Technosol rehabilitation strategies drive soil physico-chemical properties and fauna diversity on a former coking plant area

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Abstract

Anthropic activities such as mining, resource extraction or transformation profoundly modify ecosystems and may lead to Technosol formation. Post-industrial areas are examples of potentially degraded lands, due to soil contamination with metals or organic pollutants, as well as soil structure damage. Soil biodiversity being closely involved in many soil functions such as organic matter decomposition, formation and stabilization of soil structure, the recovery of degraded soil functions partly depends on soil fauna colonization. However, the relationship between Technosol abiotic parameters and soil fauna colonization is still to be disentangled. In an attempt to fill this gap, we studied a former coking plant area in north-eastern France, composed of Technosols resulting from coking plant embankments or thermally-treated industrial soils and compared them with two local soils considered as references. We hypothesized that the taxonomic and trophic diversity of Technosol-dwelling invertebrates would be more diverse and abundant in the soils with the higher soil physico-chemical quality (i.e higher fertility and lower pollutions levels). To test this hypothesis, we studied four Technosols that were settled following two different rehabilitation strategies within the same post-industrial area and we compared them with two local soils of reference using nested ANOVAs as well as multivariate analyses of soil abiotic parameters and soil fauna community indices, both within the soil and on its surface.

The results on physico-chemical analyses showed that the substrates used for Technosol rehabilitation were impoverished in clay content when compared with local soils of reference (4.1 to 7.8-fold) and enriched in sandy materials. The use of coking plant by-products for Technosol implementation have led to poor chemical quality, with low nutrient content but high organic carbon content (41 to 51 %) resulting from the use of coal and correlated with the higher lead concentration in the area. The use of thermally-treated industrial soil has led to more fertile Technosols with significantly lower lead content. Meso and macrofauna densities did not vary significantly between the Technosols and the local reference soils. Both Technosol-dwelling fauna trophic and taxonomic community compositions were impacted by the rehabilitation strategy. Few to no earthworms were found in Technosols (mean up to 16 ind.m^{-2}) compared to the local soils of reference (mean of 118.4 and 201.6 ind.m^{-2}). Conversely, Technosols resulting from coking plant embankments and thermally-treated industrial soils were dominated by epigeic soil fauna with an intense activity of soil surface macro-saprophages and micro-arthropods, as well as *Formicidae*. Our results suggest that the use of technogenic elements in the rehabilitation of post-industrial area led to the development of specific soil invertebrate communities, different from the reference. The gap between the high level of activity of epigeic organisms that we found on Technosols and the low trophic diversity of the litter and soil-dwelling communities suggest that the soil fauna community on a former coking plant is driven rather by soil physico-chemical properties than by colonization constraints.

Keywords: Anthropogenic soil, Lumbricina, Mesofauna, Metacommunity, Soil fertility

1. Introduction

The human footprint on ecosystems is continually increasing (Kareiva et al., 2007; Vitousek et al., 1997). Over recent decades, a growing environmental concern has emerged while degradations of ecosystems by human activity have been evidenced by numerous studies (Isbell et al., 2015; Millennium Ecosystem Assessment, 2005; Moreno-Mateos et al., 2017). Soil systems are particularly affected by human activities, as testified to by urban expansion, agriculture intensification, or resource

extraction and transformation such as mining, coal or steel industries. In Europe, the ceasing of industrial activities has left behind degraded ecosystems, including brownfield, mining and resource-transformation areas (Frouz et al., 2001; Mudrák et al., 2010; Šourková et al., 2005; Wong and Bradshaw, 2003). Degradation can include contamination by metals or polycyclic aromatic hydrocarbons (PAH), or the overall removal of vegetation and arable soil, such as in post-mining sites. Technosols, which are highly anthropized soils, containing at least 20 % of artefacts within the first 100 cm, or have a cemented or indurated layer below 10 cm depth, or a continuous geomembrane or have technic hard material starting above 5 cm depth (IUSS Working Group WRB, 2015). They usually result directly from past industrial activities (Morel et al., 2015), but may also be a consequence of the rehabilitation strategy of a polluted site. In the past, the rehabilitation goal was sometimes limited to aesthetic properties, or allowing convenient succession of the area (heaps, burrowing, leveling), resulting in Spolic Technosol, with human-transported soil material (IUSS Working Group WRB, 2015). Nowadays the aim of rehabilitation is focused more on sanitary and ecological matters and might be used to improve the ecosystem services provided by a given area (Beroigui et al., 2020; Séré et al., 2008; Sheoran et al., 2010; Sopper, 1992). Constructed Technosols have thus emerged as one way to achieve such rehabilitation. Technogenic inputs into the soil might result from a former activity (industrial wastes), the decline of the activity (dismantling of the buildings, embankments) or from the soil rehabilitation strategy itself (input of exogenous substrates). This phenomena, called “Technosolisation” (El Khalil et al., 2013), may change the soil fauna community composition and limit its colonization (Eijsackers, 2010) and may change the soil microbial and physicochemical properties (Piotrowska-Długosz and Charzyński, 2015). Yet, soil fauna is known to play key roles in soil functioning, such as carbon and nutrient cycling, organic matter decomposition, soil structure formation and stabilization (Orgiazzi et al., 2016). Thus, rapid Technosol colonization by fauna in the first years after rehabilitation could enhance the recovery of degraded soil functions and provide insight into the quality of the rehabilitation strategy (Pruvost et al., 2020; Uzarowicz et al., 2020).

While studies have been conducted of the dynamics of highly anthropized soil fauna colonization in a given rehabilitation strategy, usually revegetation or spontaneous succession of open-mining sites (Frouz et al., 2006; Frouz and Nováková, 2005; Wanner and Dunger, 2002), the ways by which the rehabilitation strategies shape the aboveground-belowground relationships on Technosol are still to be disentangled (Kardol and Wardle, 2010). Taxonomical and functional approaches of Technosol-dwelling fauna colonizers have recently been receiving more attention (Burrow, 2018; Pey, 2010; Vergnes et al., 2017), yet the conclusions remain limited (Villenave et al., 2018) and further research could provide useful clues as to how to optimize forthcoming rehabilitation strategies and increase their sustainability. In an attempt to fill this gap, we studied the soil fauna metacommunity of a former coking plant area, composed of several Technosols in north-eastern France. Since the dismantling of the coking plant in 1985 in this area, different strategies have been set up such as embankments with coking plant by-products, a depollution process of excavated soil to reduce PAH concentration level and *in situ* Technosol construction (Séré et al., 2008), as well as organic matter inputs, resulting in the presence of different type of Technosols in a single geographical area. This mosaic of Technosols may lead to different patterns of soil fauna colonization and thus to different spatiotemporal soil function recoveries. The goals of our study were to establish (i) the influence of the soil substrates used in the different rehabilitations on the soil physical and chemical fertility parameters, (ii) the recovery of the soil taxonomical and trophic invertebrate communities in Technosols of the former coking plant area in comparison with local soils of reference. A final goal was to establish if there is a link between the quality of the Technosol physico-chemical properties (i.e. fertility, nutrient content, pollution) and the level of biodiversity. We hypothesized that the physico-chemical quality of the Technosol (i) would depend on the nature of substrates used for the rehabilitation, and (ii) would be lower in Technosol constituted by coking plant embankments than in depolluted soils, and in soils of reference. Finally, we hypothesized that Technosols with a better physico-chemical quality would exhibit a more diverse taxonomic and trophic soil fauna community in comparison with the others. To test our hypothesis, we assessed the soils' abiotic parameters and the soil fauna taxonomical and trophic community composition of Technosols resulting from two different rehabilitation strategies. We added to the study two local soils of reference, resulting from natural pedogenetic processes and located in the

same area to compare both their fertility parameters and fauna community composition to those of Technosols.

2. Material and methods

2.1. Site and soils studied

The study was carried out at a former coking plant site (32 ha), in north-eastern France (49°12'49.87"N, 05°59'43.10"E, 225 – 250 m above sea level) of the group of scientific interest on soil study (GISFI) experimental station at Homécourt (www.gisfi.univ-lorraine.fr). The mean annual rainfall in the area is 720 mm and the mean annual temperature is 11°C. Two coking plants succeeded each other between 1923 and 1980, the latter being dismantled in 1985. Their activities led to soil contamination with heterogeneous levels of heavy metals and polycyclic aromatic hydrocarbons (PAH) (Biache et al., 2013). The site studied is now composed of a mosaic of ecological units, such as meadow, grassland, woodland, spontaneously developing or artificially implanted on different Technosols.

On the former coking plant site, six sub-sites were studied and considered as follows: four Technosols were chosen based on their historical background concerning the rehabilitation method they received. Simultaneously to the four Technosols, a woodland (named WOOD) and a meadow (named MEAD) located in the same area close to the former industrial

site were selected as soils of reference, hereafter called “REF”. Sampling sub-site localizations are presented in Fig. 1.

The first type of substrate that composed the first two Technosols studied (COAL and EMB, Fig.1) was embankments with coal tailing and remnants from the buildings dismantled in 1985, hereafter called “CPE”. These embankments were created between 1986 and 1989 to level the soil, with no addition of organic matter nor any depollution (LECES, 2001). The absence of cemented or indurated

129 layer starting in the first ten centimeters of the profil and the proportion of artefact exceeding 20%
130 within the first 100 cm of the profile allow to classify the soils as Technosol. The first Technosol
131 (named COAL) is a Spolic Technosol composed of more than 50 cm of coal embankments on which a
132 herbaceous stratum has developed; the second, (named EMB) is a Spolic Technosol composed of a
133 mixture of embankments more than 1.3 meters deep, with a spontaneously developed forest composed
134 of *Populus tremula*, *Robinia pseudoacacia* and *Betulus pendula* (pioneer plants of the former coking
135 plant studied).

