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# Functional structure and composition of Collembola and soil macrofauna communities depend on abiotic parameters in derelict soils

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1           **Functional structure and composition of Collembola and soil**  
2           **macrofauna communities depend on abiotic parameters in**  
3           **derelict soils**

4  
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9  
10   **ABSTRACT**

11   In the last decades, anthropogenic disturbances have altered the ability of soils to provide diverse  
12   functions. Certain anthropogenic soils, with a low fertility level and often contaminated, ended up  
13   underused and derelict. Although derelict for humans, these soils may be refuges for biodiversity, but  
14   their biological functioning remains poorly understood. To this end, a trait-based approach of soil  
15   invertebrate communities might be an effective predictor of ecosystem state. The present work aims to  
16   highlight the *in situ* links between the abiotic characteristics of derelict soils and the taxonomic and  
17   functional structure and composition (through a trait-based approach) of macrofauna and Collembola  
18   communities inhabiting these soils. We studied 6 different derelict soils: two soils from coking plants,  
19   one soil from a settling pond, two constructed soils, and an inert waste storage soil. We measured  
20   fifteen abiotic soil parameters that inform on fertility and contamination. We took into account sixteen  
21   traits and ecological preferences to characterize the functional structure and composition of  
22   Collembola and macrofauna communities. Soil fertility (organic matter content, C:N ratio, P, Ca and

23 Mg concentrations, cation-exchange capacity, and clay content) and moderate contamination (Pb, Cd,  
24 Zn, and PAH concentrations) altered the taxonomic and functional composition of Collembola and  
25 macrofauna communities by selecting traits such as body length, pigmentation, vertical distribution,  
26 diet type, and habitat preference. Compost-amended constructed soil properties selected taxonomic  
27 and functional community composition of slightly disturbed soil. In contrast, metal-contaminated  
28 constructed soil harbored a higher proportion of Collembola displaying the traits and ecological  
29 preferences of instable ecosystems. The study of functional profiles of Collembola and macrofauna  
30 communities in the derelict soils evidenced that they support different communities with more or less  
31 wide functional potential. It underlines the interest of multiple biotic component studies to reach a  
32 better ecosystem description.

33

## 34 **HIGHLIGHTS**

35 Collembola and macrofauna communities from derelict soils were characterized.

36 Links between fauna community composition and soil characteristics were studied.

37 Fertility and contamination altered invertebrate community structure and composition.

38 Compost-amended constructed soil selected typical slightly disturbed soil species.

39 Collembola species traits in contaminated and constructed soil were typical of instable ecosystems.

40

## 41 **KEYWORDS**

42 Derelict soils, Functional diversity, Traits and ecological preferences, Soil invertebrates, Technosol

43

## 44 **1. INTRODUCTION**

45 Soils are complex ecosystems, described as multifunctional systems because many components  
46 interact inside them (Kibblewhite et al., 2008; Briones, 2014). Nevertheless, over the last decades  
47 growing evidence has emerged about the negative impact of anthropogenic disturbances on the ability  
48 of soils to provide functions (Levin et al., 2017) and occasionally to host biodiversity (Orgiazzi et al.,  
49 2016). In this context, the closing down of steel, shipbuilding or metal manufacturing industries  
50 because of economic issues and the closing down of mining sites in different European countries have  
51 resulted in land abandonment and altered ecosystem functioning (Wong and Bradshaw, 2002).  
52 Sometimes called greenfields, wastelands, uncultivated/vacant/abandoned lands, the soils of these  
53 derelict lands can be disturbed, *i.e.* characterized by a low fertility level (Dickinson, 2003) and/or  
54 sometimes by contamination (Morel et al., 2005). These specific abiotic parameters can alter soil  
55 functions likely to be important for agriculture and lead to surfaces being unmanaged and underused  
56 (Cundy et al., 2016). In Vincent et al. (2018), we showed that derelict soils could have low organic  
57 matter and nitrogen contents, a low cation exchange capacity, alkaline conditions with cations  
58 occasionally lacking or in excess, and moderate organic and inorganic contamination linked to their  
59 history. Biotic parameters (*i.e.* plant, fauna and microorganism density and richness) co-varied more  
60 with soil fertility proxies than with soil contamination parameters in moderately contaminated derelict  
61 soils. Once soils are underused and abandoned by humans, they may turn into refuges for biodiversity  
62 provided that abiotic parameters are not extreme for life (Baranova et al., 2014). Derelict soils have  
63 been reported to harbor a rich invertebrate biodiversity: insects (Bonthoux et al., 2014), beetles (Eyre  
64 et al., 2003), carabids (Small et al., 2006), earthworms and Collembola (Butt and Briones, 2017).  
65 However, the biological functioning of derelict soils remains poorly understood as compared to forest  
66 or agricultural lands.

67 In this vein, trait-based approaches focusing on the characteristics of individuals provide an interesting  
68 tool to assess soil functioning (Verberk et al., 2013). Pey et al. (2014) defined traits in soil invertebrate  
69 studies as “morphological, physiological, phenological or behavioral features measurable at the  
70 individual level, from the cell to the whole-organism level, without reference to the environment or  
71 any other level of organization”. Traits could be considered as functional because they impact

72 organism fitness directly and indirectly (Violle et al., 2007). Finally, functional traits can help to  
73 understand the effect of environmental stressors on soil communities (Auclerc et al., 2009;  
74 Vandewalle et al., 2010; Hedde et al., 2012; Salmon and Ponge, 2012). In recent years, traits have  
75 been recognized as effective predictors of exposure to disturbances (metal contamination in Hedde et  
76 al., 2012; restoration practices in Rosenfield and Müller, 2017), or of management strategies such as  
77 intensive agriculture, polyculture and monoculture (Wood et al., 2015; Sechi et al., 2017) to better  
78 understand the soil functional community structure and composition.

79 The functional community composition of the soil fauna is linked to soil abiotic parameters. For  
80 example, in urban soils, the proportion of Collembola with a sexual reproduction type was positively  
81 correlated with total Cu and Ni concentrations, and the proportion of pigmented Collembola was  
82 positively correlated with total Cr, Pb and Zn concentrations (Santorufu et al., 2015). The proportion  
83 of Collembola living belowground (with the following trait attributes: small size, reduced or absent  
84 sensorial organs and furca, non-sexual reproduction type) in coal mine spoil tip soils was found  
85 associated to a coarser soil texture and higher nitrogen and organic matter concentrations (Vanhee et  
86 al., 2017). In parallel, the proportion of macroinvertebrates with a soft body decreased when metal  
87 contamination increased (Hedde et al. (2012), and the body size of ants was found driven by soil  
88 granulometry (Costa-Milanez et al. (2017). Moreover, other authors showed that soil age played a key  
89 role in the functional community composition by selecting certain traits such as moisture or light  
90 requirement in carabid communities (Aubin et al., 2013) or the feeding group for macrofauna  
91 communities (Frouz et al., 2013). To our knowledge, existing studies dealing with trait-based  
92 approaches in anthropogenic sites focussed on only one group of soil invertebrates (Collembola or  
93 carabids or macrofauna) and were carried out on highly contaminated and/or low fertile soils.  
94 Furthermore, there are too few studies considering the links between soil chemistry parameters and  
95 trait-based invertebrate community composition (*e.g.* Salmon and Ponge, 2012; Santorufu et al., 2014,  
96 Santorufu et al., 2015; Martins da Silva et al., 2016).

97 The present work aims to characterize which environmental factors shape macrofauna and Collembola  
98 invertebrate communities and their functional structure and composition in derelict soils characterized

99 by moderate contamination and/or low fertility. We hypothesized that the soil characteristics related to  
100 past industrial activities and/or to the materials used for construction drove the composition of  
101 invertebrate communities by selecting certain traits and ecological preferences. We studied 6 different  
102 derelict soils: two soils from coking plants, one soil from a settling pond, two constructed soils, and an  
103 inert waste storage soil (Vincent et al., 2018). We took into account sixteen traits and ecological  
104 preferences to characterize the functional structure and composition of the soil invertebrate  
105 communities.

106

## 107 **2. MATERIALS AND METHODS**

### 108 ***2.1. Derelict soils and fauna sampling methods***

109 We studied six soils from open industrial derelict sites located in north-eastern France in a historically  
110 industrial region, with many former coking plant sites and steel factories. The climate in this region is  
111 continental with annual mean temperature of 10.8°C. For the sampling year (2015), monthly mean  
112 temperatures ranged between 1.8 and 22.1°C and cumulated annual rainfall was around 500 mm. Soil  
113 and fauna were sampled between the 8<sup>th</sup> and 29<sup>th</sup> of April 2015 (Vincent et al., 2018), during the  
114 period of highest invertebrate activity.

115 Soil named “CS” (for constructed soil) was a 1.13 ha experimental constructed soil set up on the site  
116 of a former coking plant (Séré et al., 2008). Soil named “WL” (for waste landfill) was from a 0.7 ha  
117 non-hazardous waste landfill. Soils named “CP1” and “CP2” (for coking plant site 1 and 2,  
118 respectively) were from former coking plant sites. These two soils differed in metal trace element  
119 concentrations. Soil named “SP” (for settling pond) was from a settling pond site filled with steel  
120 sludge. Lastly, soil named “CCS” (for constructed and contaminated soil), was an experimental 0.09-  
121 ha constructed soil. See Table 1 for more details.

