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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 --Manuscript Draft--

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Abstract:	<p>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 functional types (Raunkiaer growth forms and Grime life strategies) up to the decrease of the number of nesting yellow-legged gulls (<i>Larus michahellis</i> 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).</p> <p>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.</p> <p>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.</p>
Response to Reviewers:	

Title: 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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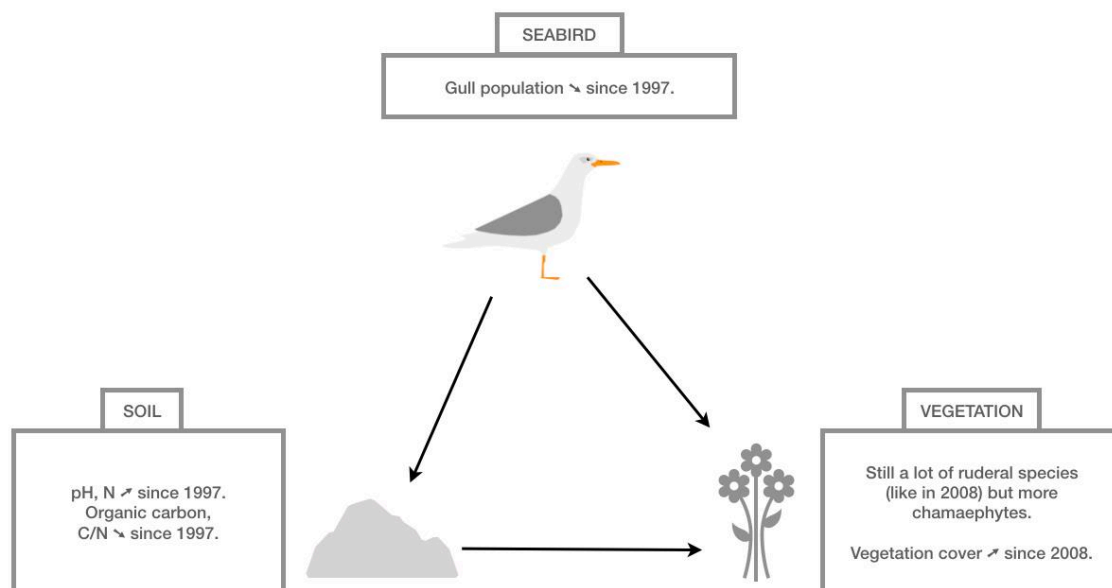
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Graphical abstract



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

3

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15

16 **Highlights**

17 - Soil parameters alterations (notably nutrients increase) induced by seagulls persist
18 after the colony declines.

19 - Ruderal plant species and more chamaephytes still occurred after the gull colony
20 decline.

21 - Vegetation cover increased with the decline of gull colony.

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16 **Abstract**

17 Seabird colonies have a strong influence on both the physical and chemical soil parameters and plant
18 communities of the islands where they settle to nest. Scientists have studied the effects of the
19 demographic explosion of seabird populations, but few have explored the long-term effects when the
20 colonies were in decline. The aim of this study was to investigate diachronic changes over a 24 year
21 period of soil parameters, floristic composition and plant functional types (Raunkiaer growth forms
22 and Grime life strategies) up to the decrease of the number of nesting yellow-legged gulls (*Larus*
23 *michahellis* Naumann, 1840) on Mediterranean islands. We used 78 permanent plots to survey the
24 vegetation and the soil parameters on 9 islands and one mainland area within the Calanques National
25 Park (south east of France), for three periods (i.e., 1997, 2008, 2021).

26 Since 1997, the increase of nesting gulls has caused a nitrogen and pH increase and organic carbon and
27 C/N ratio decrease, although the values were still higher than mainland plots without nesting gulls. This
28 has led to changes in plant species composition e.g., higher values of N favouring the development of

29 ruderal plant species, still present in high frequency in 2021. Furthermore, plant species highly tolerant
30 to disturbances (i.e., R Grime strategy) in harsh environments were still favoured even after the decline
31 of gull abundance. However, both the frequency of the chamaephytes and the vegetation cover has
32 increased with the decline of gull colony. In 2021, measures of trace elements' concentrations and
33 calculation of pollution load index (Cu, Pb and Zn) reveals relatively low multi-contamination levels on
34 the mainland and the archipelagos.

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

38

39 **Key words:** Long-term diachronic survey, seabirds, trace elements, plant community, land-use history.

40 1 Introduction

41 Manmade global change has had a profound impact on biodiversity (Vié, Hilton-Taylor and Stuart,
42 2009), especially in the Mediterranean basin which is considered one of the biodiversity hotspots
43 (Cunningham and Beazley, 2018). An important part of Mediterranean plant diversity is linked to the
44 occurrence of 10,000 small islands, islands being refuges for rare and threatened mainland plant species
45 (Médail, 2017). However, the Mediterranean basin has been subjected to an increase in human activity,
46 particularly in coastal and island habitats (UNEP/MAP-Plan Bleu, 2009). Human activities alter
47 ecosystem properties and services (Hooper *et al.*, 2005), especially when they affect biotic factors
48 (Chapin *et al.*, 1997).

49 In this insular context, populations of the yellow-legged gull (*Larus michahellis*, hereinafter referred to
50 as gulls) have greatly increased over the past few decades (Thibault *et al.*, 1996; Bellout *et al.*, 2021).
51 Indeed, the high availability and predictability of food resources (Bosch *et al.*, 1994), provided by open
52 compartments of landfills during their operation on the close mainland, is known to have driven and
53 shaped gull colony distribution and demographic explosion on the studied islands (Duhem *et al.*, 2002,
54 2003, 2007, 2008). Gulls have therefore been considered as a superabundant bird species in the
55 Mediterranean basin (Vidal, Médail & Tatoni, 1998) that conflict with island biodiversity conservation

56 programmes (e.g. Médail, 2017; De La Peña-Lastra *et al.*, 2021; Mouga *et al.*, 2021). Gulls, like other
57 seabirds, are chemical and physical ecosystem engineers (Ellis, 2005; Grant *et al.*, 2022). Due to the
58 high spatial heterogeneity of their feeding, nesting and defecation behaviour, seabirds can have
59 contrasting impacts on ecosystems. On the one hand, their presence can lead to an increase of plant
60 biomass and height (Ellis, 2005) and seed dispersal (Nogales *et al.*, 2001; Calvino-Cancela, 2011). On
61 the other hand, high seabird densities can prevent plant growth owing to the uprooting of plants for nest
62 building, trampling and soil compaction (Sobey and Kenworthy, 1979). Many studies have shown that
63 large seabird colonies can alter soil characteristics, increasing the quantity of nitrogen, phosphorus,
64 potassium, magnesium, total salts (Sigurdsson and Magnusson, 2010; Bouyahmed and Moulai, 2018;
65 Aerts *et al.*, 2020), heavy metals (García *et al.*, 2002; Ziółek, Bartmiński and Stach, 2017; Otero *et al.*,
66 2018), organic matter (García *et al.*, 2002; Ghermaoui, Hassaine and Moulai, 2016) and soil depth
67 (Ishida, 1997; Mulder and Keall, 2001). They also usually lead to a decrease of soil pH (Mulder and
68 Keall, 2001; Sigurdsson and Magnusson, 2010). Other soil characteristics can also be altered, but the
69 trend can be both upward or downward such as for calcium, carbon content, water retaining capacity
70 and soil moisture (Ellis, 2005). These different alterations may cause changes in plant communities –
71 with high pressure and duration, exotic, ruderal or nitrophilous plant species may develop that may lead
72 to a reduction of the abundance of native plant species (Vidal *et al.*, 1998, 2000; Baumberger *et al.*,
73 2012; Bou, Vilar and Carreras, 2020). The reduction of food availability following the closure of open
74 compartments of landfills is indicated as the main driver for a long term reduction on gull population
75 size (Duhem, 2007, 2008) and the negative density-dependent breeding investment contributed to
76 population decline (Real *et al.*, 2017).

