull nest density (number of nests) was estimated and we also considered the cover of the resting places per plot being an indication of gull pressure.

2.4. Floristic inventories

Three plant species inventories (1997, 2008 and 2021) were carried out within the same 78100m^2 concentric plots from April to May using Tison et al. (2014) flora. The plant cover in the different layers was estimated (2008, 2021) for each species present on each plot using the 6 cover abundance categories (0: cover = 0 %, 1: 0 % < cover <10 %, 2: 10 % ≤ cover <25 %, 3: 25 % ≤ cover <50 %, 4: 50 % ≤ cover <75 %, 5: cover ≥75 %). The following easily accessible plant functional types, *i.e.*, Raunkiaer growth form (Raunkiaer, 1934) and Grime life strategy (Grime, 1977), for each plant species, were extracted from the BASECO data base (Gachet et al., 2005).

2.5. Soil, droppings sampling and chemical analysis

The soil was sampled in 1997 (56 plots only on the islands) and in 2021 (56 plots on the islands and 22 on the mainland). In 1997, organic carbon, total nitrogen, and pH were measured within the plots. In 2021, soil parameters included organic carbon, total nitrogen, pH, conductivity, total phosphorus, potassium, sodium, copper, lead, zinc and stable isotopes (δ15N and δ13C).

The soil samplings were performed once between March and April, when most of the gulls were nesting and after the winter rainfall. Within each plot, five soil subsamples of 200 mL each were collected (one in the center and four on each side, approximately 50 cm from the 100m^2 radius boundary) and pooled in a composite soil sample, in order to make a composite sample representative of the plot. Soil subsamples were collected from the top 15 cm layer after litter removal and sieved at 2 mm directly on site. The soil samples were dried before analysis (at 40 °C up to constant weight). Dry gull droppings were sampled on nine different plots in the

Table 2
Mesological parameters measured in the 500 m^2 circles for each plot.

Environmental variables measured in the 500 m^2 circles	Measures and estimations made
Altitude	GPS measures.
Exposure	1: North, 2: North-East, 3: West, 4: South-East, 5: South
Distance from the coastline	Reflects the amount of salt deposited on the ground (Barbour, 1978).
Slope	Slope was estimated visually using 6 categories: 0: flat, 1: 0 % < slope < 10 %, 2: 0 % ≤ slope < 25 %, 3: 25 % ≤ slope < 50 %, 4: 50 % ≤ slope < 75 %, 5: slope ≥ 75 %.
Cover rate of each substrate type: rock, block *i.e.* Ø > 20 cm, stone *i.e.* Ø < 20 cm, bare ground	Cover was estimated visually using respectively 6 categories: 0: cover = 0 %, 1: 0 % < cover <10 %, 2: 10 % ≤ cover <25 %, 3: 25 % ≤ cover <50 %, 4: 50 % ≤ cover <75 %, 5: cover ≥75 %.
Vegetation cover and the different layers (High arborescent h (height) > 10 m, Arborescent 10 > h > 4 m, High shrub 4 > h > 2 m, Shrub 2 > h > 0.5 m, Herbaceous h < 0.5 m)	
Gull nest density (number of nests)	Is considered as an indicator of gull pressure intensity. Following Thompson and Rothery (1991), gull nest density was measured by counting the number of both occupied – with eggs - and empty nests during the egg-laying period in the 78 plots for the three years 1997, 2008 and 2021.
Cover of the resting places per plot	Measured on a semi-quantitative basis using the 6 cover abundance categories previously described, used as a measure of pressure by gulls.

Frioul and Riou archipelagos in 2021. They were collected on rocks to avoid contact with soil.

To assess the soil organic matter percentage (SOM), the method of Mathieu and Pieltain (2003) was used: the samples were first weighed and then heated several times at high temperature. The samples were heated first at 220 °C for 16 h (bound water elimination), then heated again at least three times at 450 °C for 4 h (loss of organic matter by combustion, and SOM was estimated by mass loss between 220 and 450 °C). The organic carbon was estimated using the values of the organic matter multiplied by 0.50, based on the assumption that the soil organic matter contains 50 % carbon (Pribyl, 2010).

To determine the pH and the conductivity, the samples were extracted with osmosed water (ratio 1:5 *V*/V), then agitated for at least 1 h, decanted for one more hour and finally the conductimeter (WTW Multi 3420) and the pH-meter (Orion 2 Star Thermo Scientific SM30B) could be used (according to norm ISO 11265 (1995) and ISO 10390 (2005) respectively; Baize and Girard, 1992).

The total nitrogen, carbon, δ15N and δ13C content in ground soil samples (ground to <0.2 mm with RETSH 22, agate mortar) and droppings samples ($n = 9$, not composites) were performed on an elemental analyzer (Flash HT Plus, Thermo Fisher Scientific) coupled with a mass spectrometer (Delta V Advantage, Thermo Fisher Scientific). Elemental analysis of carbon and nitrogen were performed in a combustion reactor (1000 °C) under a carrier gas (Helium: 100 mL/min) with samples weighing approximately 800 μg sealed in tin capsules, introduced *via* an automatic injector. The gases were separated on a chromatographic column in an oven at 45 °C before being quantified *via* the thermal conductivity detector (TCD) of the elemental analyzer. The gases were injected into the Delta V spectrometer for isotopic analysis. The calibration of the catharometric detector and the ratio-isotopic mass spectrometer was performed with a secondary standard, EDTA (tetra-acetic ethylene diamine acid). The analyses (samples or standards) of the ratio 13C/12C were calculated in delta value which represents the deviation from an international standard and is calculated as follows:

$$\delta^{13}C = \left(\frac{R_{Sample}}{(R_{Standard})} - 1\right) \times 1000\ (‰)$$

The international standard for δ13C is Vienna PeeDee Belemnite (VPDB), Rstandard = 0.011237. The δ15N is expressed in the same way in relation to atmospheric nitrogen with a conventional value of 0 ‰.

The results of δ13C and δ15N analyses are produced with an uncertainty of +/− 0.5 ‰. The δ15N and the δ13C were analysed because they can give an indication of the trophic transfer, being robust and effective in tracing the path of the organic matter and the trophic relationships within the ecosystems (Post, 2002).

The analysis of the other elements (Cu, K, Na, P, Pb and Zn) in the soil and the droppings samples was carried out after acid mineralization. Samples were digested in a microwave mineralizer (Milestone Start D) using aqua regia (1/3 HNO_3 (Fisher chemical, Trace metal grade 67–69 %) and 2/3 HCl (Fisher chemical, Trace metal grade 35–38 %)). After mineralization, the samples were filtered through a 0.45 μm cellulose ester membrane filter and stored at 4 °C until analysis (mineralization protocol for pseudo-total concentration determination in soil, adapted from norm ISO 11466, 1995). Then element concentrations in samples were carried out by ICP-OES (Inductive Coupled Plasma, Optical Emission Spectrometry, Jobin Yvon Horiba Spectra 2000). Quality controls and accuracy were checked using standard soil reference materials (CRM 049-050 from RTC-USA), with accuracies within 100 ± 10 %).

