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Soil Fauna and Ecosystem Services in Agroecological Cropping Systems: Focus on Experimental Open-Field Market Gardens

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Abstract: Agroecological practices can be used to optimise ecological functions and improve the health of agroecosystems. The present study aimed to determine the effects of two agroecological systems (AG and AGSPP) on soil biodiversity and ecosystem services in tropical market gardens. The AG (agroecological) cropping system allows the use of organic phytosanitary products, unlike the second one (AGSPP, agroecological without phytosanitary products). The cropping systems were established in the open field and compared in terms of (i) soil fauna, (ii) soil fertility, (iii) soil aggregation, (iv) pest regulation, and (v) crop production. A total of eighteen months after the establishment of the experiment, the macrofaunal communities of the two cropping systems were significantly different. The AGSPP cropping system was characterised by a higher abundance of predators, a better soil structure, a higher tomato fruit set rate, and a lower pest proliferation. The increase in plant diversity and the non-use of phytosanitary products could modify the macrofaunal communities and, consequently, the provision of some ecosystem services. We also observed an effect of repellent and host plants on pest control in both systems, promoting high crop production. Overall, we showed that small changes in agroecological practices can have positive effects on soil biodiversity, pest regulation, and crop production.

Keywords: biodiversity; management of agricultural systems; push–pull pest management; refuge plants; soil aggregates; tropical agroecosystems

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1. Introduction

Soils are the most species-rich habitats of terrestrial ecosystems. They host a tremendous diversity, in terms of abundance, with a high number of species and functions of microorganisms, mesofauna and macrofauna [1]. Soil organisms provide essential ecological functions such as nutrient cycling, organic matter decomposition, maintenance of soil structure, or the control of pests and diseases in agricultural and natural ecosystems. These functions are the basis for the provision of ecosystem services [2]. Moreover, soil organisms may be used as bioindicators of the effect of human activity on soil [3].

Among the soil fauna, soil microarthropods (mainly collembola and mites) are an important component of terrestrial ecosystems due to their major role in regulating microbial populations and decomposing belowground detritus and nutrient mineralisation [4]. Moreover, the use of microarthropods to indicate soil quality has been much discussed due to their cosmopolitan distribution and different degrees of soil adaptation [5]. In particular, these organisms are often used to evaluate cropping systems [6]. Soil macrofauna (i.e., macroarthropods and earthworms) are also of key importance. They have the greatest potential to modify the soil environment through their activities [2,7]. Soil macrofauna organisms are able to improve soil physical structure and hydrology, stimulate organic matter decomposition, and influence nutrient and energy fluxes [8]. In agroecosystems, soil macrofauna can also play an important role in maintaining crop quality and soil fertility [9].

Agriculture is a vital activity for human societies that is expected to feed some 9 billion people by 2050. Currently, one of the main challenges for agriculture is to provide enough food for the growing world population while preserving the environmental quality [10,11]. Agroecology offers concepts, tools, and practices allowing the coherent use of ecological processes and the valuation of natural resources [12]. It uses methods based on multifunctionality and biodiversity to enhance ecological processes and the related ecosystem services [13]. Reduction in tillage, crop rotation and the increase in plant diversity, organic fertilisation, or permanent soil cover, are all popular practices in agroecological production systems [14]. All of these strategies share the same objective of minimizing or suppressing the use of synthetic inputs, enhancing organic matter recycling, and improving the health of agroecosystems, while maintaining high production levels [15]. However, the effect of these diverse agroecological practices on soil fauna communities remains poorly documented, in particular in the Caribbean region [11,16]. Growing awareness and increasing evidence that soil biodiversity is inextricably linked to the provision of soil-based ecosystem services appears in the literature [17]. Therefore, defining and designing cropping systems that better consider the belowground biodiversity and soil ecological processes are fundamental [18,19].

Since agroecological production systems integrate a large diversity of agricultural practices [14,20], these different processes can affect soil fauna differently. For these reasons, it is essential to analyse the influence of different agroecological practices on soil fauna communities. In this study, the "push and pull" strategy was used. This strategy consists of introducing plants with repellent properties ("push") and attractive trap plants ("pull") within the plot to keep pests away from the main crop [21]. It is based on a series of stimuli that alter pest behaviour. These stimuli can be visual, olfactory, tactile, or gustatory and can occur at different stages of the plant cycle [22]. We evaluated the effects of two sets of agroecological practices in tropical vegetable cropping systems on soil fauna diversity, soil properties and ecosystem services. For this purpose, we assessed the impact of a diversity of repellent and host plants on the abundance and the diversity of soil meso- and macrofauna, soil chemical characteristics, soil aggregation, and soil ecosystem services (crop production and pest regulation). We hypothesised that a higher level of plant diversity would increase the abundance and diversity of the soil fauna along with associated soil functions and soil-based ecosystem services.