136 The following two Technosols studied (TDT and CONS, Fig.1) share a common rehabilitation
137 strategy, hereafter called "ITS". Implemented in 2003, this was conducted to reduce the soil PAH
138 concentration level as required by French policy. The main substrate of the two Technosols was a
139 thermally-treated industrial soil. Both soils contained more than 20% of artefact within the first 100
140 cm of the profile and neither exhibited a cemented or indurated layer within the first ten centimeters
141 thus were defined as Technosols (IUSS Working Group WRB, 2015; Séré et al., 2008). A Technosol
142 (named TDT) settled in 2003, which was composed of 30 cm of this substrate, without any further
143 material addition. The last Technosol studied (named CONS) was constructed in 2008 and is
144 composed of 100 cm of a mixture of paper mill sludge and thermally-treated substrate covered by ten
145 centimeters of green-waste compost. This strategy was conducted to recover potential economic value
146 and to allow an improvement of the ecosystem services provided by a part of the area, using pedo-
147 engineering processes (see Séré et al. (2008) for more details).

148

149 *2.2. Technosols and soils of reference abiotic parameter characterization*

150 All the samples were collected between the 25th and the 30th of April, 2018. At each of the 6 sub-sites,
151 five samples were taken (except for COAL sub-site for which N=4) in order to characterize abiotic
152 parameters (i.e. soil chemical and physical analyses) to quantify the quality of the four Technosols and
153 two soils of reference. A cross-shaped pattern was chosen for the sampling strategy, with the center of
154 the cross chosen randomly and the other four points were ten meters distant from the center and at
155 least 5 m away from the edges to avoid any edge effect (Fig. 2).

156

157 A total of 21 abiotic variables representing generally-studied soil fertility parameters and
158 contamination levels were measured. At each sampling point (N=5, except for COAL N=4), four 500
159 g soil samples, taken from the first 0-20 cm soil layer, were pooled into one composite sample (Fig. 2
160 squares "1"). Prior to analyses, soils were air-dried for 72 h then sieved at 2 mm. In order to study
161 comparable materials, we used two successive soil homogenization techniques: first reducing the size
162 of the overall sample to 500 g using an open-bin riffle splitter (Schumacher et al., 1990), then using a
163 rotary splitter coupled with a vibratory feeder with a V-shaped channel (Laborette 24, Fritsch), thereby
164 providing two homogeneous samples. One was kept in the laboratory for chemical analyses and the
165 other was sent for particle size distribution analysis (NF X 31-107, Laboratoire d'Analyses des Sols,
166 www6.hautsdefrance.inra.fr/las).

167 Soil pH was measured on 5 mg of 2 mm-sieved soil in 25 mL distilled water (v/v) (ISO 10390) with
168 three replicates for each sample.
169 For the following analysis, soil samples were ground to less than 250 µm using a mixer mill (MM 400,
170 Retsch). Organic carbon and total nitrogen were measured using an elementary analyzer (vario
171 MICRO, Elementar) after soil sample combustion. Decarbonation was performed prior to analysis for
172 organic carbon by adding 2 µL of chloridric acid (4 mol L^{-1}) until gassing ceased (ISO 10694). Total
173 and exchangeable cation exchange capacity (CEC) were measured using the cobalthyhexamine
174 method (ISO 23470). Available P was estimated by measuring soluble P in sodium bicarbonate (Olsen
175 method, ISO 11263). Measurements of total and DTPA-extractable soil elements were made using
176 inductively coupled plasma with optical emission spectroscopy (ICP-OES) (NF ISO 11466 and NF
177 EN 13651 respectively).
178
179 Finally, one soil corer (5 cm) was sampled at 5 cm depth in order to measure the bulk density (Fig. 2
180 square "2"). Soil bulk density (Bd) was calculated using the ratio of the soil dried mass at 105 °C (P_s)
181 to the volume of the sampled corer (NF EN ISO 11272):

182 $$Bd = \frac{Soil\ dry\ weight}{Corer\ volume}$$

183 Water holding capacity (WHC) was assessed using a porous membrane press according to the standard
184 NF EN ISO 11274.
185
186 *2.3. Soil fauna community analysis*
187 *2.3.1 Soil fauna sampling and identification*
188 At the time of the abiotic sampling and at close proximity (10 cm to 45 cm), three types of invertebrate
189 communities were studied using combination of soil sampling and pitfall traps to assess the density
190 and activity of both macrofauna and mesofauna, as previously performed on industrial areas (Hedde et
191 al., 2018).
192
193 Firstly, the litter and soil-dwelling macrofauna (organisms > 2 mm) was sampled using the normalized
194 TSBF method adapted to temperate regions (ISO 23611-5). One soil monolith of 625 cm² was
195 extracted to a depth of 30 cm, including any litter layers at a given sub-site (Fig. 2, square "3"). All
196 organisms were hand sorted and immediately stored in 70 % (v/v) ethanol solution.
197 Litter and soil-dwelling micro-arthropods (0.1 to 2 mm) were sampled within the first 10 cm of each
198 soil using successively 5 cm deep and 10 cm diameter corers (Fig. 2, circle "4"). The corers were
199 placed in a high-temperature gradient extractor (Macfadyen, 1961) to extract micro-arthropods then
200 stored in a 70 % (v/v) ethanol solution.
201 Finally, in order to study soil surface-dwelling invertebrates, we placed three pitfall traps 1 meter apart
202 and 45 cm from each abiotic parameter sampling point and soil-dwelling invertebrate sampling points
203 for a total of 15 pitfall traps (12 pitfall traps for COAL) carried out on each sub-site (Fig. 2, circles
204 "5"). The traps are composed of a plastic cup, filled with glycol and soap with a 100:1 ratio (v/v). The
205 87 traps were collected after one week and the animals were transferred and stored in 70 % (v/v)
206 ethanol before identification.
207
208 All soil fauna identification was done using a stereomicroscope (MZ FLIII, Leica) at a magnification
209 of x8 for macrofauna and x45 for micro-arthropods. Macro-invertebrates were identified at
210 taxonomical levels of the class, order, sub-order or family depending on the group (see Table 2 for

litter and soil-dwelling macrofauna sampled in litter and soil monoliths; Table 3 for soil surface dwellers sampled by pitfall traps method). Then, in order to study the functional profile of the soil fauna communities across the 6 soils studied, we assigned a trophic type to each zoological group as previously done in many studies (Hedde et al., 2018; Salmon et al., 2006). The trophic assignments are shown in Tables 2 and 3.

Finally, soil micro-arthropods were identified as: collembolas (saprophages), oribatid mites (saprophages) and other mites (mostly represented by mesostigmates; predators). Distinction between Oribatida and Mesostigmata mites were performed based on the presence of both anal and genital plates on the abdomen of Oribatida mites (Balogh and Balogh, 1992; Karg, 1993).

2.3.2 Taxonomic and trophic fauna community indices calculation

Ecological indices describing edaphic fauna communities were calculated for each Technosol and soil of reference: litter and soil-dwelling taxonomic richness for macrofauna and micro-arthropods (mean of zoological groups sampled at each sub-site), total macrofauna and micro-arthropods densities per m² (mean of the densities sampled at each sub-site). The number of ants and snails were not taken into account in the calculations of the litter and soil-dwelling communities because of their high aggregation capacity and the number of empty gastropod shells (Petersen and Luxton, 1982). The trophic indices of litter and soil dwelling community were also calculated: the abundance and proportion of macro-saprophages, or macro-geophages or macro-predators, and trophic richness (number of trophic groups in the community).

The Shannon index (H) was calculated for soil and litter-dwelling macrofauna in each of the four Technosols and two soils of reference studied as follows:

$H = -\sum_{i=1}^{S} p_i \log_2 p_i$, where $pi = \frac{x_i}{\sum_{i=1}^{S} x_i}$

where p_i = proportion of organisms belonging to the zoological group "*i*", S = total number of zoological groups and x_i= number of organisms belonging to the zoological group "*i*".

For the surface soil-dwelling organisms (collected by pitfall traps), we considered that the 3 pitfalls installed at a given sampling point were dependent on each other because of their proximity, but were independent from the other sampling points of a given sub-site. Consequently, abundances of invertebrates sampled in the 3 dependent pitfall traps were gathered, and we considered N=5 (=15/3) for one given site (N=4 for COAL). From this sampling method, we calculated 6 indices that described the soil surface-dwelling community for each of the Technosols and soils of reference: the taxonomical richness, the number of macro-organisms and micro-arthropods, the number of macro-saprophages and the proportion of macro-saprophages and macro-zoophages in pitfall traps.

2.4. Statistical analyses

Mean comparison of Technosols and soils of reference physical and chemical parameters and invertebrate communities were performed, with the soil substrate as a random effect and the sub-site as a fixed effect, using nested ANOVA after ensuring that homoscedasticity and normality of the residuals of the linear model were met. Post-hoc tests were performed for multiple mean comparison using the TukeyHSD test and using Bonferroni correction in order to reduce the risk of falsely rejecting the null hypothesis.

In order to assess the heterogeneity of our data sets, two principal component analyses (PCA) were performed using the dudi.pca function of the ade4 package in R software. The first PCA was done on abiotic parameters and the second PCA was carried out on fauna communities' taxonomical and trophic indices calculated for the three types of communities.

In order to assess the relationships (co-variation) between abiotic and biotic variables, the coinertia function of the ade4 package was used to perform a co-inertia analysis between abiotic and biotic PCAs. For the two PCAs, variables were normalized in order to ensure equal row weights for the co-inertia. The statistical significance of the co-structure between the two data sets was tested by the Monte Carlo test (RV score) with 1000 permutations with the randtest function of the ade4 package. All statistical analyses were performed using RStudio software (version 1.1.383, 2017).