Concerning Cu, Pb and Zn, considered as potentially toxic elements (PTE), contamination factors in soil (*CF*) were calculated as followed:

$$CF_{PTE} = [PTE]_{pseudo-total\ in\ soil} / [PTE]_{local\ background\ value}$$

where $[PTE]_{local\ background\ value}$ are 43, 66 and 7.5 mg.kg^{-1} for Pb, Zn and Cu respectively (Affholder et al., 2014). The potential multi-contamination level of soils was estimated by calculating an integrative index *i.e.* pollution load index (PLI) according to the formula (Affholder et al., 2014; Rashed, 2010):

$$PLI = \sqrt[3]{CFPb\ x\ CFZn\ x\ CFCu}$$

2.6. Statistical analysis

Since plant names have been revised between different study periods, we followed the taxonomy of Gargominy and collaborators (Gargominy et al., 2020). In order to understand patterns of change of soil parameters, we used boxplots in pairs for contrasting years, and separated to compare Riou, Frioul and the mainland. We used Student tests for variables with normal distribution and homosedasticity or pairwise Wilcoxon in the other cases. To measure the potential effects of the gulls on the soil parameters, linear models were used (*stats* package). We pooled all the plots from the two archipelagos and considered the number of counted nests or the cover of resting places as explaining variables for the soil parameters measured in 2021. We excluded mainland plots from this analysis to avoid confounding effects. When conditions were not met for model residuals (normality, homoscedasticity and independency), outliers were removed and/or the variables were log transformed. To compare Na and conductivity mean values properly without the confounding effect of the sea shore distance, we selected a subsample of plots from the mainland area. We selected only plots within 188 m distance from the sea shore, which is the maximum distance from the sea shore of island plots.

With the aim of describing the flora trajectory and to know whether there was a flora niche alteration due to climate change or only to gulls pressure, different analyses were carried out. Non-metrical multidimensional scaling (NMDS) was performed to view the alterations in the flora on the islands between the three dates. Using the coordinates of groups in the NMDS, we used Wilcoxon paired tests to verify whether the changes are significatively different. To quantify the changes, mean comparisons were made between years with paired Wilcoxon tests, using the number of species, Grime life strategies and Raunkiaer growth forms.

In order to compare the vegetation cover between 2008 and 2021, we performed an Ascending Hierarchical Classification (AHC) (*stats* package) with the data of 2021 (mesological and soil parameters) in order to have different groups of plots and to carry out paired Wilcoxon tests between them.

The observations made on the islands could be explained by more global alterations such as climate change (Heilmeier, 2019; Ahrens et al., 2020). To comprehend the flora ecological requirement changes with the environmental alterations due to gulls pressure or/and climate change between 1997, 2008 and 2021, we compared Ellenberg-Pignatti factors (Organic Matter, Nutrient, Soil Acidity, Humidity, Light, Salinity, Temperature) with paired pairwise Wilcoxon tests and Generalized Additive Models (GAM) (*mgcv* package). The variables included were the different Pignatti factors: organic matter, nutrient, soil acidity, humidity, light, salinity, temperature; and the explained variable was the number of nests. As variables responses are expected to be non-linear, we used Generalized Additive Models with gaussian family to evaluate the stastistical link between Pignatti factors and the number of nests. The indicators were adapted for the Mediterranean species by Saatkamp et al. (2022), so that the bioindications given by plants fit better than the initial values.

All statistical analyses were performed with R software (R version 4.2.2: R Core Team, 2022). Null hypotheses were rejected when the p-value was below 0.05.

3. Results

3.1. Nesting gulls and dynamic of the soil parameters

The number of nests has decreased since 1997 (Fig. 3. A). The cover of resting places decreased less on the Frioul archipelago compared to the Riou archipelago between 2008 and 2021 (Fig. 3. B).

Soil acidity decreased during the study period (see Supplementary Materials Table S1 for a summary of all means values ± SD), with mean pH in 2021 significantly higher than in 1997 (Fig. 4. A., $p < 0.001$). Soil pH was lower on Riou islands (mean ± standard deviation, 7.89 ± 0.47, $n = 30$) compared to the mainland (8.18 ± 0.28, $n = 22$) in 2021 ($p < 0.05$). There was no significant difference between soil pH values on Riou and Frioul islands whatever the year considered.

Organic carbon in soils of the archipelagos decreased during the study period (Fig. 4. B, $p < 0.01$), but was not significantly different between islands in 1997 ($p = 0.332$) and 2021 ($p = 0.091$), respectively, and between islands and the mainland in 2021 (64.07 ± 27.01, 53.06 ± 20.70 and 56.06 ± 31.12 mg/g for Riou, Frioul ($n = 26$) and the mainland respectively; mainland *vs* Frioul $p = 0.70$, mainland *vs* Riou $p = 0.34$, Frioul *vs* Riou $p = 0.09$).

Soil total nitrogen content of Frioul and Riou samples was significantly higher in 2021 than in 1997 (Fig. 4. C, $p < 0.01$). Soil total nitrogen on Riou islands (9.14 ± 3.63 mg/g) was significantly higher than on the mainland (5.86 ± 2.45 mg/g) and also than on Frioul islands (7.18 ± 2.84 mg/g) in 2021 ($p < 0.001$). Total nitrogen values for Riou and Frioul in 1997 were not significantly different from the mainland in 2021 ($p = 0.161$ and $p = 0.088$, respectively). Total nitrogen content of droppings (44.50 ± 8.34 mg/g) was significantly higher than in any soils ($p < 0.001$).

The C/N ratio was significantly lower for Riou (13.57 ± 6.86) and Frioul (17.95 ± 6.88) in 2021 than the values for Riou (21.97 ± 13.22) and Frioul (18.24 ± 2.88) in 1997, and than the mean value for the mainland (19.03 ± 6.15) in 2021 (Fig. 4. D, $p < 0.001$).

3.2. Additional chemical characterisation of soils and impacts of gull presence on edaphic parameters

No difference was shown for the soil conductivity between the archipelagos ($p = 0.96$), nor for islands *versus* mainland (mainland *vs* Frioul $p = 0.99$, mainland *vs* Riou $p = 0.23$), mean values from 0.64 to 1.07 mS/cm, not presented here, Table 3).

