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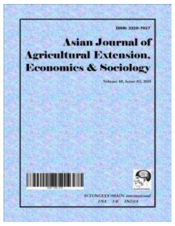

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The Impact of Agricultural Practices on Soil Organisms: Lessons Learnt from Market-gardens

Coraline Moulin[1,2], Victor Vaillant[1], Jean-Louis Diman[3], Valérie Angeon[4], Fred Burner[1] and Gladys Loranger-Merciris[2*]

[1]AgroSystèmes Tropicaux (ASTRO), INRA, 97170, Petit-Bourg (Guadeloupe), France.
[2]Equipe Biologie de la Mangrove, UMR ISYEB-MNHN-CNRS-Sorbonne Université-EPHE, Université des Antilles, UFR Sciences Exactes et Naturelles, Campus de Fouillole, 97157 Pointe-à-Pitre Cedex (Guadeloupe), France.
[3]INRA centre des Antilles-Guyane domaine de Godet Plateforme Expérimentale sur le Végétal et les Agrosystèmes Innovants en Milieu Tropical (UE PEYI), INRA, 97170, Petit-Bourg (Guadeloupe), France.
[4]UR Ecodéveloppement, INRA, 84914, Avignon, France.

Authors' contributions

This work was carried out in collaboration among all authors. Author GLM designed the study and wrote the protocol. Author CM performed the statistical analysis and wrote the first draft of the manuscript. Authors CM, VV, JLD, VA and FB managed the analyses of the study. Author CM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Intensive agriculture practices have an important impact on soil biota, which can affect dramatically soil quality. In order to limit this impact, alternative agricultural practices are more and more applied. However, these practices are still in progress and thus, it is necessary to investigate their impact on soil activity. In this context, we studied the impact of agricultural practices (intensive and agroecological) in vegetable cropping systems in Guadeloupe. The first aim of this study was to

**Corresponding author: E-mail: Gladys.Loranger@univ-antilles.fr;*

identify practices developed in vegetable cropping systems and explain their level of eco-agriculture. We conducted a survey on the whole territory which gave us a better understanding of vegetable cropping systems in Guadeloupe. We selected a representative subset of 18 farms located on vertisols. The second aim of the study was to establish a typology of cropping practices in these vegetable cropping systems in vertisol. We performed a PCA and a HCA on the 18 farms. These methods allowed us to build a typology in which farms were distributed between two types. In type A, farmers are using intensive agricultural practices while in type B, farmers are using alternative agroecological farming practices. Then, we collected soil fauna, during the rainy season in type A and type B farms in order to demonstrate the relationship between cropping systems and the quality of soils proxied by biological indicators. We hypothesized that the use of synthetic fertilizers and herbicides in intensive agriculture affected soil fauna activity. The results showed no significant difference between soil fauna abundance in both types. However, the taxonomic richness and the abundance of litter transformers were higher in type B. Taxonomic richness and soil fauna functional diversity thus strongly depend on agricultural practices in vegetables cropping systems in Guadeloupe.

Keywords: Vegetable cropping systems; agroecology; survey; soil fauna; functional diversity.

1. INTRODUCTION

Intensive agriculture relied heavily on the use of synthetic inputs and low genetic diversity [1,2,3]. It is well known that conventional intensive agriculture had negative impacts on natural resources such as soil (soil pollution, erosion), water quality (pollution of rivers, lakes and streams), biodiversity loss and human health (inadequate use of pesticides) [4,5,6,7,8,9]. Therefore, such unsustainable models need to be modified to agroecosystems that can optimize ecological functions while maintaining high productivity [9]. Since the 1990s, there has been a growing interest in developing alternative sustainable farming strategies. All of these strategies share the same objective in terms of minimizing the use of synthetic inputs (or even promoting non-use at all), enhancing organic matter recycling and improving the health of agroecosystems while maintaining a high production level [10,11,12]. These strategies belong to the field of agroecology as they promote the development of practices based on the mobilization of natural regulations. According to Pretty [13], sustainable agriculture jointly produces food and goods for farmers and the environment.