3. Results

3.1 Technosol physico-chemical characteristics according to the rehabilitation strategy

A PCA was conducted on the 21 measured abiotic variables (Fig. 3). The first two axes represent 60.4% of the total variation, with the first and second axes representing 33.7% and 26.1% of the variation respectively. Mean values and standard deviations of the abiotic parameters studied at each sub-sites are presented in Table 1 with the results of the corresponding nested ANOVAs. The first axis of the PCA is negatively correlated with clay content, WHC, potassium and phosphorus concentration and positively correlated with C:N ratio, sand content, total and DTPA extractable lead. The second axis of the PCA is negatively correlated with pH values and Mg concentrations and is positively correlated with total nitrogen concentration and exchangeable Mg. The first axis of the PCA separates the characteristics of the REF soils of reference sub-sites from the ones of the CPE rehabilitation strategy while the second axis mostly separates the Technosols of the ITS strategy from the REF and CPE. Although the PCA exhibits three clusters of points for the abiotic parameters, only 5 out of the 21 parameters differed significantly between rehabilitation strategies and soils of reference (Table 1). Organic carbon content was significantly higher in the Technosols of the CPE rehabilitation strategy with respectively 506.83 and 409.85 g kg^{-1} in COAL and EMB (p-value = 0.016), which is one order of magnitude greater than in TDT sub-site. Significantly different clay and sand contents between the Technosols and soils of reference resulted from the different substrates used for rehabilitation. Clay content was higher in the REF soils of reference, with respectively 495 and 507 g kg^{-1} in sub-sites MEAD and WOOD (p-value = 0.001), while the two rehabilitation strategies showed a significantly higher sand content than the soils of reference, with a maximum of 646 and 756 g kg^{-1} respectively in COAL and TDT (p-value =0.013). Lead concentration was significantly higher in the Technosols resulting from CPE rehabilitation strategy, with mean contents of 271.2 and 282.3 mg kg^{-1} respectively found in Technosol COAL and EMB (p-value = 0.018). Finally, the total potassium content of the soils was significantly higher in the REF soils of reference with a mean of 6739 and 6516 mg kg^{-1} in sub-sites MEAD and WOOD respectively (p-value = 0.007), which is two to five times higher than the mean concentration found in CPE and ITS. All soils were neutral to slightly alkaline with pH ranging

291 from 7.5 for MEAD and COAL to 8.4 for TDT, the observed differences differing statistically if we
292 accept a threshold alpha of 0.051. While the other parameters did not differ significantly between
293 rehabilitation strategies, some of them exhibit high variability between soils sampled. The lowest C:N
294 ratio was 26 and was found in MEAD reference soil, while it reached a mean of 84 in Technosol
295 COAL. Nitrogen content varied from 1.3 to 8.4 g kg^{-1} in Technosols TDT and EMB respectively.
296 Metals showed a wide variability between soils, even within a given rehabilitation strategy. Zinc
297 especially varied from 284 in COAL to 825 in EMB Technosol. A very low bulk density was
298 measured in the Technosol COAL with a mean value of 0.69.

299

300 *3.2 Soil fauna communities on the studied area*

301 Overall, 50,236 organisms were sampled in the study. The density per m² or the number of organisms
302 within the 3 traps of each sub-site and for each soil zoological group collected are shown in Table 2
303 for litter-soil dwelling macrofauna and micro-arthropods (sampled with TSBF and corer methods), and
304 in Table 3 for soil surface dwelling organisms (sampled with pitfall traps). The indices calculated for
305 the three types of soil fauna communities are shown in Table 4.

306

307 *3.2.1 Litter and soil-dwelling communities*

308 Quantitatively, a similar soil fauna diversity was found for the two rehabilitation strategies and for the
309 soils of reference. The density of macro-organisms in the litter and soil-dwelling community found in
310 the study area varied between 230.4 ± 209.7 and 483.2 ± 203.1 individuals m^{-2} in TDT and MEAD
311 respectively and the density of micro-arthropods varied between 21862 ± 6661 and 105232 ± 77889
312 individuals m^{-2} in WOOD and COAL respectively and no statistical differences were found between
313 the rehabilitation strategies (Table 2). The maximum mean of Isopoda, Diplopoda, larvae of Diptera
314 and Lepidoptera and Lumbricina were found in REF (WOOD and MEAD). The maximum mean of
315 Chilopoda, Protoura, Mesostigmata and Oribatida were found in Technosols COAL or EMB. Finally,
316 the maximum mean number of Araneae, Collembola, and Coleoptera were found in Technosols TDT

317 or CONS. Yet, out of the 19 taxonomical groups found in the studied soils, only the total number of
318 Lumbricina varied significantly with the nature of the substrate used in soil rehabilitation strategy (p-
319 value = 0.034). The number of earthworms varied from 0 individuals m^{-2} in the EMB Technosol to
320 201.6 ± 165 individuals m^{-2} in the MEAD soil of reference. Significantly more earthworms were found
321 in the soils of reference than in the Technosols following CPE and ITS rehabilitation strategies.
322 Epigeic earthworms were found in one Technosol resulting from each rehabilitation strategy. Only 3.2
323 ± 7.2 individuals m^{-2} were found in COAL Technosol and none were found in the three other
324 Technosols. Finally, only 9.6 ± 8.8 endogeic earthworms were found per square meter in the CONS
325 Technosol, while none were found in the three other Technosols.
326 No statistical differences were found for the Shannon index, the zoological richness and the trophic
327 richness (Table 4).
328 The litter and soil-dwelling community exhibited trophic differences across the studied sub-sites. The
329 proportion of macro-zoophages was higher in CPE sub-sites than in ITS and REF, with respectively 66
330 ± 17 and 57 ± 18% of zoophages in the COAL and EMB Technosols (p-value = 0.048). In the MEAD
331 and WOOD soils of reference, both the density and the proportion of macro-geophages were higher
332 than in the Technosols resulting from the two rehabilitation strategies (p-value = 0.034 and 0.017
333 respectively).

334 *3.2.3 Soil surface-dwelling invertebrates*

335 Within the studied area, the number of macro-organisms collected on the soil surface by pitfall traps
336 method varied significantly between the different rehabilitations' strategies (p-value = 0.029). The
337 highest number of soil surface macro-organisms in the coking plant area was found in ITS
338 rehabilitation. No statistical differences were found for the mean number of micro-arthropods sampled
339 in pitfall traps. Quantitatively, only the total number of Hymenoptera varied significantly between the
340 rehabilitation strategies (p-value = 0.040). The highest number of Hymenoptera were sampled in the
341 two Technosols resulting from the ITS rehabilitation and most organisms belonged to the Formicidae
342 family (Table 3).

343 The trophic composition of the soil surface-dwelling invertebrate community varied across the
344 different rehabilitation strategies (Table 4). The proportion of saprophages sampled at the surface of
345 the Technosols from the CPE rehabilitation strategy was higher (p-value = 0.048) than the proportion
346 of saprophages sampled at the surface of the Technosols that were subject to the ITS rehabilitation
347 strategy. The lowest proportion of soil surface-dwelling zoophages were sampled at the Technosol of
348 the ITS rehabilitation strategy (p-value = 0.040).

349 *3.3 Relationship between soil fauna communities' indices and soil physico-chemical characteristics*

350 A co-inertia analysis was conducted in order to test the co-structure between the abiotic parameters
351 and the soil fauna community indices (Fig. 4) for the four Technosols and two soils of reference. The
352 first two axes of the co-inertia represented 87.2% of the total co-inertia and a significant co-variation
353 between the abiotic and biotic data sets was revealed by the Monte Carlo test (RV = 0.58, p-value =
354 0.001). For a given rehabilitation strategy (CPE, ITS) or for the soils of reference), the centroids of the
355 two data sets (abiotic and biotic) were close to each other, indicating a relationship between the soil
356 abiotic parameters and the fauna indices (Fig. 3a). The first axis of the co-inertia analysis explained
357 51.2% of the total inertia and discriminated the two soils of reference from the four Technosols (Fig.
358 3b). For the litter and soil dwelling community, the soils with the highest fertility parameters,
359 corresponding to the two soils of reference, exhibited the highest soil fauna trophic and zoological
360 richness, higher Shannon indexes and the highest densities of macro-saprophages, the lowest density
361 of micro-arthropods and the higher proportion of geophages in the community. The second axis of the
362 co-inertia analysis explained 36.0% of the total inertia and mostly discriminated between the
363 Technosols resulting from the two different rehabilitation strategies. Technosols COAL and EMB
364 (CPE strategy) were characterized by soil contamination variables such as soil total Zn, Pb and Cd
365 concentration, DTPA exchangeable Zn and Pb concentration, and, organic matter related variables,
366 such as organic carbon content, and total nitrogen content. These variables co-varied positively with
367 the proportion of predators in the soil and at the soil surface and with the proportion of saprophages of
368 the community sampled at the soil surface. The Technosols TDT and CONS that resulted from ITS
369 rehabilitation strategy were characterized by high soil pH values and lower metal concentrations and
370 metal availability than the CPE Technosols. These variables co-varied with the highest soil surface
371 fauna activity, as attested to by the number of both macro-organisms and macro-arthropods sampled in
372 pitfall traps.

4. Discussion

4.1 Technosol physico-chemical characteristics according to the rehabilitation strategy

Our results on the physico-chemical characteristics of the soils from the former coking plant of Homécourt support our hypothesis of a higher soil fertility in ITS than from the CPE rehabilitation strategy. Technosols from the area have a lower physico-chemical quality that the REF soils of reference. Our results showed that the rehabilitation methods have in fact, led to pronounced abiotic parameter heterogeneity at the site scale, because of the difference between the studied Technosols. As expected, the rehabilitation of the former coking plant area has resulted in sandy Technosols with significantly less clay content than the soils of reference. Indeed, Technosols of industrials areas often exhibit a high proportion of coarse elements resulting in low fine earth contents (Burghardt, 1993) associated with the nature of the industrial residues, wastes, or other technogenic substrates used (Burghardt, 1994). The high pH value that we measured in Technosols is in accordance with pH values of former industrial or urban areas, which are usually neutral to slightly alkaline (Galvín et al., 2012; Joimel et al., 2016; Morel et al., 2005) as the result of the high carbonate content found in building blocks (Burghardt, 1994).