122 We measured eleven abiotic variables that describe soil fertility: organic matter (OM) content, water  
123 holding capacity (WHC), clay content, exchangeable Ca, K, Mg and Na cation concentrations, Olsen  
124 phosphorus content, pH, cation-exchange capacity (CEC), C:N ratio. We also measured four chemical  
125 variables to quantify the contaminant levels in the soils, *i.e.* PAH and available Cd, Zn and Pb  
126 concentrations. We also took into account the time span since the last anthropogenic action on each  
127 site. The abiotic characteristics are summarized in Table 1 (for more details see Vincent et al. 2018)).

128 We took five soil samples from each derelict site (except for CCS where four samples were taken),  
129 along a 20-m transect with 5 m distance between each sample, in accordance with the Tropical Soil  
130 Biology and Fertility (TSBF) method (Anderson and Ingram 1993). We characterized communities in  
131 open areas (*i.e.* not forested areas) and adjusted our transect strategy to avoid potential edge effects for  
132 one given site. Collembola communities were sampled using soil cores and MacFadyen method, and  
133 macrofauna communities were sampled by soil blocks and hand-sorting method. Collembola were  
134 sampled on the 6 plots, on 10 cm depth, using two 5-cm deep corers (according to the ISO 23611-2  
135 standard), fitted one above the other. The microarthropods were extracted using a high-temperature  
136 gradient extractor (MacFadyen, 1961) and identified to the species level. The soil macrofauna  
137 communities were studied on 5 sites by excavating 0.25×0.25×0.30 m soil blocks, according to the  
138 ISO 23611-5 standard. Macrofauna community from CCS was not studied because the destructive  
139 method would have caused high disturbances on the experimental plots. Macrofauna organisms were  
140 hand-sorted in laboratory, and kept in a 70% (v/v) ethanol solution. They were all identified down to  
141 the family level, and further down to the species level for rove beetles, ground beetles and  
142 earthworms. Ants were removed from all analyses because these social insects are highly aggregated  
143 in space (Nahmani and Rossi 2003).

## 144 ***2.2. Functional study (trait-based approach) of Collembola and macrofauna*** 145 ***communities***

146 We selected 7 traits for the trait-based approach of the Collembola study: body length (BLN), body  
147 shape (BSH), number of ocelli (OCE), presence of a post antennal organ (PAO), pigmentation (PIG),

148 motion strategy (MS), reproduction type (REP), and 3 ecological preferences: vertical distribution  
149 (DIST), micro-habitat preference (MHABI), and habitat preference (HABI). As for the macrofauna,  
150 we selected 3 traits: body length (BLN), presence of an integument (INT), and mouth part type  
151 (MthT), and 3 ecological preferences: diet type (DIET), micro-habitat preference (MHABI), and  
152 habitat preference (HABI). These traits were chosen because they are commonly used to characterize  
153 the dispersal abilities of organisms in a given ecosystem, or to describe habitats and environmental  
154 stressors (Makkonen et al., 2011).

155 We gathered values (*e.g.* attributes) of the traits and ecological preferences of species from various  
156 sources (aggregated data, books, literature, *etc.*) but mainly from the BETSI (Biological and  
157 Ecological Traits of Soil Invertebrates - <http://betsi.cesab.org>) database. We used 8,200 Collembola  
158 data and 1,400 macrofauna data. The different traits/ecological preferences and attributes we assessed  
159 are listed in Table 2.

160 To analyze attribute data for a given taxon, we performed a fuzzy coding analysis. This method was  
161 developed by Chevene et al. (1994) and is widely used for trait approaches. Calculations were  
162 performed according to the method of Hedde et al. (2012). The information obtained from each source  
163 was coded by an affinity score for a given taxon and for a given trait attribute ranging from 0 to 4  
164 (from no (0) to very high affinity (4) of the taxon to a trait attribute, respectively). Subsequently, the  
165 affinity scores obtained from all the sources were added up and transformed into a percentage to build  
166 the trait profile of each species/taxon. Finally, for each trait attribute, the mean affinity for the entire  
167 Collembola or macrofauna community, called Community Weighted Mean (CWM), was calculated  
168 according to Garnier et al. (2004). The CWM calculation was performed using equation 1,

169 (Eq. 1) 
$$CWM = \sum_{i=1}^n P_i \times T_i,$$

170 where  $P_i$  is the relative abundance of species/taxon  $i$ ,  $n$  is the number of Collembola or macrofauna  
171 taxa, and  $T_i$  is the relative trait/ecological preference attribute affinity of species/taxon  $i$ .

172 CWMs were calculated separately for Collembola and macrofauna communities, for each trait  
173 attribute in each sample, using the vegan package (Oksanen et al., 2017) in R software (version 3.1.3,



174 R Development Core Team, 2015).

### 175 ***2.3. Taxonomic and functional diversity indices of Collembola and*** 176 ***macrofauna communities***

177 We measured different ecological indices that describe taxonomic or functional community structure  
178 because they are commonly used to assess ecosystem stability and functioning (Tilman, 2001; Tilman  
179 et al., 2014; Bukvareva, 2017). For a taxonomic description of the communities sampled in each  
180 derelict soil, we estimated taxonomic richness (TRic) and taxonomic evenness (TEve) using the vegan  
181 package (Oksanen et al., 2017) in R software. TRic was the number of taxa composing the Collembola  
182 or macrofauna communities sampled in each derelict soil, and TEve was the partitioning of individuals  
183 among the different taxa across each community.

184 For a functional description of Collembola and macrofauna community structure, we calculated  
185 functional richness (FRic) and functional evenness (FEve) according to (Villéger et al., 2008), using  
186 trait values (Laliberté et al., 2014). FRic was the volume created by attribute values in a  
187 multidimensional trait space. FEve was the evenness with which attributes were distributed in the  
188 multidimensional functional space. These functional indices were calculated using R software and the  
189 FD package (Laliberté et al., 2014).

### 190 ***2.4. Statistical and multivariate analyses***

191 To test the differences in functional community composition among soils, we independently  
192 performed univariate tests on CWMs for each attribute of a given trait. We also performed univariate  
193 tests on TRic, TEve, FRic and FEve to compare taxonomic and functional diversity levels among  
194 soils. As no dataset followed the conditions of parametric tests (we checked normality with Shapiro  
195 Wilk's test and homogeneity of variances with Bartlett's test), we performed Kruskal-Wallis (K-W)  
196 tests followed by the Dunn's test of multiple comparisons with Bonferroni adjustment to control the  
197 experimentwise error rates (Dinno, 2017). We used R Software for data processing, and performed all  
198 univariate tests with a 95% significance level.

199 To highlight the relationships between the trait/ecological preferences and abiotic parameters of the  
200 derelict soils, we performed RLQ analyses (Dolédec et al., 1996). RLQ analysis is a generalization of  
201 co-inertia analysis (Dray et al., 2003) that couples multiple data sets and identifies co-relationships  
202 between them. RLQ analysis performs a double inertia analysis of two arrays (tables R and Q) with a  
203 link expressed by a contingency table (table L). RLQ analysis is a method to highlight how the  
204 environment filters certain species traits (Dray et al., 2014). We used it to provide simultaneous  
205 ordination, and to analyze the joint structure of three datasets: the abiotic parameter dataset of each  
206 sample (table R), the relative abundance of taxa in each sample (table L), and the attribute trait values  
207 for each taxon (table Q). We tested the significance of the relationship between taxon traits and abiotic  
208 parameters using a Monte Carlo test (999 permutations). We performed RLQ analysis for Collembola  
209 and macrofauna communities separately, using the ade4 package (Dray and Dufour, 2007) in R  
210 software. This approach is one of the most integrated methods to analyze trait-environment  
211 relationships (Dray and Dufour, 2007; Kleyer et al., 2012). We tested linear regressions with the  
212 lmtest package in R, and correlations between abiotic and biotic parameters with the Pearson  
213 correlation coefficient (Hothorn et al., 2015).

## 214 **3. RESULTS**

### 215 ***3.1. Collembola communities from all 6 derelict soils***

216 The density of Collembola ranged between 17,000 and 91,000 individuals *per* m<sup>2</sup> on average, and their  
217 taxonomic richness between 3.4 and 7 per sample (Table 3). As regards the taxonomic approach,  
218 Collembola species richness was the highest in SP, CP2 and CCS, and significantly different from CS  
219 (K-W test; P=0.005). The evenness of Collembola species did not significantly differ among soils,  
220 with mean values ranging from 0.46 to 0.74. As for the trait-based approach, Collembola functional  
221 richness (between 0.02 and 0.16) was the highest in CP1, SP and CP2, and significantly different from  
222 WL and CCS (K-W test; P<0.001). No difference in the functional evenness of Collembola  
223 communities was found among soils, with mean values ranging between 0.62 and 0.71.

224 Figure 1 shows the CWM of each attribute measured for each of the ten traits/ecological preferences  
225 of the Collembola communities sampled in each of the six derelict soils. For habitat preference, the  
226 Collembola collected through the study are forest and grassland taxa (81% of the community on  
227 average for the 6 soils) and preferred soil as a micro-habitat (64% of the community on average for the  
228 6 soils).