In 2017, worldwide agricultural production of vegetables reached 182 million metric of tomatoes, 97 million metric of onions, 83 million metric of cucumbers and gherkins, 71 million metric of cabbages and other brassicas and 52 million metric of eggplants [14]. China, India and the United States of America were the main producers in 2017 [14]. Market-gardening has a major place in agriculture production and in human health as it provides elements such as vitamin A and C, minerals, folic acid and fibres [15,16].

In Guadeloupe, agriculture is one of the most important economic sectors. It is a major source of exported goods, mostly based on the agroindustrial models developed with banana and sugarcane. The agricultural land area has been declining mainly due to urbanization (e.g. from 57 385 ha in 1981 to 30 965 ha in 2013 [17]. However, it still covers one-third of the archipelago. In 2016, the island's main crops were sugarcane (590 299 tones) and banana (66 208 tones). The other crops were vegetables (28 841 tones) and tubers (4 370 tones) [18]. Sugarcane and banana were the most studied cropping systems in Guadeloupe [19,20] as they represent dominant agricultural systems, because of the engagement of farmers in market channels and professional and public organizations. Sugarcane and banana also benefit from major public subsidies, which helped farmers invest and maximize their production. In contrast, we have little knowledge of vegetable cropping practices though they are models of alternative diversified systems, assumed to be less dependent on chemical inputs. Therefore, the study focused on identifying agricultural practices in vegetable farming systems in Guadeloupe. As we know agricultural practices impacted soil fauna activity; however, we wanted to know what kind of alternative practices are used in vegetable cropping systems and to what extent such practices affect soil biota. Considering the lack of scientific knowledge regarding the influence of vegetable cropping systems on soil organisms, this article intends to fill this gap by providing consistent information on the functioning of such agroecosystems. Thus, this paper aims at (i) identifying the practices developed in vegetable cropping systems and explaining their degree of eco-agriculture. (ii) On this basis, a typology of cropping practices in these agrosystems in Guadeloupe was established. (iii) Using this typology, we demonstrate the relationship between cropping systems and the quality of soils proxied by biological indicators. We hypothesized that there was a positive correlation between the quality of practices developed in vegetable cropping systems and soil organism abundance and diversity. Soil is then considered as an indicator of the quality of the practices. Based on the identification of cropping systems in Guadeloupe, we selected farmers from vertisols to demonstrate the relationship between cropping systems and the quality of soils proxied by biological indicators (abundance and diversity of soil fauna).

2. MATERIALS AND METHODS

2.1 Research Area

The study was carried out in Guadeloupe (French West Indies), which is a part of the Windward Islands, in the eastern Caribbean Sea. This archipelago includes two main islands with distinct environments. Basse-Terre (848 km^2) is dominated by a mountain chain oriented North-West to South-East. The annual temperature ranges from 20.1 and 31.9°C (France Meteorological Service, http://www.meteo.gp). This island is characterized by a humid tropical climate and a variety of soil types: ferralsols, nitisols, andosols and vertisols [20]. The mean annual rainfall in Basse-Terre is comprised between 1400 mm and 3500 mm (France Meteorological Service, http://www.meteo.gp). On the contrary, Grande-Terre (586 km^2) is characterized by a slightly undulating surface, and the relief rarely exceeds 40 m [20]. The climate is tropical, with a mean annual rainfall between 1300 mm and 1600 mm, and soils are mostly vertisols.

2.2 Farm Surveys and Typology

To collect data on the practices set up in vegetables cropping systems, a survey was carried out between September and November 2016. 49 farms were randomly sampled: 21 in Grande-Terre and 28 in Basse-Terre. We only targeted farms, which have all or a part of their productions devoted to vegetable cropping systems. We visited and interviewed those farmers to describe their practices. In the survey, we used variables that best described and discriminated farms. Some variables are intangible (i.e. soil type) while others depend on farmers' strategies: crops rotation, soil tillage, irrigation, use of pesticides, weed control, use of synthetic fertilizer or organic amendment, mulch and management of crop residues. Based on cropping systems of the initial set of 49 farms on the whole territory, we selected a representative subset of 18 farms developed on vertisols in Grande-Terre. This selection was due to the fact that in Guadeloupe, vegetable cropping systems are mostly concentrated on vertisol [21]. Indeed, these soils are rich in calcium, magnesium, potassium and they maintain a pH neutral to slightly basic [22]. In addition, the large diversity of soils in Basse-Terre makes it difficult to build a typology.