This study focuses on the island of Guadeloupe (Caribbean region), where the agricultural landscape is characterised by a wide variety of production systems, reflecting the history of the territory and the socioeconomic constraints specific to tropical island environments. In Guadeloupe, agriculture is an important economic sector and a source of exports, based mainly on agro-industrial models developed with bananas and sugar cane. These two cropping systems have been well studied in Guadeloupe compared to vegetable cropping systems [23]. In order to have a better understanding of the vegetable cropping systems in Guadeloupe, a previous study was conducted on the whole territory [24]. This study showed that the practices used by local market gardeners do not promote soil biodiversity and do not optimise soil functions. Therefore, agroecological practices should be implemented in the vegetable production systems to contribute to the ecological transition of agriculture in this territory [24].

2. Materials and Methods

First, we organised two participatory workshops with farmers to design agroecological vegetable cropping systems that reduce soil degradation and provide organic resources. At the end of the workshops, two agroecological systems were designed based on the farmer's suggestions. Both systems (AG for agroecological; AGSPP for agroecological without phytosanitary products) included a combination of agroecological practices: (i) soil tillage must be shallow and performed with a disc harrow; (ii) crop cover: application of wood mulch as weed control; (iii) vermicompost is used as organic fertiliser; (iv) "push–pull" strategy: repellent and host plants have to be introduced in both systems: *Thymus vulgaris* L. (Lamiaceae), *Ocimum basilicum* L. (Lamiaceae), *Plectranthus neochilu* Schltr. (Lamiaceae), *Zea mays* L. (Poaceae), *Rosmarinus officinalis* L. (Lamiaceae) and *Hibiscus sabdariifa* L. (Malvaceae).

In the first system (AG) an additional recommendation was added: (v) in case of pest infestation or disease, the use of certified organic phytosanitary products was applied. The following substances were used: (i) Dipel® (organic insecticide, active ingredient: *Bacillus thuringiensis* subsp. *kurstaki*), (ii) the insecticide/acaricide Oviphyt® (active ingredient: petroleum jelly oil) and (iii) the Bordeaux mixture (fungicide, active ingredients: copper sulphate and calcium oxide).

In the second system (AGSPP), the farmers proposed to add a second barrier of plants to regulate pests and prohibited the use of pesticides including those approved for organic farming. Consequently, the following repellent and host plants were added in AGSPP plots: (v) *Plectranthus amboinicus* (Lour.) Spreng. (Lamiaceae), *Cosmos sulfureus* Cav. (Asteraceae), and *Tagetes patula* L. (Asteraceae). Based on their knowledge, farmers emphasised the fact that this second barrier of repellent and host plants can be time consuming. The main difference between both experimental systems was the way pests were controlled.

To facilitate monitoring and data collection, the two cropping systems were set up in an agricultural experiment station. These systems are characterised by operating under agro-pedoclimatic conditions close to those of the farmers. This experimentation was carried out on the island of Grande-Terre (Guadeloupe, French West Indies), which is characterised by a slightly undulating surface and a relief that rarely exceeds 40 m (above sea level) [23]. This island has an annual rainfall of 1500 mm, with temperatures ranging from 22 °C to 31 °C (Météo-France, https://meteofrance.gp/fr/climate, accessed on 1 September 2020). The experimental station (INRAE Godet) is located in the city of Petit-Canal (16°40′ N and 61°48′ W). The two cropping systems (Figure 1) were set up on a vertisol.

Figure 1. Agroecological market-gardening cropping systems AG and AGSPP (INRAE experimental station, Godet Petit-Canal, Guadeloupe).