77 Few studies (Baumberger *et al.*, 2012; Otero *et al.*, 2015; De La Peña-Lastra *et al.*, 2021) have
78 investigated the long-term patterns of change in plant communities and soil factors after the decrease of
79 gull populations, showing that the environmental effects of the colonies may persist for a long time. For
80 example, high concentrations of phosphorus (P) have been observed 5 (De La Peña-Lastra *et al.*, 2021)
81 and 14 years (Otero *et al.*, 2015) after the decline of gull populations. The amount of P generated by the
82 colony did not decrease and can be considered as an irreversible impact for the plant community (Otero
83 *et al.*, 2015; De La Peña-Lastra *et al.*, 2021). The Mediterranean basin has a particular climate with low

84 precipitation. In these semi-arid ecosystems, alterations linked to trophic shift can lead to a persisting
85 imprint of eutrophication in the soil (Saatkamp, Henry and Dutoit, 2020) and the impact on plant
86 communities is linked to higher P, C:N and organic matter. The threats to the Mediterranean islands are
87 exacerbated by climate change because of the limited habitat availability and climatic range limitations
88 which may hamper the expansion of the species' range (Vogiatzakis, Mannion and Sarris, 2016).
89 Our study focused on nine islands in the two Marseille archipelagos, Frioul and Riou (Calanques
90 National Park, SE France), which are under the influence of breeding gulls (*Larus michahellis*) in
91 comparison with the nearby mainland coastal area without gull colonies. Previous studies have shown
92 that the high pressure of gull colonies leads to a ruderalisation of the floristic community (Vidal *et al.*,
93 1998, 2000). This pattern has persisted (Baumberger *et al.*, 2012) despite four open landfills having been
94 closed in the Marseille area during the last decade, which has caused a decline in the nesting gull
95 population (Calanques National Park monitoring). We have extended monitoring of the vegetation
96 changes up to 24 years and added information with additional analysis of nutrients and trace elements
97 in the soil according to the fluctuations in the nesting gull density. Because of the strong relationships
98 within the gull/soil/plant system, we expected to demonstrate a resilience in plant communities despite
99 the persistent effect of gull colonies on soil chemistry.

100

101 2 Material and Methods

102 2.1 Study area

103 The study was conducted on two archipelagos and on the mainland area near Marseille (SE France)
104 (Fig.1). The sampling took place on two archipelagos of Marseille: the Riou archipelago (43°11'N,
105 5°21'E; five islands and two islets), and the Frioul archipelago (43°16'N, 103 5°18'E; four islands) (Fig.
106 1). The Riou archipelago islands studied are from 50 to 3525m distant from the mainland (Table 1).
107 Concerning the Frioul archipelago, the two islands studied are 1800 and 2800m away from the mainland.
108 The mainland area was considered as a habitat not subjected to gull pressure (no gulls nesting on the
109 studied mainland area). These islands and the mainland area are included in natural protected areas

110 managed by the Calanques National Park (CNP). Situated within the thermo-Mediterranean bioclimatic
111 belt (Quézel & Médail, 2003), these islands and the mainland area have semi-arid climatic conditions,
112 with lower precipitations on the islands (e.g., Planier, an island located 9km from Marseille: 342mm)
113 compared to the mainland (Marseille 524mm), however little reliable data exists (Météo France). The
114 studied sites are composed of compact limestone on the surface of which soils are limited to thin proto-
115 rendzina patches, and are calcareous, skeletal and oligotrophic (Vidal, 1998).
116 The plants on the islands and the mainland coastal area are subjected to stresses both hydric (low
117 precipitation and frequent strong wind episodes) and haline (with salt input from the sea and the toxicity
118 of the salt within the tissues). The islands are mainly covered by low vegetation from halophyte plants
119 to matorral shrub species (Baumberger *et al.*, 2012). Vegetation on the mainland shows a similar
120 composition, with however higher species richness compared to islands of similar size (Martín-Queller
121 *et al.*, 2017).

122

123 Yellow-legged gull status is considered as Least Concern in the IUCN European Red List, it is
124 a protected specie in France and a determining specie of natural areas of ecological, faunistic and floristic
125 interest (INPN MNHN, 2023). Gull colonies are nesting in the Mediterranean basin and the Atlantic
126 coast from Morocco to the southern Brittany (Duhem, 2004). Gull colonies can be found on all the
127 islands close to Marseille. However, nesting gull abundance and densities are not homogenous between
128 the archipelagos, and depend on local habitats. The gull population increased in the Riou and Frioul
129 archipelagoes between 1997 and 2005, with a growth rate ranging from 6% for the Riou archipelago to
130 177% for the Frioul archipelago (Duhem *et al.*, 2008). The fluctuations of gull population size in the
131 two archipelagos are presented in figure 2, between 1923 and 2021. Data were compiled by the CNP.
132 Gulls' census on the islands of Marseille is part of a CNP program taking place every five years as well
133 as the national census every ten years. Gull estimation was carried out by counting the number of nests
134 (empty and with eggs) exhaustively on each island until 2021.

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

138 The main available anthropogenic food resources, four landfills (with open compartments during their
139 operation) located within a radius of 60 kms, were closed in 2008, 2010 and 2013 and led to a decline
140 in gull population size (Calanques National Park monitoring). The decrease of easily accessible food
141 resources led to the decline of the nesting population by 63% in the Riou archipelago and 37% in the
142 Frioul archipelago between 2005 and 2015 (Fig. 2). However, an increase was recorded in 2021 with
143 the difference being about 1100 nesting couples.

144

145 2.2 Sampling design

146 The vegetation was surveyed on the 56 island plots and on the 22 mainland plots in 1997, 2008 and
147 in 2021 (Tab. 1). The number of plots was proportional to the size of the island in order to take into
148 account the heterogeneity of the zones studied and the different vegetation types. A plot consisted of
149 two concentric circles, a first one of 500m² where environmental variables and gull density were
150 measured, and, a second of 100m² where floristic inventories and soil sampling took place (Vidal, 1998).

151

152 2.3 Mesological parameters

153 Environmental variables were measured in the 500 m² circles for each plot to better qualify and
154 quantify the environmental effects (see table 2 for further details). Measures and estimations were made
155 during the floristic inventories from April to May in 1997, 2008 and 2021. The environmental variables
156 measured were the elevation above sea level, the distance from the coastline, the slope, the exposure,
157 and the cover rate of each substrate type: rock, block, stone, bare ground, the vegetation cover of the
158 different layers.

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

161

162 2.4 Floristic inventories

163 Three plant species inventories (1997, 2008 and 2021) were carried out within the same 78
164 100m² concentric plots from April to May using Tison *et al.* flora (2014). The plant cover in the different

165 layers was estimated (2008, 2021) for each species present on each plot using the 6 cover abundance
166 categories (0: cover = 0%, 1: 0% < cover < 10%, 2: 10% ≤ cover < 25%, 3: 25% ≤ cover < 50%, 4: 50%
167 ≤ cover < 75%, 5: cover ≥ 75 %). The following easily accessible plant functional types, i.e., Raunkiaer
168 growth form (Raunkiaer, 1934) and Grime life strategy (Grime, 1977), for each plant species, were
169 extracted from the BASECO data base (Gachet, Véla and Tatoni, 2005).

170

171 2.5 Soil, droppings sampling and chemical analysis

172 The soil was sampled in 1997 (56 plots only on the islands) and in 2021 (56 plots on the islands
173 and 22 on the mainland). In 1997, organic carbon, total nitrogen, and pH were measured within the plots.
174 In 2021, soil parameters included organic carbon, total nitrogen, pH, conductivity, total phosphorus,
175 potassium, sodium, copper, lead, zinc and stable isotopes ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$).

176 The soil samplings were performed once between March and April, when most of the gulls were nesting
177 and after the winter rainfall. Within each plot, five soil subsamples of 200mL each were collected (one
178 in the center and four on each side, approximately 50cm from the 100m² radius boundary) and pooled
179 in a composite soil sample, in order to make a composite sample representative of the plot. Soil
180 subsamples were collected from the top 15cm layer after litter removal and sieved at 2mm directly on
181 site. The soil samples were dried before analysis (at 40°C up to constant weight). Dry gull droppings
182 were sampled on nine different plots in the Frioul and Riou archipelagos in 2021. They were collected
183 on rocks to avoid contact with soil.

