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# 1 Fast improvement of macrofauna communities and soil quality in plantain crops 2 converted to agroecological practices

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15

## 16 ABSTRACT

17 Plantain (*Musa paradisiaca* AAB) is one of the main staple food crops in tropical areas, particularly in  
18 the Caribbean region. Therefore, supporting a sustainable production of plantain in this zone is  
19 crucial to secure food and to provide income to millions of people. We hypothesized that  
20 agroecological practices based on multi- functionality and biodiversity and that preserve soil should  
21 i) increase macrofauna abundance, ii) enhance soil chemical fertility, iii) improve soil physical  
22 structure, iv) reduce plant infestation by parasitic nematodes, and v) immediately achieve similar  
23 yield as in conventional systems. For this purpose, we compared plantain conventional and  
24 agroecological systems at the farm scale. The agroecological system consisted in a combination of  
25 three innovations: i) inputs of vermicompost to replace mineral fertilizers, ii) use of healthy planting  
26 material and iii) use of a mulching of living crop to control weeds. Ten months after the plantation,  
27 soil macrofauna abundance had doubled and taxonomic richness had increased by 45% in the  
28 agroecological system. In addition, soil structure was improved in the agroecological system (52% of  
29 biogenic aggregates in the agroecological system vs. 21 % in conventional systems), as well as the  
30 abundance of free-living nematodes associated to plantain roots increased by 73 % in the  
31 agroecological system. The abundance of *Radopholus similis*, one of main plant parasitic nematodes,  
32 decreased in the agroecological system. Moreover, the agroecological system achieved similar crop  
33 yield level than conventional systems. Agroecological practices are thus an efficient option to allow a  
34 fast transition from conventional to environmentally friendly cropping systems.  
35

36 Keywords: Legume cover crop, Plants Issued from Fragments (PIF), Soil aggregates, Soil fauna,  
37 Tropical agroecosystems, Vermicompost  
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## 40 1. Introduction

41  
42 One of the most relevant challenges of the 21st century is to accelerate the transition of  
43 conventional intensive agricultural systems to agroecological, while maintaining high levels of yields,  
44 quality of products and enhance the provision of soil-based ecosystem services (Dendoncker et al.,  
45 2018). However, the green revolution paradigms supporting crop production are still in use and, at a  
46 global scale, generate major environmental concerns (Tilman et al., 2002; Den doncker et al., 2018).

47 The intensive agricultural practices are at the origin of massive pollution of ecosystems and soil  
48 degradation. These intensive agricultural practices also greatly decrease soil biological diversity and  
49 activity (Clermont-Dauphin et al., 2014; Tsiafouli et al., 2015; Lavelle et al., 2022) and ecosystem  
50 regulation services (e.g., decrease in water quality, increase of greenhouse gases in the atmosphere,  
51 pollution) (Millennium Ecosystem Assessment (MEA), 2005; Lavelle et al., 2014). Development of  
52 new, more environmentally friendly cropping systems, preventing the depletion of natural resources,  
53 is currently a priority for stakeholders, legislators and consumers, according to the growing interest  
54 in developing alternative sustainable farming strategies driven in the 1990s (Nkonya et al., 2016). All  
55 of these strategies share the same objective of minimizing or suppressing the use of synthetic inputs,  
56 enhancing organic matter inputs, and improving agroecosystems health, while maintaining high  
57 production level (Altieri, 1999; Andres and Bhullar, 2016; Meynard, 2017). These agroecological  
58 strategies promote the development of practices based on the use of organic resources produced on  
59 farm and the enhancement of natural ecological processes. According to Pretty (2008), sustainable  
60 agriculture jointly produces food and goods for farmers and the environment. In these agroecological  
61 systems, pests and diseases are supposed to be controlled by natural predators and parasites, and  
62 favourable soil structure to be maintained by the roots and macrofauna activities (Kibblewhite et al.,  
63 2008). However, these agroecological systems still need to be evaluated in terms of agronomic and  
64 environmental impact and economic feasibility (El Mujtar et al., 2019). A critical issue is the decrease  
65 in production generally observed in the early stages of transition (Schrama et al., 2018). The  
66 restoration of soils degraded by aggressive practices may last several years (Mosier et al., 2021). This  
67 delay may be a severe obstacle to the adoption of environmentally friendly practices in the absence  
68 of supporting public policies. Practices able to accelerate this transition are needed (Peters, 1991;  
69 Zinati, 2002).

70 Plantain (*Musa paradisiaca* AAB), a staple food grown throughout the tropics, constitutes a  
71 major source of carbohydrates for millions of people in Africa, the Caribbean, Latin America, Asia and  
72 the Pacific (e.g., Robinson, 1996; Tchango et al., 1999; Lescot, 2004; Ekunwe and Ajayi, 2010). In  
73 2020, plantain was grown in 54 countries and more than 43 million tons were produced worldwide  
74 (FAOSTAT, 2021). This crop provided food security and income for small growers who represent the  
75 majority of producers in the tropics (Kahane et al., 2013). Latin America and the Caribbean produced  
76 18 % of the global production of plantain (FAOSTAT, 2021). Therefore, sustainable production of  
77 plantain in this region is crucial to provide food security and income to millions of people (Picq et al.,  
78 1998). Pests are a major constraint for plantain production (Godefroid et al., 2017). Thus, there is a  
79 potential for yield gains through pest control improving. Plant-parasitic nematodes are major  
80 underground pests of plantain that impair the transport of nutrients and water to the main stem,  
81 causing plant toppling and yield reduction (Gowen et al., 2005). Nematodes are mainly controlled by  
82 synthetic pesticides that have negative effects on other soil living organisms (Lavelle et al., 2004;  
83 Carrascosa et al., 2014). Weeds can also affect plantain production by competing for water and  
84 nutrient resources, and by hosting parasites and diseases that affect plantain (Obiefuna, 1989). These  
85 weeds are mainly chemically controlled. Herbicide treatments are usually carried out at the  
86 beginning of plantation, and can be repeated every month. This chemical control has environmental  
87 and economic costs. The availability and quality of plantain planting material is also one of the  
88 limitations for the development of this crop. Farmers often used suckers already infested with pests  
89 and diseases as their only source of planting material. Due to the high disease and pest pressure, the  
90 lifetime of the majority of French West Indies plantain plantations is very short, i.e., 2–3 years for  
91 plantains vs. 7 years or more for intensively managed dessert bananas (Qu'én'éhervé, 2009).  
92 However, some plantain plantations easily last about twenty years in South America or in Africa

93 (Gold, 1991). It is particularly important to develop methods which increase crop longevity and  
94 reduce soil biological degradation due to the excessive use of chemical inputs.