229 CS harbored a higher proportion of Collembola that have a furca and inhabiting decaying woods (*ca.*  
230 24%) than in CP1, SP and CP2. CCS was characterized by a higher proportion of Collembola with the  
231 biggest size (2-3 mm; *ca.* 49%) compared to WL, SP and CP2. The percentage of Collembola with a  
232 PAO was higher in CCS (*ca.* 88%) than in WL. Collembola in soil CCS have a higher number of  
233 ocelli (5, 6, 7 or 8 pairs; *ca.* 100%), they are more pigmented (*ca.* 88%) compared to soils CP1 and SP,  
234 and have a sexual reproduction type (*ca.* 88%), with an epiedaphic ecological preference (*ca.* 93%, a  
235 significant higher value compared to CS, CP1 and SP). CCS harbored the lowest proportion of  
236 Collembola inhabiting forests and grasslands (62% of the community) but the highest proportion of  
237 Collembola inhabiting agricultural (22% of the CCS community) and wetland habitats (14% of the  
238 community).

239 According to Figure 2A, the first two RLQ analysis axes accounted for 88% of total Collembola  
240 community variance (69 and 19%, respectively). The Monte-Carlo permutation test evidenced a global  
241 link between physico-chemical soil variables and the traits/ecological preferences of Collembola (P  
242 value: 0.052). The projection of the centroid calculated for each soil separated them into 4 groups:  
243 CCS; WL-CP1-CP2; CS; SP. Species composition is given in Figure 2B. *Isotomurus fucicolus*,  
244 *Isotomurus antennalis*, *Desoria violacea*, *Proisotoma minuta* and *Entomobrya lanuginosa* were in the  
245 highest density in CCS as compared to the other soils. *I.fucicolus*, *I.antennalis* and *P.minuta* were only  
246 sampled in this soil. Likewise, CP2 hosted *Smithurinus schoetti*, *Sphaeridia pumilis* and *Sminthurinus*  
247 *elegans* in a higher abundance than the other soils. *S.schoetti* was only sampled in CP2. *Metaphorura*  
248 *affinis*, *Cyphoderus albinus* and *Paratullbergia callipygos* had the highest density in SP. The other  
249 soils (CS, WL, CP1, and CCS) did not host exclusive Collembola species (*i.e.* sampled in only one of  
250 the six soils).

251 Figure 2C shows that the highest proportion of Collembola inhabiting mineral micro-habitats was  
252 associated with the highest C:N ratio, pH and Ca concentration and a small quantity of clay, which  
253 were the abiotic characteristics of SP. The higher proportions of forest- and grassland-inhabiting  
254 Collembola were associated with high OM contents and low trace elements (Cd, Zn, Pb)  
255 concentrations in soils. These trait-abiotic parameter relationships were characteristic of CS, and to a  
256 lesser extent of WL, CP1 and CP2. CCS had the highest Cd, Zn and Pb concentrations and the lowest  
257 OM content. It hosted the highest proportion of Collembola with a high number of pairs of ocelli (*i.e.*  
258 5, 6, 7 or 8), and the highest proportion of Collembola inhabiting wetland habitats. The highest  
259 proportion of Collembola inhabiting in root and soil micro-habitats was associated with the highest  
260 soil CEC values in CS and to a lesser extent in WL, CP1 and CP2. Finally, the highest proportion of  
261 Collembola with a low number of ocelli (*i.e.* 1, 2, 3 or 4) was associated with the highest soil CEC and  
262 PAH concentrations, such as measured in CS. The other traits/ecological preferences were not clearly  
263 linked to measured physico-chemical parameters. Moreover, the time span since the last anthropogenic  
264 action on each site (*i.e.* “age”) did not seem to influence trait selection across the sites.

### 265 **3.2. Macrofauna communities in 5 derelict soils**

266 The average macrofauna density ranged between 118 and 668 individuals *per* m<sup>2</sup>, and the average  
267 taxonomic richness of the macrofauna community ranged between 3.0 and 11.6 per sample (Table 3).  
268 Taxon richness (between 6.0 and 16.2) was significantly higher in CS and WL than in SP and CP2 (K-  
269 W test; P=0.001). No significant difference in the evenness of macrofauna taxa was measured among  
270 soils, with mean values ranging from 0.53 to 0.71. Functional richness (between 0.06 and 0.14) was  
271 significantly higher in CS than in SP, CP1 and CP2 (K-W test; P=0.041). As for Collembola  
272 community results, no difference in functional evenness was measured among soils, with mean values  
273 ranging from 0.74 to 0.78.

274 Figure 3 shows the CWM of the six traits/ecological preferences of the macrofauna communities  
275 sampled in the five soils. For habitat preference, the macro invertebrates of the 5 soils are forest and

276 grassland habitat taxa (around 50% of the community in the 5 soils, without significant difference  
277 among sites).

278 CS was characterized by a significantly higher proportion of invertebrates without a specific  
279 mouthpart (mainly earthworms; *ca.* 40%) compared to other soils; CS harboured also a higher  
280 proportion of geophageous trophic group (*ca.* 24%) compared to WL, SP and CP2 and a higher  
281 proportion of invertebrates inhabiting a mineral micro-habitat (*ca.* 58%). SP was characterized by a  
282 higher proportion of small invertebrates (2.5-5 and 5-10 mm; *ca.* 40%) than in the other soils, and a  
283 higher proportion of invertebrates with a chewing mouthpart type (*ca.* 92%). SP was also  
284 characterized by higher proportion of zoophagous trophic groups (*ca.* 58%) and of wetland habitat  
285 taxa (*ca.* 37%).

286 The first two RLQ analysis axes accounted for 87% of total macrofauna community variance (71 and  
287 16%, respectively) (Figure 4A). The Monte-Carlo permutation test indicated a highly significant  
288 ( $P=0.01$ ) link between physico-chemical variables and traits/ecological preferences of soil macro-  
289 invertebrates. The projection of the centroid calculated for each soil delineated 3 groups: CS; WL-  
290 CP2; CP1-SP. Taxon composition is presented in Figure 4B. *Athous* click-beetle, Dermaptera,  
291 *Allolobophora chlorotica*, *Allolobophora oculata* and *Aporrectodea longa* earthworms had a higher  
292 density in CS than in the other soils. The Miridae group were in a higher density in WL and CP2 than  
293 in the other soils. Limacidae, the spider family Linyphiidae, the centipede family Geophilidae and the  
294 millipede order Julida (with especially the species *Ommatoiulus sabulosus*) had a higher density in  
295 CP2 than in the other soils. Finally, Steninae and Staphylinidae were in a higher density in SP than in  
296 the other soils.

297 Figure 4C shows that the highest proportions of macrofauna without a mouthpart, geophagous  
298 invertebrates and animals with a preference for agricultural habitats were associated with higher soil  
299 CEC and WHC, which were characteristic of CS. A weak but significant positive correlation was  
300 observed between earthworm density and soil CEC values ( $R^2=0.40$ ; T-test;  $P<0.001$ ) and between  
301 earthworm density and OM content ( $R^2=0.26$ ; T-test;  $P=0.01$ ). The highest proportion of invertebrates

302 inhabiting mineral micro-habitats was associated with the highest soil PAH, phosphorous, and  
303 available Cd concentrations and the highest OM content. The highest proportion of invertebrates with  
304 a wetland habitat preference was associated with the highest soil Mg, Ca and Pb concentrations, the  
305 highest C:N ratio and the lowest soil K concentration, characteristic of CP1 and SP. The highest  
306 proportion of individuals with a sclerotized integument was associated with the highest available soil  
307 Zn concentrations and lowest clay contents. The time span since the last anthropogenic action on each  
308 site (*i.e.* “age”) did not seem to have any impact on functional community composition.

309

## 310 **4. DISCUSSION**

311

312 The use of functional traits of edaphic fauna highlighted differences in Collembola and  
313 macrofauna communities structures among the studied derelict soils. CS (a constructed compost  
314 amended soil) and WL (a non-hazardous waste landfill soil) had the highest taxonomic and functional  
315 macrofauna richness, but the lowest taxonomic and functional Collembola richness of the studied  
316 sites. These soils probably contained a high quantity of food resources and many potential different  
317 niches possibly linked to a high plant density, with no metal contamination. Focusing on earthworms,  
318 CS hosted the highest density of the studied sites. The presence of earthworms is currently considered  
319 as a good indicator of the absence of disturbance such as metal contamination and land-use  
320 intensification (Nahmani and Lavelle, 2002; Pérès et al., 2011; Cluzeau et al., 2012). We can suggest  
321 that competition for resources between meso- and macro-organisms can occur at one given time. For  
322 example, Eisenhauer (2010) showed negative impacts of endogeic earthworms due to competition for  
323 food resources with microarthropods such as Collembola. Earthworms can also affect the Collembola  
324 community by modifying, maintaining, creating or destroying habitats (Eisenhauer, 2010; Wright et  
325 al., 2012). At the opposite, CCS (an experimental constructed and contaminated soil) with the lowest  
326 fertility level and the highest metal concentration of the study, harbored the highest taxonomic

327 diversity but a low functional diversity of Collembola. This might suggest functional redundancy of  
328 species within the community, defined as several species contributing in equivalent ways to an  
329 ecosystem function such that one species may substitute for another (Bruno et al., 2016). Species that  
330 are functionally redundant act as ‘spare wheels’ during a disturbance to maintain ecosystem functions  
331 (Cole et al., 2006). Functional redundancy of species in a given community might be interesting in  
332 disturbed habitats, and then a community composed of species with similar functional traits might be  
333 more resilient to a new disturbance (Gerisch, 2014; Hodecek et al., 2016).