184 To assess the soil organic matter percentage (SOM), the method of Mathieu & Pieltain (2003) was used:
185 the samples were first weighed and then heated several times at high temperature. The samples were
186 heated first at 220°C for 16 hours (bound water elimination), then heated again at least three times at
187 450°C for four hours (loss of organic matter by combustion, and SOM was estimated by mass loss
188 between 220 and 450°C). The organic carbon was estimated using the values of the organic matter
189 multiplied by 0.50, based on the assumption that the soil organic matter contains 50% carbon (Pribyl,
190 2010).

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

195 The total nitrogen, carbon, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ content in ground soil samples (ground to less than 0.2mm
196 with RETSH 22, agate mortar) and droppings samples (n = 9, not composites) were performed on an
197 elemental analyzer (Flash HT Plus, Thermo Fisher Scientific) coupled with a mass spectrometer (Delta
198 V Advantage, Thermo Fisher Scientific). Elemental analysis of carbon and nitrogen were performed in
199 a combustion reactor (1,000°C) under a carrier gas (Helium: 100mL/min) with samples weighing
200 approximately 800 μg sealed in tin capsules, introduced via an automatic injector. The gases were
201 separated on a chromatographic column in an oven at 45°C before being quantified via the thermal
202 conductivity detector (TCD) of the elemental analyzer. The gases were injected into the Delta V
203 spectrometer for isotopic analysis. The calibration of the catharometric detector and the ratio-isotopic
204 mass spectrometer was performed with a secondary standard, EDTA (tetra-acetic ethylene diamine
205 acid). The analyses (samples or standards) of the ratio $^{13}\text{C}/^{12}\text{C}$ were calculated in delta value which
206 represents the deviation from an international standard and is calculated as follows :

$$207 \quad \delta^{13}\text{C} = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000 (\text{‰})$$

208 The international standard for $\delta^{13}\text{C}$ is Vienna PeeDee Belemnite (VPDB), $R_{\text{standard}} = 0.011237$. The
209 $\delta^{15}\text{N}$ is expressed in the same way in relation to atmospheric nitrogen with a conventional value of 0‰.
210 The results of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analyses are produced with an uncertainty of +/- 0.5 ‰. The $\delta^{15}\text{N}$ and
211 the $\delta^{13}\text{C}$ were analysed because they can give an indication of the trophic transfer, being robust and
212 effective in tracing the path of the organic matter and the trophic relationships within the ecosystems
213 (Post, 2002).

214 The analysis of the other elements (Cu, K, Na, P, Pb and Zn) in the soil and the droppings samples was
215 carried out after acid mineralization. Samples were digested in a microwave mineralizer (Milestone Start
216 D) using aqua regia (1/3 HNO_3 (Fisher chemical, Trace metal grade 67-69%) and 2/3 HCl (Fisher
217 chemical, Trace metal grade 35-38%)). After mineralization, the samples were filtered through a 0.45 μm

218 cellulose ester membrane filter and stored at 4°C until analysis (mineralization protocol for pseudo-total
219 concentration determination in soil, adapted from norm ISO 11466, 1995). Then element concentrations
220 in samples were carried out by ICP-OES (Inductive Coupled Plasma, Optical Emission Spectrometry,
221 Jobin Yvon Horiba Spectra 2000). Quality controls and accuracy were checked using standard soil
222 reference materials (CRM 049-050 from RTC-USA), with accuracies within 100±10%).

223 Concerning Cu, Pb and Zn, considered as potentially toxic elements (PTE), contamination factors in soil
224 (CF) were calculated as followed: $CF_{PTE} = [PTE]_{\text{pseudo-total in soil}} / [PTE]_{\text{local background value}}$

225 where $[PTE]_{\text{local background value}}$ are 43, 66 and 7.5 mg.kg⁻¹ for Pb, Zn and Cu respectively (Affholder *et al.*,
226 2014). The potential multi-contamination level of soils was estimated by calculating an integrative index
227 i.e. pollution load index (PLI) according to the formula (Affholder *et al.*, 2014; Rashed, 2010):

$$228 \text{ PLI} = \sqrt[3]{CF_{\text{Pb}} \times CF_{\text{Zn}} \times CF_{\text{Cu}}}$$

229

230 2.6 Statistical analysis

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

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

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

255 The observations made on the islands could be explained by more global alterations such as climate
256 change (Heilmeier, 2019; Ahrens *et al.*, 2020). To comprehend the flora ecological requirement changes
257 with the environmental alterations due to gulls pressure or/and climate change between 1997, 2008 and
258 2021, we compared Ellenberg-Pignatti factors (Organic Matter, Nutrient, Soil Acidity, Humidity, Light,
259 Salinity, Temperature) with paired pairwise Wilcoxon tests and Generalised Additive Models (GAM)
260 (*mgcv* package). The variables included were the different Pignatti factors: organic matter, nutrient, soil
261 acidity, humidity, light, salinity, temperature; and the explained variable was the number of nests. As
262 variables responses are expected to be non-linear, we used Generalized Additive Models with gaussian
263 family to evaluate the statistical link between Pignatti factors and the number of nests. The indicators
264 were adapted for the Mediterranean species by Saatkamp *et al.* (2022), so that the bioindications given
265 by plants fit better than the initial values.

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

268 3 Results

269 3.1 Nesting gulls and dynamic of the soil parameters

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

272

273 Soil acidity decreased during the study period (see Supplementary Materials Table S1 for a summary of
274 all means values \pm SD), with mean pH in 2021 significantly higher than in 1997 (Fig. 4. A., $p < 0.001$).

275 Soil pH was lower on Riou islands (mean \pm standard deviation, 7.89 ± 0.47 , $n = 30$) compared to the
276 mainland (8.18 ± 0.28 , $n = 22$) in 2021 ($p < 0.05$). There was no significant difference between soil pH
277 values on Riou and Frioul islands whatever the year considered.

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

283 Soil total nitrogen content of Frioul and Riou samples was significantly higher in 2021 than in 1997
284 (Fig. 4. C, $p < 0.01$). Soil total nitrogen on Riou islands (9.14 ± 3.63 mg/g) was significantly higher than
285 on the mainland (5.86 ± 2.45 mg/g) and also than on Frioul islands (7.18 ± 2.84 mg/g) in 2021 ($p < 0.001$).
286 Total nitrogen values for Riou and Frioul in 1997 were not significantly different from the mainland in
287 2021 ($p=0.161$ and $p=0.088$, respectively). Total nitrogen content of droppings (44.50 ± 8.34 mg/g) was
288 significantly higher than in any soils ($p < 0.001$).

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

292

293 3.2 Additional chemical characterisation of soils and impacts of gull presence on
294 edaphic parameters

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

298 Regarding nutrient concentrations in soils, the mean amount of P in soils of the mainland (Table 3) was
299 significantly lower than in the soils of the archipelagos (Fig. 5. A, ($p < 0.001$), and total P concentrations
300 were significantly higher in the soils of Riou compared to Frioul (Fig. 5. A, $p < 0.01$). The concentration
301 of P appeared to be higher in droppings than in the soils. The K values were significantly higher in the
302 soils of the Riou archipelago than on the mainland (Fig. 5. B, $p < 0.05$), but there was no significant
303 difference between the soils of the archipelagos ($p=0.58$). The droppings appeared to be less
304 concentrated in K than the soils. No significant difference was observed for Na concentration whatever
305 the soils on the islands or on the mainland (Fig. 5. C, mainland *vs* Frioul $p=0.33$, mainland *vs* Riou
306 $p=0.08$, Frioul *vs* Riou $p=0.87$), and Na contents were higher in droppings.