Regarding nutrient concentrations in soils, the mean amount of P in soils of the mainland (Table 3) was significantly lower than in the soils of the archipelagos (Fig. 5. A, ($p < 0.001$), and total P concentrations were significantly higher in the soils of Riou compared to Frioul (Fig. 5. A, $p < 0.01$).

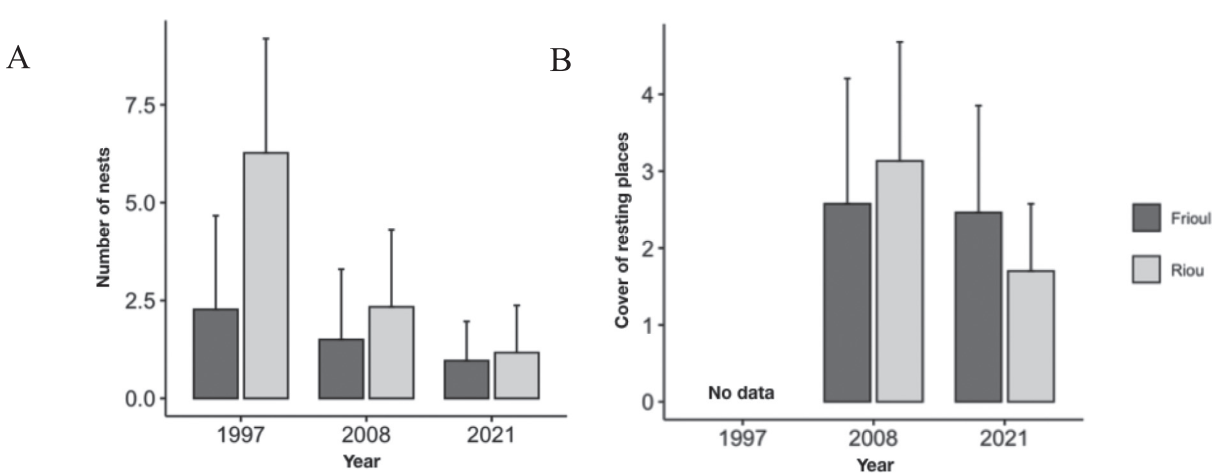

Fig. 3. A. Mean number of nests (mean + SD) at plots in 1997, 2008 and 2021 on Frioul ($n = 26$) and Riou ($n = 30$) islands. B. Mean cover of resting places in 2008 and 2021 at the same sites.

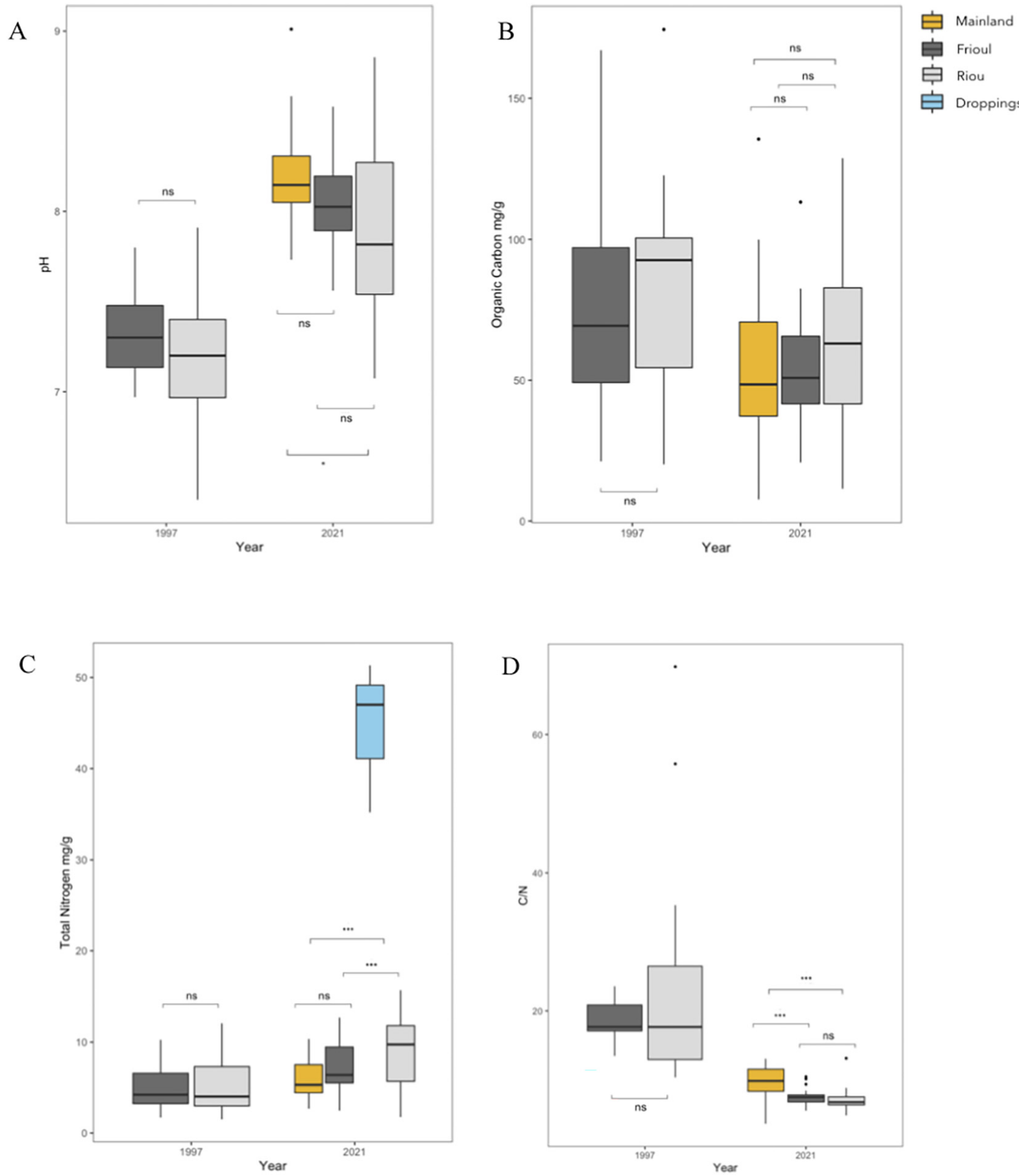

Fig. 4. Changes in soil parameters during the monitoring period (1997 to 2021) on Frioul (dark grey) and Riou (light grey) islands and the mainland (yellow) and data from droppings (light blue) (for total nitrogen in 2021), non-significant (ns): *p*-value >0.05, *: p-value <0.05, **: p-value <0.01, ***: p-value <0.001. A. The pH of the soil. B. Soil organic carbon (mg/g dry matter (DM)). C. The total nitrogen (mg/g DM). D. The soil C/N ratio. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The concentration of P appeared to be higher in droppings than in the soils. The K values were significantly higher in the soils of the Riou archipelago than on the mainland (Fig. 5. B, $p < 0.05$), but there was no significant difference between the soils of the archipelagos ($p = 0.58$). The droppings appeared to be less concentrated in K than the soils. No significant difference was observed for Na concentration whatever the soils on the islands or on the mainland (Fig. 5. C, mainland *vs* Frioul $p = 0.33$, mainland *vs* Riou $p = 0.08$, Frioul *vs* Riou $p = 0.87$), and Na contents were higher in droppings.