Our two experimental cropping systems were established in an area previously planted with yams. As suggested by the farmers, before the first planting, the soil was superficially ploughed with a disc harrow and the beds were prepared. In the station, a total of ten experimental plots were set up (5 replicates for each cropping system). Each plot had a surface of 25 m^2 (5 m × 5 m) and was distant from each other by 10 m. Farmers designed the experiment as a theoretical prototype. It was implemented in the field to assess the agroecological systems' performance and risk [15]. Tomato (*Solanum lycopersicum* L., Heat Master variety) and lettuce (*Lactuca sativa* L.) were planted as commercial crops in both systems. The repellent and host plants were planted in March 2017. After one month, a number of 27 tomato plants and 50 lettuce plants were planted in each plot. We incorporated 100 g of vermicompost at the base of each tomato and lettuce plant. After the end of the tomato and lettuce harvest in July 2017, beans (*Phaseolus vulgaris* L.) were planted in each plot; 100 g of vermicompost were incorporated at the bottom of each bean plant. From October to December 2017, we realised a fallow with peas (*Vigna unguiculata* L. Walp.). In January 2018, a new cycle of tomato and lettuce crops were planted and 100 g of vermicompost were added at the bottom of each tomato and lettuce plant.

We achieved soil sampling at the beginning, in March 2017 (T0, on bare soil) and at the end of the experiment, in September 2018 (T18). In each experimental plot, one soil sample of 25 cm (length) × 25 cm (width) × 20 cm (deep) was taken from the middle of the plot for soil macrofauna extraction following the ISO 23611-S methodology. We collected only a single sample from the middle of each plot to avoid estimation errors due to autocorrelation and border effect. Macro-organisms were collected in alcohol, enumerated and identified at the morphospecies level under a dissecting microscope (Nikon E200 Led Trino). Species richness and Shannon index were calculated (using excel software, Excel 2021, version 16.0). The macro-organisms were also gathered in functional groups: litter transformers, predators, and ecosystem engineers [2], (Table S1).

From the middle of each experimental plot, one soil sample, 20 cm (length) × 20 cm (width) × 15 cm (depth), was taken for soil mesofauna extraction. Due to the size of the plots and the fact that we cannot take more than one sample per plot, we decided to take a larger sample than usual. Microarthropods were collected in alcohol using the Berlese extraction method, counted, and identified at the taxonomic level under a dissecting microscope. The organisms were classified into Acarina (subclass), Collembola (class), and other invertebrates.

Soil samples for chemical analysis (9 cm diameter × 15 cm depth) and soil aggregation assessment (8 cm diameter × 8.5 cm height cylinder) were taken from the centre of each plot at the beginning (T0, on bare soil) and end of the experiment (T18).

For chemical analysis, the soil samples were analysed at the SADEF (soil testing laboratory in France). The Dumas method was used to analyse total N [25]. Total C was measured according to NF ISO 10694. ICP-MS (NF EN ISO 17294 and NFX 31-147) was used to measure total P and total K. Finally, cation-exchange capacity (CEC) was measured using the IF07-10D (NFX 31-130) method and pH-H_2O was measured using NF ISO 1770, 3696 and 1146.

For soil aggregation, each sampled block was gently separated, air dried, and then sieved at 4 mm. All of the soil retained by the sieve was placed on filter paper and the different components were separated by gently breaking the soil along the lines of the natural fractures. We then sorted these components into different categories: (i) biogenic aggregates (rounded forms) created by macroinvertebrates, mainly earthworms, (ii) physical aggregates (angular forms) produced by the physical processes of the environment (especially alternating dry and wet periods), (iii) plant debris including roots, leaves, fragments of stems, seeds, and pieces of wood, (v) stones, and (vi) diverse (other elements). The separated samples were put in an oven at 60 °C for 15 days and weighed [26].

At the beginning of the plantation, 50 tomato plants and 50 lettuce plants were randomly selected, in each agroecological cropping system (10 plants per plot). We monitored the number of flower buds, flowers, and fruits on the 100 selected plants. Furthermore, we calculated the flowering rate (flowers/buds*100, %) and the fruit set rate (%). At the end of each crop cycle, we separated the above-ground biomass from the roots of each selected plant, in the laboratory. After 72 h in an oven at 70 °C, we measured the dried shoot and root biomass of the selected plants. We also weighed the tomato fruits collected from the selected plants in both treatments.

With the aim of counting pests and beneficials, we visually observed the aerial biodiversity in the tomato and lettuce plantations on a weekly basis for four months in 2018. Each week, the different plants were meticulously examined to identify the invertebrates present on the leaves and stems as well as signs of necrosis. Various invertebrates were identified at the morphospecies level. They were then classified into two categories: crop beneficials and crop pests. The presence or absence of the different morphospecies was noted according to the cropping system (AG or AGSPP).