307 Regarding potentially toxic elements (PTE), Pb soil concentrations were higher on the mainland
308 than on the archipelagos (Fig. 5. D, $p < 0.01$ between the mainland and Riou and $p < 0.001$ between the
309 mainland and Frioul). Pb concentrations were lower in droppings (mean of 4.34 mg/kg). With regards
310 to Cu and Zn soil concentrations, no significant difference was observed whatever the soils on the islands
311 or on the mainland (Cu: mainland *vs* Frioul $p=0.99$; mainland *vs* Riou $p=0.44$; Frioul *vs* Riou $p=0.77$;
312 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
313 and Zn contents were higher in droppings than in soils. In order to estimate the potential soil
314 contamination by PTE, contamination factors (CF) were calculated for Cu, Pb and Zn, in relation to the
315 local contamination background proposed for the Calanques hills (Affholder et al, 2014). The highest
316 CF values (Table 4) were measured for Pb in mainland soils (8.23 ± 6.90) and for Cu in soils of the Frioul
317 archipelago (6.87 ± 12.94), and these values reflected a high contamination ($CF > 5$). CF values for Pb
318 in soils of the archipelagos reflected a low contamination rate (low contamination estimated when $CF <$
319 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

320 reflected a medium contamination rate (medium when $3 < CF < 5$, 4.26 ± 1.48 at Riou and 3.68 ± 1.57 on
321 the mainland). Concerning Zn, CF values reflected a low contamination rate whatever the sites (values
322 between 2.39 and 3.22). The pollution load index (PLI) for Cu, Pb and Zn estimates the potential multi-
323 contamination level of soils. This index, revealed a relatively low multi-contamination level whatever
324 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
325 the mainland).

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

328

329 The analysis of the stable isotopes showed an enriched signature of the $\delta^{15}N$ for soils of the two
330 archipelagos compared to the reference plots of the mainland (Fig. 6.), with higher values for Riou ($>$
331 5‰). Concerning the $\delta^{13}C$, values did not show a clear pattern.

332

333 Analyses of potential impacts of a colony of gulls on physical and chemical parameters of the islands'
334 soil in 2021 showed that the concentrations of K were significantly and positively correlated with the
335 number of nests ($p < 0.01$, Adjusted $R^2 = 0.1123$), P concentrations ($p < 0.05$, Adjusted $R^2 = 0.08533$)
336 and Na concentrations ($p < 0.05$, Adjusted $R^2 = 0.08361$). These results also showed that the pH values
337 were significantly and negatively correlated with the number of nests ($p < 0.05$, Adjusted $R^2 = 0.09594$).
338 Moreover, the resting places were positively correlated with conductivity ($p < 0.05$, Adjusted $R^2 =$
339 0.1728).

340 Concerning the other parameters, no significant correlations were observed neither with the number of
341 nests (Cu: $p=0.51$, Pb: $p=0.99$, Zn: $p=0.82$, Conductivity: $p=0.08$, N: $p=0.27$, Organic Matter: $p=0.65$)
342 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:
343 $p=0.09$, N: $p=0.95$, Organic Matter: $p=0.73$).

344

345 3.3 Changes in plant communities

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

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

358 No pattern of change was detected on the salinity axis (axis 1) when using the coordinates of the NMDS,
359 (1997 vs 2008 $p=0.11$, 1997 vs 2021 $p=0.44$, 2008 vs 2021 $p=0.19$).

360

361 The Pignatti nutrient ecological indicator indicated by the flora community on the islands was
362 significantly lower in 2021 and 2008 compared to 1997 ($p < 0.05$). The humidity factor decreased in
363 2021 compared to 1997 on the islands ($p < 0.05$). The light factor decreased in 2021 compared to 1997
364 and 2008 on the islands ($p < 0.05$). The soil acidity indicated by the flora community was not
365 significantly different between years for islands plots (1997 vs 2008 $p=0.48$, 1997 vs 2021 $p=0.16$, 2008
366 vs 2021 $p=0.057$). Generalized Additive Models (GAM) showed no relation with the number of nests
367 counted in 2021 (nutrient $p=0.72$, humidity $p=0.64$, light $p=0.06$, soil acidity $p=0.83$).

368 The modification of the temperature indicated by the flora community on the islands showed a
369 diminution in 2021 compared to 1997 and 2008 ($p < 0.01$). In addition, there was a positive correlation
370 with the number of nests ($p < 0.05$). However, a diminution of the temperature in 2008 and 2021 ($p <$
371 0.05) was registered with the mainland plots, where there were no gull nests.

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

375

376 Results of mean comparisons showed that the total number of species was not different between years
377 on the islands (1997 vs 2008: $p=0.669$, 1997 vs 2021: $p=0.2446$, 2008 vs 2021: $p=0.5376$). However,
378 for the mainland, differences were observed between 1997 and 2008 ($p < 0.05$) and between 2008 and
379 2021 ($p < 0.001$) with the lowest value in 2008.

380 When analysing Grime plant strategies, ruderals (the most strongly represented Ruderals (R): *Sonchus*
381 *tenerrimus*, Ruderal-Competitives (RC): *Parietaria judaica*, Ruderal-Stress tolerants (RS): *Lobularia*
382 *maritima*, Stress tolerant- Ruderals (SR): *Euphorbia linifolia*) increased between 1997 and 2008 ($p <$
383 0.001) and this pattern remained in 2021 ($p < 0.001$). Moreover, intermediate plant strategies
384 (Competitive-Stress tolerant-Ruderals (CSR), such as *Cistus albidus*, *Euphorbia characias*, *Lotus*
385 *cytisoides*) decreased significantly on the islands from 1997 to 2008 ($p < 0.05$) and slightly increased
386 again to 2021, with no significant difference between 1997/2021 ($p=0.06277$) and 2008/2021
387 ($p=0.8016$).

388 Island vegetation showed a significant increase of geophytes, hemicryptophytes and therophytes ($p <$
389 0.001) in 2008, remaining constant to 2021. Chamaephytes on the islands decreased from 1997 to 2008
390 ($p < 0.001$) and afterwards remained stable ($p > 0.005$). Chamaephytes on the mainland continuously
391 decreased from 1997 through 2008 ($p < 0.01$) to 2021 ($p < 0.001$), and annual plants increased
392 continuously. No significant pattern of change was detected for geophytes (1997 vs 2008 $p=0.38$, 1997
393 vs 2021 $p=0.59$, 2008 vs 2021 $p=0.85$) and hemicryptophytes (1997 vs 2008 $p=0.77$, 1997 vs 2021
394 $p=0.037$, 2008 vs 2021 $p=0.99$) on the mainland. No pattern of change was detected for the
395 nanophanerophytes and the phanerophytes at any site.

396

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

400 4 Discussion

401 *Dynamic of the soil parameters and characterisation*

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

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

425 The values of conductivity and Na concentrations measured in soils in 2021 showed no differences
426 between the mainland and the islands, which means gull presence today has no impact with regards to

427 these characteristics. Usually, conductivity and Na concentrations have been shown to increase with the
428 presence of seabird colonies (Ellis, 2005; Zwolicki *et al.*, 2015). However, another study also did not
429 register salinization (De la Peña-Lastra *et al.*, 2021), probably due in their case to high precipitations
430 and leaching (Otero *et al.*, 2015).

431 In 2021, we also added to the analysis trace elements (or PTE) in soils, and the determination of pollution
432 load index (PLI), integrating Cu, Pb and Zn, reveals relatively low multi-contamination levels on the
433 mainland and the archipelagos, with values around 2.2. These PLI values correspond to those calculated
434 for soils in the Calanques hills (mean value of 2.3) some distance away from the urbanized area of
435 Marseille and from current and former industrial activities (Affholder *et al.*, 2014). We observed higher
436 values for the amount of Pb in soils of the mainland than in those of the archipelagos. We can argue that
437 the origin is mostly anthropic, notably with the use of leaded gasoline, coal burning and waste
438 incineration (Erel, Veron and Halicz, 1997; Komárek *et al.*, 2008), but mainly with the former lead
439 smelter sites located on the south-east coast of Marseille (Daumalin *et al.*, 2016; Heckenroth *et al.*, 2016,
440 2022; Affholder *et al.*, 2014;). The values of Cu and Pb are comparable to the results of a previous
441 study on the impact of waterbird colonies in the Mediterranean semiarid floodplain (Laguna *et al.*, 2021),
442 but we cannot argue for a direct effect of the gulls on these PLI. However, the literature shows the
443 importance of pollutants transport, such as Cu, Pb, Zn, by seabirds (Shoji *et al.*, 2019; Castro *et al.*,
444 2021; Grant *et al.*, 2022).

