Management practices and incidence of pests in plantain (Musa paradisiaca AAB) crops. Consequences on the sustainability of the cropping systems

Gladys Loranger-Merciris, Gaëlle Damour, Brunise Deloné-Louis Jeune, Harry Ozier-Lafontaine, Marc Dorel, Jorge Sierra, Jean-Louis Diman, Patrick Lavelle

Management practices and incidence of pests in Plantain (*Musa paradisiaca* AAB) crops. Consequences on the sustainability of the cropping systems.

Gladys Loranger-Merciris[a,*], Gaëlle Damour[b], Brunise Deloné-Louis Jeune[c], Harry Ozier-Lafontaine[c], Marc Dorel[b], Jorge Sierra[c], Jean-Louis Diman[d], Patrick Lavelle[e]

[a] Université des Antilles, UMR ISYEB-MNHN-CNRS-Sorbonne Université-EPHE, UFR Sciences Exactes et Naturelles, Campus de Fouillole, 97157 Pointe-à-Pitre Cedex (Guadeloupe), France

[b] CIRAD UPR GECO, Site de Neufchâteau, Sainte Marie, 97130 Capesterre-Belle-Eau, Guadeloupe, France

[c] ASTRO Agrosystèmes tropicaux, INRAE, 97170, Petit-Bourg (Guadeloupe), France

[d] UE PEYI, INRAE, 97170, Petit-Bourg (Guadeloupe), France

[e] Institut de Recherche pour le Développement/ Université Pierre et Marie Curie IEES, 32 rue Henri Varagnat, 93143 BONDY Cedex, France

* Corresponding author at : Université des Antilles, UMR ISYEB-MNHN-CNRS-Sorbonne Université-EPHE, UFR Sciences Exactes et Naturelles, Campus de Fouillole, 97157 Pointe-à-Pitre Cedex (Guadeloupe), France

E-mail address: Gladys.Loranger@univ-antilles.fr

ABSTRACT

Plantain (*Musa paradisiaca* AAB) is one of the most important staple crops in the tropics, particularly in the Caribbean. Pests are the main constraint to plantain production and yield increases may be possible by improving pest management. However, there is a lack of data on these cropping systems and a need to identify new elements of improved production systems that can control pests in line with the principles of agroecological transition. In this study, we test the hypothesis that crops grown in good quality soils are less susceptible to pests. To this end, an agroecological diagnosis of the biological, physical, morphological and chemical soil conditions and the occurrence of pests, in particular plant-parasitic nematodes, was carried out on 21 plantain plots with contrasting management in Guadeloupe (French West Indies). After classifying these plots according to their management practices, from conventional to agroecological, we searched for relationships between cropping systems, soil quality and pests using a series of synthetic quality indices. Four different cropping systems were identified and compared: conventional intensive, intermediate, low-input and agroecological, according to the type and amount of agrochemicals used. Our data showed that the Chemical Index was significantly improved in the agroecological systems due to increases in pH, CEC, base saturation and total C and N content. The Morphological Index increased regularly from intensive to agroecological systems and was significantly higher in agroecological systems with higher proportions of biogenic aggregates. Soil macroinvertebrate communities were significantly influenced by production systems, with the highest values of the Macrofauna Index in low input and agroecological production systems. We also showed that plant parasitic nematodes were better regulated in agroecological production systems. Furthermore, the agroecological system achieved similar levels of crop production to conventional systems, without the use of pesticides. In addition, these agroecological cropping systems extend the duration of plantain plots, which is an indicator of the good health of these systems.

Keywords: Agroecological diagnosis; Pest control; Plant health; Soil biodiversity; Tropical agroecosystems

1. Introduction

Plantain (*Musa paradisiaca*, AAB) is a major food resource in the tropics. This crop plays an important socio-economic role for developing countries in tropical and subtropical zones. Indeed, plantain provided food security and income for small growers who represent the majority of producers in the tropics (Kahane et al., 2013). It generates an important source of income for producing countries (Tchango Tchango et al., 1999) and constitutes the staple diet of more than 400 million people living in many developing countries, particularly in Africa, Latin America and the Caribbean (Lassoudière, 2011). In 2020, plantain was grown in 54 countries and more than 43 million tons were produced worldwide (FAOSTAT, 2021). 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). In spite of this, plantain is confronted to numerous sanitary constraints, which affect its sustainability. Accordingly, production and yield gains can be increased through pest control improving, indeed the major constraint for plantain production (Godefroid et al., 2017).

Soil organisms provide essential ecological functions in agricultural and natural ecosystems. These functions are the basis for the provision of ecosystem services (Bardgett and Van der Putten, 2014; Adhikari and Hartemink, 2016; Brussaard, 2021). Agriculture is one of the human activities that relies on the soil as a support, but also as a resource. However, artificializing practices of conventional agriculture have often had negative impacts on the environment, such as groundwater contamination, biodiversity loss and soil degradation (Tamburini et al., 2020; Lavelle et al., 2022). These environmental disturbances result in the degradation of some of the ecosystem services provided by soils (Millennium Ecosystem Assessment, 2005).