334         Following the RLQ analyses, the differences in fertility levels and contaminant concentrations  
335 among the 6 anthropogenic derelict soils appeared to be associated with different composition of  
336 Collembola and macrofauna communities at the taxonomic and functional levels, with difference of  
337 response for both communities.

338 Firstly, the OM content was associated with the presence of Collembola *Lepidocyrtus lanuginosus* and  
339 *Isotomiella minor*, found at high densities in soils with high OM contents (Santorufu et al., 2014) and  
340 in coal mine spoil tip soils (Vanhee et al., 2017). These species are considered as forest-inhabiting  
341 species (Heiniger et al., 2015). They have been showed to prefer soils with dense vegetation (high  
342 plant biomass) and rich in OM (Gillet and Ponge, 2004; Fjellberg, 2007; Dunger and Schlitt, 2011).  
343 The OM content, which was the highest in CS owing to compost addition, appeared to positively  
344 influence the density of forest- and grassland-inhabiting Collembola in our study, but had no effect on  
345 the macrofauna. Collembola communities could be more driven by fine OM (only OM smaller than  
346 2 mm was assessed in this study) than macrofauna because of the size of the food they eat. Secondly,  
347 the highest soil C:N ratio was linked to the highest proportion of wetland-inhabiting macrofauna  
348 sampled in SP and CP1 (settling pond and coking plant soils, respectively). Wetlands harbor plant  
349 communities with a high C:N ratio that are decomposed slowly (Plum, 2005) and can in turn result in  
350 a high soil C:N ratio. Thirdly, the soil CEC value was linked to the proportion of invertebrates without  
351 a mouthpart, mainly represented by earthworms, in WL. The selection of earthworm populations  
352 (geophageous invertebrates without a mouthpart) by high soil CEC has already been observed in soils  
353 of oil palm plantations and agricultural areas (Sabrina et al., 2009; Hedde et al., 2012). The authors

354 underlined that the effects of CEC on earthworm populations was similar to the effects of organic  
355 carbon. In our study, a weak correlation was observed between earthworm density and OM content or  
356 CEC values. The soil CEC value also seemed to be an important factor on Collembola species  
357 characterized by trait attributes linked to a high dependence on soil as a habitat (*i.e.* “soil-inhabiting”,  
358 “inhabiting root micro-habitats” and “low number of ocelli”). Finally, Ca and Mg concentrations in the  
359 soils also appeared to alter the proportion of chewing mouth-part type macrofauna that we assumed to  
360 use herbaceous litter as food. An explanation of this abiotic-biotic link could be that the Ca  
361 concentrations in plants and consequently in litter originate from the soil. Thus, in the studied soils,  
362 litter calcium might have come from the materials used for constructing soils, and may have  
363 influenced the functional composition of soil invertebrates by selecting certain species with a specific  
364 mouth-part type.

365 Metal concentrations seemed also to influence the density of certain species and to alter the functional  
366 community composition of the soil biodiversity, especially for Collembola. In this vein, *Proisotoma*  
367 *minuta* was only found in the soil with the highest metal concentration (CCS). *P.minuta* has already  
368 been shown as an indicator of manure or slurry pollution and predominates in decaying sewage sludge  
369 (Dunger and Schlitt, 2011). It seems to be a generalist species adapted to different ecosystems likely to  
370 be altered. Euedaphic Collembola are considered as the most sensitive living forms to metal  
371 contamination according to several studies (Fountain and Hopkin, 2004; Parisi et al., 2005; Joimel,  
372 2015). Epedaphic Collembola, are more resistant to pollutants than euedaphic Collembola because  
373 they have a higher movement ability and a lower direct contact with soil particles (Fountain and  
374 Hopkin, 2004). This result is consistent with our findings: the derelict soil with the highest metal  
375 concentrations (CCS) did not host euedaphic Collembola. In the present study, the metal concentration  
376 also appeared to positively drive the proportion of Collembola with a maximum number of ocelli, as  
377 observed previously for soil Pb concentrations (Joimel, 2015). The number of ocelli is an indicator of  
378 the dispersal ability of Collembola since species with a complete visual apparatus can disperse rapidly  
379 (Ponge et al., 2006; Salmon et al., 2014). Several authors underlined that Collembola with a high  
380 dispersal ability were present in disturbed environments (Auclerc et al., 2009; Salmon et al., 2014;



381 Joimel, 2015). Thus, the metal concentrations of our soils, though low as compared to other studies on  
382 anthropogenic soils, appeared to have selected Collembola with a high dispersal ability linked to  
383 specific morphological traits. In the same vein, the highest proportion of Collembola with sexual  
384 reproduction was observed in CCS, which contained the highest metal concentrations. A higher  
385 proportion of sexual reproduction species as compared to parthenogenetic Collembola species has  
386 been reported in copper-polluted environments (Niklasson et al., 2000). The reproduction type of  
387 Collembola is associated with survival or colonizing strategies (Salmon et al., 2014). Sexual  
388 reproduction favors polymorphism and is an advantage for colonizing disturbed ecosystems like  
389 polluted soils on a long term (Austruy et al., 2016). According to the trait-based approach, individuals  
390 with a long body, several ocelli, a PAO organ, a sexual reproduction type, an epiedaphic living form  
391 and a pigmented body mainly represented the Collembola community in soil F. All of these trait  
392 attributes are characteristic of organisms inhabiting in urban environments (Santorufu et al., 2014),  
393 and are linked to a good dispersal ability that allows adaptation to disturbed habitats. The age effect  
394 was not a major factor explaining the functional composition of communities according to the RLQ.  
395 Yet, we may expect links between the fact that CCS was the youngest plot and that it hosted a  
396 Collembola community rich in high dispersal capacity species, which are best adapted for site  
397 colonization.

398 Regarding macrofauna community, available soil Pb concentrations seemed to influence earthworm  
399 density: the highest earthworm density was found in soils with low metal contamination (CS and WL)  
400 as compared to other soils. This impact of Pb concentrations on earthworm communities has been  
401 shown by L  v  que et al. (2015), who observed a low earthworm density in soils near a Pb-recycling  
402 factory containing a high total Pb concentration (2,010 mg.kg<sup>-1</sup> of Pb on average, that is a higher  
403 concentration than in our soils). Pi  l and Josens (1995) also observed a low earthworm density in soils  
404 with a moderate Pb concentration (89 ind.m<sup>-2</sup> in a soil containing 108 mg.kg<sup>-1</sup> of total Pb) as compared  
405 to a soil with a low Pb concentration (490 ind.m<sup>-2</sup> in a soil containing 25 mg.kg<sup>-1</sup> of total Pb). In our  
406 study, we found 42 and 48 earthworms.m<sup>-2</sup> on average in the soils with the highest total Pb  
407 concentrations (346 and 339 mg.kg<sup>-1</sup> for CP1 and SP, respectively) and 112 and 45 earthworms.m<sup>-2</sup> on

408 average in the soils with the lowest total Pb concentrations (41 and 37 mg.kg<sup>-1</sup> for WL and CP2,  
409 respectively). Other authors have also shown that earthworms were sensitive to metal pollution  
410 (Nahmani and Lavelle, 2002; Nahmani et al., 2005). As Collembola, earthworms abundance and  
411 diversity are dependent of soil properties, that highlight their bioindicator potential (Ponge et al., 2003;  
412 Pérès et al., 2011; George *et al.*, 2017). Furthermore, a higher available soil Zn concentration was  
413 associated with a higher density of sclerotized macrofauna individuals. We can hypothesize that  
414 organisms with sclerotized integuments are more protected against pollutants because sclerotized  
415 integuments provide defence against chemical attacks (Linz et al., 2016). By contrast, soft-body  
416 individuals may be directly exposed to pollution by direct skin contact. A negative correlation has  
417 already been observed between the proportion of soft-body individuals and metal soil concentrations  
418 (Hedde et al., 2012).

419 Finally, at a larger spatial scale, the surrounding landscape would have to be taken into  
420 account in order to better understand the variability of community composition across sites.  
421 Collembola and macrofauna communities can be both affected by surrounding environment and  
422 vegetation in derelict soils (Cortet et al., 2013; Baranova et al., 2014; Vanhee et al., 2017). Although  
423 no geostatistical analyses were performed in the present study, some hypotheses might be suggested  
424 on species traits selection. For instance, we found that communities were dominated by forest and  
425 grassland habitat taxa, which can be explained by the surrounding landscapes around the sites. CP1,  
426 SP and CP2 were surrounded by forests, while CS, WL and CCS were surrounded by grasslands. This  
427 could explain the significant higher proportion of euedaphic, blind and non-pigmented Collembola in  
428 CP1 and SP, that are characteristics traits of forest-inhabiting species (Salmon et al., 2014). Moreover,  
429 the proportion of macrofauna inhabiting wet habitats was higher in SP than in CS, WL and CP2,  
430 which could be explained by the proximity to a river (*ca.* 70 m away). The proportion of Collembola  
431 inhabiting wetland habitats was higher in CCS. The inefficient irrigation system in this experimental  
432 constructed soil probably allowed for colonization by wet-habitat species. Moreover, these species  
433 may have come from a nearby pond located at 300 m distance and been brought by trucks and human  
434 activities during the soil construction process or wind or animals (Costa et al., 2013).