95 We tested the hypotheses that agroecological practices based on multi-functionality and  
96 biodiversity and that preserve soil should be able to i) increase macrofauna abundance and benefit  
97 from their favourable activities as ecosystem engineers (Lavelle et al., 2016), ii) enhance soil fertility  
98 associated to organic fertilization, iii) improve soil physical structure as a result of enhanced biogenic  
99 aggregation, iv) reduce plant infestation by plant-parasitic nematodes associated to direct control by  
100 earthworms (Blouin et al., 2005; Lafont et al., 2007), and v) achieve similar yield as in conventional  
101 systems. In order to test these hypotheses, the conventional intensive practices in three farms and  
102 an innovative cropping system were compared on the basis of agronomic and ecological criteria.  
103 Reduction of agrochemical inputs is the intended goal, especially in French West Indies where  
104 ecosystems have attained high levels of contamination (Ozier-Lafontaine and Lesueur-Jannoyer,  
105 2014). To achieve this goal, we used: i) healthy plants issued from the Plants Issued from Fragments  
106 (PIF) method (Lefranc et al., 2010; Sodom et al., 2010), a method of vegetative propagation instead  
107 of suckers which are most of the time already infected by pests, ii) nutrient supply with organic  
108 fertilization with vermicompost instead of mineral fertilizers, and iii) use of a cover crop instead of  
109 herbicides to control weeds.

110

## 111 **2. Material and methods**

112

### 113 2.1. Site information and experimental design

114

115 The study was carried out in the Western part of Guadeloupe where most plantain  
116 plantations are found. In order to carry out our experimentation, three farmers' plots were chosen.  
117 These farms were located from 0 to 150 m altitude, with annual rainfall ranging from 2000 and 3000  
118 mm year<sup>-1</sup> and mean annual temperature around 23°C (France Meteorological Service,  
119 <http://www.meteo.gp>). Each plot had uniform management, soil type and topography. Soils are  
120 Haplic Nitisols dominated by halloysite clay minerals (FAO-UNESCO classification, Driessen et al.,  
121 2001; Clermont-Dauphin et al., 2004). The first two plots farms (Farm 1 and Farm 2) were located at  
122 "La Sarde" in the city of Capesterre-Belle-Eau (respectively, 16° 6' 88" N, 61° 34' 12" W, and 16° 6'  
123 15" N, 61° 34' 69" W). The third one was located at "Valombreuse", in the city of Petit-Bourg (16° 10'  
124 44" N, 61° 38' 97" W). The experimentations were set up during the dry season between February  
125 and March 2013. Before the plantation, the three plots have been left in fallow since at least two  
126 years (Table 1).

127 Two cropping systems were set up in each of the three farms. The first one was the  
128 conventional cropping system of each farmer which is described in Table 1. Planting material  
129 (suckers) was collected from an old unproductive field, where suckers were separated from their  
130 mother plant with a machete. The suckers' corms have been carefully peeled with a machete and the  
131 pseudostems were cut off a few centimeters above the corm. Peeling of the corm was supposed to  
132 delay the development of nematode infestation, while cutting the pseudostem reduces bulkiness and  
133 improves early growth of the newly planted sucker.

134 The second cropping system was agroecological and integrated 3 innovations (Table 1): i)  
135 healthy plants, obtained through the PIF technique (Lefranc et al., 2010; Sodom et al., 2010), were  
136 used in order to reduce pest infestations at the beginning of the plantation; ii) vermicompost  
137 (mixture of cattle manure and green wastes transformed by local epigeic earthworms) was applied in  
138 order to fertilize plants and stimulate soil food web; and iii) a living vegetal covering using *Arachis*

139 pintoï Krapov. and W.C. Greg (Fabaceae) was used to control weeds through mulching. Ultimately,  
140 we added 18.75 t ha<sup>-1</sup> of fresh vermicompost (corresponding to 11 t ha<sup>-1</sup> of dry matter) during the  
141 experiment, in the planting hole mixed with soil at the beginning, then at the soil surface, 2 and 6  
142 months after the start of the experiment (Table 1). Characteristics of the vermicompost were: pH 7.5,  
143 Total C 215 g.kg<sup>-1</sup>, Total N 20.3 g kg<sup>-1</sup>, C/N 12.8, Total P 5.4 g kg<sup>-1</sup>, Total K 13.3 g kg<sup>-1</sup>, Total Mg 6.2 g kg<sup>-1</sup>,  
144 Total Ca 86.3 g kg<sup>-1</sup>, NO<sub>3</sub>-N 2449 mg kg<sup>-1</sup>, NH<sub>4</sub>-N 9.7 mg kg<sup>-1</sup>. *Arachis pintoï* forms a very dense mat  
145 that remarkably controls weeds. Seven weeks after its implantation, the plant already covered partly  
146 the soil and reached 100 % of coverage in six months. *Arachis pintoï* was allowed to senesce naturally  
147 within the plantain cropping field.

148 In each farm, an experimental plot involved 150 plantain plants divided between the two  
149 treatments with 3 repetitions by treatment (Fig. 1A). Each elementary experimental unit contained 9  
150 central plantains and 16 border plantains (Fig. 1B). Spacing between the plantain rows was 2.5 m and  
151 2 m within the row (i.e., 2000 plants per ha). Before plantation, the soil was ploughed in order to  
152 burry weeds. Vegetal material (suckers or PIF) was planted immediately after field preparation. At  
153 the flowering stage, 10 months after the plantation, soil chemical, morphological and biological  
154 characteristics were measured. Plant health (root necrosis index and plant parasitic nematodes com-  
155 munities) and yield were also measured.