The major underground pests in plantain cropping systems are nematodes (mainly *Radopholus, Pratylenchus* and *Helicotylenchus*) and black weevils (Gold and Tinzaara, 2008; Quénéhervé, 2009). Plant parasitic nematodes attack roots, inducing plant toppling and yield reduction. The banana black weevil, *Cosmopolites sordidus*, attacks the plant underground corm, causing stem breakage. At the present time, these pests are mainly controlled by synthetic pesticides which has generated major side effects on environment (soil and water pollution, disappearance of domestic biodiversity and auxiliary fauna, ...) but also on human health (Millennium Ecosystem Assessment, 2005). As an example, in Guadeloupe, the use of chlordecone to control *C. sordidus* in dessert banana plantations has resulted in a severe long-term pollution of soils and water and has reinforced the anxiety of consumers about the quality and safety of food production (Cabidoche et al., 2009; Levillain et al., 2012). There is a critical need for alternative plantain cropping systems that better conserve environmental quality while sustaining crop yield and regulating pests (Loranger-Merciris et al., 2022). Reduction of agrochemical inputs is the target proposed, especially in Guadeloupe where ecosystems have attained high levels of contamination (Ozier-Lafontaine and Lesueur-Jannoyer, 2014).

Soil organisms but also physical and chemical properties of soil affect plant vigour. Low soil biodiversity is actually associated with greater vulnerability to pests, due to altered natural regulation of these pests (Nielsen et al., 2015). Moreover, some studies showed an unexpected positive relationship between the frequency of pesticide applications and the occurrence of pests and diseases (Altieri and Nicholls, 2000). On the other hand, only few studies have actually reported a positive relationship between soil quality, plant health and pest regulation (e.g., D'Hose et al., 2014), and none to our knowledge, has been done in plantain plantations.

This study aimed at identifying elements of cropping systems that would reduce the impact of pests and diseases and, thus, decrease the need for pesticides. For this, we realized an extensive comparative diagnosis of biological, morphological, physical and chemical soil conditions and plant disease occurrence in 21 farms with contrasted management of plantain in Guadeloupe (French West Indies). Plots were classified according to their management practices. We then calculated synthetic indexes to summarize the information collected for soil quality and plant health at each farm, and we linked theses indexes to the types of management practices. Throughout this study, we tested the hypothesis that plants grown in good quality soils are less prone to pests.

2. Material and Methods

2.1. Site information and study design

The study was carried out in the western island (Basse-Terre) of the Guadeloupe archipelago (15°59'-16°9' N, 61°34'-61°43' W) in the Caribbean, where most plantain plantations are found. We selected a plot in twenty-one farms. Farms were selected on the basis of a preliminary survey of 100 farms to have a representation of all production systems. Plots were all located between 0 m and 150 m altitude, with annual rainfall ranging from 2 to 3 m and mean annual temperature around 23°C. Soils are Haplic Nitisols (FAO-UNESCO classification, Driessen et al., 2001) developed on volcanic ashes. They are clayey and are mainly composed of halloysite (Clermont-Dauphin et al., 2004). Nitisols are similar to Ferralsols, but they are younger and therefore less evolved, less desaturated and generally less acidic. The cation contents (Ca, Mg and K) are typically higher than in Ferralsols.

For each plot, cropping systems were described with seven variables: the origin of plants (plants issued for tissue culture vs. suckers); the previous crop (fallow, plantain or pineapple); the longevity of the plot (perennial vs. annual); the number of pesticide applications (0, 1 or 2 applications of Nemathorin® per year); herbicide applications (0 to 2 or 3 to 5 applications of Basta® per year); fertilization (organic manure, low input chemical -2 to 3 applications of N20-P20-K20 fertilizer per year-, high input chemical -4 to 8 applications of N20-P20-K20 fertilizer per year-); and soil tillage before plantain plantation (with or without). All plots were planted with French cultivar.

In each plot, soil chemical, morphological and physical parameters, soil macroinvertebrate and plant-root parasitic nematode communities were assessed next to the stem of five plants selected at random at the flowering stage. Data collected within each plot were averaged to provide mean values for each of the 21 selected plots. Thus, for each measured variable within each plot values represent means of five replicates.