Regarding potentially toxic elements (PTE), Pb soil concentrations were higher on the mainland than on the archipelagos (Fig. 5. D, $p < 0.01$ between the mainland and Riou and $p < 0.001$ between the mainland and

Table 3
Complementary soil parameters measured on archipelagos and mainland plots, and on gulls' droppings (mean ± SD) in 2021.

Area	Conductivity (mS/cm)	P (mg/g dry matter (DM))	K (mg/gDM)	Na (mg/gDM)	Cu (mg/gDM)	Pb (mg/gDM)	Zn (mg/gDM)	Number of plots
Frioul	1.07 ± 1.78	1671.42 ± 939.93	8897.83 ± 2663.84	1467.50 ± 1531.58	48.12 ± 90.62	96.50 ± 98.26	150.18 ± 82.03	26
Riou	0.75 ± 0.35	3300.35 ± 2020.55	9705.64 ± 2597.42	1339.63 ± 714.84	29.85 ± 10.37	133.48 ± 81.75	157.64 ± 58.31	30
Mainland	0.64 ± 1.19	472.26 ± 205.22	8165.27 ± 2692.98	1125.71 ± 2246.57	25.74 ± 10.99	337.90 ± 299.36	212.70 ± 138.27	22
Droppings	NA	6767.72 ± 5106.96	4217.13 ± 3671.31	3665.08 ± 1401.69	71.53 ± 72.36	4.34 ± 14.03	396.13 ± 146.16	9

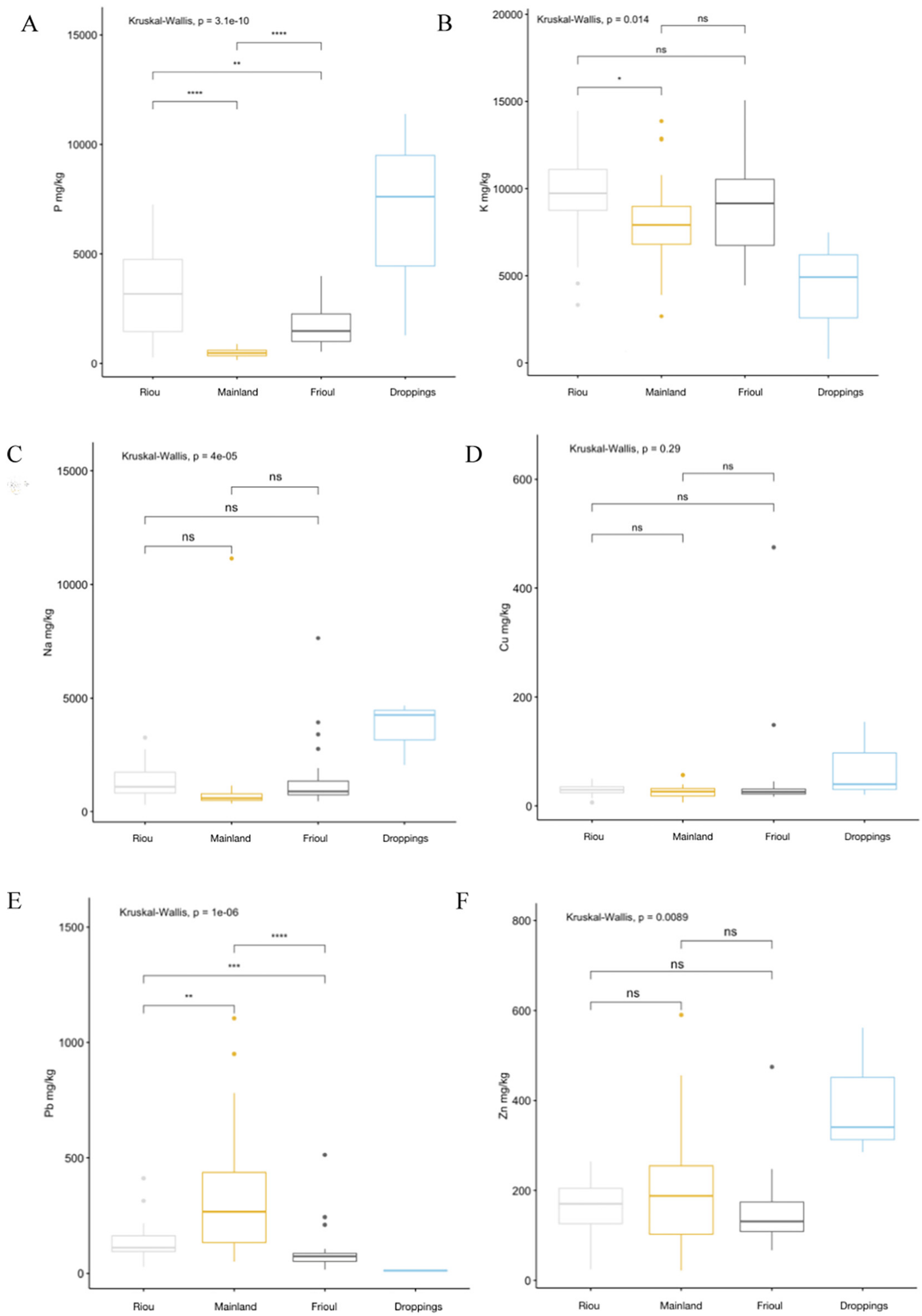

Fig. 5. Boxplots of the soil measured physical and chemical parameters in 2021 in the Frioul (n = 26) and Riou (n = 30) archipelagos, on the nearby mainland (n = 22) (south-eastern France) and in the droppings (n = 9), non-significant (ns): ns: p-value >0.05, *: p-value <0.05, **: p-value <0.01, ***: p-value <0.001, **** p-value <0.0001. A. The total phosphorus (mg/kg DM). B. The soil potassium (mg/kg DM). C. The soil sodium (mg/kg DM). D. The soil copper (mg/kg DM). E. The soil lead (mg/kg DM). F. The soil zinc (mg/kg DM).