On the 18 farms, we performed a PCA and a HCA. These methods allowed us to build a typology, by gathering farms based on their characteristics and practices. This analysis was realized by using the following variables: (i) soil tillage separated farms into 3 classes: deep, superficial and manual tillage; (ii) the type of pesticides used divided farms in 3 classes: chemical pesticides, pesticides used in biological agriculture or no pesticides; (iii) use of synthetic herbicides distributed farms in 3 classes: intensive, intermediate and occasional; (iv) weed control separated farms in two classes: mechanical or manual; (v) amendment divided farms in 4 classes: application of synthetic fertilizer, application of organic matter, application of both, and no fertilization; (vi) use of mulch separated farms in 2 classes: presence or absence; (vii) management of crop residues divided farms in three classes: removed from the field, incorporated into the soil, and left in the plot; (viii) application of slash-and-burn practices distributed farms in two classes: with or without slash-and-burn practices; (ix) finally, the observation of soil biodiversity on the surface separated farms in four classes: high, medium, low and no activity.

2.3 Soil Fauna

From December 2016 to January 2017, in each selected farms on Vertisol, five soil samples of 25 cm (length) × 25 cm (width) × 20 cm (deep) were taken for soil macrofauna extraction using TSBF method [23]. Each sample was separated at least 200 m from the others and was collected 1 km far away from any road and walking path. Animals were collected in alcohol, counted and identified at the taxonomic level under a dissecting microscope. The following taxonomic groups of soil fauna were identified: Oligochaeta, Formicidae, Isoptera, Isopoda, Diplopoda, Dictyoptera, Coleoptera, Diptera, Lepidoptera, Gasteropoda, Homoptera, Orthoptera, Heteroptera, Arenaidae, Chilopoda, Dermaptera, Turbellaria, Insect larvae, and Other Insects. They were gathered in different functional groups: litter transformers, predators and ecosystem engineers, and we calculated taxonomic richness. This functional approach can provide information on soil framework and vegetation quality [24,25].

2.4 Data Analysis Methods

To establish a typology of farming practices in vegetable cropping systems, a principal component analysis (PCA) was performed. PCA is a multivariate data analysis based on projection methods. It is a useful technique for reducing the dimensionality of such datasets, increasing interpretability but at the same time minimizing information loss [26]. Based on the PCA, a hierarchical cluster analysis (HCA) was performed. HCA builds a tree diagram, which groups similar observations into a dataset. These analyses were performed through R statistical software (http://www.r-project.org/) using the R Commander package (Rcmdr). With regards to the relation between the two types of farming practices and soil fauna, we used Welch's t-test. That test was carried out using R software.

3. RESULTS AND DISCUSSION

3.1 Description of 49 Farms Based on Surveys

The first aim of this study was to identify practices developed in vegetable cropping systems and explain their level of eco-agriculture. We conducted a survey that showed the diversity of agricultural practices in vegetable cropping systems in Guadeloupe. In Basse-Terre and in Grande-Terre, we saw similar crops such as lettuce, zucchini, tomatoes, melon, chilli pepper, and eggplant. In addition, in Basse-Terre, we also observed cucumber, pumpkin, cabbage, okra and chives. We also observed various types of cropping systems, from monoculture to polyculture, and a wide range of practices, from conventional to agroecological.