2.2. Soil chemical characteristics

Soil chemical properties were measured 30 cm apart from each selected plantain plant. For each plant, a sample was taken from a soil block and analysed for total soil C and N using an auto-analyser (NF ISO 13878, 1998). Available P was measured using the Olsen method (Dabin, 1967). Soil mineral N ($N0_3^-$ and NH_4^+) was measured by colorimetry after extraction with a 0.5M KCl solution. Exchangeable Ca^{2+}, Mg^{2+}, 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. Soil physical and morphological characteristics

Soil physical properties were measured 50 cm apart from each selected plantain plant. Three undisturbed 100 cm^3 soil cores (50 mm in diameter × 50 mm in length) were collected in order to measure bulk density, water content, useful water reserve and water retention at two different potentials, pF 2 (-0.01 MPa) and pF 4.2 (-1.5 MPa).

A morphological assessment of soil macroaggregates and other elements (Velasquez et al., 2007b) provided an integrative measure of accumulated soil biological activity (Lavelle et al., 2014). An undisturbed soil sample taken with an 8 cm diameter × 8.5 cm height cylinder was collected 50 cm apart from each selected plantain plant. 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 five categories: i) biogenic aggregates of rounded forms, created by macroinvertebrates, ii) root aggregates, iii) physical aggregates of angular forms, produced by the physical processes of the environment (especially alternating dry and wet periods), iv) non-macro aggregated soil (soil passing through the 2 mm sieve), and v) other components (roots, stones, litter, wood…). The separated elements were put in an oven at 60 °C for 15 days and weighed (Velasquez et al., 2007b).

2.4. Macroinvertebrate communities

Soil macro-invertebrates were hand sorted from soil monoliths taken 30 cm apart from the 5 selected plants of each plot, following the ISO 23611-S methodology (ISO, 2011). A central monolith 25 cm × 25 cm × 20 cm was completed with two lateral 25 cm × 25 cm × 10 cm blocks located 1 m N and S, respectively, apart from the central point. Macro-invertebrates were classified into fifteen groups: Diplopoda, Ants, Termites, Earthworms, Coleoptera, Chilopoda, Isopoda, Dermaptera, Blattodea, Araneidae, Heteroptera, Gasteropoda, terrestrial Turbellaria, Homoptera and Orthoptera. Macroinvertebrate density at each point was taken as the sum of the three monoliths. Individuals were also classified in three functional groups: ecosystem engineers, litter transformers and predators (Turbé et al., 2010).

2.5. Pests and plant characteristics

Primary roots were removed from a 25 cm × 25 cm × 30 cm soil block located 30 cm apart from the 5 sampled plants. Plant-feeding nematodes were extracted from an aliquot of the roots (100 g) using a centrifugal-flotation method (Coolen and d'Herde, 1972). Populations were counted in aliquots and expressed as number of nematodes per 100 grams of root fresh biomass. The main plant-parasitic species were identified and counted under a light microscope.

To assess the severity of root damage, a 25 cm × 25 cm × 30 cm soil block located 30 cm apart from the 5 sampled plants was removed. Roots were removed in the whole volume of soil, carefully washed and cut longitudinally. Necrosis rates on the respective external and internal surfaces of these roots were scanned independently using the WinRHIZO 2009a Software (Regent Instruments Canada, Inc.). The colour of root necrosis due to soil-borne pathogens varied from reddish to black while healthy roots were white. The necrosis index was expressed as necrosed surface area over total root surface area.

Weevil *C. sordidus* populations were estimated using pheromone-baited pitfall traps (Reddy et al., 2008). One trap was put in the middle of each plot and was collected after 30 days (one sample by plot). Weevils were trapped in soapy water. Plant yield was estimated by bunch weight for each selected plantain plant. The average harvest time is 12 months from planting.

2.6. Data analyses

All the data sets used for statistical treatments are grouped in Supplementary Table S1. All analyses were performed with the R software (R Core Team, 2013, R 3.1.2).

A multiple correspondence analysis (MCA) was run on the 7 variables describing the cropping systems (function “dudi.pca”, package “ade4”, Chessel et al., 2004). A hierarchical cluster analysis using the Ward linkage method (minimum variance criterion) and Euclidian distances was run on MCA-axes 1 and 2 scores, to analyse distances between plots and group plots according to their cropping systems. Differences in MCA-axes 1 and 2 scores among groups were further tested by one-way ANOVAs (normality was assessed with Shapiro-Wilk tests), followed by Tukey post hoc tests (function “Tukey HSD”, package “stats”).

Principal Component Analysis (PCA) of each of the 5 sets of data (chemical soil properties, physical soil properties, soil morphological characteristics, macroinvertebrate communities, and pests) were performed. Monte Carlo tests on the coordinates of plots on the factorial axes allowed identifying significant differences among cropping systems. These analyses were done with the ade4 library (Chessel et al., 2004).