435

436

## 437 **5. CONCLUSION**

438           The diversity indices of Collembola and macrofauna communities showed different results  
439 attributable to differences in living modes between the two soil invertebrate communities (e.g. feeding  
440 groups and niche scales). It shows that the derelict soils support different communities with more or  
441 less wide functional potential depending on their physico-chemical characteristics. Our study revealed  
442 that derelict soil characteristics have more consequences on taxonomical and functional profiles of  
443 Collembola communities than macrofauna. In this sense, we can assume that Collembola are more  
444 relevant bioindicators of derelict soil characteristics than macrofauna. For instance, the studied more  
445 fertile and less contaminated compost-amended constructed soil exhibited taxonomic and functional  
446 community structures and composition of slightly disturbed soil. In contrast, the metal-contaminated  
447 constructed soil harbored a higher proportion of Collembola with the traits and ecological preferences  
448 of both unstable and scarcely vegetated ecosystems. Our study underlines the interest of trait-based  
449 approach and multi traits studies to assess the diversity of derelict soils and to reach a better  
450 understanding of soil ecosystem. However, in-depth analysis of direct relations between Collembola  
451 and macrofauna in these soils was limited due to different traits and attributes between both fauna  
452 groups in existing databases.

453           Since we studied invertebrate communities at one given season, it might be interesting to characterize  
454 the community response patterns at different seasons. We previously measured the potential  
455 mineralization activity of these derelict soils (Vincent et al., 2018), but *in situ* measurement of soil  
456 functions, such as organic matter decomposition - by litter bag method - or soil respiration, might add  
457 complementary information to link functional traits of the fauna with the derelict soil functioning.

458

459

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469

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1 Table 1: Abiotic parameters of the six derelict soils. Means  $\pm$  SD (n=5, except for soil F where n=4).  
2 Soil classification according WRB (2014); localization in the Lambert 93 projection in m; age is the  
3 time lapse from the last anthropogenic action (years); clay and WHC in %; CEC in  $\text{cmol}^{\dagger}.\text{kg}^{-1}$  dry soil;  
4 soil pH in water; Olsen Phosphorous in  $\text{mg}.\text{kg}^{-1}$  dry soil; OM in %; Exchangeable Ca, K, Mg, Na in  
5  $\text{mg}.\text{kg}^{-1}$  dry soil, Available and total Cd, Pb, Zn in  $\text{mg}.\text{kg}^{-1}$  dry soil; and PAH (Polycyclic Aromatic  
6 Hydrocarbons) concentrations in  $\text{mg}.\text{kg}^{-1}$  dry soil. For more details, see Vincent et al. (2018).

| Soil abbreviation                                  | CS  | WL  | CP1                           | SP  | CP2                            | CCS  |
|--|---|---|-------------------------------|---|--------------------------------|--|
| Soil name correspondence with Vincent et al., 2018 | A   | B   | C                             | D   | E                              | F  |
| Site type and name                                 | Experimental constructed soil (Biotechnosol)  | Non-hazardous waste landfill (Retonfey)   | Coking plant site (Homécourt) | Settling pond site (Moyeuivre-Petite)       | Coking plant site (Micheville) | Experimental constructed and contaminated soil (Jeandelaincourt)           |
| Soil classification                                | Spolic Garbic Technosol   | Skeletal Technosol                        | Spolic Technosol              | Spolic Technosol                            | Spolic Technosol               | Spolic Technosol   |
| Composition  | paper mill waste, thermal desorption-treated PAH-contaminated soil, and green-waste compost | ground construction and demolition wastes | former coking plant site      | settling pond site filled with steel sludge | former coking plant site       | biopile-treated PAH-contaminated soil mixed with metal-contaminated sludge |
| Year of construction                               | 2007  | 2011                                      |                               |   |                                | 2013   |
| Year of abandonment                                |   |   | 1980                          | 1981  | 1975                           |  |
| Age  | 8   | 4   | 35                            | 34  | 40                             | 2  |
| Localization                                       | E:918202<br>N:6905686   | E:942352<br>N:6897630                     | E:918487<br>N:6905891         | E:920222<br>N:6911528                       | E:942262<br>N:6897475          | E:938477<br>N:6864617  |
| Texture  | Silt loam   | Silty clay loam                           | Loamy sand                    | Sandy loamy                                 | Loam                           | Silt loam  |
| Clay   | 11  | 40  | 6                             | 4   | 27                             | 15   |
| WHC  | 95 $\pm$ 7  | 59 $\pm$ 8                                | 63 $\pm$ 5                    | 58 $\pm$ 4                                  | 70 $\pm$ 1                     | 64 $\pm$ 1   |
| CEC  | 22.0 $\pm$ 2.9  | 17.2 $\pm$ 3.3                            | 17.2 $\pm$ 1.8                | 11.3 $\pm$ 0.7                              | 15.5 $\pm$ 1.4                 | 10.1 $\pm$ 0.4   |
| pH   | 7.9 $\pm$ 0.2   | 7.9 $\pm$ 0.1                             | 7.9 $\pm$ 0.1                 | 8.4 $\pm$ 0.2                               | 7.2 $\pm$ 0.2                  | 8.3 $\pm$ 0.4  |
| Olsen Phosphorous                                  | 62 $\pm$ 5  | 25 $\pm$ 17                               | 39 $\pm$ 16                   | 44 $\pm$ 10                                 | 36 $\pm$ 2                     | 44 $\pm$ 10  |
| C:N  | 30 $\pm$ 6  | 28 $\pm$ 6                                | 26 $\pm$ 5                    | 65 $\pm$ 20                                 | 20 $\pm$ 3                     | 37 $\pm$ 16  |
| OM   | 39.7 $\pm$ 5.9  | 3.2 $\pm$ 1.4                             | 16.7 $\pm$ 6.3                | 13.3 $\pm$ 2.8                              | 4.8 $\pm$ 3.0                  | 2.8 $\pm$ 0.8  |
| Ca <sub>exchangeable</sub>                         | 292 $\pm$ 44  | 713 $\pm$ 144                             | 903 $\pm$ 405                 | 2031 $\pm$ 240                              | 786 $\pm$ 84                   | 1123 $\pm$ 130   |
| K <sub>exchangeable</sub>                          | 706 $\pm$ 105   | 491 $\pm$ 24                              | 155 $\pm$ 36                  | 377 $\pm$ 30                                | 131 $\pm$ 50                   | 218 $\pm$ 36   |
| Mg <sub>exchangeable</sub>                         | 84 $\pm$ 14   | 152 $\pm$ 38                              | 103 $\pm$ 6                   | 312 $\pm$ 47                                | 47 $\pm$ 15                    | 72 $\pm$ 34  |
| Na <sub>exchangeable</sub>                         | 37 $\pm$ 19   | 34 $\pm$ 28                               | 11 $\pm$ 3                    | 42 $\pm$ 11                                 | 14 $\pm$ 14                    | 55 $\pm$ 29  |
| Cd <sub>available</sub>                            | 0.22 $\pm$ 0.05   | 0.03 $\pm$ 0.01                           | 0.16 $\pm$ 0.05               | 0.15 $\pm$ 0.01                             | 0.10 $\pm$ 0.03                | 9.07 $\pm$ 1.5   |
| Pb <sub>available</sub>                            | 13 $\pm$ 3  | 14 $\pm$ 10                               | 46 $\pm$ 14                   | 18 $\pm$ 5                                  | 14 $\pm$ 6                     | 110 $\pm$ 60   |
| Zn <sub>available</sub>                            | 29 $\pm$ 9  | 8 $\pm$ 6                                 | 45 $\pm$ 20                   | 25 $\pm$ 6                                  | 7 $\pm$ 2                      | 308 $\pm$ 189  |
| Cd <sub>total</sub>                                | 1.1 $\pm$ 0.5   | 0.1 $\pm$ 0.2                             | 0.1 $\pm$ 0.7                 | 1.4 $\pm$ 0.1                               | 0.1 $\pm$ 0.1                  | 23.6 $\pm$ 6.9   |
| Pb <sub>total</sub>                                | 150 $\pm$ 53  | 41 $\pm$ 26                               | 346 $\pm$ 106                 | 339 $\pm$ 50                                | 37 $\pm$ 10                    | 460 $\pm$ 73   |
| Zn <sub>total</sub>                                | 345 $\pm$ 37  | 131 $\pm$ 2                               | 1162 $\pm$ 396                | 1196 $\pm$ 122                              | 116 $\pm$ 23                   | 1813 $\pm$ 302   |
| $\Sigma$ 16 PAH (US-EPA)                           | 170 $\pm$ 49  | 12 $\pm$ 12                               | 179 $\pm$ 136                 | 97 $\pm$ 54                                 | 142 $\pm$ 90                   | 10 $\pm$ 4   |