Farming practices are mainly territorially anchored. Tillage is used to enhance soil conditions in relation to the water balance and crop growth, to loose upper soil layers to prevent soil compaction, to diminish weed growth and to prepare the seedbed [27,28,29,30]. Our results showed that in Grande-Terre, most farmers used deep tillage (76%) compared to superficial tillage (24%). In this region, vertisols – rich clay soils which are extremely hard when they dry, including cracks and polygonal structures [31] – are predominant. Deep tillage is therefore used to prepare the field for the next culture, by moving and mixing the topsoil with crop residues, which are incorporated into the soil [28]. On the contrary, farmers from Basse-Terre used superficial tillage (71%) rather than deep tillage (29%), due to the type of soils found in that region. Ferralsols have loose and friable fragments [22]. Nitisols are very similar to ferralsols but at an earlier stage. Finally, andosols are slightly sticky and friable to very friable [32]. Tillage reduced soil organic matter availability by accelerating decomposition and by increasing soil erosion and soil degradation [33]. Moreover, it has a detrimental effect on environmental quality because of its impact on greenhouse gas emissions [34,35]. Soil disturbance such as tillage has a strong influence on soil fertility and water availability [36]. In contrast, by minimizing mechanical disturbance of soil and macro-aggregate destruction, reduced tillage strongly decreases soil erosion [37,38] and improves water use efficiency [39]. Reduced tillage thus has positive effects on nutrient cycling and soil biodiversity [40,41].

Throughout the survey, we observed that the use of synthetic pesticides was widely spread among the different farms. In Guadeloupe, crop yield was affected by pest damage and diseases, mainly during the rainy season. Farmers usually prevent economic loss due to pest by spreading heavy pesticides treatments [42]. Additionally, the application rate of herbicides depended on the area. Farmers from Grande-Terre combined herbicides and deep tillage. The mixture of those two methods regulated the abundance of weed species in the field [43]. In fact, Chauhan and Johnson [44] showed that when seeds were deeply buried, the emergence rate was very low.

33% of farmers in Grande-Terre and 11% of farmers in Basse-Terre applied mineral fertilizers. Agricultural production has increased, since the 1950s, due to the large input of mineral fertilizers

[45]. However, the intensive use of mineral fertilizers has a negative impact on soil fertility (soil acidification) and yield production [46]. 25% of farmers applied organic matter in Basse-Terre and 24% in Grande-Terre. Organic fertilizers are used as an alternative to synthetic ones, in order to restore or enhance soil physical, chemical and biological properties [47]. Organic matter is not only a source of plant nutrients in soils but also plays an important part in preserving soil fertility, reducing soil erosion, nutrient cycling, water retention and disease suppression [48,49]. During the study, we noticed that in most cases, farmers mixed organic matter and mineral fertilizer together, 54% in Basse-Terre compared to 33% in Grande-Terre. A meta-analysis, across sub-Saharan Africa, demonstrated that the use of both input types leads to greater crops production [50]. Other studies have reported that organic input prevents the rapid leaching of nitrogen fertilizer by immobilizing the nitrogen temporarily [51,52,53].

As for the management of crops residues, most farmers left crops residues in the plot (68% and 52% for Basse-Terre and Grande-Terre respectively). Some farmers removed crop residues from the field – 29% in Grande-Terre and 18% in Basse-Terre – or incorporated them into the soil (19% and 14% for Grande-Terre and Basse-Terre respectively). Crop residues can serve as a nutrient source for soil organisms [54]. Moreover, crop residues can improve soil structure, increase organic matter in soil and reduce evaporation [55]. At the same time, we examined soil biodiversity activity on the soil surface (observation of ant nests and earthworm casts), and most farms had an activity between high and medium. The presence of ant nests and earthworm casts may be an indicator of soil health. Our primary results gave us a better understanding of vegetable cropping systems in Guadeloupe and the impact of each practice on soil health.