Both CPE and ITS rehabilitation strategies reduced the total potassium content in the Technosols in comparison with the soils of reference, but this was not the case for the exchangeable K that we measured. According to Vincent et al. (2018), exchangeable potassium might be an important limiting factor for plant growth on derelict soils of industrial areas, but the exchangeable K found in the studied Technosols and the soils of reference is within range of the content expected to be found in the Lorraine region (French monitoring network RMQS).

The highest proportion of soil organic carbon in CPE in comparison with the other Technosols studied and soils of reference, with respectively 40 and 50 %, found in EMB and COAL Technosols, might result from the charcoal and other coal by-products used as embankments for the leveling of the area (Biache et al., 2013). The proportion of organic carbon contents above 12% that we measured in the CONS Technosol, most likely resulted from the compost used during the initial settlement of the

Technosol (Cortet et al., 2013). Organic carbon is often used as an indicator of soil fertility, as it contributes to the nutrient pool, formation of stable aggregates, water retention or cation exchange capacity (Fardeau, 2014; Golchin et al., 1994), especially in nutrient-poor systems (Tiessen et al., 1994). Yet, in our study, organic carbon is not correlated with other fertility parameters such as clay content, water holding capacity or cation exchange capacity, but covaried positively with metal contamination. The co-variation of organic carbon with Technosol metals that we found on the Technosols resulting from CPE rehabilitation might be explained by the presence of coal by-products in the soil (Colombini et al., 2020) that are known to have a high sorption capacity with metals (Zevenbergen et al., 1999). The presence of polycyclic aromatic hydrocarbons as a source organic pollutants that have a high C content and are usually found in soils close to coking plants in addition to metals (Biache et al., 2013; Liu et al., 2013; Rachwał et al., 2015; Yuan et al., 2014) might be another explanation for this correlation. Within a given Technosol, various sources of organic carbon might exist and can be exogenous, such as coal-products, fly ashes or compost input or neo-formed such as leaf litter, living and decaying roots or fauna feces (Colombini et al., 2020). Thus, the proportion of each different C source is to be considered and organic carbon content *per se* does not necessarily inform on Technosol fertility. The use of coking plant by-products in the CPE rehabilitation strategy have led to the lowest soil chemical quality with total lead and zinc respectively 10 and 7 times higher in EMB Technosol than in the geochemical background of the region (Darmendrail et al., 2000). Nevertheless, these concentrations remain relatively low compared with soils affected by zinc smelter or iron industry deposits. For example, Gillet and Ponge (2002) recorded 34800 mg kg^{-1} and 5840 mg kg^{-1} of Zn and Pb respectively in soils surrounding an active zinc smelter, while Huot et al. (2013) measured 24800 and 21100 mg kg^{-1} DW of Zn and Pb respectively in a Technosol of a former settling pond in the Lorraine region. Finally, a Zn concentration 2.5 times higher in the WOOD Cambisol than the mean of the geochemical background (Darmendrail et al., 2000) was found, which might result from coal fly ashes aerial deposition during the coking plant's activity (Nelson Beyer et al., 1985), as confirmed by micromorphological observations (Colombini et al., 2020).

427 *4.2 Taxonomical and trophic composition of Technosol fauna communities according to the*
428 *rehabilitation strategy*

429 On the studied former coking plant, the densities of litter and soil-dwelling organisms (sampled in
430 monoliths) were relatively low, regardless of the rehabilitation strategy. The total macrofauna and
431 micro-arthropods densities were lower in the woodland soil of reference than in comparable temperate
432 deciduous forests (Deleporte and Tillier, 1999; Schaeffer and Shauermann, 1990). However, litter and
433 soil-dwelling macrofauna densities sampled in soils from the coking plant were similar to those
434 already observed in highly anthropized soils with natural succession (Huot et al., 2018; Nahmani and
435 Lavelle, 2002), or post-mining sites rehabilitated with an alder plantation (Frouz et al., 2007a).

436 The number of earthworms found for the meadow (MEAD) soil of reference in our study was
437 comparable with the density of earthworms found in other meadows in temperate regions (Curry,
438 1989), while it was relatively low in the woodland (WOOD) soil of reference of the studied former
439 coking plant compared to the density in other woodlands, where earthworm density can reach more
440 than 600 ind m^{-2} in temperate regions (Cardinael et al., 2019; Lavelle and Spain, 2001).

441 We found a high proportion of macro-zoophages (mostly Chilopoda) in the litter and soil-dwelling
442 community and a high proportion of soil surface zoophages and saprophages (Araneae, Isopoda and
443 Diplopoda respectively) in CPE Technosols resulting from the embankments of coking plant by-
444 products. Similar edaphic community composition has been reported in Technosols composed of
445 dumping from settling ponds with a similar spontaneously developed vegetation (Huot et al., 2018).
446 This soil fauna community composition is similar to the soil fauna community found in the moder
447 form of humus, but with lower densities of both micro-arthropods and macro-saprophages such as
448 Diplopoda and Isopoda (Salmon et al., 2006).

449 In comparison, the community of the two ITS Technosols was mostly composed of a high number of
450 organisms belonging to a few taxonomic and trophic groups as revealed by the number of macro-
451 organisms and collembola sampled in pitfalls traps and by the low Shannon index found in these two
452 Technosols. Such community compositions indicate an early stage of colonization of reclaimed
453 degraded area by the soil fauna (Frouz et al., 2001; Hedde et al., 2018) and occurred in the most recent
454 rehabilitation strategy of the studied site. Micro-arthropods are usually efficient colonizers of

455 Technosols during their early evolution stages (Frouz et al., 2001; Joimel et al., 2018) and might
456 benefit from a low top-down regulation according to the small proportion of epigeic zoophages that
457 we found in the pitfall traps on the TDT and CONS Technosols. When earthworms have not yet
458 colonized reclaimed post-industrial soils, one might well expect a lower bottom-up regulation of the
459 mesofauna community, resulting from the feeding activity of earthworms (Ponge, 2003), which might
460 lead to high mesofauna taxonomic diversity in industrial soils (Joimel et al., 2017).
461

462 *4.3 Relationship between soil fauna community indices and soil physico-chemical characteristics*

463 Our results showed that only the soils of reference, with higher physical (clay content) and chemical
464 (lower Zn and higher K contents) quality, supported an earthworm's population comparable to similar
465 ecosystems (Cluzeau et al., 2009; Curry, 1989). The sandy texture or the high metal concentration
466 might explain the low density or the absence of anecic and endogeic earthworms in the Technosols, as
467 described in many other moderately to highly-polluted soils (Bradshaw, 1983; Gillet and Ponge, 2002;
468 Nahmani and Rossi, 2003). While Eijsackers (2010), showed that earthworms are capable of
469 colonizing a wide range of habitats related to different rehabilitation strategies, earthworm populations
470 are often reported to be low if not absent from sandy soils resulting from industrial activities
471 (Emmerling and Paulsch, 2001).

472 ITS Technosols resulting from the depollution of the industrial substrate presented a gap between high
473 number of organisms in pitfall traps and a low soil trophic richness, thus evidencing the fact that the
474 rehabilitation promoted the recovery of the soil surface community rather than the edaphic one, in
475 terms of both taxonomical and trophic diversity. While the addition of organic matter has been
476 reported to enhance the colonization of degraded soils by earthworms (Emmerling and Paulsch, 2001),
477 this was not the case for the CONS Technosol that received green waste compost. In this same
478 Technosol, Hedde et al. (2018) found more earthworms in the early stage of colonization indicating
479 that the soil substrate did not fit their long term establishment. The increasing abundance of
480 Formicidae that we found in the soil surface community in comparison with their study might
481 highlight the development of a top-down regulation of earthworm populations by ants (Passera and

Aron, 2005). On the other hand, the populations of Diptera and Coleoptera larvae seems to have established more durably on CONS. Investigating their interactions with Technosol substrates after rehabilitation would be of interest to specify interactions between soil fauna and Technosols functions. For example, Bibionidae larvae are known to be involved in the development of the upper soil layer in the latter stage of a post-mining chronosequence (Frouz et al., 2001).

On CPE Technosols resulting from the embankments of coking plant by-products, the development of a moder humus form fauna community is in agreement with latter stage of succession found in highly anthropized soils such as Technosols resulting from industrial settling pond activity (Huot et al., 2018). This result indicates that, additionally to the substrate used in rehabilitation, the development of the vegetation and more precisely the litter layers might be a driver of the soil fauna community on Technosols and would be in agreement with studies conducted on post-mining sites (Frouz et al., 2007b; Mudrák et al., 2010). Recently, Colombini et al., (2020) showed that most of soil fauna saprophage activity on the CPE Technosols resulting from the embankments of coking plant by-products, occurred in the neo-formed organic layers on the soil surface, with footprints of enchytreids, collembolas, isopods and diplopods feces. Action of saprophagous mites was revealed by feces in decaying roots and woody fragments in the neo-formed organic layer and in roots within the technogenic layer (Colombini et al., 2020), thus indicating that mites are less sensitive to the nature of the embankments than previously- cited organisms.