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8 Table 2: Traits/Ecological preferences of the Collembola and macrofauna sampled in the 6 derelict  
 9 soils. Codes are used in Figures 1 to 4.

|                          | Trait/Ecological preference | Code of Trait/Ecological preference  | Attribute                   | Code of attribute          |
|--------------------------|-----------------------------|--------------------------------------|-----------------------------|----------------------------|
| Collembola               | Body length                 | BLN                                  | <1 mm                       | _ <lt1< td=""> </lt1<>     |
|                          |                             |                                      | [1:2] mm                    | _1_2                       |
|                          |                             |                                      | [2:3] mm                    | _2_3                       |
|                          |                             |                                      | >3 mm                       | _>3                        |
|                          | Body shape                  | BSH                                  | Spherical                   | _sph                       |
|                          |                             |                                      | Cylindrical                 | _cyl                       |
|                          | Ocelli (visual organ)       | OCE                                  | No ocellus                  | _0                         |
|                          |                             |                                      | 1 or 2 pair of ocelli       | _1_2                       |
|                          |                             |                                      | 3 or 4 pair of ocelli       | _3_4                       |
|                          |                             |                                      | 5, 6, 7 or 8 pair of ocelli | _5_8                       |
|                          | Post Antennal Organ*        | PAO                                  | PAO present                 | _present                   |
|                          |                             |                                      | PAO absent                  | _absent                    |
|                          | Pigmentation                | PIG                                  | Pigmented                   | _present                   |
|                          |                             |                                      | Non-pigmented               | _absent                    |
| Motion strategy          | MS                          | Furca present                        | _furca                      |                            |
|                          |                             | Furca absent                         | _no.furca                   |                            |
| Reproduction             | REP                         | Sexual reproduction type             | _sex                        |                            |
|                          |                             | Asexual reproduction type            | _asex                       |                            |
| Vertical distribution    | DIST                        | Epigenic                             | _epi                        |                            |
|                          |                             | Hemiedaphic                          | _hemi                       |                            |
|                          |                             | Euedaphic                            | _eu                         |                            |
| Micro-habitat preference | MHABI                       | Inhabiting in decaying micro-habitat | _dec                        |                            |
|                          |                             | Inhabiting in mineral micro-habitat  | _min                        |                            |
|                          |                             | Inhabiting in root micro-habitat     | _root                       |                            |
|                          |                             | Inhabiting in soil micro-habitat     | _soil                       |                            |
|                          |                             | Inhabiting in vegetal micro-habitat  | _veg                        |                            |
| Habitat preference       | HABI                        | Inhabiting in wet micro-habitat      | _wet                        |                            |
|                          |                             | Inhabiting in forest and grassland   | _forest_grassland           |                            |
|                          |                             | Inhabiting in agricultural area      | _agri                       |                            |
|                          |                             | Inhabiting in artificial area        | _arti                       |                            |
|                          |                             | Inhabiting in wetland                | _wet                        |                            |
| Macrofauna               | Body length                 | BLN                                  | <2.5 mm                     | _ <lt2.5< td=""> </lt2.5<> |
|                          |                             |                                      | [2.5:5] mm                  | _2.5_5                     |
|                          |                             |                                      | [5:10] mm                   | _5_10                      |
|                          |                             |                                      | [10:20] mm                  | _10_20                     |
|                          |                             |                                      | >20 mm                      | _>20                       |
|                          | Integument                  | INT                                  | Sclerotized                 | _scl                       |
|                          |                             |                                      | Non-sclerotized             | _no.scl                    |
|                          | Mouth-part type             | MthT                                 | Absent                      | _absent                    |
|                          |                             |                                      | Piercing-sucking            | _piercing.sucking          |
|                          |                             |                                      | Swallowing                  | _swallowing                |
|                          |                             |                                      | Sucking                     | _sucking                   |
|                          | Diet                        | DIET                                 | Chewing                     | _chewing                   |
|                          |                             |                                      | Zoophagous                  | _zoo                       |
|                          |                             |                                      | Phytophagous                | _phyto                     |
| Geophagous               |                             |                                      | _geo                        |                            |
| Detritivore              |                             |                                      | _detri                      |                            |
| Micro-habitat preference | MHABI                       | Inhabiting in decaying micro-habitat | _dec                        |                            |
|                          |                             | Inhabiting in mineral micro-habitat  | _min                        |                            |
|                          |                             | Inhabiting in vegetal micro-habitat  | _veg                        |                            |
| Habitat preference       | HABI                        | Inhabiting in forest and grassland   | _forest_grassland           |                            |
|                          |                             | Inhabiting in agricultural habitat   | _agri                       |                            |
|                          |                             | Inhabiting in artificial habitat     | _arti                       |                            |
|                          |                             | Inhabiting in wetland                | _wet                        |                            |

\* The Post Antennal Organ (PAO) is an organ composed of thermo-, hygro-, or chemo-sensitive receptors.

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Table 3: Taxonomic and functional indices for Collembola communities in the six derelict soils and for macrofauna communities in 5 derelict soils. Means  $\pm$  SD (n=5, except for CCS where n=4). Different letters indicate significant differences among soils (P< 0.05; Kruskal-Wallis test followed by multiple comparisons of rank distribution with Fisher's LSD test). TRic=Taxonomic richness; TEve=Taxonomic evenness; FRic=Functional richness; FEve=Functional evenness. CS=constructed soil; WL=waste landfill soil; CP1=coking plant soil 1; SP=setling pond soil; CP2=coking plant soil 2; CCS=constructed and contaminated soil.

|   |              | Soils                     |                           |                          |                          |                          |                          |
|---|--------------|---------------------------|---------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
|   |              | CS                        | WL                        | CP1                      | SP                       | CP2                      | CCS                      |
| Indices for <b>Collembola</b> community |              |                           |                           |                          |                          |                          |                          |
| <b>Taxonomic</b>                        | <b>TRic</b>  | 3.4 $\pm$ 1.3 <b>b</b>    | 4.2 $\pm$ 0.8 <b>ab</b>   | 6 $\pm$ 1.4 <b>ab</b>    | 7 $\pm$ 0.8 <b>a</b>     | 7 $\pm$ 2.2 <b>a</b>     | 5.8 $\pm$ 1 <b>a</b>     |
|   | <b>TEve</b>  | 0.67 $\pm$ 0.23           | 0.63 $\pm$ 0.18           | 0.46 $\pm$ 0.12          | 0.52 $\pm$ 0.1           | 0.52 $\pm$ 0.12          | 0.74 $\pm$ 0.12          |
| <b>Functional</b>                       | <b>FRic</b>  | 0.07 $\pm$ 0.04 <b>ab</b> | 0.04 $\pm$ 0.03 <b>b</b>  | 0.13 $\pm$ 0.04 <b>a</b> | 0.14 $\pm$ 0.03 <b>a</b> | 0.16 $\pm$ 0.04 <b>a</b> | 0.02 $\pm$ 0.01 <b>b</b> |
|   | <b>FEve</b>  | 0.62 $\pm$ 0.10           | 0.56 $\pm$ 0.22           | 0.68 $\pm$ 0.15          | 0.65 $\pm$ 0.08          | 0.71 $\pm$ 0.04          | 0.68 $\pm$ 0.15          |
| Indices for <b>macrofauna</b> community |              |                           |                           |                          |                          |                          |                          |
| <b>Taxonomic</b>                        | <b>TRich</b> | 16.2 $\pm$ 4.4 <b>a</b>   | 13.8 $\pm$ 4.9 <b>a</b>   | 8.7 $\pm$ 3.1 <b>ab</b>  | 6.6 $\pm$ 3.2 <b>b</b>   | 6.0 $\pm$ 3.8 <b>b</b>   | NA                       |
|   | <b>TEve</b>  | 0.53 $\pm$ 0.06           | 0.62 $\pm$ 0.11           | 0.65 $\pm$ 0.27          | 0.71 $\pm$ 0.14          | 0.71 $\pm$ 0.23          | NA                       |
| <b>Functional</b>                       | <b>FRich</b> | 0.14 $\pm$ 0.01 <b>a</b>  | 0.10 $\pm$ 0.05 <b>ab</b> | 0.06 $\pm$ 0.05 <b>b</b> | 0.07 $\pm$ 0.05 <b>b</b> | 0.07 $\pm$ 0.05 <b>b</b> | NA                       |
|   | <b>FEve</b>  | 0.76 $\pm$ 0.03           | 0.76 $\pm$ 0.07           | 0.78 $\pm$ 0.12          | 0.77 $\pm$ 0.10          | 0.74 $\pm$ 0.14          | NA                       |

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## 1 **FIGURE CAPTIONS:**

2 Figure 1: Community Weighted Mean (CWM) values of Collembola communities sampled in each  
3 derelict soil, calculated for the following traits: number of ocelli, body length, vertical distribution,  
4 presence of furca, body shape, presence of PAO, pigmentation, reproduction type, habitat preference,  
5 and micro-habitat preference. Means (n=5, except for CCS where n=4). Different letters indicate  
6 significant differences among the 6 soils (P< 0.05) using Kruskal-Wallis tests followed by the Dunn's  
7 test of multiple comparisons with Bonferroni adjustment. CS=constructed soil; WL=waste landfill  
8 soil; CP1=coking plant soil 1; SP=settling pond soil; CP2=coking plant soil 2; CCS=constructed and  
9 contaminated soil.

