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

Keywords: Legume cover crop, Plants Issued from Fragments (PIF), Soil aggregates, Soil fauna, Tropical agroecosystems, Vermicompost

1. Introduction

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

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

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

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

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

2. Material and methods

2.1. Site information and experimental design

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

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

The second cropping system was agroecological and integrated 3 innovations (Table 1): i) healthy plants, obtained through the PIF technique (Lefranc et al., 2010; Sadom et al., 2010), were used in order to reduce pest infestations at the beginning of the plantation; ii) vermicompost (mixture of cattle manure and green wastes transformed by local epigeic earthworms) was applied in order to fertilize plants and stimulate soil food web; and iii) a living vegetal covering using Arachis pintoï Krapov. and W.C. Greg (Fabaceae) was used to control weeds through mulching. Ultimately, we added 18.75 t ha^{-1} of fresh vermicompost (corresponding to 11 t ha^{-1} of dry matter) during the experiment, in the planting hole mixed with soil at the beginning, then at the soil surface, 2 and 6 months after the start of the experiment (Table 1). Characteristics of the vermicompost were: pH 7.5, Total C 215 $g.kg^{-1}$, Total N 20.3 g kg^{-1}, C/N 12.8, Total P 5.4 g kg^{-1}, Total K 13.3 g kg^{-1}, Total Mg 6.2 g kg^{-1}, Total Ca 86.3 g kg^{-1}, NO_3-N 2449 mg kg^{-1}, NH_4-N 9.7 mg kg^{-1}. Arachis pintoï forms a very dense mat that remarkably controls weeds. Seven weeks after its implantation, the plant already covered partly the soil and reached 100 % of coverage in six months. Arachis pintoï was allowed to senesce naturally within the plantain cropping field.

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

2.2. Soil chemical characteristics

Soil chemical properties were measured in each of the 18 experimental units (6 experimental units × 3 farms). In each experimental unit, soil samples were taken with an 8 cm diameter × 15 cm height cylinder, near the 9 central plants (Fig. 1). These 9 samples were mixed in a composite sample in which chemical analyses were done. Total soil C and N were determined using an auto-analyser (NF ISO 13878, 1998). Available P was measured using the Olsen-Dabin method (Dabin, 1967). Soil mineral N ($N0_3$ and NH_4) was measured by colorimetry after extraction with a 0.5 M KCl solution. Exchangeable Ca, Mg, K and Na were determined after extraction with ammonium acetate (NF X 31108). Cation-exchange capacity (CEC) was measured with IF07–10D (NFX 31–130) method and pH-H_2O and pH-KCl with NF ISO 1770, 3696 and 11464.

2.3. Morphology of soil aggregates

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

2.4. Soil biological characteristics

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

2.5. Plant health and yield

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

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

2.6. Statistical analysis

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

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

3. Results

3.1. Soil chemical characteristics

Soils were acidic to slightly alkaline, with average values of pH-H_2O between 4.5 and 7.0. Soil pH, N-NH_4, N-NO_3, 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 ± 34.0 (mean ± SE) individual m^{-2} in conventional systems compared to 416.6 ± 72.0 individual m^{-2} 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 ± 349 ind 0.100 g $roots^{-1}$ in conventional systems and 4150 ± 275 ind 0.100 g $roots^{-1}$ in the agroecological system (Table 4). The root necrosis index (65 ± 9 % in conventional systems and 57 ± 11 % in agroecological systems) was not significantly different among systems ($F_{1,14}$ = 0.79, p = 0.389).

Bunch weight and estimated plantain yield were not significantly different among cropping systems. The average bunch weight was 24 ± 3 Kg by plant (corresponding to 48 ± 6 t ha^{-1}) in agroecological systems and 28 ± 2 Kg by plant (corresponding to 57 ± 5 t ha^{-1}) in conventional systems ($F1,14 = 1.67$, $p = 0.218$).

3.5. Agroecological systems versus conventional systems

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

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

4. Discussion

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

4.1. Agroecological practices and soil macrofauna

The significant increase in macrofauna abundance (due to increase of earthworm abundance) and taxonomic richness within the agroecological system may be firstly due to non-application of herbicides, pesticides and inorganic fertilizers in this agrosystem. In fact, herbicides used in 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 fosthiazate 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. pintoi 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).