Kruskal–Wallis tests were used to compare cropping systems' fauna, aggregation, and chemical soil characteristics at T18 for AG and AGSPP. The significance level threshold was set at 0.05. Wilcoxon Mann–Whitney tests were used to compare dry biomass, and the number of flower buds, flowers, and fruits. A rank abundance curve (RAC) of the cropping systems macrofauna was carried out to display relative species abundance. Analysis of Similarity (ANOSIM) was performed to compare macrofauna communities in both systems. All statistical analyses were performed using R software, version 3.5.0 [27].

3. Results

3.1. Soil Fauna

Regarding soil macrofauna abundance, we found at T0 an average of 446 ± 149 individuals·m^{-2}. At T18, we found 586 ± 353 individuals·m^{-2} and 1530 ± 368 individuals·m^{-2}, respectively, in AG and AGSPP. However, there was no significant difference in soil macrofauna abundance between AG and AGSPP. At T18, the abundance of ecosystem engineers and litter transformers were not significantly different between cropping systems (respectively, K = 4.88; p = 0.08 and K = 2.51; p = 0.28). Nevertheless, the abundance of predators was significantly higher in AGSPP (662 ± 191 individuals·m^{-2}) than in AG (90 ± 50 individuals·m^{-2}) (K = 8.81; p = 0.01). This difference was mainly due to the high abundance of Arachnida, Chilopoda, and Formicidae predators in AGSPP.

The total of number of macrofauna species collected at T18 was the same (20) in AG and AGSPP. The Shannon index ranged between 1 and 4.5. The mean Shannon index was 2.10 in AGSPP and 2.04 in AG at T18. Some species were present in both cropping systems, such as *Solenopsis invicta* Buren, *Camponotus sexgutattus* Cristobal, *Cardiocondyla emeryi* Forel (Formicidae), *Tetragnathidae* sp. (Arachnida), *Aphididae* sp. (Hemiptera), *Platyarthridae* sp. and *Philosciidae* sp. (Isopoda), the earthworm *Polypheretima elongata* Perrier, the Coleoptera *Colopterus* sp., the Dermaptera *Euborellia annulipes* Lucas, the Arachnida Thomisidae sp. and the Myriapoda *Geophilidiae* sp. Some other species were only found in AGSPP, such as the Formicidae *Cyphomyrmex minutus*, the Staphilinidae *Cafius* sp. and the earthworm *Pontoscolex corethrurus* Müller. The macrofauna communities differed significantly in both treatments (ANOSIM, R = 0.46, p = 0.024). The rank abundance curve showed that *P. elongata* and *Technomyrmex difficilis* Forel (Formicidae) were the two main abundant species in AG compared to *S. invicta* and *Colopterus* sp. in AGSPP (Figures 2 and 3). Regarding earthworms, we found an average of 144 ± 46 ind·m^{-2} in AG plots compared to an average of 70 ± 28 ind·m^{-2} in AGSPP plots. However, there were no significant differences between cropping systems (K = 3.84; p = 0.17). *P. elongata* was present in both systems (144 ± 46 ind·m^{-2} in AG and 32 ± 17 ind·m^{-2} in AGSPP). *P. corethrurus* was only present in AGSPP plots (7 ± 4 ind·m^{-2}).

Regarding the Acarina, 15,160 ± 5053 individuals·m^{-2} were found at T0. At T18, the abundance of Acarina was not significantly different in AGSPP (42,556 ± 1074 individuals·m^{-2}) compared to AG (42,134 ± 22,018 individuals·m^{-2}) (K = 5.77; p = 0.06). At T0, for the Collembola, we collected 573 ± 191 individuals·m^{-2}. The abundance of Collembola at T18 was not significantly different in AGSPP (5726 ± 2184 individuals·m^{-2}) compared to AG (3677 ± 988 individuals·m^{-2}) (K = 3.82; p = 0.07).