156

## 157 2.2. Soil chemical characteristics

158

159 Soil chemical properties were measured in each of the 18 experimental units (6 experimental  
160 units × 3 farms). In each experimental unit, soil samples were taken with an 8 cm diameter × 15 cm  
161 height cylinder, near the 9 central plants (Fig. 1). These 9 samples were mixed in a composite sample  
162 in which chemical analyses were done. Total soil C and N were determined using an auto-analyser  
163 (NF ISO 13878, 1998). Available P was measured using the Olsen-Dabin method (Dabin, 1967). Soil  
164 mineral N (NO<sub>3</sub> and NH<sub>4</sub>) was measured by colorimetry after extraction with a 0.5 M KCl solution.  
165 Exchangeable Ca, Mg, K and Na were determined after extraction with ammonium acetate (NF X  
166 31108). Cation-exchange capacity (CEC) was measured with IF07–10D (NFX 31–130) method and pH-  
167 H<sub>2</sub>O and pH-KCl with NF ISO 1770, 3696 and 11464.

168

## 169 2.3. Morphology of soil aggregates

170

171 The morphological assessment of soil macroaggregates provides an integrative index of soil  
172 biological activity. An undisturbed soil sample using an 8 cm diameter × 8.5 cm height cylinder was  
173 taken at 50 cm from the central plantain (plant n° 5, Fig. 1B) in each of the 18 experimental units. In  
174 the laboratory, blocks were gently separated and the samples were air-dried then sieved at 2 mm.  
175 The soil retained by the sieve was placed on a filter paper and the various elements were separated  
176 according to their origin and shape. The elements were sorted according to categories: i) biogenic  
177 aggregates of rounded forms, created by macroinvertebrates, ii) physical aggregates of angular  
178 forms, produced by the physical processes of the environment (especially alternating dry and wet  
179 periods), iii) non-macroaggregated soil (soil passing through the 2 mm sieve), and iv) other  
180 components (roots, stones, litter, wood). The separated samples were put in an oven at 60°C for 15  
181 days and weighed (Velasquez et al., 2007).

182

## 183 2.4. Soil biological characteristics

184

185 Ten months after the plantation, at the end of the wet season, soil macro-invertebrates were  
186 hand sorted from soil monoliths of 25 cm x 25 cm x 20 cm, taken at 50 cm from the central plantain  
187 in each of the 18 experimental units, following the ISO 23611-S methodology (ISO, 2011). Soil macro-  
188 invertebrates were counted and classified into eighteen taxonomic groups: Diplopoda, Formicidae  
189 (ants), Isoptera (termites), Lumbricina (earthworms), Coleoptera, Coleoptera larvae, Chilopoda,  
190 Isopoda, Dermaptera, Blattaria, Araneae, Gastropoda, terrestrial Turbellaria, Hemiptera, Orthoptera,  
191 Diptera larvae, Lepidoptera larvae and Thysanoptera (Table 2). Taxonomic richness was calculated  
192 based on these groups. Earthworms were identified at the morphospecies level.

193

## 194 2.5. Plant health and yield

195

196 Plant parasitic and root-associated free-living nematodes were extracted from primary roots  
197 removed from a 25 cm x 25 cm x 30 cm soil block taken at 50 cm from the central plantain in each of  
198 the 18 experimental units. Nematodes were extracted in a mist chamber (Viglierchio and Schmitt,  
199 1983). Individuals were counted in aliquots and expressed as number of nematodes per 100 g of root  
200 fresh biomass. The main plant parasitic nematodes species were identified under a light microscope.

201 To assess the severity of root damage, a 100 cm<sup>3</sup> volume of soil was taken at the base of the  
202 central plant for each of the 18 experimental units. Roots were removed, carefully washed and cut  
203 longitudinally. Necrosis rates on the internal surfaces of these roots were evaluated. The color of  
204 root necrosis due to soil-borne pathogens varied from reddish to black while healthy roots were  
205 white. Notations were rated with a root necrosis index (RNI) based on different classes: 0, no lesion;  
206 1, 1–25% of root area is necrotic; 2, 26–50%; 3, 51–75%; and 4, more than 75% (Bridge and Gowen,  
207 1993). Average sums of necrosis notations obtained for each plant were calculated for each  
208 treatment. In each experimental unit, the bunches of the 9 central plantains (Fig. 1B) were collected  
209 and weighted at the end of the experiment (11–12 months after plantation). Plant yield was  
210 estimated by bunch weight.

211

## 212 2.6. Statistical analysis

213

214 Generalized linear mixed models (GLMM, Bolker et al., 2009) were used to analyse the  
215 relationships between cultural practices and soil physico-chemical and biological features. In GLMM,  
216 the linear predictor contains random effects in addition to fixed effects. The inclusion of random  
217 effects allows reporting the effect of variables that create variance and contain unobserved  
218 heterogeneity but that are not important to test (Duyck et al., 2012). In our study, we treated “Farm”  
219 as a random effect and “Cropping system” as a fixed effect. These analyses were made using XLSTAT®  
220 software. Analysis of Similarity (ANOSIM) was performed in order to compare earthworm  
221 communities in both systems, using XLSTAT® software (XLSTAT-R, vegan package).

222 In addition, we performed principal component analyses (PCA) on biological and chemical  
223 soil parameters, respectively. Biological parameters comprised main groups of soil macrofauna,  
224 morphological characteristics, root necrosis index, nematode communities and plant yield. Soil  
225 parameters comprised a set of 12 standard variables describing soil chemistry (Table 3). Monte Carlo  
226 tests on coordinates of sampling points on factorial axes allowed to test for significant differences  
227 among farms and experimental situations. These analyses were done with the Ade4 library in the R  
228 environment (Thioulouse et al., 2018).

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## 230 3. Results

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### 3.1. Soil chemical characteristics

Soils were acidic to slightly alkaline, with average values of pH-H<sub>2</sub>O between 4.5 and 7.0. Soil pH, N-NH<sub>4</sub>, N-NO<sub>3</sub>, total N, total C, CEC, K, Na, Ca, Mg and P content did not significantly differ among the two cropping systems (Table 3).

### 3.2. Soil morphological characteristics

Non-macro aggregated soil represented on average 50.0 % of the total soil mass in conventional systems and 28.0 % in agroecological systems. In contrast, biogenic aggregates represented on average 20.7 % of the total soil mass in conventional systems and 52.1 % of the total soil mass in agroecological systems. Agroecological systems had significantly higher proportions of biogenic aggregates ( $F_{1,14} = 127.80$ ,  $p < 0.0001$ ), and lower proportions of non-macro aggregated soil ( $F_{1,14} = 36.99$ ,  $p < 0.0001$ ) than conventional systems. Proportion of physical aggregates was not significantly different in both systems (respectively 27.9% in conventional systems and 19.0% in agroecological systems,  $F_{1,14} = 3.24$ ,  $p = 0.09$ ), Fig. 2.