We then calculated synthetic indexes, defined as a set of statistically selected soil attributes that incorporate key functions, which for our study corresponded to: soil physical properties, soil morphological characteristics, soil chemical properties, macroinvertebrate communities, and plant pests. Synthetic indicators were designed and calculated for each point using a methodology proposed by Velasquez et al. (2007a). Briefly, for each PCA, we selected, for the two first axes, the variables with highest contributions (with a weight at least higher than 50% of the maximum contribution calculated for F1 and F2 of the PCA). Then, the values of each variable set, adjusted to a range of 0.1 to 1.0 by a homothetic transformation, were multiplied by their corresponding weight factors and summed, giving i) Physical Index, ii) Morphological Index, iii) Chemical Index, iv) Macrofauna Index, and v) Pest Index (for the calculation details, see Rodriguez et al., 2021).

In a last step, a PCA analysis of all plots characterized by the set of the 5 synthetic indexes generated allowed to analyse co-variations among the indicators and localize each plot in the factorial space thus defined. Finally, a Monte Carlo test on plot coordinates allowed to test significant differences among cropping systems. These analyses were done with the ade4 library (Chessel et al., 2004).

3. Results

3.1. Cropping systems

The first two axes of the MCA run on the seven variables related to the cropping system (Supplementary Table S1) explained 46.9% of the total variance of the observations (data not shown). The first axis alone explained 33.6% of this variance and opposed sites with highly intensive practices (tillage, 5 to 6 applications of chemical fertilizer, repeated pesticide applications and annual cropping systems with local seeds), to sites with agroecological practices (organic fertilization, zero application of chemical fertilizer, limited use of herbicides and planting with vitroplant seeds in perennial crops), (Supplementary Fig. S1). Plots were divided in 4 clearly separated groups (Fig. 1; Supplementary Fig. S2).

Groups 1, 2 and 3 are annual plots planted with suckers separated along axis 2 of the analysis according to their relative degree of intensification that increases from 3 to 1 (Table 1). Group 1, called “intensive” cropping system, is characterized by high levels of pesticides

(2 applications during the crop cycle), herbicides (3 to 5 applications) and mineral fertilizers use (4 to 8 applications). Group 2, called “intermediate” cropping system, is characterized by an intensive use of herbicides (3 to 5 applications during the plantation cycle), moderate use of pesticides (1 application at the plantation) and moderate use of mineral fertilizers (2 to 3 applications during the plantation cycle). Group 3, referred as “low input” cropping system, is characterized by moderate levels of pesticides and mineral fertilizer applications (respectively 1, and 2 to 3 applications during the plantation cycle) and no herbicides. Group 4 (called “agroecological” system) is separated from the other 3 along axis 1 of the MCA (Fig. 1). It is comprised of perennial plots, planted with seeds issued from tissue culture conducted with organic fertilization (manure). Pesticides were not used and 0 to 2 applications of herbicides had occurred in the last 12 months. In this group, unlike the others, there was no tillage.

3.2. Soil chemical characteristics

PCA analysis performed on the matrix of chemical characteristics significantly separated the four production systems ($p<0.01$). Factor 1 (48.61% explained variance) separated the agroecological system, with better chemical conditions (Fig. 2a, 2b). Analyses of variance showed that soil pH-H_2O and pH-KCl were significantly higher in agroecological systems compared to other systems. Soil N-NH_4, N-NO_3, total N, total C, CEC, K, Mg, P and Na content did not significantly differ among the four cropping systems. Despite this, the highest total C and N contents were observed in the agroecological system. Moreover, Ca content was significantly higher in agroecological systems compared to intensive systems. Therefore, the Chemical Index was significantly enhanced in agroecological systems compared to other systems, due to high pH, CEC, base saturation and total C and N contents (Fig. 2c).

3.3. Soil physical and morphological characteristics

PCA analysis performed on the matrix of physical characteristics did not separate the four production systems ($p>0.01$). Soils generally had rather low bulk densities around 0.9, especially in the conventional cropping systems (Supplementary Table S1). Soil in the agroecological systems were comparatively more compact, although with bulk densities of less than 1.2, and a remarkably low value of water retention at pF 4.2 which indicate of a very low proportion of pores of ≤ 0.15 µm. The Physical Index did not exhibit significant differences among cropping systems.

PCA analysis performed on the matrix of morphological characteristics significantly separated the agroecological system from the others ($p<0.01$, Fig. 3a, 3b). On average, a rather large proportion (49.4%) of the soil volume was macro-aggregated with large variations from 14.1 to 81.3% depending on treatments and sites. Biogenic aggregates comprised 31.4% of the total soil mass and physical aggregates 5.9%. There was a clear trend for soils to have a larger proportion of biogenic aggregates along the sequence from high inputs (23.8% of the total soil weight on average), to intermediate and low and agroecological cropping systems (46.1% of the total soil weight). Agroecological systems had significantly higher proportions of biogenic aggregates than the other three, and lower proportions of physical aggregates and non-aggregated soils than intensive and low input systems. Subsequently, the non-aggregated soil volume was higher in other systems (54.8%) compared to agroecological systems (33.9%). The proportion of physical aggregates was also higher in intensive systems (8.7%) as compared to low input systems (4.7%). The Morphological Index regularly increased from intensive to agroecological systems; it was significantly higher in agroecological than in conventional systems (Fig. 3c).