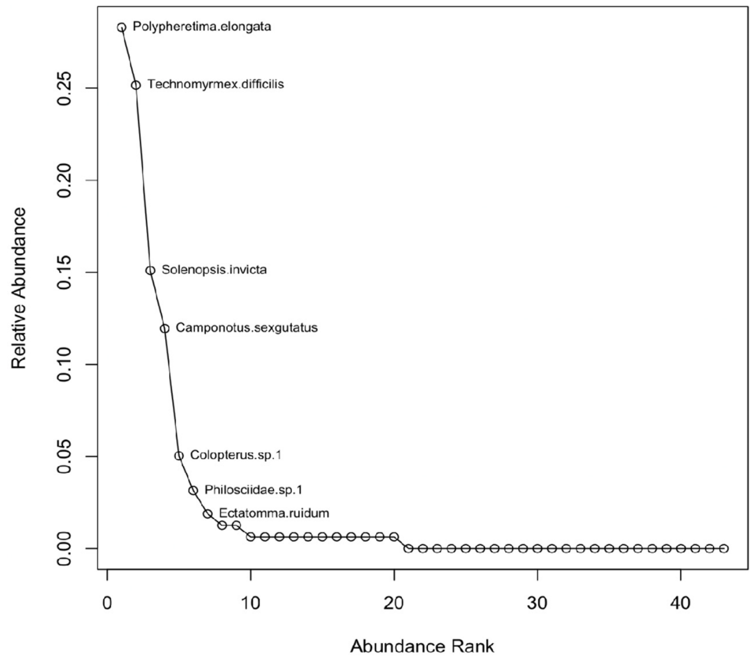

Figure 2. Rank abundance curve ("Whittaker plots"), showing the relative abundance of species characterizing in agroecological market-gardening cropping system (AG), 18 months after the experiment setup (Godet Petit-Canal, Guadeloupe).

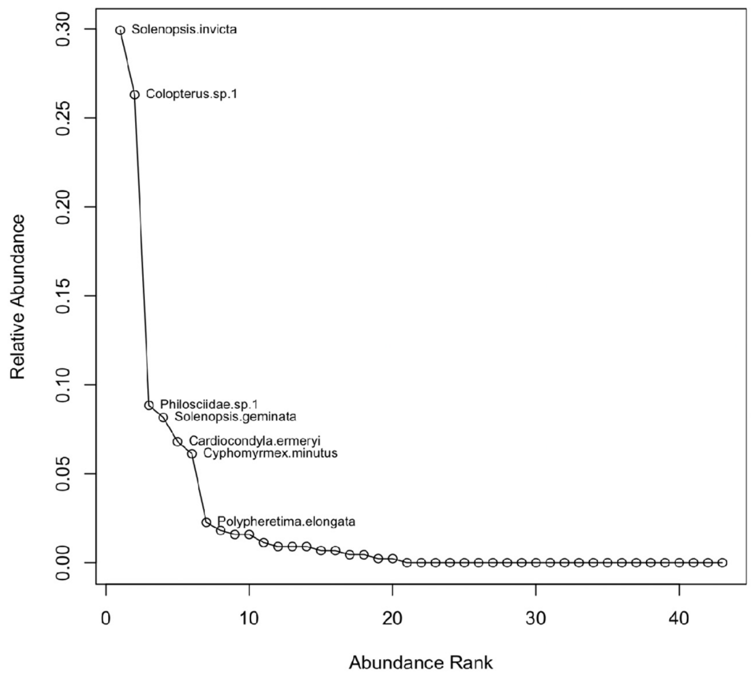

Figure 3. Rank abundance curve ("Whittaker plots"), showing the relative abundance of species characterizing in agroecological market-gardening cropping system (AGSPP), 18 months after the experiment setup (Godet Petit-Canal, Guadeloupe).

3.2. Soil Characteristics

Regarding the soil chemical properties, total N was significantly higher in AG compared to AGSPP. However, total P was greater in AGSPP than in AG (Table 1).

At T0, there was an average of 61% non-aggregated soil, 23% physical aggregates, and 10% biogenic aggregates. At the end of the experiment (T18), there was an average of 86% physical aggregates, 4% non-aggregated soil and less than 1% biogenic aggregates in the AG plots. There was an average of 55% biogenic aggregates, 31% non-aggregated soil, and 4% physical aggregates, in the AGSPP plots. At T18, the biogenic aggregates amount was significantly higher in AGSPP than in AG (K = 16.08; $p = 0.0003$). The percentage of non-aggregated soil was significantly higher in AGSPP compared to AG (K = 16.07; $p = 0.0003$). The physical aggregates amount was significantly higher in AG than in AGSPP (K = 12.16; $p = 0.002$).

Table 1. Soil chemical characteristics of two alternative market-gardening cropping systems (AG and AGSPP) on vertisol (Godet, Petit-Canal) 18 months after the setting up of the experiment. Means with the same letter are not significantly different according to Kruskal–Wallis test.