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

448 The results of stable isotopes $\delta^{15}\text{N}$ reflected higher values for the two archipelagos and the droppings,
449 with values around 10‰ for the droppings and even higher than 15‰ for the Riou archipelago. The
450 values of previous studies were on the same scale (Ellis, 2005). High $\delta^{15}\text{N}$ derived from the droppings,
451 and hence explained the values of the archipelagos, the seabirds being positioned high in the trophic
452 chain (García *et al.*, 2002; Wait, Aubrey and Anderson, 2005; Laguna *et al.*, 2021). The values of the
453 mainland higher than 0‰, derived from the matter of the vegetation (Post, 2002). There was no

454 significant difference concerning the $\delta^{13}\text{C}$, which resulted mostly from the autochthonous organic
455 matter even on the island (Torres *et al.*, 2012).

456 An increase of pH was observed but there was still a negative link with gull density, as in other studies
457 (Vidal, 1998; Ellis, 2005). Moreover, cover of the resting places had a positive link with conductivity.
458 Except for pH, K, P, Na, we did not find the same links as in 1997 with positive correlations between
459 nest density and the organic matter nor the nitrogen content (Vidal, 1998). Moreover, the results also
460 indicated that the amounts of Na, P and Zn were higher in the droppings than in soils. According to these
461 observations, we could expect existing links between gull densities and today's values in the islands'
462 soils. However, with the absence of links as shown before, we believe that the levels of nutrients and
463 other elements found today could still be linked with the density of nests of the last decades. Actual
464 observations have been shown to retrace land-use history and be linked to it even millennia after in dry
465 ecosystem (Mizutani *et al.*, 1991; Saatkamp, Henry and Dutoit, 2020). As previously seen, changes in
466 soil P driven by seabird colonies have persistent effects (Myrcha & Tatur, 1991; Holdaway *et al.*, 1999;
467 Sun *et al.*, 2000; Otero *et al.*, 2015; De la Peña-Lastra *et al.*, 2021). The remanence in soil is also the
468 case for other nutrients and contaminants such as N or Selenium (Hawke & Wu, 2012; Jaunatre *et al.*,
469 2014; De la Peña-Lastra *et al.*, 2021). The retention and so the remanence time for nutrients or
470 contaminants can vary with several factors, such as successional state and ecosystem type, demand or
471 retention capacity, land-use history, type of soils, topography, climate and the rate, timing and type of
472 deposition as was shown for N inputs (Matson *et al.*, 2002).

473

474 *Vegetation dynamics*

475 *Lag dynamics between soil and vegetation*

476 The previous hypothesis, according to which the current observations would be explained by
477 previous gull pressure, is reinforced by the study of the flora community because we highlighted that
478 the plant community on the island is still different from 1997, being as ruderal as in 2008. This
479 observation could find an echo in a previous study (Purschke *et al.*, 2012) which found that current
480 factors alone could not explain today's flora pattern. This finding is similar to those of a recent study
481 (Saatkamp, Henry and Dutoit, 2020) where it was demonstrated that the use of land two thousand years

482 ago by the Romans is still modelling the vegetation and the soil today. Furthermore, we can also surmise
483 that the plant community can be firstly influenced by the mesological parameters such as the distance
484 from the mainland, the surface area, the topography, the perimeter and the maximum altitude of the
485 island (MacArthur and Wilson, 1963; Whittaker *et al.*, 2017), the direct effects of the seabird colonies
486 (Bancroft, Roberts and Garkaklis, 2005; Wait, Aubrey and Anderson, 2005), and secondly by the
487 induced soil alterations (Duda *et al.*, 2020). It appears that at the level of the species and the functional
488 traits, there have been no significant changes since 2008. Indeed, there are still more ruderal species
489 strategies (with the most represented R: *Sonchus tenerrimus*, RC: *Parietaria judaica*, RS: *Lobularia*
490 *maritima*, SR: *Euphorbia linifolia*) and more geophytes, hemicryptophytes, and therophytes in 2021
491 than in 1997 on the islands. The differences observed on the islands means that the plant species which
492 are highly tolerant to disturbances in harsh environment are still favoured even with the decline of the
493 pressure induced by the presence of the gull (Baumberger *et al.*, 2012).

494 The decrease of the chamaephytes recorded in 2008 compared to 1997 is no longer occurring in 2021
495 on the island. This is noticeable because certain of the heritage/endangered plant species of the
496 archipelagos are chamaephytes and specialists of this environment (e.g., *Astragalus tragacantha*,
497 *Limonium pseudominutum*, *Frankenia hirsuta*, *Euphorbia pithyusa*, *Plantago subulata*). However,
498 further analyses and studies are needed to conclude more precisely on the dynamics of each of the
499 species mentioned above. Nevertheless, this observation still permit to underline the vulnerability of
500 these species (Bou, Vilar and Carreras, 2020) being not ruderal and jeopardized by the eutrophication
501 of the soil. These observations also raise questions regarding their protection and the support of the
502 viable populations until the habitat returns, or not, to a previous state (Knoerr, 1960 ; Molinier 1936,
503 1939 in Vidal, Médail, Tatoni *et al.*, 1998). On this time scale, we may inquire about the expression of
504 the seed banks, which are considered essential for plant communities because of their contribution to
505 ecological processes, in terms of resilience, the persistence of the community and the restoration of the
506 ecosystems (del Cacho and Lloret, 2012; Kiss *et al.*, 2018).

507 An increase in the vegetation cover was registered between 2008 and 2021 especially on island plots.
508 As supported by the previous results on functional types, it was not a sign of the resilience of the
509 functional flora community such as there was in 1960 (Knoerr 1960 in Vidal, Médail, Tatoni *et al.*,

510 1998) – with more stress-tolerant species. However, it was a sign of the resilience of the flora developed
511 since then, being more ruderal. Concerning the mainland plots where vegetation cover increased, we
512 can assume that in 24 years and without major disturbances (fire, rockslide), the plants followed a natural
513 dynamic and so the aboveground vegetation cover increased.

514

515 *Interactive effect of gulls and climate change*

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

530 We could also observe differences on the mainland concerning the temperature, with plants indicating
531 a decrease in 2021 compared to 2008. The fact that there were no significant differences between 2021
532 and 1997 on the mainland, regarding the temperature, could perhaps point to a fluctuation being due to
533 the meteorology, with dryer or wetter years. However, we could also note that there were fewer CSR
534 strategies in 2008 than in 1997 on the islands and fewer in 2021 compared to 1997 on the mainland.
535 This could be explained by a natural fluctuation, with the renewal rate of these plants, which here in the
536 Calanques National Park are *Cistus albidus*, *Cistus monspeliensis*, *Cistus salvifolius*, *Euphorbia*
537 *characias*, *Halimione portulacoides*, and *Lotus cytisoides* (mostly nanophanerophytes). On the

538 mainland, we also observed the increase of the therophytes. These observations could also be linked
539 with the increase of more generalist and fewer thermophilous species, the closure of the vegetation or
540 the pattern with less rainfall (Kimball *et al.*, 2010).

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

550

551 5 Conclusions

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

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

562

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575

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Title: 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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TABLES

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
	Tiboulén de Maïre	2.3	525	47	2
Mainland part of CNP		8157.8		645	22

Table 2: Mesological parameters measured in the 500 m² circles for each plot.

Environmental variables measured in the 500 m² 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 & 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.