### 3.3. Soil biological characteristics

Earthworms were the most abundant group of macroinvertebrates (40.7%) followed by “Diplopoda” (24.6%), and “Ants” (9.7%). We found  $206.8 \pm 34.0$  (mean  $\pm$  SE) individual m<sup>-2</sup> in conventional systems compared to  $416.6 \pm 72.0$  individual m<sup>-2</sup> in agroecological systems. The density of total soil macrofauna was significantly higher in agroecological systems than in conventional systems ( $F_{1,14} = 7.45$ ,  $p = 0.016$ ). The abundance of “Earthworms” was significantly higher in agroecological systems compared to conventional systems ( $F_{1,14} = 7.91$ ,  $p = 0.014$ ). However, there was no significant difference between agricultural systems for other macroinvertebrates taxonomic groups (Fig. 3, Table 2). Yet, the taxonomical richness (number of taxonomic groups) was significantly higher in agroecological systems than in conventional systems ( $F_{1,14} = 7.61$ ,  $p = 0.015$ ); 14 taxonomic groups were found in conventional systems compared to 17 in agroecological systems (Table 2). Two species of earthworms were found in the conventional system: *Pontoscolex corethrurus* (Müller) and an undetermined species. Four species were found in the agroecological system: *P. corethrurus*, *P. spiralis* (Borges and Moreno) and two undetermined species. The endogeic earthworm species *P. corethrurus* prevailed in the earthworm community in both treatments (91 % of earthworm community in conventional systems and 81 % in agroecological system). The community of earthworms was significantly different in both treatments (ANOSIM,  $R = 0.218$ ,  $p = 0.007$ ).

### 3.4. Plant health and yield

Population of *Radopholus similis* (Cobb) was significantly higher in conventional systems compared to agroecological systems ( $F_{1,14} = 4.98$ ,  $p = 0.042$ ). Moreover, the abundance of free-living nematodes associated to plantain roots was significantly higher in agroecological systems than in conventional systems ( $F_{1,14} = 17.91$ ,  $p = 0.001$ ). We found  $2399 \pm 349$  ind 0.100 g roots<sup>-1</sup> in conventional systems and  $4150 \pm 275$  ind 0.100 g roots<sup>-1</sup> in the agroecological system (Table 4). The root necrosis index ( $65 \pm 9$  % in conventional systems and  $57 \pm 11$  % in agroecological systems) was not significantly different among systems ( $F_{1,14} = 0.79$ ,  $p = 0.389$ ).

277 Bunch weight and estimated plantain yield were not significantly different among cropping  
278 systems. The average bunch weight was  $24 \pm 3$  Kg by plant (corresponding to  $48 \pm 6$  t ha<sup>-1</sup>) in  
279 agroecological systems and  $28 \pm 2$  Kg by plant (corresponding to  $57 \pm 5$  t ha<sup>-1</sup>) in conventional  
280 systems ( $F_{1,14} = 1.67$ ,  $p = 0.218$ ).

281

### 282 3.5. Agroecological systems versus conventional systems

283

284 Principal Component Analyses of the data matrix confirmed the trend expressed above. PCA  
285 of biological parameters (Fig. 4) significantly separated conventional from agroecological plots (18 %  
286 variance explained,  $p < 0.01$ ). Axis 1 opposed sites with high abundance and diversity of  
287 macroinvertebrates and free-living nematodes with predominant biogenic aggregates or non-  
288 macroaggregated soil, on the left end side, to sites with dominance of physical macroaggregates,  
289 high plant yield, and plant parasitic nematodes of genera *Meloidogyne*, *Helicotylenchus* and  
290 *Radopholus*, on the right end. Axis 2 opposed sites with high proportions of biogenic aggregates and  
291 high general abundance of Myriapoda and macroinvertebrates in general to sites with dominant non-  
292 macroaggregated soil and high root necrosis index. Points with agroecological farming practices were  
293 associated with highest macro-invertebrate abundance, biogenic macroaggregation and high  
294 densities of free-living nematodes while points with conventional systems, with lower abundance of  
295 macroinvertebrates, projected closer to plant parasitic nematodes and physical macroaggregation.

296 Farms were also significantly separated (26 % explained variance,  $p < 0.01$ ) independent of  
297 the systems, with Farm 1 on the left end side with higher abundance of *Pratylenchus* sp., non-  
298 macroaggregated soil and root necrosis and the other two farms on the opposite side, with higher  
299 yield and physical macroaggregation. PCA of chemical parameters did not significantly separate  
300 conventional from agroecological plots.

301

302

## 303 4. Discussion

304

305 The major finding of this study was that changes in practices in plantain agrosystems  
306 significantly affected macrofauna taxonomical richness, soil morphological characteristics and  
307 nematodes communities, in only 10 months. This shows a fast transition from conventional to  
308 agroecological cropping systems, with no significant loss of production. As expected, the  
309 agroecological plantain system was characterized by a higher soil macrofauna richness, a better soil  
310 structure (higher proportions of biogenic aggregates), a decrease in plant parasitic nematodes and an  
311 increase of the abundance of free-living nematodes associated to plantain roots. However, the  
312 agroecological plantain system did not affect significantly soil chemical parameters. Similar  
313 experiments in several places have shown that, while soil macro-invertebrates communities respond  
314 immediately to any changes in soil conditions, physical parameters change with some time lag and  
315 chemical only in the long term (Velasquez and Lavelle, 2019).