4.4 Guidance for rehabilitation of post-industrial sites

The low number of earthworms and consequently of geophages that we found in the Technosols resulting from the two rehabilitation strategies in the studied site, highlights the importance of the nature of the substrate to be used in post-industrial area rehabilitation scenario. Technosol rehabilitation should focus on fast recovery of soil functions, promoting ecosystem services and biological diversity. As suggested by our results, Technosols' physico-chemical properties that were highly interrelated with the quality of the substrates used in a rehabilitation scenario may limit the colonization of edaphic fauna, such as endogeic and anecic earthworms that play an important role in the formation of soil structure (Amezketa, 1999; Blouin et al., 2013; Foster, 1991). Earthworms, as

509 ecosystem engineers, play an important role in nutrient cycling, soil structure formation and
510 stabilization (Angst et al., 2017, 2019; Pey et al., 2014; Vidal et al., 2019) and can limit the erosion of
511 polluted soils (Blouin et al., 2013; Scullion and Malik, 2000). The re-establishment of local earthworm
512 populations should be one of the goals of post-industrial area, and can be achieved with the addition of
513 organic carbon at the initial stage of the rehabilitation. Studies show that direct input of organic matter
514 through organic waste materials or indirect input through neo-formed litter resulting from afforestation
515 can improve the community and activity of earthworms on open-cast coal mining sites (Emmerling
516 and Paulsch, 2001; Frouz et al., 2006). A low number of earthworms may alter the incorporation of
517 soil surface organic matter, such as tree litter. Indeed, soil surface organic matter accumulation has
518 been evidenced by many authors in different anthropized ecosystems such as meadow or deciduous
519 forest with high metal concentrations (Gillet and Ponge, 2002; Nahmani and Rossi, 2003) and might
520 explain the soil fauna community resembling the moder humus form that we found in the COAL and
521 EMB Technosols. This community composition might be a general pattern of intermediate stages of
522 vegetation for Technosols with extreme soil physico-chemical characteristics, since it has been
523 reported in many studies related to metal -contaminated soils (Grelle, 2000; Huot et al., 2018).
524 The overall ability of soil surface saprophages to colonize Technosols regardless of their physico-
525 chemical characteristics, when organic matter is added, could represent a promising way to enhance
526 the recovery of soil processes such as nutrient cycling and bioturbation. It can be achieved by a
527 coupled inoculation of local soil surface saprophages and organic matter, as has previously been done
528 in post-mining sites (Frouz et al., 2007b).
529 Yet, in order to obtain a better insight into the relationships between the fertility parameters and the
530 soil fauna communities of the Technosols, the nature of the soil organic carbon should be taken into
531 account to discriminate between both the sources and the role of technogenic and neo-formed organic
532 matter and their interaction with the soil saprophages.
533 Finally, the creation of ecological corridors at the site scale could improve the rate of earthworms and
534 other saprophagic organism colonization, which usually occurs within 5 years for pioneer earthworm
535 species (Snyder and Hendrix, 2008), but would not be sufficient if the nature of the soil substrates
536 used does not fit their long-term requirements. The development of different trophic networks over

time could induce a top-down or bottom-up regulation, but a frequent sampling would be needed in order to prove a competitive exclusion of certain taxa. Moreover, different colonization dynamics may occur as a function of the dispersal strategy. Indeed, the presence of Diptera and Coleoptera larvae on Technosols, even in earlier stages of colonization can be explained by the dispersion of flying adults, while endogeic earthworms would need suitable ecological corridors to colonize new environments (Eijsackers, 2010). Thus, studies of soil fauna functional traits that improve the colonization success might help us to improve our understanding of the actual diversity of the soil fauna community on post-industrial sites. Finally, the gap between the high level of activity of epigeic organisms that we found on Technosols and the low trophic diversity of the litter and soil-dwelling communities suggest that the soil fauna community on a former coking plant is driven rather by soil physico-chemical properties than by colonization constraints. Our results suggest that the physico-chemical and biological properties of the studied Technosols are evolving. Following the dynamics of the physico-chemical and biological properties of the Technosols studied in future years to decades could be help to improve our understanding of their evolution pathways and lifespan.

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Figures & Captions

Fig. 1. Localization of the studied former coking plant and its 6 sampled sub-sites: 4 Technosols and 2 soils of reference. WOOD: woodland, MEAD: meadow, COAL: Spolic Technosol composed of coal embankments, EMB: Spolic Technosol with multiple embankments from a dismantled coking plant, TDT: Technosol composed of thermally-treated industrial soil, CONS: constructed Technosol composed of a mixture of paper mill sludge, thermally-treated industrial soil and green waste compost.

Fig. 2. Sampling design followed for the characterization of (i) the physico-chemical quality and (ii) the fauna communities of the 4 Technosols and 2 soils of reference (N=5, except for COAL, N=4). Numbers on the right part of the figure indicate the sampling procedure: (1) Sampling for chemistry analyses. (2) Sampling of a soil corer for the bulk density assessment. (3) Litter and soil-dwelling macrofauna sampling. (4) Soil corer for the litter and soil-dwelling micro-arthropod sampling. (5) Pitfall traps for the sampling of the soil surface-dwelling invertebrates.

Fig. 3. Principal Component Analysis (PCA) obtained for the abiotic parameters measured for the 4 Technosols and 2 soils of reference. Thicker symbols represent the barycenter for the 10 samples of the REF soils of reference (WOOD and MEAD) or the ITS (Technosols COAL and EMB) and CPE (Technosols CONS and TDT) strategy (9 samples for CPE). Pb = lead concentration; Zn = zinc concentration; K = potassium concentration; Mg = magnesium concentration; CEC = cation exchange capacity; WHC = water holding capacity; Ca = calcium concentration; Cd = cadmium concentration; C_{org} = organic carbon content; N_{tot} = nitrogen content; P_2O_5 = available P concentration; DTPA: Diethylene *triamine* penta-acetic acid extractible metals.

Fig. 4. Co-inertia analysis between the two PCA on abiotic parameters and soil fauna indices. Axis1 = first projected axis, Axis2: second projected axis. A) Projection of the Technosols that followed 2

rehabilitation strategies and the soils of reference on the two first axes, grey squares represent centroids for soil fauna indices used in the PCA and blue dots represent centroids for abiotic parameters. Large squares and dots are centroids for the 10 points (9 points for CPE). B) Projection of the 2 soils' classification (Technosols or Cambisol) on the two first axes, grey squares represent centroids for soil fauna indices used in the PCA and blue dots represent centroids for soil abiotic parameters. Large squares and dots are centroids for the 10 points (9 points for CPE). C) Scatter plot of the co-inertia, abiotic parameters and fauna indices from Technosols and soils of reference are encoded, see Tables 1 to 4 for correspondences.

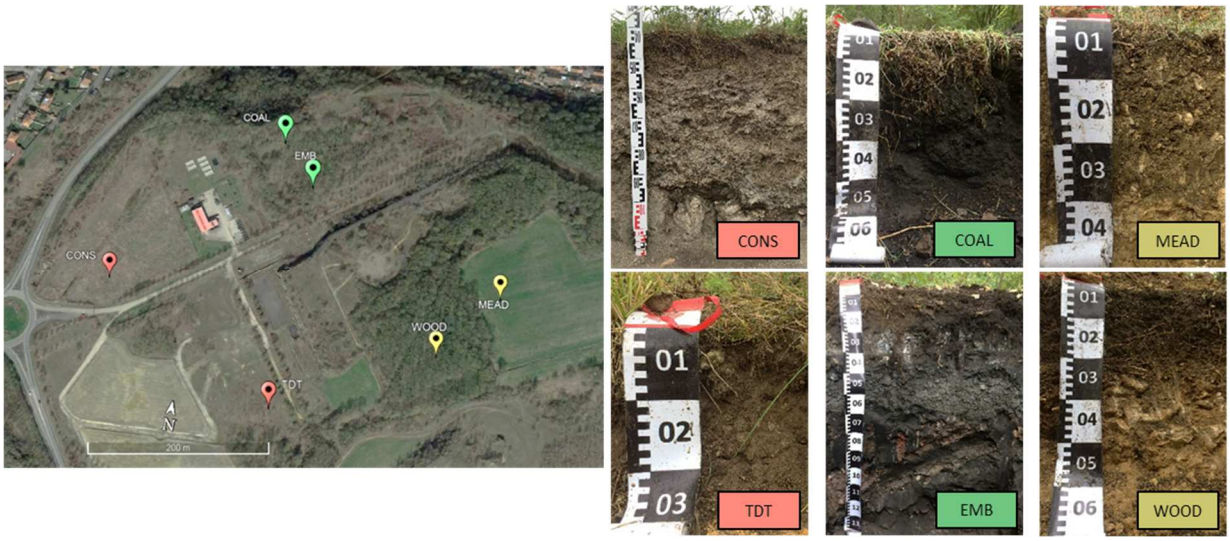

Fig. 1.