Frioul). Pb concentrations were lower in droppings (mean of 4.34 mg/kg). With regards to Cu and Zn soil concentrations, no significant difference was observed whatever the soils on the islands or on the mainland (Cu: mainland *vs* Frioul $p = 0.99$; mainland *vs* Riou $p = 0.44$; Frioul *vs* Riou $p = 0.77$; and Zn: mainland *vs* Frioul $p = 0.15$; mainland *vs* Riou $p = 0.56$; Frioul *vs* Riou $p = 0.61$) (Fig. 5. E, F). Cu and Zn contents were higher in droppings than in soils. In order to estimate the potential soil contamination by PTE, contamination factors (*CF*) were calculated for Cu, Pb and Zn, in relation to the local contamination background proposed for the Calanques hills (Affholder et al., 2014). The highest *CF* values (Table 4) were

Table 4
Contamination factors calculated for Cu, Pb, Zn and the Pollution Load Index for Frioul and Riou archipelagos and the mainland area (mean ± SD).

Area	*CF* Cu	*CF* Pb	*CF* Zn	PLI
Frioul	6.87 ± 12.94	2.24 ± 2.28	2.28 ± 1.24	2.10 ± 0.54
Riou	4.26 ± 1.48	3.22 ± 1.83	2.39 ± 0.88	2.10 ± 0.30
Mainland	3.68 ± 1.57	8.23 ± 6.90	3.22 ± 2.09	2.33 ± 0.56

measured for Pb in mainland soils (8.23 ± 6.90) and for Cu in soils of the Frioul archipelago (6.87 ± 12.94), and these values reflected a high contamination ($CF > 5$). *CF* values for Pb in soils of the archipelagos reflected a low contamination rate (low contamination estimated when $CF < 3$, 3.22 ± 1.83 at Riou and 2.24 ± 2.28 at Frioul), and those for Cu in soils of Riou and the mainland reflected a medium contamination rate (medium when $3 < CF < 5$, 4.26 ± 1.48 at Riou and 3.68 ± 1.57 on the mainland). Concerning Zn, *CF* values reflected a low contamination rate whatever the sites (values between 2.39 and 3.22). The pollution load index (PLI) for Cu, Pb and Zn estimates the potential multi-contamination level of soils. This index, revealed a relatively low multi-contamination level whatever the sites studied, with PLI values around 2 (2.10 ± 0.30 at Riou, 2.10 ± 0.54 at Frioul, and 2.33 ± 0.57 on the mainland).

It was noticeable that the mean amounts of Cu, Zn, Na and P showed a tendency to be higher in the droppings than in soils (Fig. 5. E, D, F). The contrary was observed for K and Pb (Fig. 5. B, E).

The analysis of the stable isotopes showed an enriched signature of the δ15N for soils of the two archipelagos compared to the reference plots of the mainland (Fig. 6), with higher values for Riou (>5 ‰). Concerning the δ13C, values did not show a clear pattern.

Analyses of potential impacts of a colony of gulls on physical and chemical parameters of the islands' soil in 2021 showed that the concentrations of K were significantly and positively correlated with the number of nests ($p < 0.01$, Adjusted $R^2 = 0.1123$), P concentrations ($p < 0.05$, Adjusted $R^2 = 0.08533$) and Na concentrations ($p < 0.05$, Adjusted $R^2 = 0.08361$). These results also showed that the pH values were significantly and negatively correlated with the number of nests ($p < 0.05$, Adjusted $R^2 = 0.09594$).

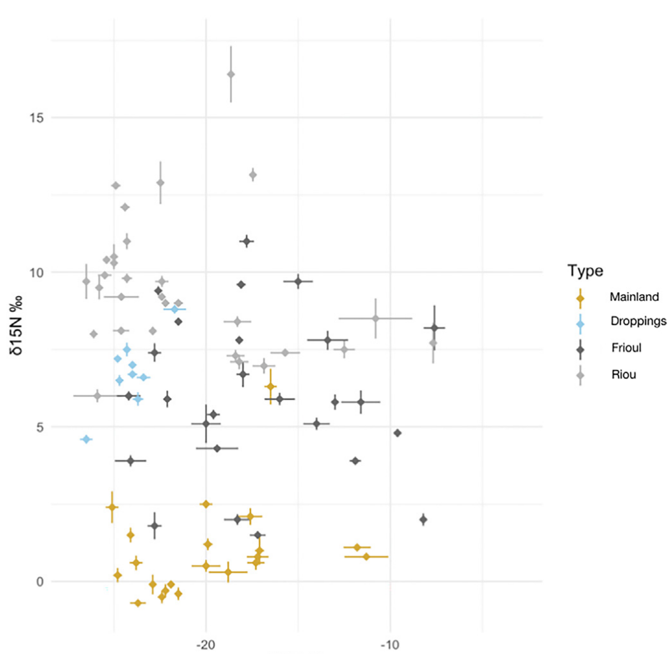

Fig. 6. The Delta (δ) of 13C *versus* δ15N (means ± SD) of stable isotopic composition in soil samples from the Frioul (n = 26) and Riou (n = 30) archipelagos, the nearby mainland (n = 22) (south-eastern France) and droppings samples (n = 9).

Moreover, the resting places were positively correlated with conductivity ($p < 0.05$, Adjusted $R^2 = 0.1728$).

Concerning the other parameters, no significant correlations were observed neither with the number of nests (Cu: $p = 0.51$, Pb: $p = 0.99$, Zn: $p = 0.82$, Conductivity: $p = 0.08$, N: $p = 0.27$, Organic Matter: $p = 0.65$) nor the resting places (Cu: $p = 0.64$, P: $p = 0.22$, Pb: $p = 0.39$, pH: $p = 0.41$, K: $p = 0.27$, Zn: $p = 0.44$, Na: $p = 0.09$, N: $p = 0.95$, Organic Matter: $p = 0.73$).

3.3. Changes in plant communities

NMDS drew a pattern of the flora community based on the three successive surveys conducted on the islands (Fig. 7.). The first axis separated the saline environment with salt-adapted plant species (*Camphorosma monspeliaca, Crithmum maritimum, Limonium echioides, Pancratium maritimum*) on the left, to the less saline environment represented by other plant species (*Avena barbata, Lonicera implexa, Rosmarinus officinalis, Urospermum picroides*) on the right. The second axis showed a gradient from the ruderal plant community (top: *Hordeum murinum, Malva arborea, Senecio leucanthemifolius, Sonchus asper* subsp. *glaucescens*) to the more stress-tolerant plant community (bottom: *Asteriscus aquaticus, Brachypodium retusum, Sedum littoreum, Teucrium flavum*).

Ruderal plants increased in the vegetation over time as highlighted by increased scores of recent compared to ancient vegetation data on the second axis. The flora in 1997 was less ruderal than in 2008 and in 2021 ($p < 0.01$). The flora in 2008 and 2021 was also different ($p < 0.01$) with more ruderal plant species in 2021.