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

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

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

3

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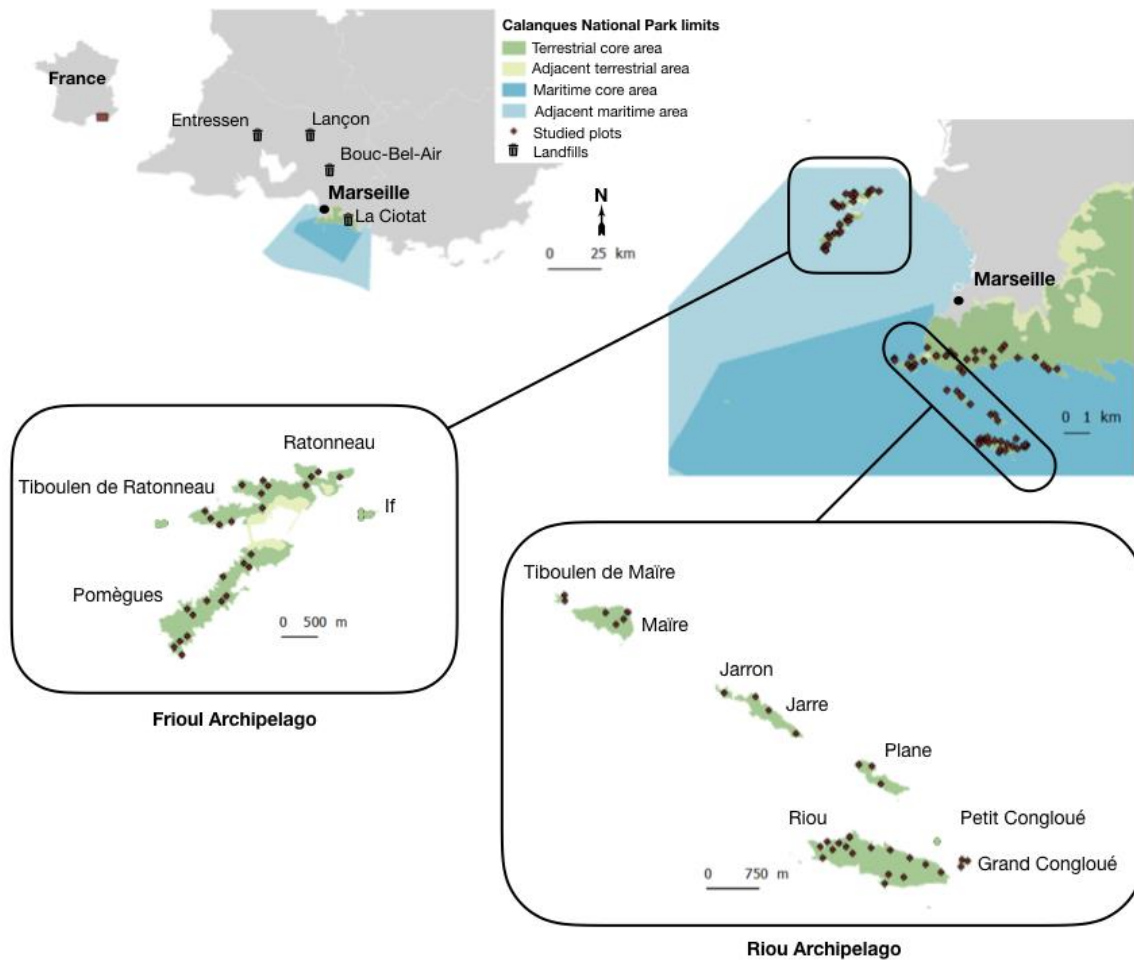
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11 CNRS), BP A5, Nouméa CEDEX 98848, New Caledonia

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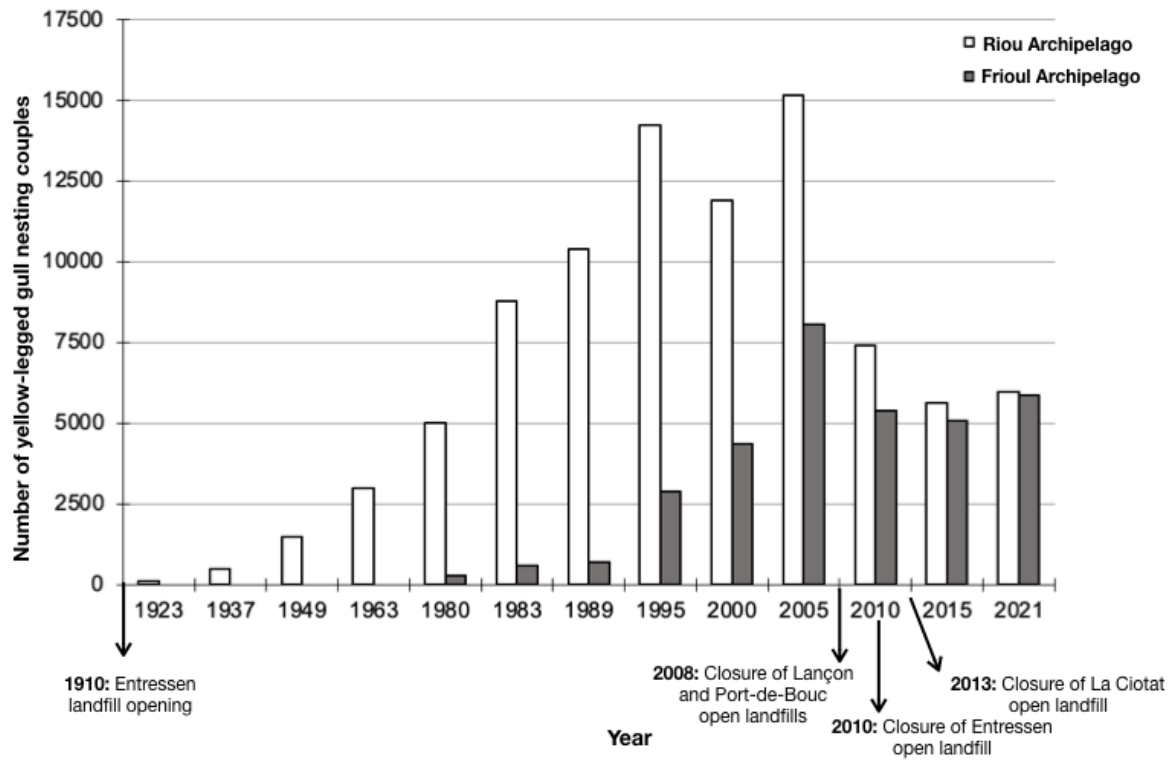
16 **FIGURES**



17

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

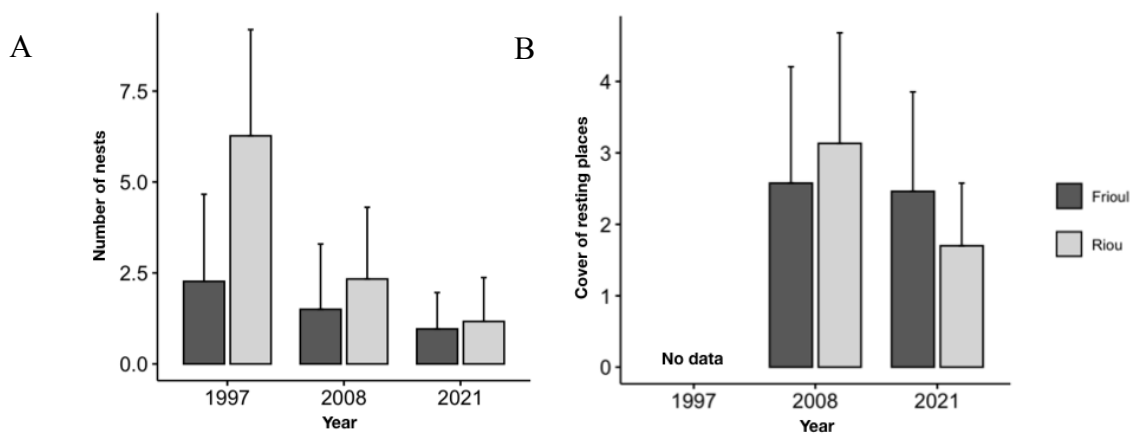
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23 Fig. 2: Gull (*Larus michahellis*) population dynamics in the Riou and Frioul archipelagos from 1923 to
 24 2021, and indications of the opening and closing of the landfills in the vicinity of Marseille.