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11 Figure 2: Projection of the coordinates of each soil replicate on the first two main components RLQ1  
12 and RLQ2 (A), mapping of Collembola species density coordinates (B), and plot of attributes of each  
13 trait linked to abiotic soil parameters (C). PAH=sum of the 16 PAH concentrations; Clay=proportion  
14 of clay; P= available phosphorous (Olsen method); OM=Organic Matter; WHC=Water Holding  
15 Capacity; CEC=Cation Exchange Capacity; C:N=carbon/nitrogen ratio; [Exchangeable cations by  
16 cobaltihexamine extraction] Ca=calcium; Na=sodium; K=potassium; Mg=magnesium. [Available  
17 elements] Pb=lead; Zn=zinc; Cd=cadmium; Age= time since the last anthropogenic action.  
18 CS=constructed soil; WL=waste landfill soil; CP1=coking plant 1 soil; SP=settling pond soil;  
19 CP2=coking plant 2 soil; CCS=constructed and contaminated soil. See Table 2 for the codes of  
20 traits/ecological preferences and see Supplementary materials, Appendix A for Collembola species  
21 codes.

22

23 Figure 3: Community Weighted Mean (CWM) values of macrofauna communities sampled in each  
24 derelict soil, calculated for the following traits: body length, diet type, integument type, mouth-part  
25 type, habitat preference, and micro-habitat preference. Means (n=5). Different letters indicate

26 significant differences among the 5 soils ( $P < 0.05$ ) using Kruskal-Wallis tests followed by the Dunn's  
27 test of multiple comparisons with Bonferroni adjustment. CS=constructed soil; WL=waste landfill  
28 soil; CP1=coking plant 1 soil; SP=setling pond soil; CP2=coking plant 2 soil.

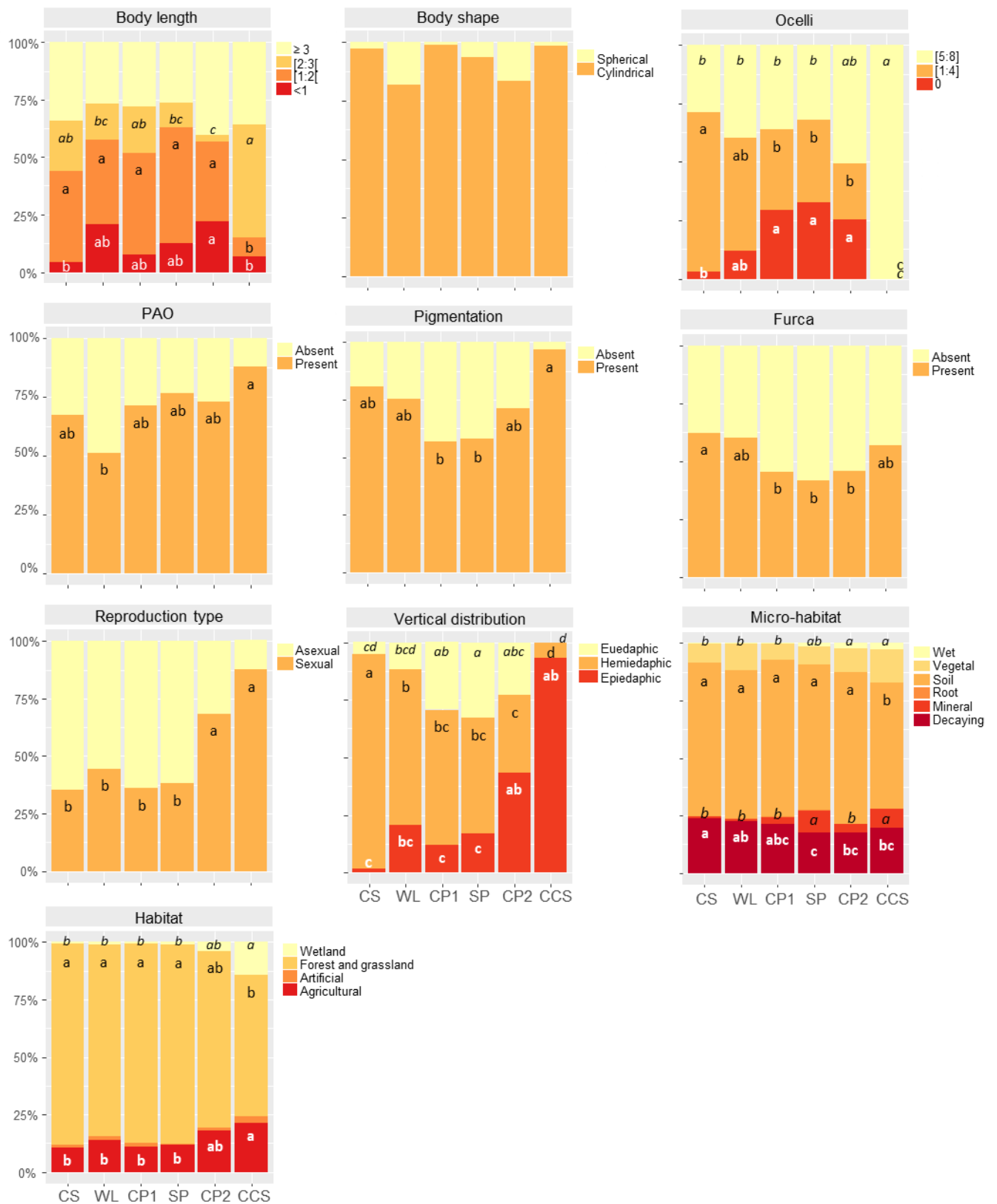
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31 Figure 4: Projection of the coordinates of each soil replicate on the first two main components RLQ1  
32 and RLQ2 (A), mapping of macrofauna taxon density coordinates (B), and plot of attributes of each  
33 trait linked to abiotic soil parameters (C). PAH=sum of the 16 PAH concentrations; Clay=proportion  
34 of clay; P= available phosphorous (Olsen method); OM=Organic Matter; WHC=Water Holding  
35 Capacity; CEC=Cation Exchange Capacity; C:N=carbon/nitrogen ratio; [Exchangeable cations by  
36 cobaltihexamine extraction] Ca=calcium; Na=sodium; K=potassium; Mg=magnesium. [Available  
37 elements] Pb=lead; Zn=zinc; Cd=cadmium; Age= time since the last anthropogenic action.  
38 CS=constructed soil; WL=waste landfill soil; CP1=coking plant 1 soil; SP=setling pond soil;  
39 CP2=coking plant 2 soil. See Table 2 for the codes of traits/ecological preferences and see  
40 Supplementary materials, Appendix B for macrofauna taxon codes.