No pattern of change was detected on the salinity axis (axis 1) when using the coordinates of the NMDS, (1997 *vs* 2008 $p = 0.11$, 1997 *vs* 2021 $p = 0.44$, 2008 *vs* 2021 $p = 0.19$).

The Pignatti nutrient ecological indicator indicated by the flora community on the islands was significantly lower in 2021 and 2008 compared to 1997 ($p < 0.05$). The humidity factor decreased in 2021 compared to 1997 on the islands ($p < 0.05$). The light factor decreased in 2021 compared to 1997 and 2008 on the islands ($p < 0.05$). The soil acidity indicated by the flora community was not significantly different between years for islands plots (1997 *vs* 2008 $p = 0.48$, 1997 *vs* 2021 $p = 0.16$, 2008 *vs* 2021 $p = 0.057$). Generalized Additive Models (GAM) showed no relation with the number of nests counted in 2021 (nutrient $p = 0.72$, humidity $p = 0.64$, light $p = 0.06$, soil acidity $p = 0.83$).

The modification of the temperature indicated by the flora community on the islands showed a diminution in 2021 compared to 1997 and 2008 ($p < 0.01$). In addition, there was a positive correlation with the number of nests ($p < 0.05$). However, a diminution of the temperature in 2008 and 2021 ($p < 0.05$) was registered with the mainland plots, where there were no gull nests.

The fluctuation of the salinity factor indicated by the flora community was significantly lower in 2008 than in 1997 on the islands ($p < 0.05$). The GAM showed a positive correlation with the number of nests ($p < 0.01$). Concerning the mainland, no other difference has been observed ($p > 0.15$).

Results of mean comparisons showed that the total number of species was not different between years on the islands (1997 *vs* 2008: $p = 0.669$, 1997 *vs* 2021: $p = 0.2446$, 2008 *vs* 2021: $p = 0.5376$). However, for the mainland, differences were observed between 1997 and 2008 ($p < 0.05$) and between 2008 and 2021 ($p < 0.001$) with the lowest value in 2008.

When analysing Grime plant strategies, ruderals (the most strongly represented Ruderals (R): *Sonchus tenerrimus*, Ruderal-Competitives (RC): *Parietaria judaica*, Ruderal-Stress tolerants (RS): *Lobularia maritima*, Stress tolerant- Ruderals (SR): *Euphorbia linifolia*) increased between 1997 and 2008 ($p < 0.001$) and this pattern remained in 2021 ($p < 0.001$). Moreover, intermediate plant strategies (Competitive-Stress tolerant-Ruderals (CSR), such as *Cistus albidus, Euphorbia characias, Lotus cytisoides*) decreased significantly on the islands from 1997 to 2008 ($p < 0.05$) and slightly increased

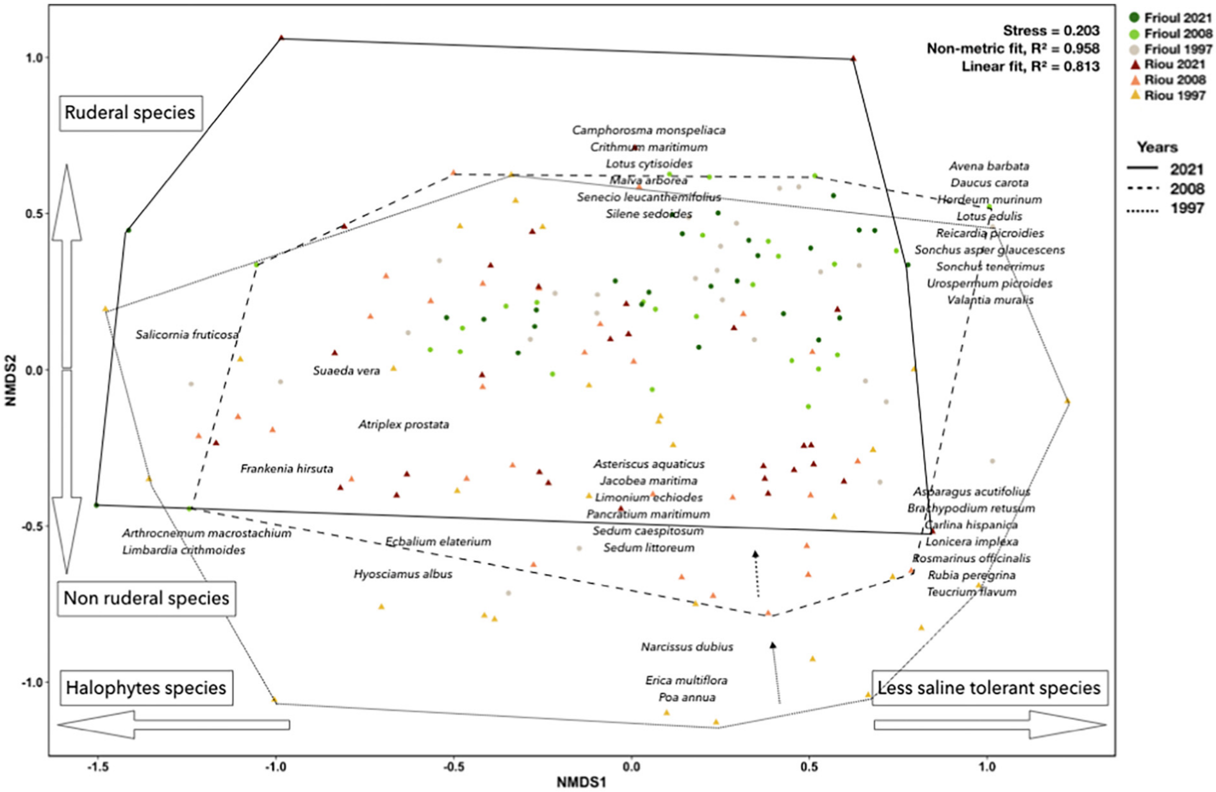

Fig. 7. Non-metrical multidimensional scaling (NMDS) of plant community composition of the three years of the survey (1997, 2008 and 2021) in the Frioul and Riou archipelagos.

again to 2021, with no significant difference between 1997/2021 (p = 0.06277) and 2008/2021 (p = 0.8016).