316

### 317 4.1. Agroecological practices and soil macrofauna

318

319 The significant increase in macrofauna abundance (due to increase of earthworm abundance)  
320 and taxonomic richness within the agroecological system may be firstly due to non-application of  
321 herbicides, pesticides and inorganic fertilizers in this agrosystem. In fact, herbicides used in  
322 conventional systems, especially Basta® (active ingredient glufosinate) and Reglone® (active



ingredient diquat) are known to negatively impact terrestrial soil invertebrates (Griffiths et al., 2008; Druart et al., 2010; Niedobova et al., 2019). Moreover, Sánchez-Moreno et al. (2009) showed that the fosythiazate pesticide (active ingredient of the nematicide Nemathorin®), usually used in conventional plantain systems, had a high toxicity to non-target fauna (including arthropods), and a high persistence in the environment. In our study, the earthworm community is very low in conventional systems. This result is supported by the study of Pelosi et al. (2014) which showed that earthworms are highly impacted by pesticides at all organization levels. The positive impact of the agroecological plantain system on soil macrofauna may be also due to vermicompost input. Few studies deal with the impact of vermicompost on earthworm populations. In the same way, Chaudhuri et al. (2016) also showed that vermicompost can increase the abundance and biomass of earthworms. It is known that inputs of organic matter such as plant-derived material usually increase the biological activity and number of trophic groups (Brussaard, 1998). At last, the presence of the legume cover crop *A. pintoï* may also impact soil macrofauna in the studied agroecological system.

As in our study, it has been showed in previous studies that *A. pintoï* significantly enhance earthworm density and fauna diversity in Amazonian pastures (Laossi et al., 2008; Velasquez et al., 2012). Earthworms may respond to litter quality or biomass, *A. pintoï* producing high amounts of organic matter (Laossi et al., 2008). *A. pintoï* produced a very dense leaf cover just above the ground and thus might also provide a better habitat for soil organisms with its complete soil cover (Perin et al., 2003).

342

#### 343 4.2. Agroecological practices and soil structure

344

Soil physical characteristics (linked to soil aggregation) were improved in the agroecological plantain system with a great increase in biogenic aggregates produced by macro-invertebrate ecosystem engineers. Besides, the abundance of earthworms was significantly higher in this cropping system. Several studies have already reported such effects (Velasquez et al., 2007, 2012). The endogeic earthworm species, *P. corethrus*, known to produce large amounts of biogenic aggregates, prevailed in the earthworm community in the present study. Their casts, which were stabilized by ageing, gave the soil high structural stability (Blanchart et al., 1999). This increase of biogenic aggregates may be enhanced by the legumes groundcover which has been showed to control soil physical characteristics via their impact on soil engineers. As an example, biogenic macroaggregates increased by 87 % in plots with the herbaceous legume *A. pintoï* compared to plots without *A. pintoï* (Velasquez et al., 2012). Moreover, in their study, Velasquez et al. (2012) showed that there was a parallel increase in earthworm abundance and decrease in soil C:N ratio under *A. pintoï*. This result suggests that earthworms benefited from improved nutrition in the presence of *A. pintoï*, thus enhancing their activity and their influence on soil structure. Soil structure enhancement associated with earthworms and growing plants could have important benefits for water capture, erosion control, gas exchange, root penetration and C stabilization in soils (Velasquez et al., 2012).

361

#### 362 4.3. Agroecological practices and regulation of pests

363

Our study also revealed that the populations of *R. similis* were lower and of root-associated free-living nematodes were significantly greater in the agroecological system compared with the conventional system. Non-use of chemical nematicides and insecticides and organic fertilization may explain this result. Other studies also showed that organic amendments increased the diversity and functional composition of soil nematode communities (Pattison et al., 2006, 2021). In particular, the

368

369 supply of organic matter boosted the populations of microbivorous nematodes, particularly  
370 bacterivores (Ferris and Bongers, 2006) and of carnivorous nematode populations (Tabarant et al.,  
371 2011) and not of plant parasitic nematodes. Thus, the input of organic matter would be an  
372 interesting alternative method to reduce plant parasitic nematodes, maintain plant health and  
373 lengthen the duration of plantain plots. Additionally, in the agroecological system, the reduction of *R.*  
374 similis population may be linked to earthworm abundance since they are known to control their  
375 impact in various ways (Blouin et al., 2005; Lafont et al., 2007; Wurst, 2010; Loranger-Merciris et al.,  
376 2012; Rowen et al., 2019).

377

#### 378 4.4. Agroecological practices, soil fertility and plantain yield

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380 Our study did not show any differences between the two plantain cropping systems  
381 regarding soil fertility (chemical properties). It is important to note that, in our study, the soil  
382 chemical properties were determined 10 months after the plantation. It has been showed that *A.*  
383 pintoï mulching significantly improved soil fertility in long-term experiments in Australia (Johns,  
384 1994) and China (Zhong et al., 2018). Vermicomposting converted organic waste into an organic  
385 product with high content of nutrients, microbial matter, and stabilized humic substances (Sierra et  
386 al., 2013). In a recent study, Sihi et al. (2017) found that long-term application of organic residues in  
387 cultivations of basmati rice favored biologically available nutrients in organic systems. Moreover, a  
388 recent meta-analysis by Chen et al. (2018) showed that the continuous application of organic  
389 amendments caused greater gains in soil organic carbon, significantly increase of Olsen P over time  
390 and increased the resilience of agronomic systems. Organic substrates stimulated soil  
391 microorganisms that produce enzymes responsible for the conversion of unavailable nutrients to  
392 plant available forms and should benefit to chemical soil fertility in the long term or if massive  
393 amendments were practiced (Lavelle et al., 2014; Velasquez and Lavelle, 2019).

394 Our study also showed that plantain yield (approximated by bunch weight) in the  
395 agroecological system was similar to the conventional systems. It had been showed in a recent study,  
396 in plantain cropping systems of Cameroon, that the highest bunch weights were measured in fields  
397 belonging to farmers who applied herbicide and nitrogen fertilizers more frequently and at higher  
398 rates (D'épigny et al., 2019). In our study, the agroecological practices (use of vermicompost, legume  
399 crop cover, healthy plant material) allow to maintain a level of plantain productivity similar to that of  
400 conventional systems. The similarity between both systems regarding plantain yield may be also  
401 linked to the fact that the soil fertility was similar in the 2 systems.

402

403

#### 404 5. Conclusion

405

406 We verified the hypothesis that there was a fast significant increase in soil macrofauna  
407 abundance and diversity and associated ecosystem services (soil aggregation, regulation of pests,  
408 production) in agroecological versus conventional plantain systems. The agroecological system  
409 improved soil quality and achieved similar plant yield levels than the conventional system, only 10  
410 months after the plantation. Agroecological practices, which promote biotic and abiotic interactions  
411 in the soil, may contribute to the goal of achieving sustainable tropical cropping systems. The regular  
412 communication of the experiment results to the producers and their own analysis developed during  
413 several seminars led them to reevaluate their production systems and consider adopting some of the  
414 proposed agroecological options. Some of plantain producers of Guadeloupe have adopted PIF

415 plants, which would ideally extend the life of their banana plantations by two years, and organic  
 416 fertilization with vermicompost (innovations produced on the farm). However, further research is  
 417 necessary to evaluate the long-term impact of agroecological practices in plantain agricultural  
 418 systems in particular on chemical soil fertility.