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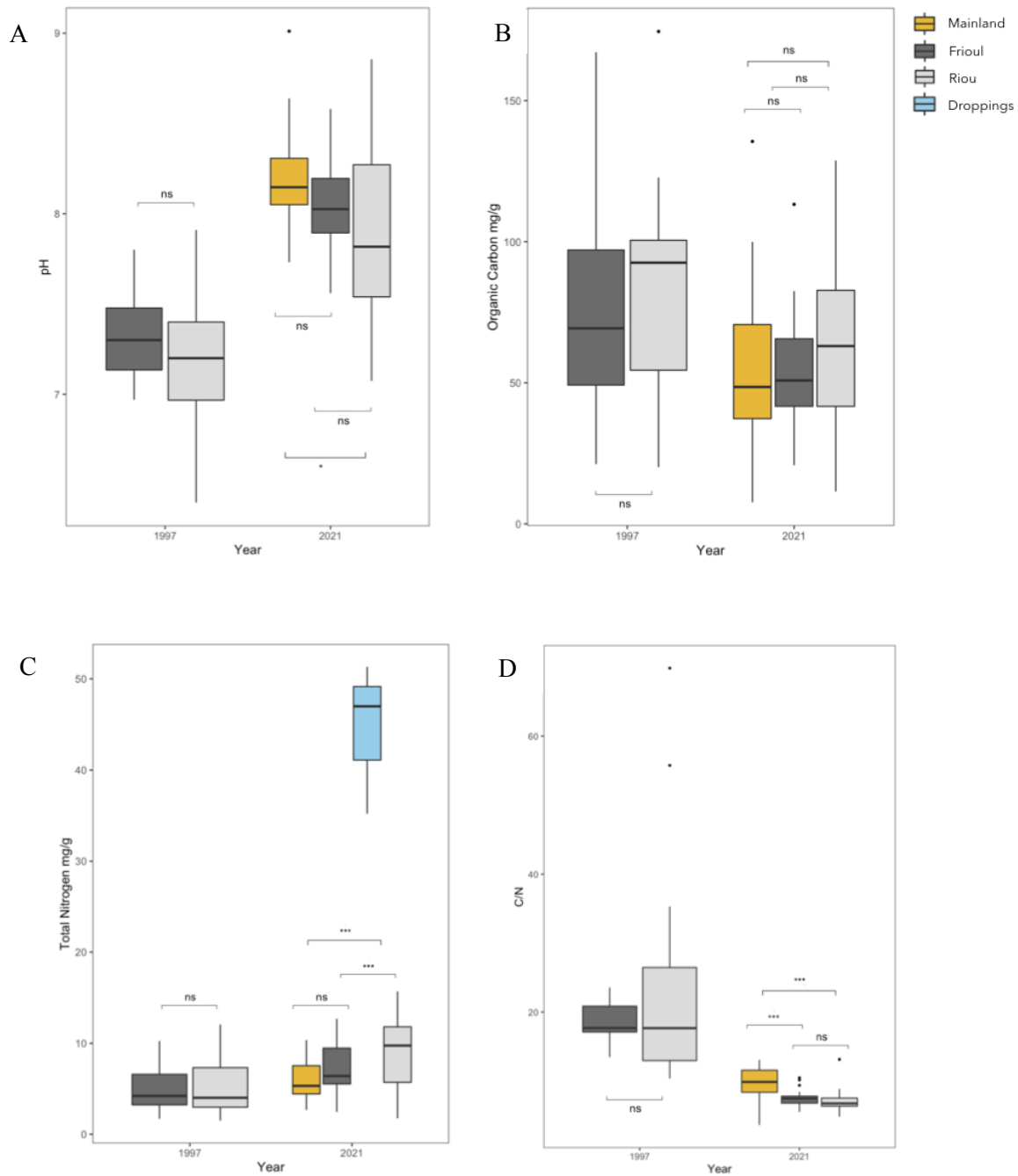


26

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

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33 Fig. 4. Changes in soil parameters during the monitoring period (1997 to 2021) on Frioul (dark grey)

34 and Riou (light grey) islands and the mainland (yellow) and data from droppings (light blue) (for total

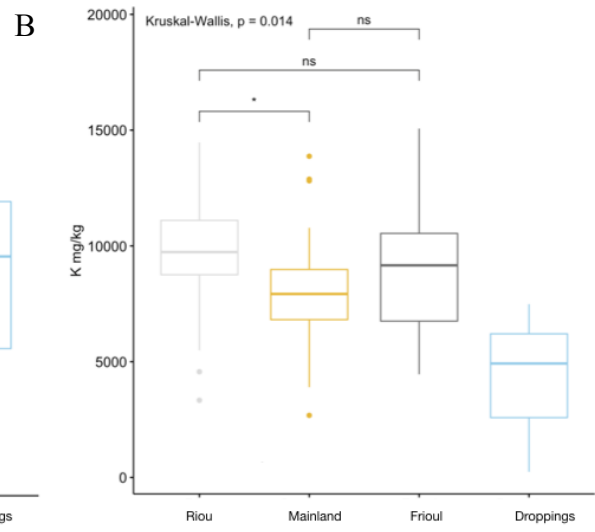
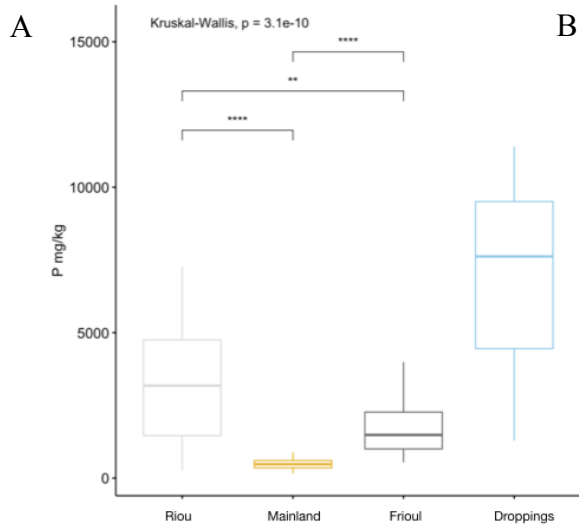
35 nitrogen in 2021), non-significant (ns): p-value > 0.05, *: p-value < 0.05, **: p-value < 0.01, ***: p-

36 value < 0.001. A. The pH of the soil. B. Soil organic carbon (mg/g dry matter (DM)). C. The total

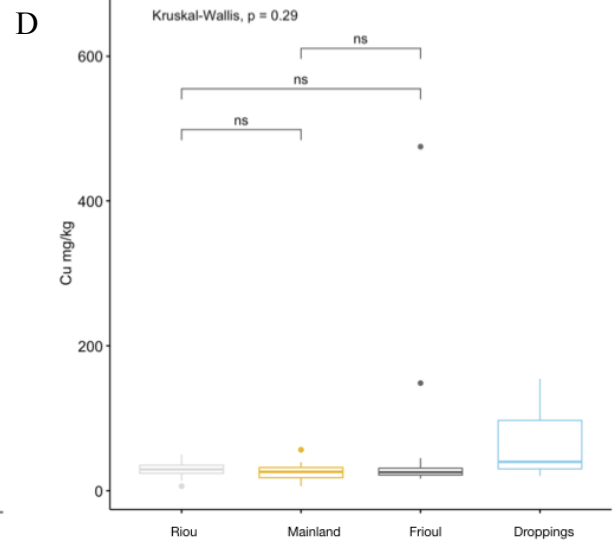
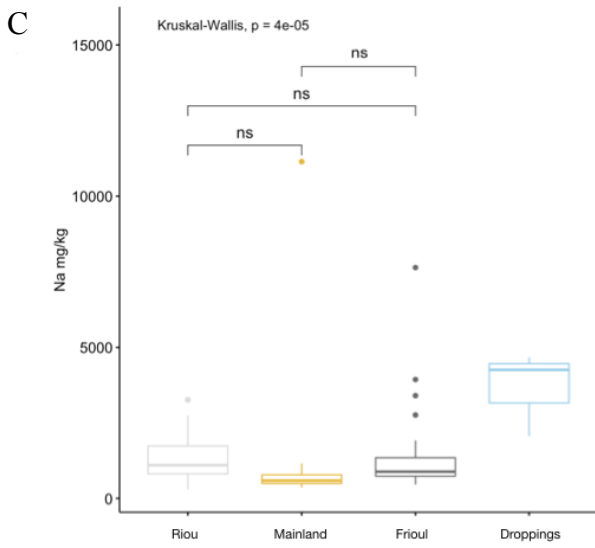
37 nitrogen (mg/g DM). D. The soil C/N ratio.