4.2. Agroecological practices and soil structure

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. corethrurus, 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. pintoi. This result suggests that earthworms benefited from improved nutrition in the presence of A. pintoi, 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).

4.3. Agroecological practices and regulation of pests

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

4.4. Agroecological practices, soil fertility and plantain yield

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

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

5. Conclusion

We verified the hypothesis that there was a fast significant increase in soil macrofauna abundance and diversity and associated ecosystem services (soil aggregation, regulation of pests, production) in agroecological versus conventional plantain systems. The agroecological system improved soil quality and achieved similar plant yield levels than the conventional system, only 10 months after the plantation. Agroecological practices, which promote biotic and abiotic interactions in the soil, may contribute to the goal of achieving sustainable tropical cropping systems. The regular communication of the experiment results to the producers and their own analysis developed during several seminars led them to revaluate their production systems and consider adopting some of the proposed agroecological options. Some of plantain producers of Guadeloupe have adopted PIF plants, which would ideally extend the life of their banana plantations by two years, and organic fertilization with vermicompost (innovations produced on the farm). However, further research is necessary to evaluate the long-term impact of agroecological practices in plantain agricultural systems in particular on chemical soil fertility.

Declaration of Competing Interest

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

Acknowledgments

This work was supported financially by the French Ministry of Ecology and Sustainable Development, France(ECOPHYTO program, project ALTERBIO). The authors thank the three farmers involved in this study. We also thank Fred Burner, Chantal Fléreau, Danielle Ramaël and Frédérique Razan (INRAE Antilles Guyane) for their technical help. The authors would also like to thank Lucienne Desfontaines (INRAE Antilles Guyane) for soil chemical analyses

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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	*Arachis pintoi* †	None	*Arachis pintoi* †	None	*Arachis pintoi* †
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^2 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.

Table 2

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

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	$F_{1,14}$	P
pH-H_2O	5.14 (0.20)^a	5.15 (0.25)^a	0.002	0.967
pH-KCl	4.45 (0.18)^a	4.49 (0.28)^a	0.035	0.853
N-NH_4^+ (mg.kg^{-1})	3.07 (0.75)^a	4.01 (0.78)^a	1.416	0.254
N-NO_3^- (mg.kg^{-1})	2.33 (0.75)^a	1.42 (0.24)^a	1.577	0.230
N (%)	0.26 (0.03)^a	0.25 (0.02)^a	0.429	0.523
C (%)	2.59 (0.24)^a	2.71 (0.21)^a	0.464	0.507
CEC (cmol.kg^{-1})	9.74 (0.74)^a	9.54 (0.79)^a	0.124	0.730
K (cmol.kg^{-1})	0.66 (0.10)^a	0.59 (0.13)^a	0.168	0.688
Na (cmol.kg^{-1})	0.08 (0.01)^a	0.08 (0.01)^a	0.630	0.441
Ca (cmol.kg^{-1})	3.76 (0.70)^a	3.88 (0.89)^a	0.027	0.871
Mg (cmol.kg^{-1})	1.28 (0.14)^a	1.34 (0.10)^a	0.390	0.542
Available P (%)	0.07 (0.004)^a	0.06 (0.002)^a	0.816	0.380