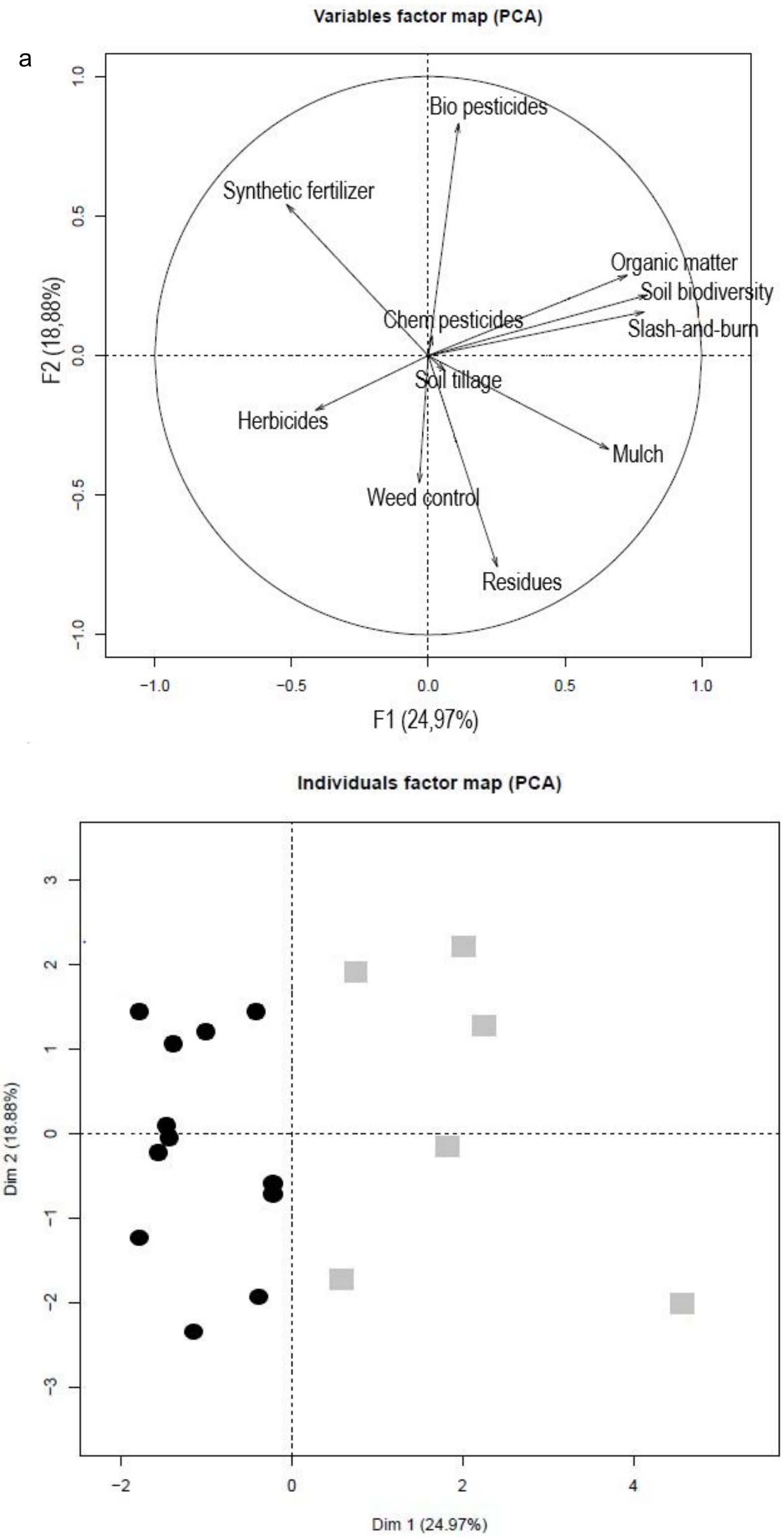
3.2 Typology of Farms Located on Vertisols

Based on the identification of cropping systems in Guadeloupe, we selected farmers from vertisols to demonstrate the relationship between cropping systems and the quality of soils proxied by biological indicators (abundance and diversity of soil fauna). We realized a typology on 18 farms located on vertisol in Grande-Terre based on PCA and AHC. The first two components of PCA explained nearly 43.85% of the total variation (Fig. 1 a). Axis F1 has a positive correlation with organic matter, soil biodiversity and slash-and-burn. At the opposite, axis F1 has a negative correlation with herbicides and synthetic fertilizer. Axis F2 opposed plots with biological pesticides to plots using weed control.