Island vegetation showed a significant increase of geophytes, hemicryptophytes and therophytes ($p < 0.001$) in 2008, remaining constant to 2021. Chamaephytes on the islands decreased from 1997 to 2008 ($p < 0.001$) and afterwards remained stable ($p > 0.005$). Chamaephytes on the mainland continuously decreased from 1997 through 2008 ($p < 0.01$) to 2021 ($p < 0.001$), and annual plants increased continuously. No significant pattern of change was detected for geophytes (1997 *vs* 2008 p = 0.38, 1997 *vs* 2021 p = 0.59, 2008 *vs* 2021 p = 0.85) and hemicryptophytes (1997 *vs* 2008 p = 0.77, 1997 *vs* 2021 p = 0.037, 2008 *vs* 2021 p = 0.99) on the mainland. No pattern of change was detected for the nanophanerophytes and the phanerophytes at any site.

The vegetation cover was significantly higher on two groups of plots in 2021 than in 2008 ($p < 0.01$ for the first group and $p < 0.05$ for the second group) (for more details and photographs, see Supplementary Materials Fig. S1 and S2).

4. Discussion

4.1. Dynamic of the soil parameters and characterisation

Comparing the fluctuation of soil parameters between 1997 and 2021, we recorded an increase of pH values. This means that the soil was less acidic in 2021 than 24 years ago. Considering the values of pH, it was still approaching neutrality so little impact on the flora was expected. Conversely, the amount of N had increased because of droppings accumulation and limited leaching. When decomposing, the organic matter increases total N concentration in soil. Moreover, organic matter decomposition explains its decrease and the decrease of C/N values. These quantities of N could help plant development as seen on a recently emerged volcanic island (Sigurdsson and Magnusson, 2010; Aerts et al., 2020). However, in the case of the Marseille archipelagos, where a flora community was already established, this could trigger a lasting alteration of plant composition. The C/N ratio plays a role in the balance of the bacterial and fungal communities of soil, with an increase of the bacterial community when C/N decreases (Grosso et al., 2016). Moreover, soil organic matter is considered as a good indicator of soil quality and high levels of organic matter are associated with nutrient availability and increased water retention capacity (Nyiraneza et al., 2017).

The values of P measured in 2021 showed that the soils in the archipelagos are still enriched with, and this observation was corroborated by other studies which showed that P enrichment by seabirds is an irreversible process (Myrcha and Tatur, 1991; Holdaway et al., 1999; Sun et al., 2000; Otero et al., 2015; De la Peña-Lastra et al., 2021). Moreover, the values in both reference and colonies plots were comparable to the study of De la Peña-Lastra et al. (2020). The lower coverage of plants when the gull colony was at its demographic peak, implying a decline in nutrient retention (Hanrahan et al., 2021), might also explain the high values of P and its accumulation in the soils. The soils of the archipelago of Riou showed the highest levels of P. This observation could be explained by the fact that the colony was first established on Riou before expanding to Frioul (Baumberger et al., 2012). Hence, its impact on the soil and the flora lasted longer and today the colony on Riou is still larger.

The values of conductivity and Na concentrations measured in soils in 2021 showed no differences between the mainland and the islands, which means gull presence today has no impact with regards to these characteristics. Usually, conductivity and Na concentrations have been shown to increase with the presence of seabird colonies (Ellis, 2005; Zwolicki et al., 2015). However, another study also did not register salinization (De la Peña-Lastra et al., 2021), probably due in their case to high precipitations and leaching (Otero et al., 2015).

In 2021, we also added to the analysis trace elements (or PTE) in soils, and the determination of pollution load index (PLI), integrating Cu, Pb and Zn, reveals relatively low multi-contamination levels on the mainland and the archipelagos, with values around 2.2. These PLI values correspond to those calculated for soils in the Calanques hills (mean value of 2.3) some distance away from the urbanized area of Marseille and from current and former industrial activities (Affholder et al., 2014). We observed higher values for the amount of Pb in soils of the mainland than in those of the archipelagos. We can argue that the origin is mostly anthropic, notably with the use of leaded gasoline, coal burning and waste incineration (Erel et al., 1997; Komárek et al., 2008), but mainly with the former lead smelter sites located on the south-east coast of Marseille (Daumalin et al., 2016; Heckenroth et al., 2016, 2022; Affholder et al., 2014;). The values of Cu and Pb are comparable to the results of a previous study on the impact of waterbird colonies in the Mediterranean semiarid floodplain (Laguna et al., 2021), but we cannot argue for a direct effect of the gulls on these PLI. However, the literature shows the importance of pollutants transport, such as Cu, Pb, Zn, by seabirds (Shoji et al., 2019; Castro et al., 2021; Grant et al., 2022).

Moreover, the values of K, Na, P and conductivity on the islands showed greater amplitudes, which led to a greater spatial variation for the chemical composition of soils, plant richness and assemblages (Wait et al., 2005).

The results of stable isotopes δ15N reflected higher values for the two archipelagos and the droppings, with values around 10 ‰ for the droppings and even higher than 15 ‰ for the Riou archipelago. The values of previous studies were on the same scale (Ellis, 2005). High δ15N derived from the droppings, and hence explained the values of the archipelagos, the seabirds being positioned high in the trophic chain (García et al., 2002; Wait et al., 2005; Laguna et al., 2021). The values of the mainland higher than 0 ‰, derived from the matter of the vegetation (Post, 2002). There was no significant difference concerning the δ13C, which resulted mostly from the autochthonous organic matter even on the island (Torres et al., 2012).

An increase of pH was observed but there was still a negative link with gull density, as in other studies (Vidal, 1998; Ellis, 2005). Moreover, cover of the resting places had a positive link with conductivity. Except for pH, K, P, Na, we did not find the same links as in 1997 with positive correlations between nest density and the organic matter nor the nitrogen content (Vidal, 1998). Moreover, the results also indicated that the amounts of Na, P and Zn were higher in the droppings than in soils. According to these observations, we could expect existing links between gull densities and today's values in the islands' soils. However, with the absence of links as shown before, we believe that the levels of nutrients and other elements found today could still be linked with the density of nests of the last decades. Actual observations have been shown to retrace land-use history and be linked to it even millennia after in dry ecosystem (Mizutani et al., 1991; Saatkamp et al., 2020). As previously seen, changes in soil P driven by seabird colonies have persistent effects (Myrcha and Tatur, 1991; Holdaway et al., 1999; Sun et al., 2000; Otero et al., 2015; De la Peña-Lastra et al., 2021). The remanence in soil is also the case for other nutrients and contaminants such as N or Selenium (Hawke and Wu, 2012; Jaunatre et al., 2014; De la Peña-Lastra et al., 2021). The retention and so the remanence time for nutrients or contaminants can vary with several factors, such as successional state and ecosystem type, demand or retention capacity, land-use history, type of soils, topography, climate and the rate, timing and type of deposition as was shown for N inputs (Matson et al., 2002).