419  
 420

#### 421 **Declaration of Competing Interest**

422

423 The authors declare that they have no known competing financial interests or personal  
 424 relationships that could have appeared to influence the work reported in this paper

425  
 426

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428

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**Table 1**

Description of the plantain cropping systems in three studied farms in Guadeloupe (conventional and agroecological practices). Number into brackets following pesticide, herbicide and fertilizer levels are the number of applications during the plantation cycle observed in the plots.

|                                     | Farm 1                 |                          | Farm 2                 |                          | Farm 3                 |                          |
|-------------------------------------|------------------------|--------------------------|------------------------|--------------------------|------------------------|--------------------------|
|                                     | Conventional practices | Agroecological practices | Conventional practices | Agroecological practices | Conventional practices | Agroecological practices |
| Planting date                       | 03.14.2013             |                          | 03.08.2013             |                          | 02.19.2013             |                          |
| Fallow duration (before plantation) | 2 years                |                          | 4 years                |                          | 5 years                |                          |
| Origin of plant material            | Sucker                 | PIF                      | Sucker                 | PIF                      | Sucker                 | PIF                      |
| Plantain cultivar                   | French                 |                          | French                 |                          | French                 |                          |
| Plot longevity                      | Annual (1 cycle)       |                          | Annual (1 cycle)       |                          | Annual (1 cycle)       |                          |
| Pesticides application              | Nemathorin® (1)        | None                     | Nemathorin® (1)        | None                     | Nemathorin® (1)        | None                     |
| ⊕ Herbicides application            | Basta® F1 (3)          | None§                    | Basta® F1 (3)          | None                     | Reglone® (3)           | None§                    |
| Mulching                            | None                   | <i>Arachis pintoï</i> †  | None                   | <i>Arachis pintoï</i> †  | None                   | <i>Arachis pintoï</i> †  |
| Fertilization                       | NPK fertilizer (5)     | Vermicompost*            | NPK fertilizer (5)     | Vermicompost*            | NPK fertilizer (5)     | Vermicompost*            |

⊕ Herbicides were applied 1 month, 5 months and 8 months after the plantation. Two months occurred between the last herbicide application and soil sampling.

§ manual weeding during the two first months, then brushcutting every 3 weeks.

† density of *Arachis pintoï*: 4 cuttings per m<sup>2</sup> at the beginning of the experiment.

\* 1.5 kg Vermicompost per plant at the beginning of the experiment; 3 kg Vermicompost per plant 2 months after the beginning of the experiment; and 3 kg Vermicompost per plant 6 months after the beginning of the experiment.

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**Table 2**

Soil macro-invertebrates (individuals.m<sup>-2</sup>) identified at crop flowering stage in two plantain cropping systems in Guadeloupe (conventional and agroecological) and compared using GLMM. Values are means of 9 experiment units. Standard errors are given in parentheses. For each taxonomic group, means with the same superscript letter are not significantly different.

| Soil macro-<br>Invertebrates<br>taxonomic group | Conventional<br>cropping systems | Agroecological<br>cropping systems | F <sub>1,14</sub> | P     |
|---|----------------------------------|------------------------------------|-------------------|-------|
| Cl. Diplopoda                                   | 46 (19) <sup>a</sup>             | 114 (39) <sup>a</sup>              | 3.026             | 0.104 |
| F. Formicidae (ants)                            | 20 (8) <sup>a</sup>              | 41 (19) <sup>a</sup>               | 1.067             | 0.317 |
| intra U. Isoptera<br>(termites) S/O             | 15 (15) <sup>a</sup>             | 19 (17) <sup>a</sup>               | 0.024             | 0.879 |
| Lumbricina<br>(earthworms)                      | 88 (17) <sup>a</sup>             | 164 (24) <sup>b</sup>              | 7.91              | 0.014 |
| O. Coleoptera                                   | 2 (2) <sup>a</sup>               | 3 (1) <sup>a</sup>                 | 0.085             | 0.774 |
| O. Coleoptera<br>(larvae)                       | 14 (2) <sup>a</sup>              | 15 (3) <sup>a</sup>                | 0.115             | 0.739 |
| Cl. Chilopoda                                   | 14 (7) <sup>a</sup>              | 19 (11) <sup>a</sup>               | 0.137             | 0.716 |
| O. Isopoda                                      | 1 (1) <sup>a</sup>               | 4 (2) <sup>a</sup>                 | 2.041             | 0.172 |
| O. Dermaptera                                   | 0 (0) <sup>a</sup>               | 3 (2) <sup>a</sup>                 | 2.703             | 0.120 |
| S/O. Blattaria                                  | 1 (1) <sup>a</sup>               | 2 (1) <sup>a</sup>                 | 0.160             | 0.694 |
| O. Araneae                                      | 2 (1) <sup>a</sup>               | 5 (2) <sup>a</sup>                 | 4.000             | 0.063 |
| Cl. Gastropoda                                  | 0 (0) <sup>a</sup>               | 4 (3) <sup>a</sup>                 | 1.455             | 0.245 |
| Cl. Turbellaria                                 | 0 (0) <sup>a</sup>               | 2 (1) <sup>a</sup>                 | 3.368             | 0.085 |
| O. Hemiptera                                    | 1 (1) <sup>a</sup>               | 4 (2) <sup>a</sup>                 | 2.041             | 0.172 |
| O. Orthoptera                                   | 2 (1) <sup>a</sup>               | 1 (1) <sup>a</sup>                 | 0.160             | 0.694 |
| O. Diptera (larvae)                             | 1 (1) <sup>a</sup>               | 16 (16) <sup>a</sup>               | 0.853             | 0.370 |
| O. Lepidoptera<br>(larvae)                      | 0 (0) <sup>a</sup>               | 1 (1) <sup>a</sup>                 | 2.286             | 0.150 |
| O. Thysanoptera                                 | 1 (1) <sup>a</sup>               | 0 (0) <sup>a</sup>                 | 1.000             | 0.332 |