Our results showed that farmers from type A are using conventional intensive agricultural practices. These farms are the most numerous in Grande-Terre (Fig. 1c) and are characterized by an intensive to the medium application of synthetic fertilizers and herbicides. In this type, farmers do not use mulch and slash-and-burn methods. The observation on the soil activity showed low biodiversity (Fig. 1a, 1b, 1c). At the opposite, farmers from type B are using alternative agroecological farming practices. In particular, these farms are characterized by the application of organic matter, the use of biological pesticides or no pesticides, slash and burn and mulch. The residues are usually left on the field. Observation of soil activity showed rich biodiversity (Fig. 1a, 1b, 1c).

In our study, farmers from type A applied mineral fertilizer, which globally, improve crop yields and food security [56,57]. Nevertheless, the overdose of mineral fertilizer contributed to soil deterioration, water pollution, and soil biodiversity through soil acidification [58,59,60]. Farmers from type A also applied a high amount of herbicides which also had a negative effect on fauna, by reducing soil fauna abundance or fitness, due to the destruction of habitat and food resources [61]. On the contrary, in type B, the application of organic matter had a beneficial effect on diverse biological processes by being a food resource for various ecological groups in the community [62,63]. In addition, farmers of type B applied slash-and-burn, an alternative agroecological method. By using this method, farmers can actually maintain carbon stock and increase biodiversity [64,65,66,67]. Mulching also had a major impact on soil fauna abundance and diversity. Mulching is a form of cover crops that remains on the surface of the soil. It can be inorganic or organic material (plastic, straw, cover crop residues or live plant) and it is used to prevent soil erosion, increase water retention, pest control and weed control [10,68,69,70]. However, few of the surveyed farmers are using this method. Farmers using the cover crop method had positive feedback based on their crop production. Though, farmers, who used plastic had trouble recycling the plastic and plan on shifting to an ecological method.

Our results showed the impact of farming practices on soil biodiversity. In order to confirm this observation with quantitative data, we performed a soil macrofauna extraction on farms.



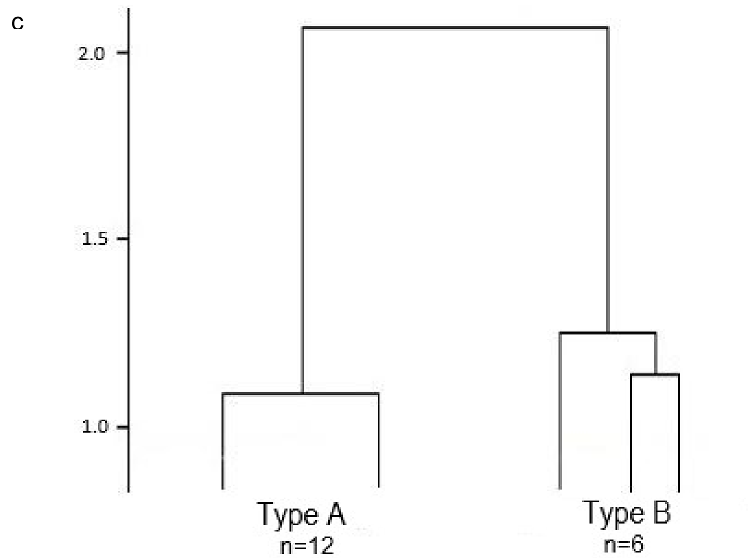


Fig. 1 (a) Projection of the variables used to elaborate the farm typology with Principal Component Analysis (PCA), (b) Representation of farms classified by type based on PCA components (● Type A and ■ Type B), and (c) Dendrogram chart obtained for the Agglomerative Hierarchical Clustering analysis (AHC) performed on components of the PCA; n represents the number of farms for each type. These analyses were carried out using R software