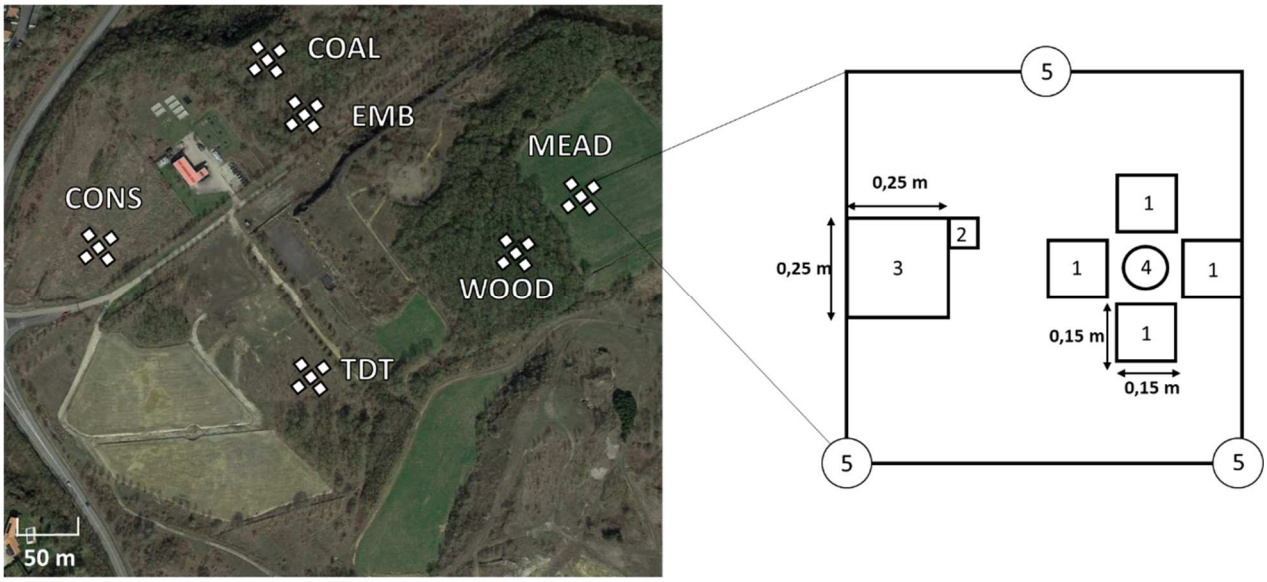
COAL
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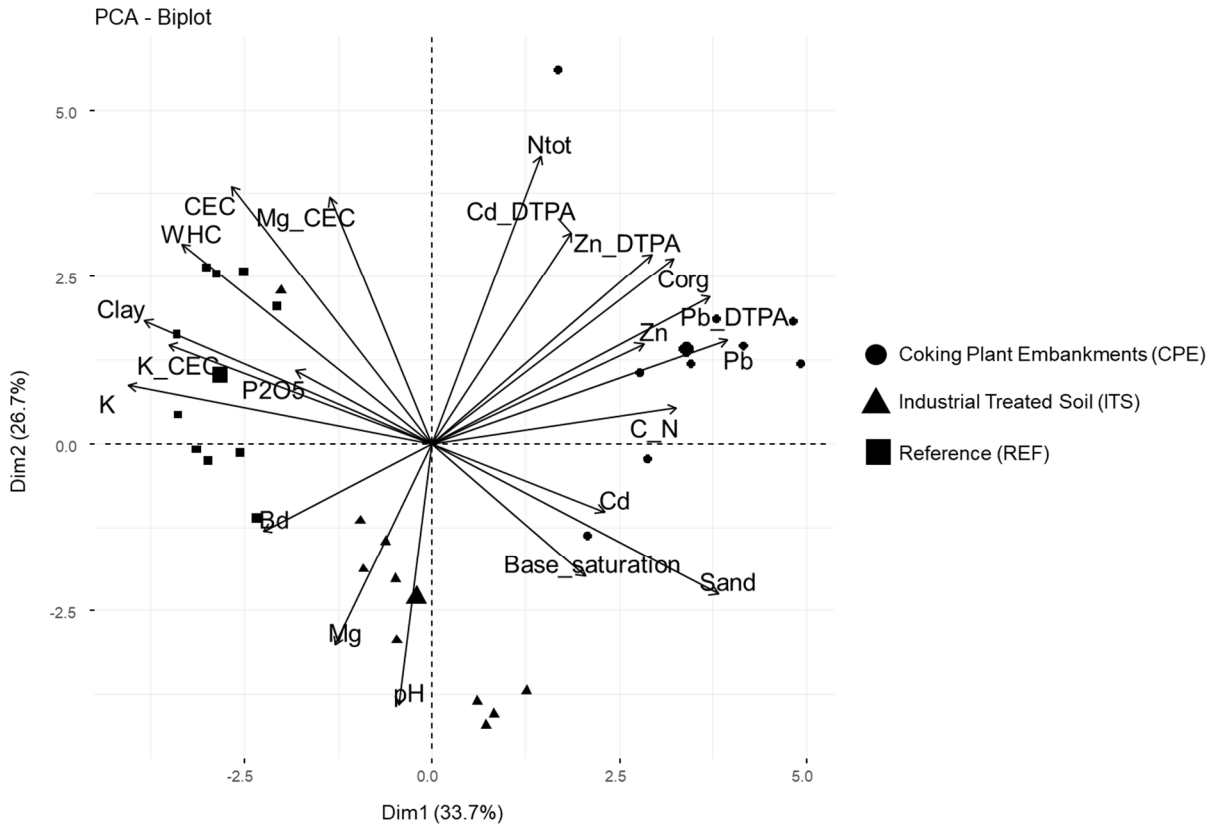
Fig. 2.


PCA - Biplot
Ntot
CEC
Mg_CEC
Cd_DTPA
WHC
Zn_DTPA
Corg
Clay
Pb_DTPA
Zn
Pb
K_CEC
P2O5
K
C_N
Cd
Pd
Base_saturation
Sand
Mg
pH
Dim2 (26.7%)
Dim1 (33.7%)
5.0
2.5
0.0
-2.5
-2.5
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2.5
5.0
Coking Plant Embankments (CPE)
Industrial Treated Soil (ITS)
Reference (REF)

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40 Fig. 3.

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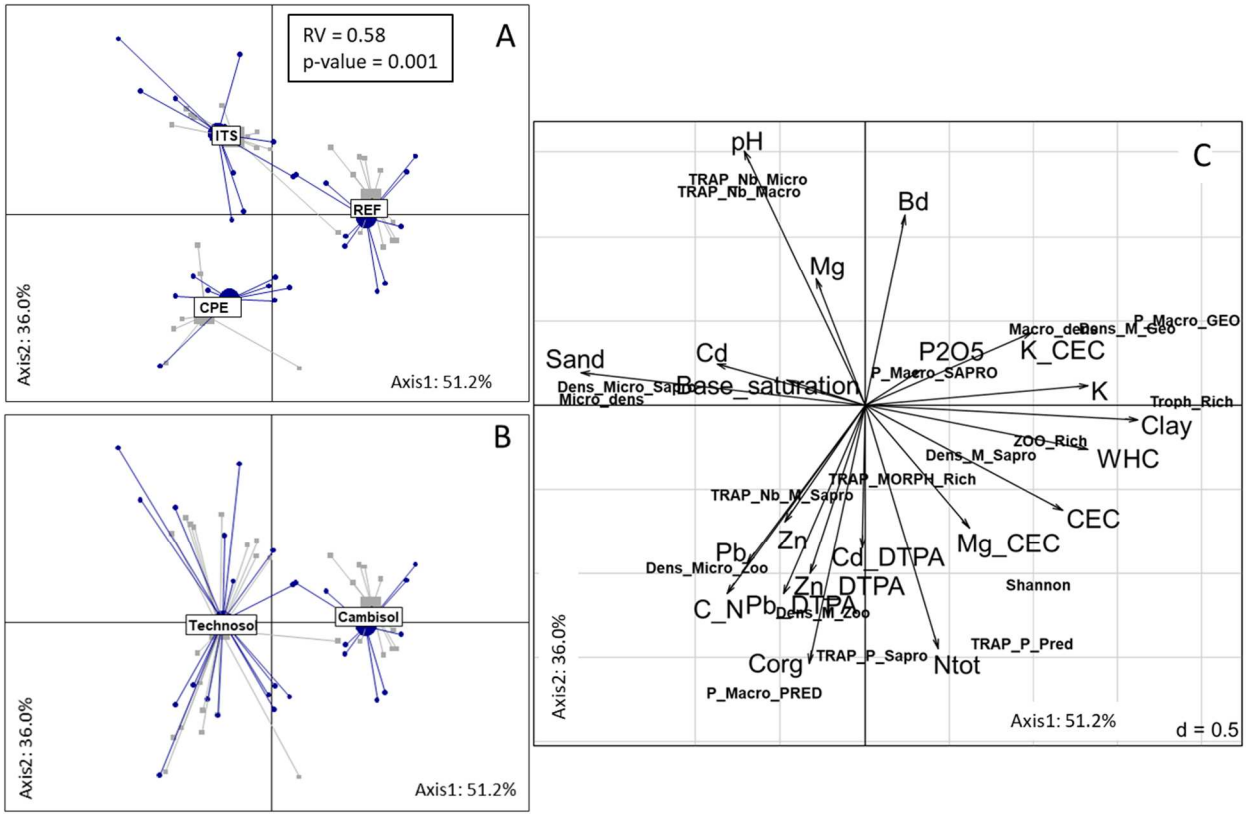
A
RV = 0.58
p-value = 0.001
ITS
REF
CPE
Axis2: 36.0%
Axis1: 51.2%
B
Technoso
Cambisol
Axis2: 36.0%
Axis1: 51.2%
C
pH
TRAP_Nb_Micro
TRAP_Nb_Macro
Bd
Mg
Sand
Cd
Base_saturation
P2O5
K_CEC
Macro_dens
Dens_M_Geo
P_Macro_GEO
P_Macro_SAPRO
K
Troph_Rich
Clay
ZOO_Rich
WHC
Dens_M_Sapro
TRAP_MORPH_Rich
TRAP_Nb_M_Sapro
CEC
Zn
Pb
Cd_DTPA
Mg_CEC
Dens_Micro_Zoo
Zn_DTPA
Shannon
C_N
Pb_DTPA
Dens_M_Zoo
TRAP_P_Pred
Corg
TRAP_P_Sapro
Ntot
P_Macro_PRED
Axis2: 36.0%
Axis1: 51.2%
d = 0.5

42

43 Fig. 4.

Tables & captions

Table 1.
Soil abiotic parameters of the 6 sub-sites (4 Technosols + 2 soils of reference) studied (mean ± sd, n = 5 except for COAL n = 4). WHC: Water Holding Capacity; Corg: organic carbon concentration; Ntot: nitrogen concentration; CEC: cation exchange capacity; P2O5: available P concentration; Cd: cadmium concentration; Pb: lead concentration; Zn: zinc concentration; K: potassium concentration; Mg: magnesium concentration, Exch: exchangeable; DTPA: Diethylene triamine penta-acetic acid extractible metals. Different letters in the same row indicate a significant difference between means tested with one-way nested ANOVA between REF, CPE and ITS, p-value < 0.05.