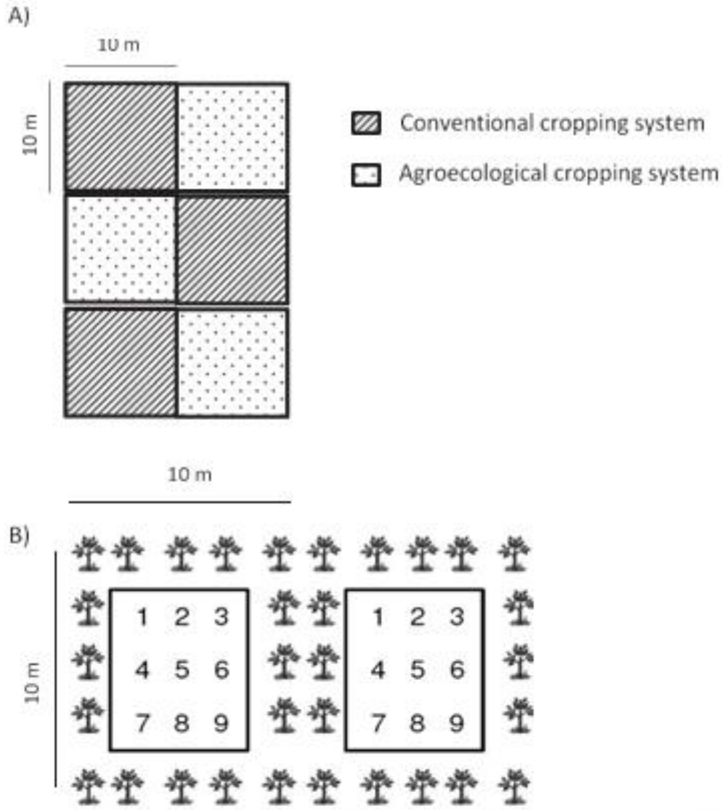

Fig. 1. A) Design of the plantain field trials carried out in each of the three farms located in the western part of Guadeloupe. B) Design of each pair of experimental units. The number within the boxes indicate the plants used for measurements.

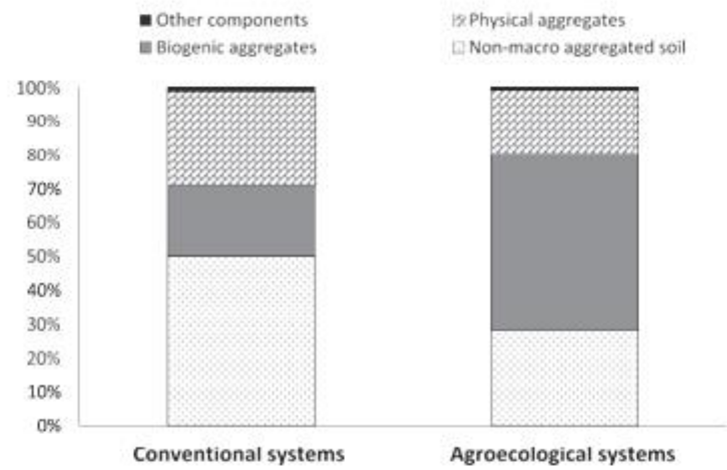

Fig. 2. Morphology of soil aggregates in two plantain cropping systems in Guadeloupe (conventional and agroecological).

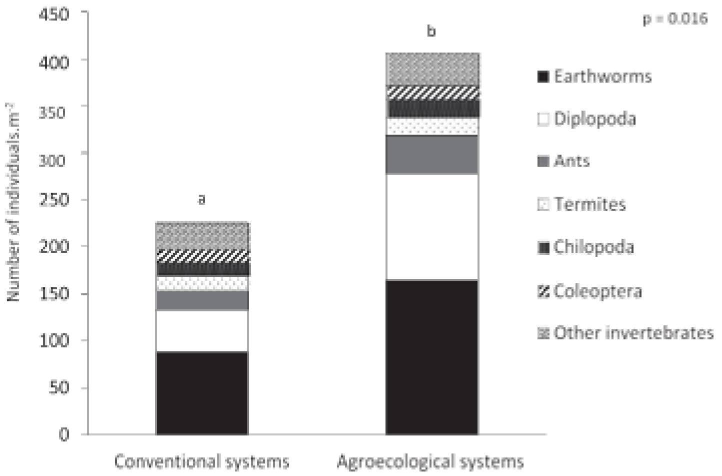

Fig. 3. Soil macrofauna abundance in two plantain cropping systems in Guadeloupe (conventional and agroecological). Only the 6 main groups were represented. The abundance of the 9 remaining groups has been gathered in the