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**Table 3**

Soil chemical characteristics measured at crop flowering stage in two plantain cropping systems in Guadeloupe (conventional and agroecological) and compared using GLMM. Values are means of 9 experiment units. Standard errors are given in parentheses. For each soil chemical characteristic, means with the same superscript letter are not significantly different.

| Soil characteristics  | Conventional cropping systems | Agroecological cropping systems | F <sub>1,14</sub> | P     |
|---|-------------------------------|---------------------------------|-------------------|-------|
| pH-H <sub>2</sub> O   | 5.14 (0.20) <sup>a</sup>      | 5.15 (0.25) <sup>a</sup>        | 0.002             | 0.967 |
| pH-KCl  | 4.45 (0.18) <sup>a</sup>      | 4.49 (0.28) <sup>a</sup>        | 0.035             | 0.853 |
| N-NH <sub>4</sub> <sup>+</sup><br>(mg.kg <sup>-1</sup> ) <sub>1</sub> | 3.07 (0.75) <sup>a</sup>      | 4.01 (0.78) <sup>a</sup>        | 1.416             | 0.254 |
| N-NO <sub>3</sub> <sup>-</sup><br>(mg.kg <sup>-1</sup> ) <sub>1</sub> | 2.33 (0.75) <sup>a</sup>      | 1.42 (0.24) <sup>a</sup>        | 1.577             | 0.230 |
| N (%)   | 0.26 (0.03) <sup>a</sup>      | 0.25 (0.02) <sup>a</sup>        | 0.429             | 0.523 |
| C (%)   | 2.59 (0.24) <sup>a</sup>      | 2.71 (0.21) <sup>a</sup>        | 0.464             | 0.507 |
| CEC (cmol.kg <sup>-1</sup> )  | 9.74 (0.74) <sup>a</sup>      | 9.54 (0.79) <sup>a</sup>        | 0.124             | 0.730 |
| K (cmol.kg <sup>-1</sup> )  | 0.66 (0.10) <sup>a</sup>      | 0.59 (0.13) <sup>a</sup>        | 0.168             | 0.688 |
| Na (cmol.kg <sup>-1</sup> )   | 0.08 (0.01) <sup>a</sup>      | 0.08 (0.01) <sup>a</sup>        | 0.630             | 0.441 |
| Ca (cmol.kg <sup>-1</sup> )   | 3.76 (0.70) <sup>a</sup>      | 3.88 (0.89) <sup>a</sup>        | 0.027             | 0.871 |
| Mg (cmol.kg <sup>-1</sup> )   | 1.28 (0.14) <sup>a</sup>      | 1.34 (0.10) <sup>a</sup>        | 0.390             | 0.542 |
| Available P (%)   | 0.07 (0.004) <sup>a</sup>     | 0.06 (0.002) <sup>a</sup>       | 0.816             | 0.380 |

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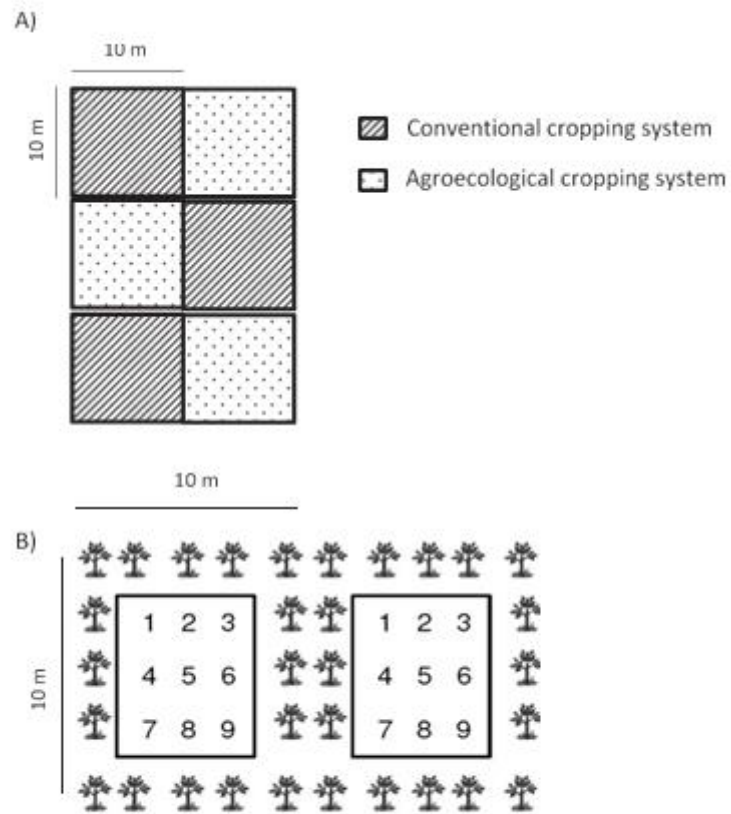
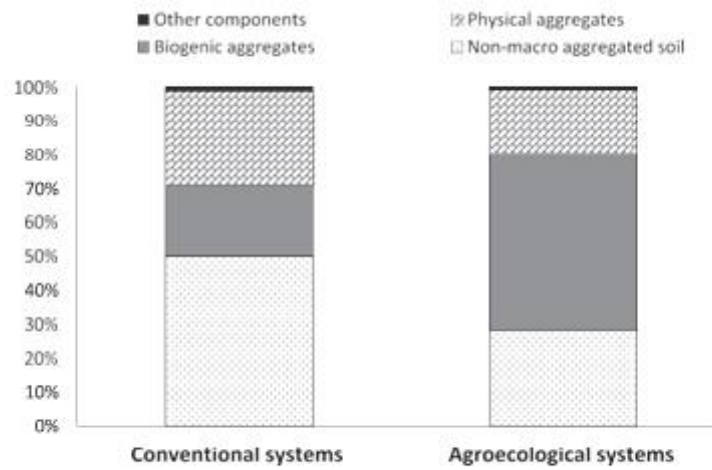