41



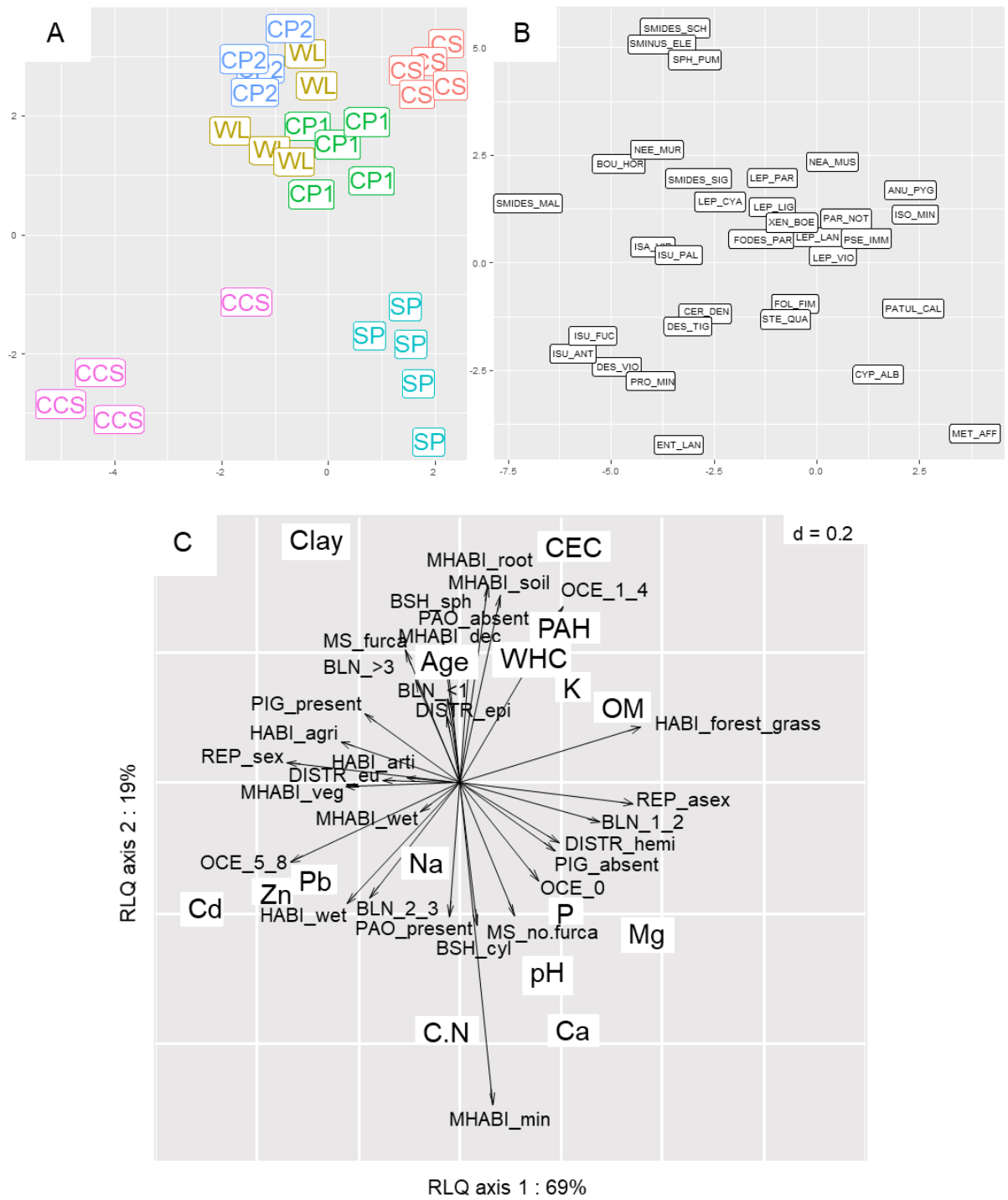


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43 Figure 1

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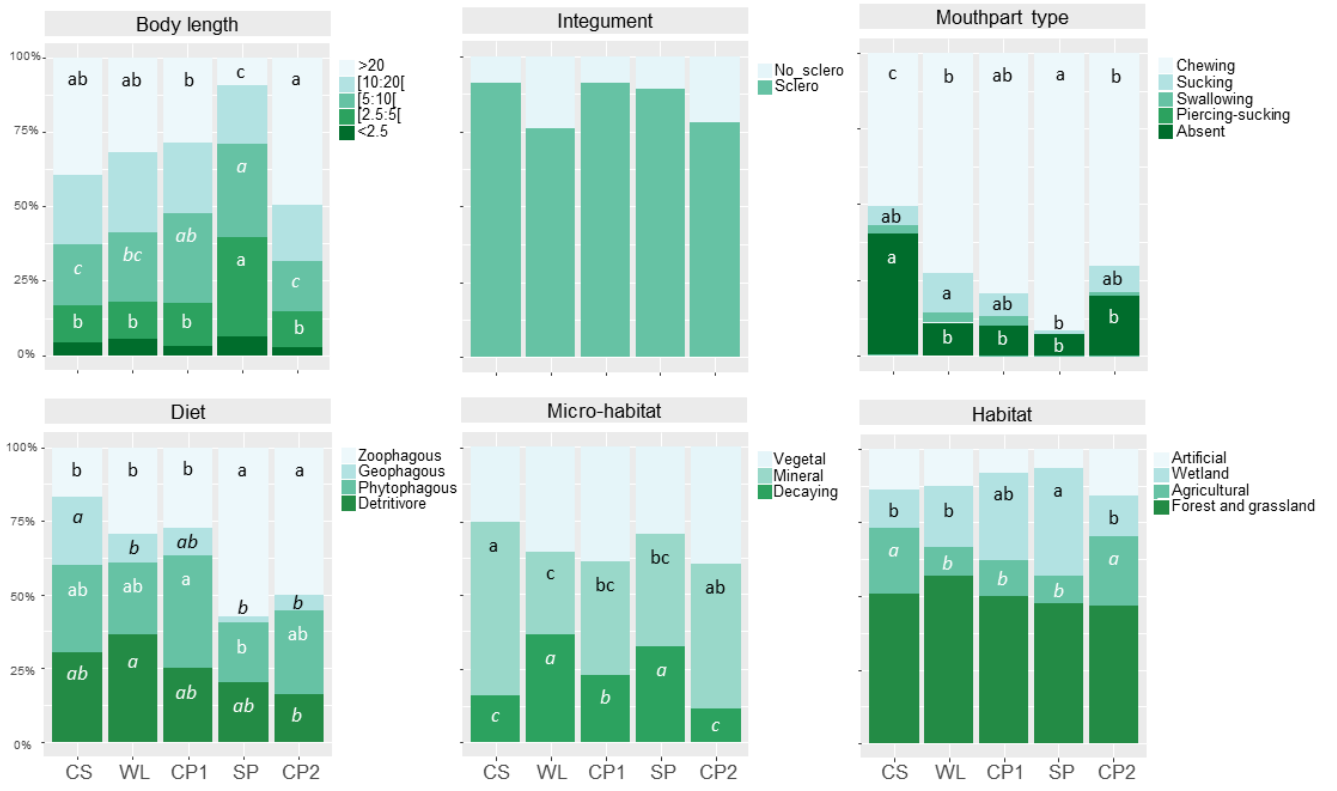
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47 Figure 2

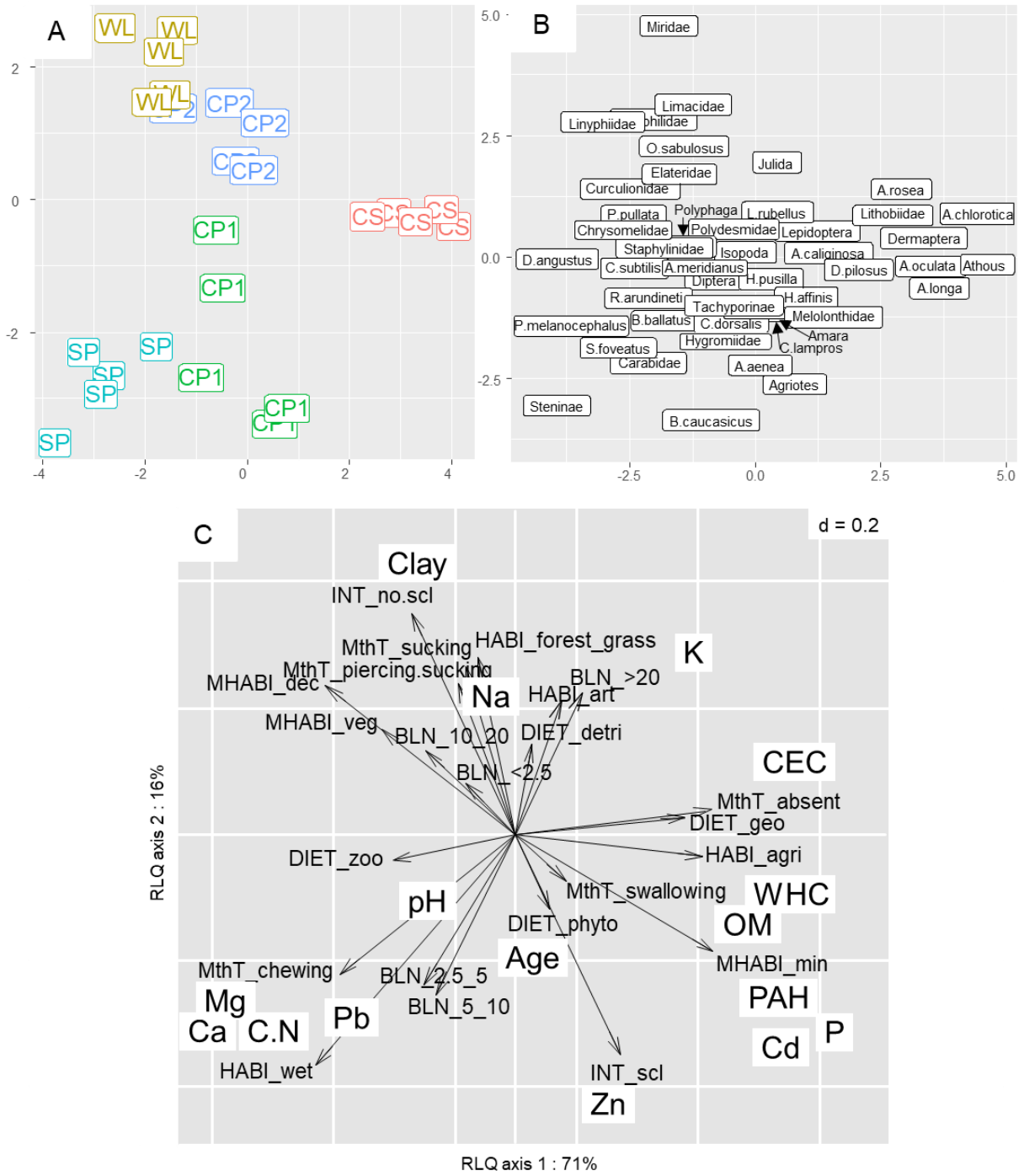
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50 Figure 3

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53 Figure 4