3.4. Soil macroinvertebrate communities

Soil macroinvertebrate communities varied among cropping systems, with respective densities ranging from a minimum value of 357 ± 48 ind.m^{-2} to a maximum of 886 ± 112 ind.m^{-2} and an overall average of 618 ± 135 ind.m^{-2}. Regardless the cropping system type, ants were the most abundant group (26%) followed by earthworms (25%), diplopods (23%) and termites (7%). Communities were significantly impacted by production systems (global PCA randtest $p<0.01$, Fig. 4a, 4b) with highest values of the Macrofauna Index in low input

(3) and agroecological (4) production systems (Fig. 4c). Taxonomic richness did not vary significantly among cropping systems.

3.5. Pests and plant production

PCA analysis performed on the matrix of pests did not separate the four production systems (p>0.01). However, plant parasitic nematode communities varied among cropping systems, ranging from 60809 ± 39413 to 180166 ± 53667 ind.100 g roots^{-1} Total population of plant parasitic nematodes was not significantly different among cropping systems. Nevertheless, *Radopholus similis* population was significantly reduced in agroecological and intensive systems and was higher in intermediate and low input systems (Table 2). *Helicotylenchus multicinctus* population, on the contrary, was significantly higher in agroecological cropping systems (Table 2).

The severity of root damage induced by parasites also varied within cropping systems. The root necrosis index was lower, although not significantly, in intensive and agroecological systems (respectively, 37 ± 3 % and 36 ± 5 %) compared to intermediate and low input systems (respectively, 54 ± 4 % and 43 ± 3 %).

Black weevil captures varied among cropping systems, ranging from 16 ± 2 ind.month^{-1} to 64 ± 3 ind.month^{-1}.The abundance of black weevils was not significantly different among cropping systems.

The Pest Index exhibited rather important variations among cropping systems, with highest values in the intermediate system and lowest on average in the intensive system despite a large variability.

Plant yield (expressed by bunch weight) averaged 15.6 ± 0.8 kg in low input systems, 16.6 ± 1.3 kg in intermediate systems, 17.2 ± 1.5 kg in agroecological systems and 19.7 ± 0.8 kg in intensive systems. Differences, however, were not significant.

3.6. Covariations

PCA analysis performed on the matrix of farm general Chemical, Physical, Morphological, Macrofauna and Pest indexes significantly separated the four production systems ($p<0.01$). Factor 1 (40% explained variance) separated the agroecological system, with better morphological and chemical conditions from the other 3 ones that had higher values of the physical indicator. Factor 2 showed a clear opposition between sites with high macrofaunal index (mostly found in low input (3) and agroecological (4) systems) and sites of production systems 1 and 2 with higher values of the Pest Index (Fig. 5a, 5b).

4. Discussion

4.1. Cropping systems and soil health

Around the world, plantain is mostly cultivated in traditional, extensive systems, and consumed locally (Tchango Tchango et al., 1999). Plantain cropping systems in Guadeloupe are comparatively more intensive with high inputs of mineral fertilizers, pesticides and herbicides. Only 14% of the plots have been classified as agroecological and 28% as low input, characterized by the predominant use of organic fertilizers, and low applications of pesticides and herbicides. In Guadeloupe, plantain plantations are mainly found in the banana crop region. They coexist with intensive banana dessert monocultures that use high amounts of pesticide and mineral fertilizers (Sierra et al., 2015). Most plantain producers indeed use similar farming practices as those used in banana dessert crops with 8-12 applications of chemical fertilizer during the growth season in monocultures (Sierra et al., 2015).

Our study showed that soil morphological, macrofauna and chemical characteristics were improved under agroecological plantain cropping systems. We observed in these systems a significant accumulation of biogenic aggregates. The high concentration of biogenic aggregates in agroecological plots can be partly explained by the reduction of tillage, which results in improved stability of the soil structure within a few years (Haynes, 2000). This can be reinforced by the maintenance of a permanent litter of plant residues on the soil surface. A previous study carried out on Guadeloupean andosols showed that deep tillage caused a decrease in soil organic matter content (Clermont-Dauphin et al., 2004). Indeed, our results suggest that in agroecological systems, favourable soil structure could be maintained by macrofaunal activity, as previously reported by Velasquez and Lavelle, 2019.

Macrofauna characteristics were also improved in low input and agroecological cropping systems. In a recent study, Lavelle et al. (2022) showed that the worldwide abundance of soil macroinvertebrate communities drastically decreases in conventional cropping systems. In our study, the increase in macrofauna abundance within the ecological friendly cropping systems may be due to moderate levels of pesticides, herbicides and mineral fertilizer applications (Sánchez-Moreno et al., 2009; Niedobová et al. 2019; Loranger-Merciris et al., 2022; Zulu et al. 2022).