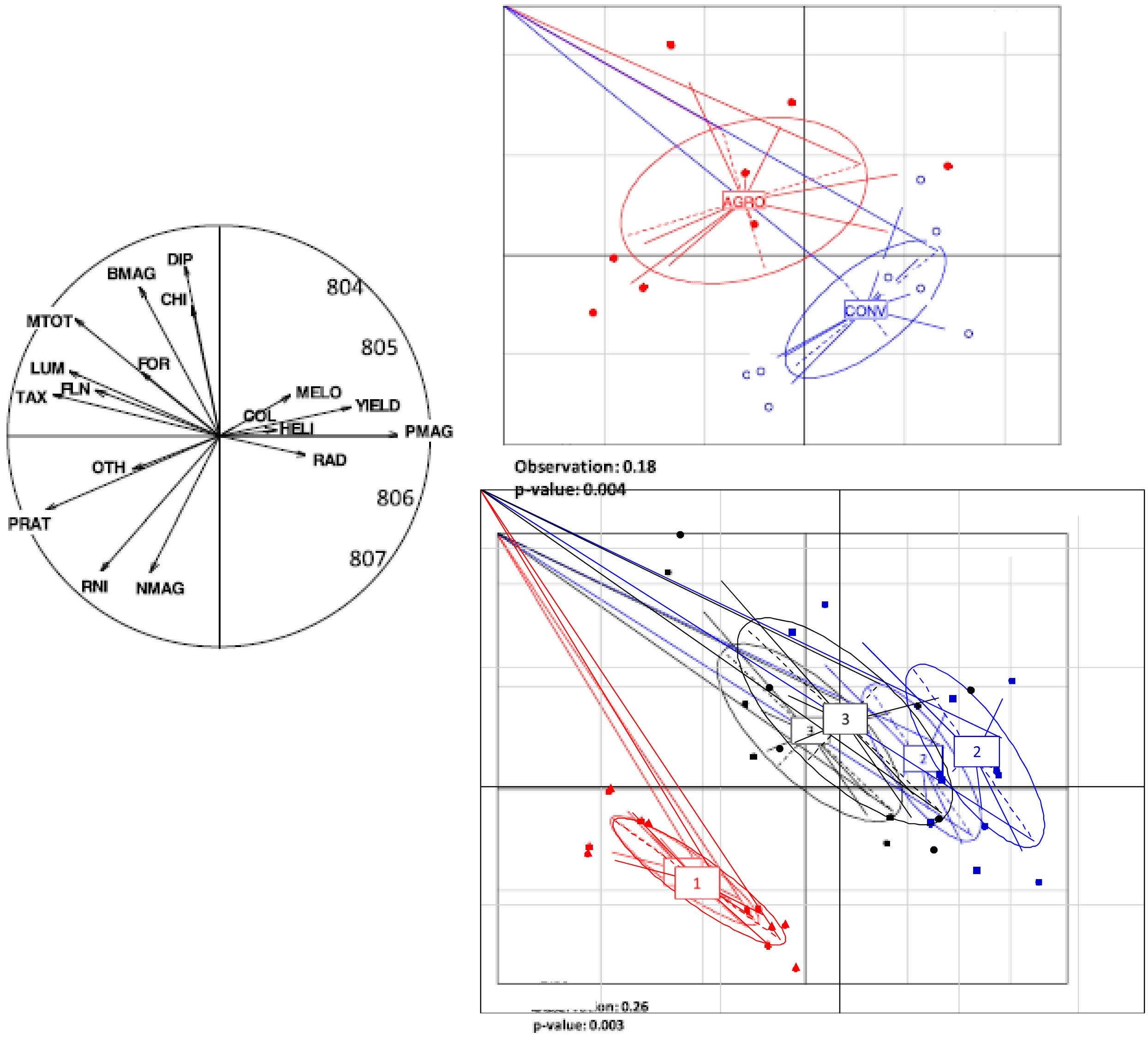

Fig. 4. Soil biological properties in cropping systems and farms. Projection in the factorial plane F1F2 of a PCA of biological variables (left) and sampling points separated among cropping systems (upper right, p < 0.01) and farms (lower right, p < 0.01). LEFT: *Macroinvertebrate community (DIP: Diplopoda, 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: Heli- cotylenchus 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*.