	AG	**AGSPP**	**K**	***p*-Value**
pH_{H2O}	7.84 ± 0.03	7.81 ± 0.07	0.54	0.47
CEC ($cmol{\cdot}kg^{-1}$)	43.50 ± 2.19	43.80 ± 1.56	0.00	1.00
N_{total} (‰)	2.99 ± 0.19 (a)	2.39 ± 0.06 (b)	6.82	0.009
C_{total} (‰)	26.72 ± 0.95	27.67 ± 0.97	0.54	0.47
K_{total} (‰)	1.77 ± 0.04	1.68 ± 0.07	1.84	0.18
P_{total} (‰)	0.55 ± 0.02 (b)	0.61 ± 0.01 (a)	4.77	0.03

3.3. Soil-Based Ecosystem Services

In the first year, the tomato harvest lasted three weeks. We obtained 6.7 $tons{\cdot}ha^{-1}$ in AGSPP and 4.69 $tons.ha^{-1}$ in AG. The plant's total dry biomass significantly differed between AGSPP and AG (W = 192; $p = 0.02$). For the lettuce crop, we obtained 3.3 $tons{\cdot}ha^{-1}$ in AGSPP and 1.76 $tons{\cdot}ha^{-1}$ in AG. There was no significant difference between AG and AGSPP for the plant's total dry biomass (W = 346; $p = 0.52$). In the second year, the tomato harvest lasted five weeks. We obtained 19.92 $tons{\cdot}ha^{-1}$ of tomato from AGSPP and 19.68 $tons{\cdot}ha^{-1}$ from AG. The plant's total dry biomass did not significantly differ across treatments (W = 1094; $p = 0.28$). We harvested 15.6 $tons{\cdot}ha^{-1}$ of lettuce in AGSPP and 13.3 $tons{\cdot}ha^{-1}$ in AG. The total dry biomass of plants varied significantly between treatments (W = 893; $p = 0.013$).

The number of flower buds was not significantly different between AG (3183 ± 4) and AGSPP (2939 ± 3.04) (W = 1462; $p = 0.14$). However, the number of flowers was significantly higher in AG (1615 ± 2.76) than in AGSPP (981 ± 1.15) (W = 1749; $p = 0.006$). The flowering rate was significantly higher in AG than in AGSPP: 51% of flower buds developed into flowers in AG compared to 33% in AGSPP (W = 1729; $p = 0.001$). Yet, there was no significant difference between AG (543 ± 1.07) and AGSPP (624 ± 0.80) regarding the number of tomato fruits (W = 1086; $p = 0.26$). Thus, the fruit set rate was significantly higher in AGSPP (64%) compared to AG (34%) (W = 350; $p < 0.0001$).

Mealybugs (*Pseudococcidae* sp.), whiteflies (*Bemisia tabaci*), and thrips (*Thrips tabaci*), which are highly damaging pests for tomatoes and lettuce, were found in both agroecological systems (Table S2). *Z. mays* mainly attracted mealybugs which are extremely harmful pests, especially for tomatoes.

Beneficial insects were also observed on the barrier of repellent and host plants (Table S2). We detected, in particular, the presence of *Danaus plexippus* (Lepidoptera Nymphalidae) in AGSPP plots. Furthermore, we observed the presence of Coccinellidae (*Coccinellidae* sp.1, *Coccinellidae* sp.2) on *Z. mays*, *O. basilicum*, *R. officinalis*, *H. sabdariifa*, *T. patula*, *P. neochilus*, and *C. sulphureus*.

4. Discussion

In this study, we studied soil fauna diversity, soil quality, and associated ecosystems services in two experimental agroecological systems. When comparing the two newly designed systems, the increase in predators in AGSPP plots could be due to the presence of refuge plants such as *C. sulphureus* and *T. patula.* Refuge plants can be a distraction to attract predators or natural enemies for natural pests [28]. *C. sulphureus* is known to attract a range of predators, such as Coleoptera (Coccinellidae, Carabidae and Staphylinidae), Hymenoptera (Formicidae, Sphecidae, Eumenidae and Vespidae) and Arachnida (Tetragnathidae, Lycosidae, Linyphiidae, and Araneidae) [29]. In the same way, *T. patula* is known to attract predators such as Coccinellidae, Staphylinidae (Coleoptera), and Arachnida [30,31].