Soil classification	Cambisol			Technosol						
Rehabilitation strategy	Soils of reference (REF)			Coking plant embankments (CPE)			Industrial treated soil (ITS)			
Site	MEAD	WOOD		COAL	EMB		TDT	CONS		p-value
WHC (%)	26.2 ± 1	26 ± 0.9		19.8 ± 3.5	21.2 ± 2.1		17.2 ± 1.9	22.1 ± 2.1		0.094
Bulk density (g $cm^{-3)}$	1.26 ± 0.22	0.97 ± 0.14		0.69 ± 0.07	0.98 ± 0.20		1.15 ± 0.25	1.11 ± 0.21		0.289
pH	7.5 ± 0.2	7.9 ± 0.1		7.5 ± 0.3	7.6 ± 1.4		8.4 ± 0.1	8.2 ± 0.1		0.051
C_{org} (g kg^{-1})	100 ± 17	186 ± 36	b	507 ± 62	410 ± 140	a	46 ± 12	122 ± 72	b	**0.016**
N_{tot} (g kg^{-1})	3.8 ± 0.4	6.2 ± 0.96		6.7 ± 1.5	8.4 ± 2.5		1.3 ± 0.2	3.6 ± 1.2		0.118
C/N	26 ± 4	31 ± 9		84 ± 26	49 ± 9		38 ± 15	32 ± 8		0.153
CEC (cmolc kg^{-1})	31 ± 2	47 ± 2		18 ± 5	28 ± 18		12 ± 4	26 ± 14		0.216
P_2O_5 (mg kg^{-1})	14 ± 5	11 ± 2		8 ± 1	10 ± 5		5 ± 2	29 ± 12		0.753
Clay (g kg^{-1})	495 ± 31	507 ± 19	a	78 ± 21	112 ± 41	b	64 ± 9	120 ± 19	b	**0.001**
Sand (g kg^{-1})	214 ± 40	157 ± 17	b	646 ± 65	640 ± 97	a	756 ± 21	577 ± 39	a	**0.013**
Cd_{tot} (mg kg^{-1})	0.5 ± 0.0	0.9 ± 0.2		1.0 ± 0.4	2.9 ± 0.8		3.0 ± 1.5	1.7 ± 0.5		0.329
Pb_{tot} (mg kg^{-1})	34 ± 3	72 ± 14	b	271 ± 190	282 ± 102	a	67 ± 13	93 ± 20	b	**0.018**
Zn_{tot} (mg kg^{-1})	148 ± 11	297 ± 80		284 ± 70	825 ± 431		224 ± 36	383 ± 134		0.449
K_{tot} (mg kg^{-1})	6739 ± 231	6516 ± 3029	a	1696 ± 327	1287 ± 225	b	2463 ± 269	3128 ± 1415	b	**0.007**
Mg_{tot} (mg kg^{-1})	5623 ± 1739	4778 ± 84		5335 ± 1237	3782 ± 627		6440 ± 518	5660 ± 997		0.307
Mg_{Exch} (cmolc kg^{-1})	2.4 ± 0.3	0.7 ± 0.1		0.9 ± 0.4	1.5 ± 1.1		0.3 ± 0.1	1.8 ± 1.3		0.883
K_{Exch} (cmolc kg^{-1})	0.7 ± 0.0	0.6 ± 0.2		0.3 ± 0.0	0.4 ± 0.1		0.4 ± 0.1	0.8 ± 0.1		0.362
Cd_{DTPA} (mg kg^{-1})	0.1 ± 0.0	0.2 ± 0.0		0.2 ± 0.1	0.6 ± 0.4		0.1 ± 0.0	0.1 ± 0.0		0.444
Pb_{DTPA} (mg kg^{-1})	4.1 ± 0.3	9.6 ± 0.9		18.9 ± 15.5	34.9 ± 13.5		3.1 ± 0.4	6.6 ± 1.5		0.089
Zn_{DTPA} (mg kg^{-1})	3.9 ± 0.6	18.4 ± 0.6		22.0 ± 11.0	109.4 ± 43.3		3.4 ± 0.4	12.9 ± 6.9		0.339
Base staturation	1.02 ± 0.02	0.86 ± 0.02		1.06 ± 0.03	0.99 ± 0.05		0.99 ± 0.15	0.99 ± 0.05		0.534

Table 2.

Density (mean number of individuals per square meter ± standard deviation) of zoological groups for litter-soil dwelling macrofauna and micro-arthropods communities sampled in the 4 Technosols and 2 soils of reference (n = 5 except for COAL n = 4). Trophic types were determined based on Salmon et al., (2006). Zoo: zoophage, mi: microphage, geo: geophage, phy: phytophage, sapro: saprophage. PCA code refers to the code used in both PCA and co-inertia analyses for the fauna indices. Different letters in the same row indicate a significant difference between means tested with one-way nested ANOVA, between REF (MEAD and WOOD), CPE (COAL and EMB) and ITS (TDT and CONS), p-value < 0.05.

Soil classification			Cambisol		Technosol				
Rehabilitation strategy			Soils of reference (REF)		Coking plant embankments (CPE)		Industrial treated soil (ITS)		
Taxonomic level	**Zoological group**	**Trophic type**	**MEAD**	**WOOD**	**COAL**	**EMB**	**TDT**	**CONS**	**p-value**
Class	**Isopoda**	Sapro	6.4 ± 8.8	44.8 ± 26.3	9.6 ± 21.5	6.4 ± 14.3	0 ± 0	0 ± 0	0.375
Class	**Chilopoda**	Zoo	16 ± 16	92.8 ± 68.3	118.4 ± 50.1	92.8 ± 59.2	12.8 ± 28.6	0 ± 0	0.128
Class	**Diplopoda**	Sapro	0 ± 0	54.4 ± 36.8	12.8 ± 17.5	44.8 ± 30.8	51.2 ± 88.7	12.8 ± 13.4	0.987
Class	**Collembola**	Sapro/mi	11237 ± 3603	8383 ± 2433	9555 ± 2683	6115 ± 2368	23263 ± 8998	6778 ± 4739	0.619
Class	**Protoura**	Sapro/mi	0 ± 0	51.0 ± 114.0	1401.4 ± 1348.3	1070.2 ± 1620.5	1248.5 ± 2511.8	25.5 ± 57.0	0.307
Order	**Araneae**	Zoo	32 ± 32	16 ± 16	41.6 ± 31.2	44.8 ± 34.7	35.2 ± 61.3	54.4 ± 26.8	0.442
Order	**Mesostigmata**	Zoo	2930.2 ± 2190	1732.6 ± 545	5478.2 ± 3661.5	7083.4 ± 6686.7	2930.2 ± 1164.2	1503.3 ± 520.6	0.106
Sub-order	**Oribatida**	Sapro	17963 ± 7667	11746 ± 4735	90199 ± 58942	26958 ± 16035	62961 ± 11811	36411 ± 37765	0.381
Order	**Diptera larvae**	Sapro	28.8 ± 39.8	12.8 ± 13.4	22.4 ± 18.2	6.4 ± 8.8	9.6 ± 14.3	22.4 ± 26.8	0.831
Order	**Lepidoptera larvae**	Phy	12.8 ± 20.9	6.4 ± 8.8	6.4 ± 8.8	0 ± 0	0 ± 0	0 ± 0	0.228
Sub-order	**Homoptera**	Phy	0 ± 0	0 ± 0	3.2 ± 7.2	3.2 ± 7.2	0 ± 0	3.2 ± 7.2	0.443
Order	**Total Coleoptera**	Zoo/phy	185.6 ± 107.1	51.2 ± 28.6	64 ± 54.3	67.2 ± 36.5	76.8 ± 61.3	294.4 ± 99.7	0.577
Order	Coleoptera larvae	Zoo/phy	96 ± 69.7	16 ± 22.6	6.4 ± 14.3	25.6 ± 33.2	3.2 ± 7.2	64 ± 134.3	0.669
Family	Curculionidae larvae	Phy	6.4 ± 8.8	6.4 ± 8.8	0 ± 0	3.2 ± 7.2	6.4 ± 14.3	44.8 ± 41.4	0.391
Family	Elateridae larvae	Phy	9.6 ± 14.3	0 ± 0	0 ± 0	16 ± 19.6	19.2 ± 26.3	83.2 ± 111.7	0.305
Family	Carabidae	Zoo	25.6 ± 21.5	0 ± 0	35.2 ± 34.7	0 ± 0	35.2 ± 44.4	60.8 ± 51.1	0.319
Family	Staphylinidae	Zoo	28.8 ± 26.3	12.8 ± 17.5	9.6 ± 14.3	16.0 ± 22.6	6.4 ± 8.8	9.6 ± 14.3	0.394
Family	Staphylinidae larvae	Zoo	0 ± 0	16 ± 19.6	3.2 ± 7.2	3.2 ± 7.2	3.2 ± 7.2	12.8 ± 13.4	0.784
Sub-order	**Total Lumbricina**	Sapro/geo	201.6 ± 165	118.4 ± 47.5 a	16 ± 16	0 ± 0 b	6.4 ± 14.3	9.6 ± 8.8 b	**0.034**
Earthworm ecological categories	Epigeic	Sapro	70.4 ± 55	28.8 ± 13.4	12.8 ± 17.5	0 ± 0	6.4 ± 14.3	0 ± 0	NT
	Anecic	Geo/sapro	9.6 ± 14.3	28.8 ± 34.7	3.2 ± 7.2	0 ± 0	0 ± 0	0 ± 0	NT
	Endogeic	Geo	121.6 ± 106.5	60.8 ± 20.9	0 ± 0	0 ± 0	0 ± 0	9.6 ± 8.8	NT

Table 3.

Activity of surface soil dwelling invertebrates (mean number of individuals collected in 3 traps ± standard deviation) and zoological richness (mean number of zoological groups ± standard deviation) (n = 5 after gathering 3 pitfalls per sampling square). Trophic types were determined based on Salmon et al., (2006). Zoo: zoophage mi: microphage, phy: phytophage, sapro: saprophage. Different letters in the same row indicate a significant difference between means tested with one-way nested ANOVA, between REF, CPE and ITS, p-value < 0.05. No test (NT) was performed when less than 5 individuals of a given group were collected across the 6 sub-sites.