In addition, our results showed that the Chemical Index was significantly enhanced in agroecological systems compared to other systems, due to high pH, CEC, base saturation and C and N contents. Sihi et al. (2017) found that long-term application of organic residues in basmati rice crop improved physical, chemical, and biological indicators of soil health. These authors observed that organic residues addition favoured biologically available nutrients in organic systems, and stimulated soil microorganisms that produce enzymes responsible for the conversion of unavailable nutrients to plant available forms. Thus, this study indicates, as ours, that agroecological farming practices may promote biotic and abiotic interactions in the soil which may support sustainable agriculture.

4.2. Cropping systems, pests and plant health

The plant-parasitic nematode communities sampled in our investigation (*H. multicinctus*, *Hoplolaimus* sp, *Meloidogyne* sp, *Pratylenchus coffeae*, *R. similis*, *Rotylenchus reniformis*) was similar to previous studies carried out on plantain cropping systems in Côte d'Ivoire (Adiko and Badou N'Guessan, 1999), Rwanda (Sebasigari, 1990), and Cuba (Rodriguez and Rodriguez, 1999). An interesting result of our study was that *R. similis,* the most destructive species on *Musa* sp., was absent in the agroecological perennial cropping systems. This can be explained by the fact that these plots were planted with vitroplants and thus were healthy at the beginning. This result highlights that particular attention should be paid to the sanitary state of the plant material used during plantain plantation for ensuring plantation durability. In this sense, it has been already observed that the use of healthy plants, obtained through the PIF technique (Lefranc et al., 2010; Sadom et al., 2010), significantly reduced pest infestations at the beginning of the plantation (Loranger-Merciris et al., 2022). In contrast, the higher density of *H. multicinctus* observed in agroecological perennial banana plantations showed that these ectoparasite nematodes are more persistent in more organic cropping systems. This same result was obtained by Pierrot et al. (2002) in plantain plantations in Cameroon. An important fact is that *H. multicinctus* is not the most damaging on banana (effect on bunch weight) as shown by Moens et al. (2006). The dynamics of plantain roots can also alter the ratio of *H. multicinctus* to *R. similis* (Quénéhervé et al., 2011). Indeed, the proportion of old roots (potential resource for *H. multicinctus*) increased in agroecological perennial plantain plots compared to that of young roots (potential resource for *R. similis*), (Tixier et al., 2008).

We also showed that pest occurrence, in particular plant-parasitic nematodes communities, was minimal in agroecological cropping systems. Our study revealed that cropping systems may impact populations of the plant parasitic nematode *R. similis* and subsequent effects on plant health. In fact, *R. similis* population was significantly reduced in agroecological systems characterized by a low use of agrochemicals, which indicates that organic amendments can regulate plant parasitic nematode populations in plantain crops, as already observed for banana (Pattison et al., 2006; Tabarant et al., 2011). These authors suggested that the regulation of these plant parasitic nematodes was associated with an increase in the diversity and functional composition of soil nematode communities. 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. The equilibrium state of communities also limits pest development (Altieri, 1999). As an example, in Senegal, millet is attacked by two main nematode species, *Tylenchorhynchus gladiolatus* and *Scutellonema cavenessi*. These two species represent more than 95% of the nematode community of these agroecosystems. When millet fields were left fallow, the number of these two nematodes decreased, while there was a marked increase in the numbers of other nematodes. Interestingly, the level of damage caused by the two main pest nematode species was reduced when they were associated with other plant-feeding nematodes such as one of those recovering during fallow periods, *Helicotylenchus dihystera* (Cadet et al., 2002).

R. similis populations were also reduced in intensive cropping systems presumably as a result of the application of chemical nematicides which protected plants, as least temporarily. In fact, chemical nematicides only allow a partial and short-term control of nematodes (Moens et al., 2004). This justifies, the local adoption of short-time duration of intensive plantain plots; e.g., 1 cycle in 85% of the cases, and 2 or more cycles in 15%. Nevertheless, these chemical nematicides can be damaging to human health and the environment (Matthews, 2006). Overall, our study highlights the fact that the agroecological system has the same performance in terms of pest control as the conventional system, but without the application of pesticides.