The lower abundance of predators in AG could also be explained by the use of biological pesticides. In AG, the insecticide Dipel® was used during the crop cycle as an alternative practice to reduce synthetic pesticide risks and resistance development. Biological pesticides are efficient against pests, and they are biodegradable with no residuals in the environment. However, the use of biological pesticides can potentially affect non-targeted soil organisms. The bacteria (*Bacillus thuringiensis var. kurstaki*) present in Dipel® is used to fight against Lepidoptera pests in crops. However, these bacteria release toxins (Cry) which can have deleterious effects on Coleoptera, Diptera, Oligochaeta, Gastropods, Hymenoptera, Hemiptera, and Nematodes. The impact of these toxins can last from six months to a year after application [32].

In the AGSPP agroecological system, the increasing plant diversity inside the plots could modify the macrofauna communities and consequently, the provision of some ecosystem services. In terms of soil aggregation, it is known that organic farming systems support higher cast production, resulting in a higher soil structure formation [33]. However, in our study only the AGSPP plots have a high percentage of biogenic aggregates. The main difference between the two cropping systems was the presence of *Pontoscolex corethrurus* only in the AGSPP plots. It has been shown that this earthworm dramatically impacted the soils macrostructure and positively impacted the proportion of large macroaggregates [34]. A favourable macroaggregate structure develops in the presence of *P. corethrurus* and organic detritus [34]. However, the significant differences between the two cropping systems may also be explained by the higher plant diversity inside AGSPP plots. In fact, in vertisols, the introduction of plants leads to significant root development, which stimulates microbial activity in the rhizosphere. This also results in a considerable input of C into the system in various forms (sugars, debris, etc.). This production of C, in contact with the clay particles, allows the development of organo-mineral aggregates [35]. However, our results need to be confirmed by further large-scale studies.

Sustainable practices employed in the present study can explain the high production level measured. Vermicompost can have a positive effect on plant growth. According to Prabha et al. [36], the application of vermicompost may increase the quantity of phosphorus, potassium, iron, and zinc in tomato plants. Vermicompost's also have a high level of plant-available nitrate (compared to regular compost). It also has a very active phospholytic enzyme system [37]. Those nutrients can improve the development of tomato roots and increase leaf area. Ravindran et al. [38] also showed that vermicompost contributes to tomato growth and fruit production. It can stimulate plant flowering by increasing the number and biomass of flowers produced.

In our study, a "push–pull" strategy was used in both agroecological cropping systems to repel undesirable invertebrates and attract beneficial ones. This strategy may have contributed to the pest regulation of tomato and lettuce crops. Mealybugs, which are highly damaging pests, especially to tomatoes, were mainly attracted by *Z. mays*. These insects can cause damage by reducing photosynthesis and plant growth, which allows mould growth and virus transmission [39]. Furthermore, we observed the presence of Coccinellidae on several refuge plants. These Coccinellidae are predators of a wide range of pests such as Hemiptera, Pseudoccoccidae, Thysanoptera, and Acarina, in all regions of the world [40].

In our agroecological cropping systems, we observed that *Bemisia tabaci* (Aleyrodidae) caused minor damage. This may be due to the presence of *R. officinalis* which produces β-caryophyllene and limonene molecules, which attract *B. tabaci* [41]. This insect can be a vector of the tomato leaf-yellowing virus or the Tomato Yellow Leaf Curl (TYLC). This disease is one of the most devastating in the tropics and subtropics. The use of extract molecules from *T. vulgaris* (thymol, p-cymene, and carvacrol) and *R. officinalis* (1,8-cineole, camphene, and camphor) can also have a deleterious effect on the eggs and nymphs of *B. tabaci* [42].

Our observations also revealed the presence of thrips in both agroecological systems but their impact on crops was minimal. These insects are vectors of Tomato Spotted Wilt Virus (TSWV) on tomatoes and L-TSWV on lettuce [43]. According to Koschier and Sedy [44], *R. officinalis* essential oils have a repellent effect against *Thrips tabaci*. In contrast, *Thrips* sp. are attracted to *Tagetes* sp. plants, which served as trap plants and distracted insects from the cropping field [30]. The effects of host and repellent plants can explain negligible Thripidae attacks in our experimental cropping systems. Planting multiple types of crops within the same crop system (companion plantings) has been shown to limit the spread of disease and pests, thereby lessening the need for pesticides and making a more sustainable farming system [45].