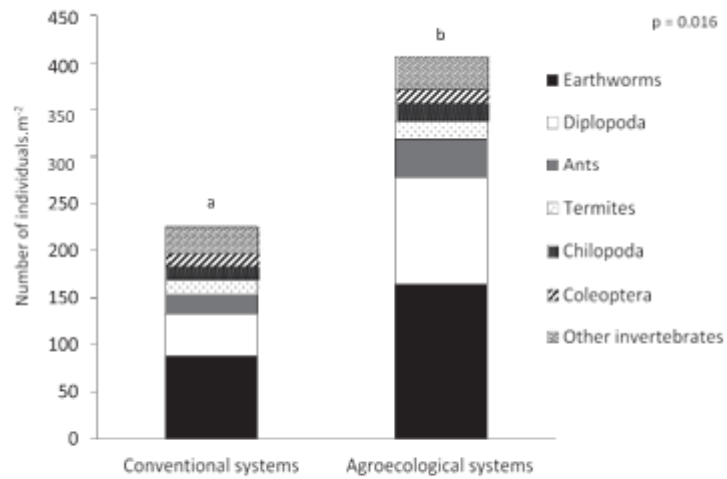
Fig. 1. A) Design of the plantain field trials carried out in each of the three farms located in the western part of Guadeloupe. B) Design of each pair of experimental units. The number within the boxes indicate the plants used for measurements.

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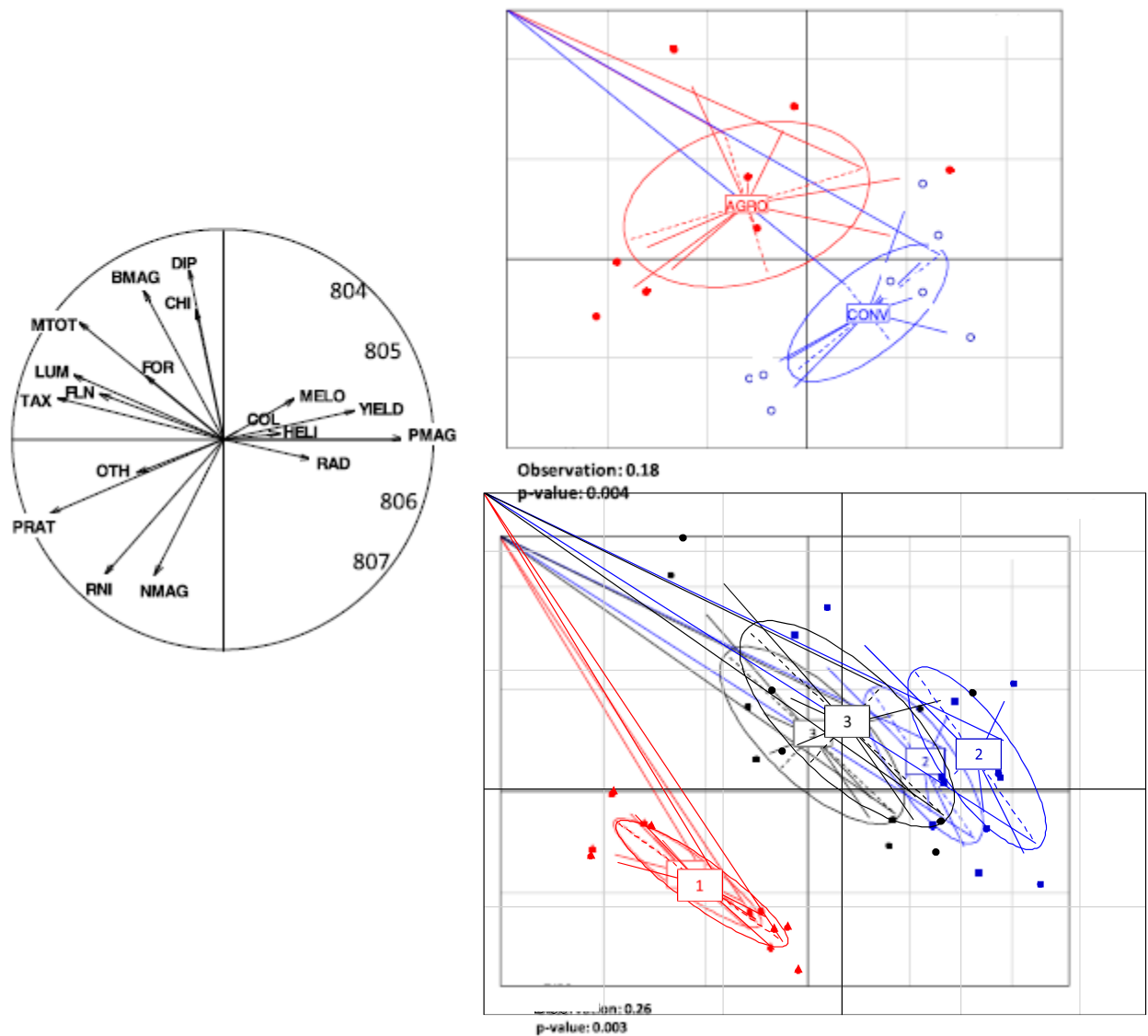


**Fig. 2.** Morphology of soil aggregates in two plantain cropping systems in Guadeloupe (conventional and agroecological).

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**Fig. 3.** Soil macrofauna abundance in two plantain cropping systems in Guadeloupe [conventional and agroecological]. Only the 6 main groups were represented. The abundance of the 9 remaining groups has been gathered in the



**Fig. 4.** Soil biological properties in cropping systems and farms. Projection in the factorial plane F1F2 of a PCA of biological variables (left) and sampling points separated among cropping systems (upper right,  $p < 0.01$ ) and farms (lower right,  $p < 0.01$ ). LEFT: *Macroinvertebrate community* (DIP: *Diplopoda*, CHI: *Chilopoda*, COL: *Coleoptera*, FOR: *Formicidae*, LUM: *Lumbricina*, MTOT: Total Macrofauna, OTH: Other invertebrates, TAX: Taxonomic richness); Soil macro aggregation status (PMAG: Physical macroaggregates, BMAG: Biogenic macroaggregates, NMAG: non macroaggregated soil); Nematodes (PRAT: *Pratylenchus* sp., MELO: *Meloidogyne* sp., HELI: *Helicotylenchus* sp., RAD: *Radopholus similis*, FLN: Free-living nematodes); RNI: Root necrosis index; YIELD: Plant yield. RIGHT: AGRO (Agroecological system), CONV (Conventional system); 1: Farm 1, 2: Farm 2, 3: Farm 3.