Conclusion

Our study clearly showed that well managed agroecological systems can provide the same level of production and plant protection than intensive conventional systems, while improving soil quality and pest regulation. As a matter of fact, our data highlighted that there was a significant improvement in Chemical, Morphological and Macrofauna indexes in agroecological plantain cropping systems as well as a better regulation of plant parasitic nematodes. Moreover, these agroecological cropping systems lengthen the duration of plantain plots (in our study, agroecological systems are cultivated for the duration of 3 to 10 cycles). This longevity is an indicator of the good health of the agroecological cropping systems. Furthermore, in these agroecological systems, production costs may be significantly reduced by eliminating costly replanting and equally costly pesticide applications, while maintaining yield levels that are at least equivalent to conventional intensive cropping systems, characterized by a strong use of agrochemicals. However, the problems faced by plantain production, particularly a high level of telluric parasitism, led the majority of farmers to promote intensive cultural practices that aim at reducing pests without restoring soil health and the sustainability of the cropping systems. Yearly plant renewal and a massive use of agrochemicals in conventional systems enable to compensate for the lower general quality of the soil. Fast transitions from conventional to agroecological systems are possible. However, the main condition for rapid adoption of these eco-friendly cropping systems is the implementation of appropriate public policies.

Acknowledgements

The authors thank all the farmers involved in this study. The authors 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.

This work was supported financially by the French Ministry of Ecology and Sustainable Development, France (ECOPHYTO program, project ALTERBIO).

References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services. A global review. Geoderma 262, 101-111. https://doi.org/10.1016/j.geoderma.2015.08.009

Adiko, A., Badou N'Guessan, A., 1999. Evolution de la nématofaune du bananier plantain (*Musa* AAB) en Côte d'Ivoire, InfoMusa 10, 26-27.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19-31. https://doi.org/10.1016/S0167-8809(99)00028-6

Altieri, M.A., Nicholls, C.I., 2000. Agroecología: teoría y práctica para una agricultura sustentable. First Ed. Programa de las Naciones Unidas para el Medio Ambiente, México.

Bardgett, R.D., van der Putten W.H., 2014. Belowground biodiversity and ecosystem functioning. Nature 515, 505-511. https://doi.org/10.1038/nature13855

Brussaard, L., 2021. Biodiversity and ecosystem functioning in soil: The dark side of nature and the bright side of life. Ambio 50, 1286-1288. https://doi.org/10.1007/s1328002101507-z

Cabidoche, Y.M., Achard R., Cattan P., Clermont-Dauphin C., Massat F., Sansoulet J., 2009. Long term pollution by chlordecone of tropical volcanic soils in the French West Indies: A simple leaching model accounts for current residues. Environ. Pollut. 157, 1697-1705. https://doi.org/10.1016/j.envpol.2008.12.015

Cadet, P., Spaull, V.W., McArthur, D.G., 2002. Role of plant parasitic nematodes and abiotic soil factors in growth heterogeneity of sugarcane on a sandy soil in South Africa. Plant Soil. 246, 259-271. https://doi.org/10.1023/A:1020624114434

Chessel, D., Dufour, A.B., Thioulouse, J., 2004. The ade4 package -I- One-table methods. R News 4:5-10.

Clermont-Dauphin, C., Cabidoche, Y.M., Meynard, J.M., 2004. Effects of intensive monocropping of bananas on properties of volcanic soils in the uplands of the French west indies. Soil Use Manage. 20, 105-113. https://doi.org/10.1111/j.14752743.2004.tb00345.x

Coolen, W.A., D'herde, C. J., 1972. A method for the quantitative extraction of nematodes from plant tissue. Ghent, State Nematology and Entomology Research Station, 77 p.

Dabin B., 1967. Sur une méthode d'analyse du phosphore dans les sols tropicaux. Colloque sur la fertilité des sols tropicaux. Tananarive, 19-25 Nov., I, 99-115.

D’Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van Bockstaele, E. and Reheul, D., 2014. The positive relationship between soil quality and crop production: a case study on the effect of farm compost application. Appl. Soil Ecol. 75, 189-198. https://doi.org/10.1016/j.apsoil.2013.11.013

Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F., 2001. Lecture notes on the major soils of the world. FAO, Rome.

Ferris H., Bongers T., 2006. Nematode indicators of organic enrichment. J. Nematol. 38, 3-12.

FAOSTAT, 2021. Food and Agriculture Organization of the United Nations. FAO Rome.

Godefroid, M., Tixier, P., Chabrier, C., Djigal, D., Quénéhervé, P., 2017. Associations of soil type and previous crop with plant-feeding nematode communities in plantain agrosystems. App. Soil Ecol. 113, 63-70. https://doi.org/10.1016/j.apsoil.2017.01.012

Gold, C.S., Tinzaara, W., 2008. Banana Weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). In: Capinera, J.L. (Ed) Encyclopedia of Entomology. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6359-6_224

Haynes, R.J., 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biol. Biochem. 32, 211-219. https://doi.org/10.1016/S0038-0717(99)00148-0

ISO, 2011. Qualité du sol - Prélèvement des invertébrés du sol - Partie 5: Prélèvement et extraction des macro-invertébrés du sol. ISO 23611-5: 2011.