5. Conclusions

In this experimental study, we observed an interesting effect on macrofauna communities by increasing plant diversity and the non-use of any phytosanitary products, in AGSPP plots. This system was characterised by a higher abundance of predators, a better soil structure (higher proportions of biogenic aggregates), a higher tomato fruit set rate, and a better pest regulation (Figure 4). Moreover, this agroecological system achieved a high crop yield level. The agroecological practices, in particular increasing plant diversity and the non-use of phytosanitary products, could thus be used to improve soil biodiversity and ecosystem services (soil structure, pest regulation, crop production). These agroecological practices may contribute to the objective of improving tropical cropping systems. Nevertheless, due to the small scale of our study, those experimental cropping systems need to be planted on a large-scale prototype with increased replication in multiple blocks, in order to confirm the effects observed in this preliminary experiment. The farmers expressed the wish to replicate this type of prototype on a larger scale. This would confirm the effects observed in this experiment. Further research is therefore needed to better understand agroecological practices and their impact on soil communities, and consequently, to think about scaling up innovations to promote the agroecological transition.

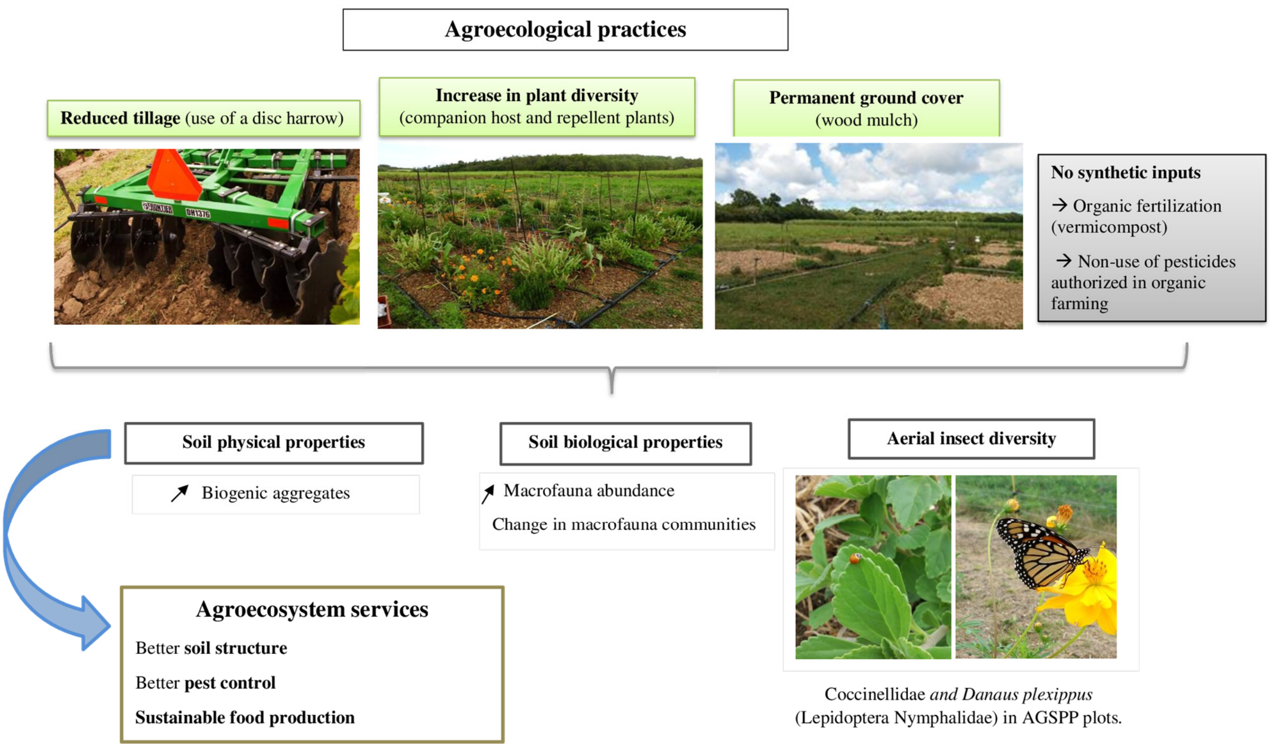

Figure 4. Assessment of the agroecological market-gardening cropping system AGSPP (increased plant diversity and non-use of phytosanitary products certified in organic farming).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/soilsystems8010026/s1, Table S1: Soil macrofauna morphospecies and functional groups in two agroecological market-gardening cropping systems on vertisol (Godet, Petit-Canal); Table S2: Aerial diversity observed on plants in two agroecological market-gardening cropping systems on vertisol (Godet, Petit-Canal).

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