4.2. Vegetation dynamics

4.2.1. Lag dynamics between soil and vegetation

The previous hypothesis, according to which the current observations would be explained by previous gull pressure, is reinforced by the study of the flora community because we highlighted that the plant community on the island is still different from 1997, being as ruderal as in 2008. This observation could find an echo in a previous study (Purschke et al., 2012) which found that current factors alone could not explain today's flora pattern. This finding is similar to those of a recent study (Saatkamp et al., 2020) where it was demonstrated that the use of land two thousand years ago by the Romans is still modelling the vegetation and the soil today. Furthermore, we can also surmise that the plant community can be firstly influenced by the mesological parameters such as the distance from the mainland, the surface area, the topography, the perimeter and the maximum altitude of the island (MacArthur and Wilson, 1963; Whittaker et al., 2017), the direct effects of the seabird colonies (Bancroft et al., 2005; Wait et al., 2005), and secondly by the induced soil alterations (Duda et al., 2020). It appears that at the level of the species and the functional traits, there have been no significant changes since 2008. Indeed, there are still more ruderal species strategies (with the most represented R: *Sonchus tenerrimus*, RC: *Parietaria judaica*, RS: *Lobularia maritima*, SR: *Euphorbia linifolia*) and more geophytes, hemicryptophytes, and therophytes in 2021 than in 1997 on the islands. The differences observed on the islands means that the plant species which are highly tolerant to disturbances in harsh environment are still favoured even with the decline of the pressure induced by the presence of the gull (Baumberger et al., 2012).

The decrease of the chamaephytes recorded in 2008 compared to 1997 is no longer occurring in 2021 on the island. This is noticeable because certain of the heritage/endangered plant species of the archipelagos are chamaephytes and specialists of this environment (*e.g.*, *Astragalus tragacantha, Limonium pseudominutum, Frankenia hirsuta, Euphorbia pithyusa, Plantago subulata*). However, further analyses and studies are needed to conclude more precisely on the dynamics of each of the species mentioned above. Nevertheless, this observation still permit to underline the vulnerability of these species (Bou et al., 2020) being not ruderal and jeopardized by the eutrophication of the soil. These observations also raise questions regarding their protection and the support of the viable populations until the habitat returns, or not, to a previous state (Knoerr, 1960; Molinier 1936, 1939 in Vidal et al., 1998a, 1998b). On this time scale, we may inquire about the expression of the seed banks, which are considered essential for plant communities because of their contribution to ecological processes, in terms of resilience, the persistence of the community and the restoration of the ecosystems (del Cacho and Lloret, 2012; Kiss et al., 2018).

An increase in the vegetation cover was registered between 2008 and 2021 especially on island plots. As supported by the previous results on functional types, it was not a sign of the resilience of the functional flora community such as there was in 1960 (Knoerr 1960 in Vidal et al., 1998a, 1998b) – with more stress-tolerant species. However, it was a sign of the resilience of the flora developed since then, being more ruderal. Concerning the mainland plots where vegetation cover increased, we can assume that in 24 years and without major disturbances (fire, rockslide), the plants followed a natural dynamic and so the aboveground vegetation cover increased.

4.2.2. Interactive effect of gulls and climate change

In the context of the alteration of the biota (*e.g.*, the yellow-legged gull colony and so the flora) linked to the land use (*e.g.*, landfills), it was interesting to explore whether the alteration of the disturbance is modulated by climate change (Perring et al., 2016), or whether they may act in synergy. This could also offer us a basis for deciding on future management actions (Perring et al., 2015). Using the bioindicators of Pignatti (Schwabe et al., 2007; Saatkamp et al., 2022) helped us to characterise the requirements of plant species between the three dates and underline the results obtained from the soil analyses. In fact, we could highlight that since 1997 there has been a decline of the nutrient factor on the islands, not correlated with the gull density in 2021. This observation is corroborated by the chemical results. Schaffers and Sýkora (2000) found that the nutrient factor is not directly linked to the nitrogen but is correlated with the productivity. Previous studies have shown that gull colonies can lead to an increase in soil moisture, which can be explained by greater water retention due to higher amounts of organic matter (Ishida, 1997; García et al., 2002). The decrease of the productivity, soil moisture and light all imply a diminution of the vegetation cover before 2021. It will be interesting to see in the future whether the increase of the cover observed today will trigger this factor.

We could also observe differences on the mainland concerning the temperature, with plants indicating a decrease in 2021 compared to 2008. The fact that there were no significant differences between 2021 and 1997 on the mainland, regarding the temperature, could perhaps point to a fluctuation being due to the meteorology, with dryer or wetter years. However, we could also note that there were fewer CSR strategies in 2008 than in 1997 on the islands and fewer in 2021 compared to 1997 on the mainland. This could be explained by a natural fluctuation, with the renewal rate of these plants, which here in the Calanques National Park are *Cistus albidus, Cistus monspeliensis, Cistus salvifolius. Euphorbia characias, Halimione portulacoides, and Lotus cytisoides* (mostly nanophanerophytes). On the mainland, we also observed the increase of the therophytes. These observations could also be linked with the increase of more generalist and fewer thermophilous species, the closure of the vegetation or the pattern with less rainfall (Kimball et al., 2010).

Climate change in the region and its impacts on flora have been synthesized in details in a recently accepted work (Saatkamp et al., 2023 *in press*), showing that there is an overall warming and drying in lowland areas, with a stronger effect inland compared to coastal areas. It seems however that climate change effects are overridden by trophic changes and long-term succession in the present data-set, since there is no clear effect of thermophilization and xerophytisation. Moreover, higher temperatures during the cold season could increase the presence of plants from higher altitudes or latitudes but not thermophilous species because on the islands this type of plant is already present. Further investigations should be undertaken linked with the precipitation and the temperature as measured and not only bio-indicated.

5. Conclusions

We highlight that seabird populations provide a link between landfills history and soil eutrophication and time-related vegetation changes on small Mediterranean islands. We observed a remanence of the effects on soil parameters. However, we were expecting more changes in plant community composition but apart from the cover, the community remained similar to 11 years ago, with more ruderal plants.

It is important to follow the patterns of change in gull populations, the flora and the physical and chemical parameters of the soil to better understand the resistance and resilience of the ecosystem post-disturbance. Furthermore, gull populations showed a slight increase in 2021. It is necessary to determine whether this a natural fluctuation between years, a stochastic event, or whether the gulls found another food resource (such as the rubbish bins in coastal cities) leading to a new demographic explosion in the coming years.

CRediT authorship contribution statement

Clémentine Mutillod: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Teddy Baumberger:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Pascale Prudent:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing, Funding acquisition. **Arne Saatkamp:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing. **Eric Vidal:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing. **Lidwine Le-Mire-Pecheux:** Conceptualization, Methodology, Resources, Supervision, Project administration, Funding acquisition. **Laurence Affre:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162948.

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