3.3 Soil Macrofauna on Farms Located on Vertisols

Soil macrofauna was collected on selected farms. We found 171 ± 52 (mean ± SE) individuals.m^{-2} in type A, and 554 ± 239 individuals.m^{-2} in type B. The abundance of soil fauna was slightly higher in type B (Fig. 2b). However, there was no significant difference in soil fauna abundance between both types (t-test Welch; $P = .13$). In general, ecosystems engineers were more abundant than litter transformers and predators (Fig. 2a). In type B, the number of ecosystem engineers (432 ± 229 individuals.m^{-2}) and predators (48.8 ± 16.88 individuals.m^{-2}) was slightly higher than in type A (ecosystem engineers: 116 ± 41 individuals.m^{-2}, biological regulators: 24 ± 6 individuals.m^{-2}). However, there was no significant difference between the number of ecosystem engineers and predators between type A and type B (t-test Welch; $P = .21$ and $P = 0.15$). On the other hand, the number of litter transformers was significantly different between the two types (t-test Welch; $P = .02$) (Fig. 2a). The number of litter transformers was higher in type B (72 ± 18 individuals. m^{-2}) than in type A (30 ± 10 individuals. m^{-2}). Also, in Fig. 2c, the taxonomic richness was significantly higher in type B (11 ± 0.4 taxonomic richness) compared to type A (6.5 ± 0.61taxonomic richness) (t-test Welch; $P < .001$).

Soil macrofauna may be used as bioindicators of soil health and contribute to ecosystems services [25]. Soil macrofauna plays an important role in soil organic matter decomposition (litter transformers), regulation of pests (predators), the formation of stable aggregates, water regulation and erosion control (ecosystems engineers) [71]. Our results showed that soil macrofauna may be directly or indirectly impacted by agricultural practices. In type A, we observed a number of intensive agricultural practices (deep tillage, application of high amounts of chemical pesticides, synthetic fertilizer, and herbicides), which are well known to have a negative impact on soil biodiversity [59]. Our study showed that litter transformers are strongly impacted by these intensive practices. They had an essential role in soil carbon sequestration [72]. As a consequence, by decreasing the number of litter transformers, intensive agriculture may have profound effects on climate change. On the contrary, by decreasing the input of synthetic