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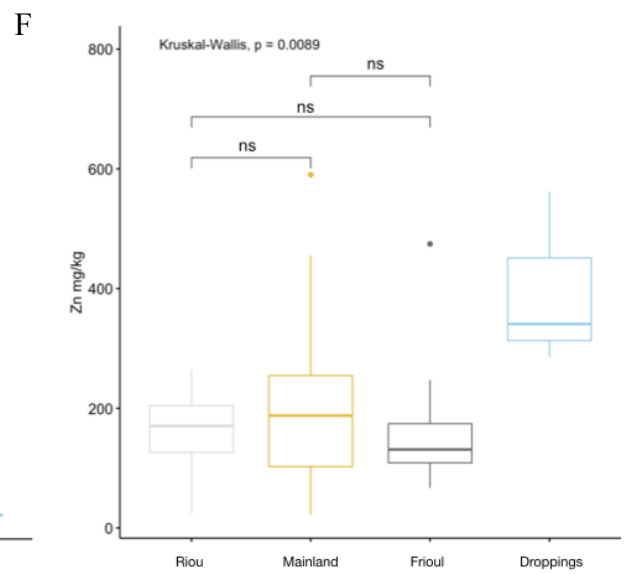
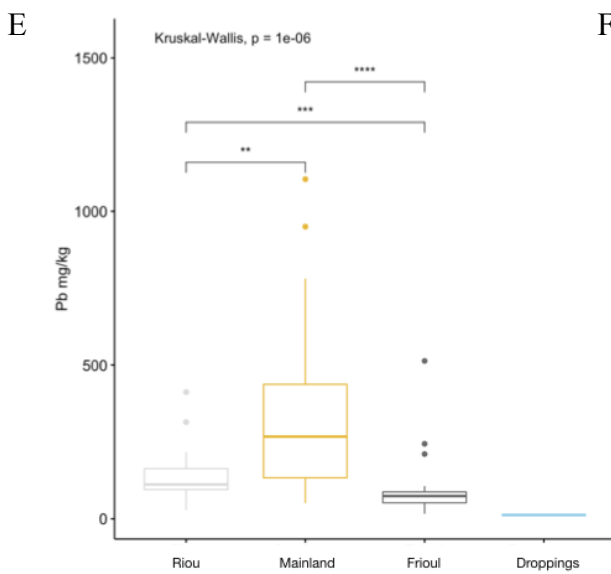
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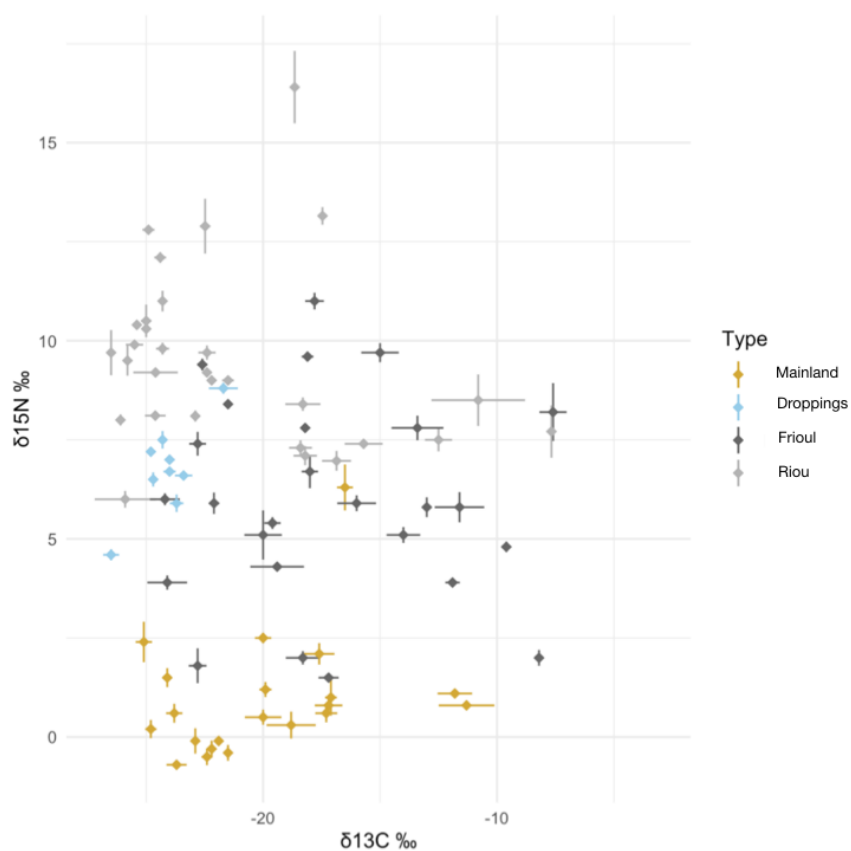
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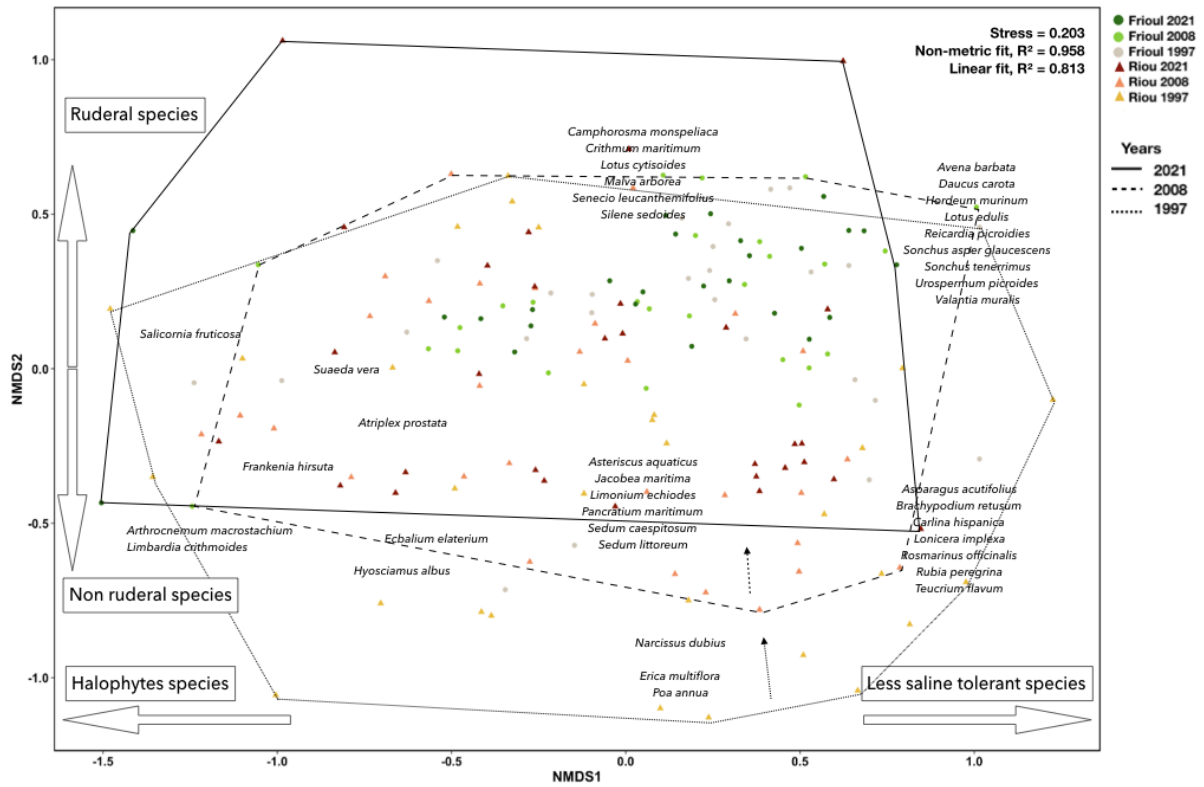
44 Fig. 5. Boxplots of the soil measured physical and chemical parameters in 2021 in the Frioul (n = 26)
 45 and Riou (n = 30) archipelagos, on the nearby mainland (n = 22) (south-eastern France) and in the
 46 droppings (n = 9), non-significant (ns): ns: p-value > 0.05, *: p-value < 0.05, **: p-value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

50



51
 52 Fig. 6. The Delta (δ) of ^{13}C versus $\delta^{15}\text{N}$ (means \pm SD) of stable isotopic composition in soil samples
 53 from the Frioul (n = 26) and Riou (n = 30) archipelagos, the nearby mainland (n = 22) (south-eastern
 54 France) and droppings samples (n = 9).

55



56

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

59



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Supplementary Material

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Title: 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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Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Pascale Prudent: Conceptualization, Methodology, Investigation, Resources, Data Curation, Writing - Review & Editing, Funding acquisition

Arne Saatkamp: Conceptualization, Methodology, Formal analysis, Resources, Writing - Review & Editing

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