Soil classification			Cambisol		Technosol				
Rehabilitation strategy			Soils of reference (REF)		Coking plant embankments (CPE)		Industrial treated soil (ITS)		
Taxonomic level	**Zoological group**	**Trophic type**	**MEAD**	**WOOD**	**COAL**	**EMB**	**TDT**	**CONS**	**p-value**
Class	**Collembola**	Sapro/mi	251.4 ± 133.8	75.4 ± 40.5	71.0 ± 20.0	61.0 ± 23.4	2246.8 ± 1359.3	220.2 ± 64.0	0.412
Sub-class	**Acari**	Zoo/sa	66.0 ± 36.2	20.8 ± 13.3	69.4 ± 59.9	10.6 ± 5.0	60.8 ± 40.1	217.8 ± 62.5	0.462
Order	**Araneae**	Zoo	17.0 ± 5.8	2.4 ± 1.8	20.0 ± 4.2	13.4 ± 3.4	23.0 ± 6.1	36.4 ± 4.8	0.275
Order	**Opiliones**	Zoo	0 ± 0	1.2 ± 1.1	0.2 ± 0.4	1.4 ± 1.1	4.8 ± 3.6	0 ± 0	0.685
Class	**Isopoda**	Sapro	6.0 ± 3.2	3.8 ± 2.2	21.0 ± 22.0	6.4 ± 4.3	3.0 ± 4.5	1.0 ±2.2	0.335
Class	**Diplopoda**	Sapro	0.2 ± 0.4	2.6 ± 0.1	3.8 ± 4.1	5.2 ± 1.3	5.6 ± 5.1	7.4 ± 8.8	0.301
Class	**Gastropoda**	Phy/sa	13.6 ± 6.3	2.4 ± 0.9	2.0 ± 2.0	2.0 ± 1.0	1.2 ± 1.1	0.4 ± 0.5	0.436
Sub-order	**Homoptera**	Phy	4.6 ± 5.4	0.2 ± 0.4	2.8 ± 2.3	0.6 ± 0.9	5.2 ± 2.2	9.2 ± 5.7	0.241
Sub-order	**Heteroptera**	Phy	0 ± 0	0.4 ± 0.5	0.2 ± 0.4	0 ± 0	1.8 ± 1.6	0 ± 0	NT
Order	**Total Hymenoptera**	Phy	12.6 ± 10.9	5.6 ± 3.6	8.2 ± 8.2	14.2 ± 10.7	259.6 ± 137.8	210.2 ± 272.7	**0.040**
Family	Formicidae	Phy/sa	12.4 ± 10.5	4.6 ± 2.6	7.8 ± 7.3	13.0 ± 9.1	258.8 ± 137.0	208.8 ± 271.0	NT
Order	**Lepidoptere larvae**	Phy	0 ± 0	0.6 ± 0.4	0 ± 0	1.0 ± 0.7	0.2 ± 0.4	0 ± 0	NT
Order	**Diptera larvae**	Sapro	1.4 ± 2.6	1.8 ± 1.9	0 ± 0	1.0 ± 0.7	0.4 ± 0.5	0.6 ± 0.9	0.290
Order	**Coleoptera**	Zoo/phy	6.2 ± 2.9	14.2 ± 4.4	5.8 ± 2.6	8.2 ± 4.0	8.2 ± 2.5	22.0 ± 12.5	0.549
Order	Coleoptera_UND	Zoo/phy	0.4 ± 0.5	0.4 ± 0.9	1.8 ± 2.0	2.0 ± 2.9	0.8 ± 0.4	9.8 ± 1.2	NT
Order	Coleoptera_larvae	Zoo/phy	0.2 ± 0.4	1.2 ± 0.4	0.2 ± 0.4	2.0 ± 1.0	0.6 ± 0.54	1.0 ± 0.7	NT
Family	Elateridae	Phy	0.6 ± 0.9	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0.6 ± 0.9	NT
Family	Chrysomelidae	Phy	0 ± 0	0.2 ± 0.4	0 ± 0	0 ± 0	0.2 ± 0.4	0 ± 0	NT
Family	Curculionidae	Phy	0 ± 0	0.4 ± 0.5	0.2 ± 0.4	0 ± 0	0.2 ± 0.4	1.8 ± 0.8	NT
Family	Carabidae	Zoo	3.8 ± 2.6	3.8 ± 2.6	1.0 ± 1.2	0.2 ± 0.4	3.2 ± 1.5	4.0 ± 2.8	0.072
Family	Staphylinidae	Zoo	1.2 ± 0.8	8.2 ± 3.2	2.6 ± 2.3	4.0 ± 2.2	3.2 ± 2.3	4.8 ± 2.2	0.880

Table 4.

Trophic indices of soil fauna communities: Litter and soil-dwelling community (LSDC): Shannon index, zoological richness, total macrofauna and microarthropods densities, trophic richness, proportion of macro-zoophages, saprophages and geophages, densities of macro-zoophages, saprophages and geophages and densities of micro-zoophages and saprophages. Soil surface-dwelling community (SSDC): trap richness, number of soil surface macro-saprophages, proportion of soil surface saprophages and zoophages, number of macro-organisms and microarthropods sampled in the 4 Technosols and 2 soils of reference studied (mean ± standard deviation) (n = 5 except for COAL n = 4). PCA code refers to the code used in both PCA and co-inertia analyses for the fauna indices. Different letters in the same row indicate a significant difference between means tested with one-way nested ANOVA between REF, CPE and ITS, p-value < 0.05.

Soil classification		Cambisol			Technosol						
		Soils of reference (REF)			Coking plant embankments (CPE)			Industrial treated soil (ITS)			
Indices	**Fauna community**	**MEAD**	**WOOD**		**COAL**	**EMB**		**TDT**	**CONS**		**p-value**
Shannon	macrofauna LSDC	1.38 ± 0.45	2.26 ± 0.25		1.76 ± 0.25	1.35 ± 0.5		0.85 ± 0.68	0.64 ± 0.17		0.150
ZOO_Rich	total LSDC	7.4 ± 1.1	7.8 ± 0.83		7.6 ± 0.9	5.4 ± 1.3		5.2 ± 1.9	6.0 ± 1.0		0.279
Macro_dens (ind m^{-2})	macrofauna LSDC	483.2 ± 203.1	403.2 ± 160.6		304 ± 143.7	268.8 ± 53.5		230.4 ± 209.7	396.8 ± 86.5		0.248
Micro_dens (ind m^{-2})	microarthropods LSDC	32130 ± 6253	21862 ± 6661		105232 ± 77889	40157 ± 214178		89155 ± 28067	44692 ± 17672		0.420
Troph_Rich	LSDC	6 ± 0.71	6.4 ± 0.89		4.75 ± 0.5	4.6 ± 0.55		4 ± 1	5.4 ± 0.55		0.135
P_Macro_PRED (%)	macrofauna LSDC	15 ± 11	33 ± 11	b	66 ± 17	57 ± 18	a	18 ± 19	29 ± 23	b	**0.048**
P_Macro_SAPRO (%)	macrofauna LSDC	24 ± 16	41 ± 5		21 ±12	22 ± 15		43 ± 39	12 ± 6		0.771
P_Macro_GEO (%)	macrofauna LSDC	24 ± 12	17 ± 7	a	0 ± 0	0 ± 0	b	0 ± 0	3 ± 3	b	**0.017**
Dens_M_Sapro (ind m^{-2})	macrofauna LSDC	35.2 ± 36.5	112.0 ± 57.7		40.0 ± 27.7	57.6 ± 41.7		60.0 ± 81.7	35.2 ± 17.5		0.726
Dens_M_Zoo (ind m^{-2})	macrofauna LSDC	48.0 ± 46.6	108.8 ± 71.0		160.0 ± 90.5	137.6 ± 51.3		48.0 ± 89.8	54.4 ± 26.8		0.010
Dens_M_Geo (ind m^{-2})	macrofauna LSDC	201.6 ± 165	118.4 ± 47.5	a	16 ± 16	0 ± 0	b	9.6 ± 8.8	6.4 ± 14.3	b	**0.034**
Dens_Micro_Sapro (ind m^{-2})	microarthropods LSDC	29200 ± 7266	21276 ± 7064		100710 ± 57381	33200 ± 16094		86224 ± 13858	43189 ± 39153		0.459
Dens_Micro_Zoo (ind m^{-2})	microarthropods LSDC	2930 ± 2190	1733 ± 545		5478 ± 3662	7083 ± 6687		2930 ± 1164	1503 ± 521		0.101
TRAP_Rich	SSDC	11.6 ± 0.9	13.9 ± 1.9		11.2 ± 1.3	14.4 ± 0.9		14.6 ± 1.3	12.6 ± 0.9		0.995
TRAP_Nb_M_Sapro (ind $trap^{-1}$)	SSDC	7.6 ± 4.3	8.2 ± 4.1		23.5 ± 25.4	12.6 ± 4.6		9.0 ± 7.1	9.0 ± 10.7		0.248
TRAP_P_Sapro (%)	SSDC	12.0 ± 6.6	22.2 ± 7.4	ab	33.4 ± 18.1	23.5 ± 6.6	a	3.5 ± 3.6	5.0 ± 6.1	b	**0.048**
TRAP_P_Pred (%)	SSDC	36.7 ± 14.6	43.1 ± 9.7	a	41.9 ± 14.9	36.5 ± 8.5	a	12.6 ± 6.5	22.3 ± 9.1	b	**0.040**
TRAP_Nb_Micro (ind $trap^{-1}$)	SSDC	317.4 ± 146.1	96.2 ± 51.7		140.4 ± 69.6	71.6 ± 21.4		2307.6 ± 1379.7	438.0 ± 123.8		0.329
TRAP_Nb_Macro (ind $trap^{-1}$)	SSDC	61.6 ± 7.2	35.2 ± 10.1	b	64.0 ± 30.0	54.8 ± 19.4	b	313.0 ± 123.9	287.2 ± 267.4	a	**0.029**

Graphical abstract