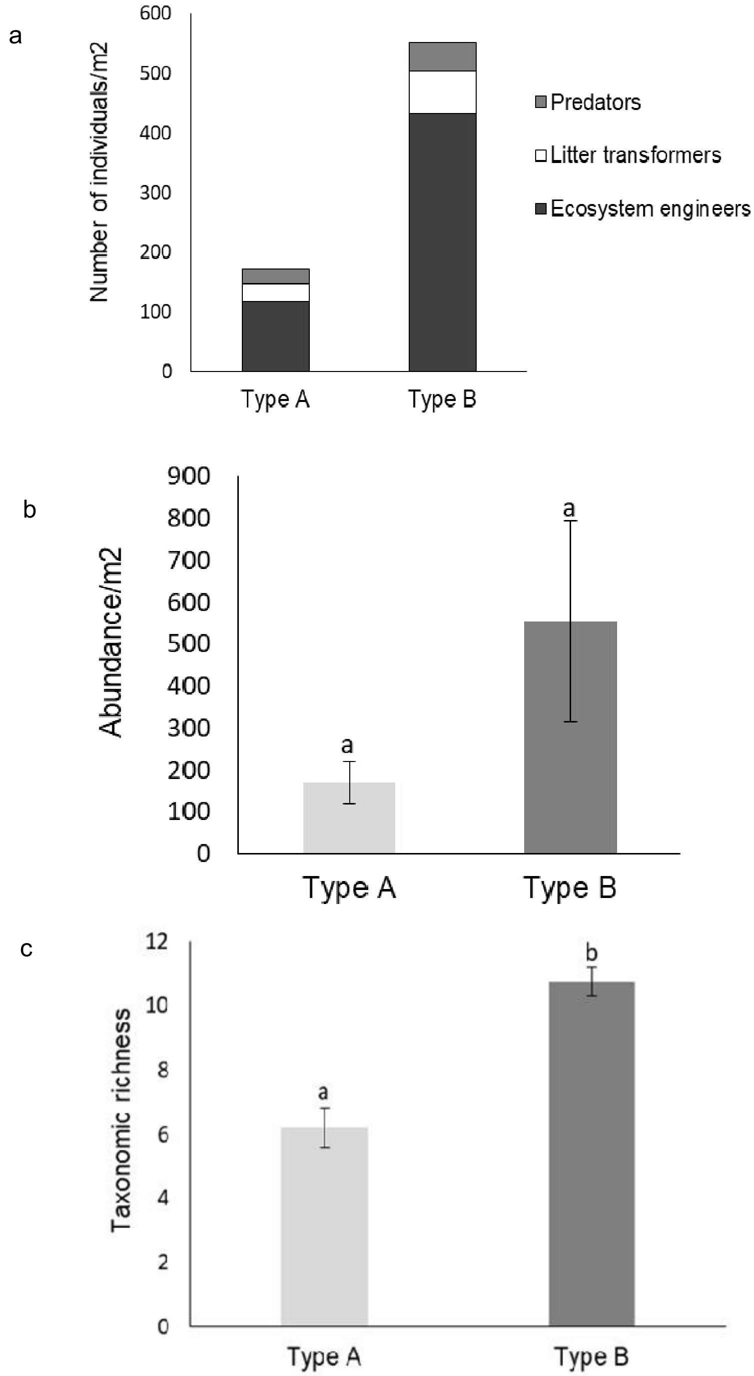


Fig. 2 (a) Soil fauna functional diversity in 9 farms (type A and type B) in Guadeloupe (Grande-Terre). (b) Soil fauna abundance in type A and B in Guadeloupe. (c) Taxonomic richness abundance in type A and type B in Guadeloupe. Values with similar letters are not significantly different (Welch t-test). These analyses were carried out using R software

fertilizers and herbicides, by reducing the rate of tillage and by increasing the application of organic matter, farmers in type B are stabilizing their soil. Moreover, type B applied mulching, which can have a positive effect on soil habitat. Mulching helps to preserve the ecosystem by reducing the rate of tillage. Sustainable agriculture also had a beneficial impact on soil physical and chemical properties, such as, aggregation and nitrogen content [73,74], which indirectly impacted soil fauna abundance and diversity. In order to overcome the impacts of intensive agriculture, sustainable agricultural methods have been developed to minimize environmental footprints and preserve natural environments and resources [75,30]. Our study showed that in Guadeloupe, farmers are looking for alternative agriculture practices in vegetable cropping systems. At the beginning of the study, we hypothesized that there was a positive correlation between the quality of practices developed in vegetable cropping systems and soil organisms. Those primary results tend to confirm this hypothesis, and in order to better understand the impact of those new agroecological practices, further physical, chemical and soil fauna analyses should be carried out.

4. CONCLUSION

Agricultural systems are continually re-designed based on a variety of parameters: climate changes, consumers demand, land reform as well as technological and scientific advances [76]. In our study, we wanted to know what kind of alternative agroecological practices are used in vegetable cropping systems in Guadeloupe, and whether such methods had positive impacts on soil biota. Thus, the survey gave us a better understanding of vegetable cropping systems and the level of eco-agriculture that actually occurs in Guadeloupe. For greater representativity, another survey should be conducted on a longer period of time. Secondly, we observed the effect of practices on soil biota in vertisol. As expected, intensive practices have a negative impact on soil biodiversity. On the other hand, alternative agroecological practices are in constant development, as a goal of improving agroecosystem health. Our study showed that in Guadeloupe, sustainable agriculture is present in vegetable cropping systems and is still in progress. Hence, further analyses should be conducted (physical, chemical and soil fauna) to assess the impact of alternative practices on soils in short and long time periods.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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