Kahane, R., Hodgkin, T., Jaenicke, H. Hoogendoorn, C., Hermann, M., Keatinge, D.J.D.H., D'arros, H.J., Padulosi, S., Looney, N.E., 2013. Agrobiodiversity for food security, health and income. Agron. Sustain. Dev. 33, 671-693. https://doi.org/10.1007/s13593-013-0147-8

Lassoudière, A., 2011. Le bananier, un enjeu mondial. Pour la Science n° 400, février 2011.

Lavelle, P., Rodríguez, N., Arguello, O., Bernal, J., Botero, C., Chaparro, P., Gómez, Y., Gutiérrez, A., Hurtado, M., Loaiza, S., Xiomara Pullido, S., Rodríguez, E., Sanabria, C., Velásquez, E., Fonte, S.J., 2014. Soil ecosystem services and land use in the rapidly changing Orinoco River Basin of Colombia. Agric. Ecosyst. Environ. 185, 106-117. https://doi.org/10.1016/j.agee.2013.12.020

Lavelle, P., Mathieu, J., Spain, A., Brown, G., Fragoso, C., Lapied, E., De Aquino, A., Barois, I., Barrios, E., Barros, M. E., Bedano, J. C, Blanchart, E., Caulfield, M., Chagueza, Y., Dai, J., Decaens, T., Dominguez, A., Dominguez, Y., Feijoo, A., Folgarait, P., Fonte, S. J., Gorosito, N., Huerta, E., Jimenez, J. J., Kelly, C., Loranger, G., Marchao, R., Marichal, R., Praxedes, C., Rodriguez, L., Rousseau, G., Rousseau, L., Sanabria, C., Suarez, J. C., Tondoh, J. E., De Valenca, A., Vanek, S. J., Vasquez, J., Velasquez, E., Webster, E. and

Zhang, C. (2022). Soil macroinvertebrate communities: a worldwide assessment. Glob. Ecol. Biogeogr. 31,1261-1276. https://doi.org/10.1111/geb.13492

Lefranc, L.M., Lescot, T., Staver, C., Nkapnang, I., Temple, L., 2010. Macropropagation as an innovative technology: Lessons and observations from projects in Cameroon. Acta Hortic. 879, 727-734. https://doi.org/10.17660/ActaHortic.2010.879.78

Levillain, J., Cattan, P., Colin, F., Voltz, M., Cabidoche, Y.M., 2012. Analysis of environmental and farming factors of soil contamination by a persistent organic pollutant, chlordecone, in a banana production area of French West Indies. Agric. Ecosyst. Environ. 159, 123-132. https://doi.org/10.1016/j.agee.2012.07.005

Loranger-Merciris, G., Ozier-Lafontaine, H., Diman, J.L., Sierra, J., Lavelle, P. (2022). Fast improvement of macrofauna communities and soil quality in plantain crops converted to agroecological practices. Pedobiologia 93-94, 150823, https://doi.org/10.1016/j.pedobi.2022.150823.

Matthews, G.A., 2006. Pesticides: health, safety, and the environment. Blackwell, Oxford, 248 p.

Millennium Ecosystem Assessment, 2005. Ecosystem and Human Well-Being: Synthesis, Island Press, 137 p.

Moens, T., Araya, M., Swennen, R., de Waele D., 2004. Enhanced biodegradation of nematicides after repetitive applications and its effect on root and yield parameters in commercial banana plantations. Biol. Fertil. Soil 39, 407-414. https://doi.org/10.1007/s00374-004-0726-6

Moens, T., Araya, M., Swennen, R., Waele, D., 2006. Reproduction and pathogenicity of *Helicotylenchus multicinctus*, *Meloidogyne incognita* and *Pratylenchus coffeae*, and their interaction with *Radopholus similis* on *Musa*. Nematology 8, 45-58. https://doi.org/10.1163/156854106776179999

Niedobová, J., Krištofová, L., Michalko, R., Hula, V., Kýnický, J., Brtnický, M., 2019. Effects of glufosinate-ammonium herbicide and pod sealant on spider *Pardosa agrestis*. J. Appl. Entomol. 143, 196-203. https://doi.org/10.1111/jen.12574

Nielsen, U.N., Wall, D.H. and Six J. (2015). Soil Biodiversity and the Environment. Annu Rev. Environ. Resour. 40, 63-90. https://doi.org/10.1146/annurev-environ-102014-021257

Ozier-Lafontaine, H., Lesueur-Jannoyer, M., 2014 (Eds). Sustain. Agric. Rev. 14, Agroecology and Global Change.

Pattison, T., Cobon, J., Sikora R., 2006. Soil quality improvement and nematode management on banana farms in Australia. XVII Reunião Internacional ACORBAT, 15-20 october 2006, Vol. 1, Joinville, Santa Catarina, Brasil, pp. 268-283.

Picq, C. Fouré, E., Frison, E.A., 1998. Bananas and Food Security. Les productions bananières : un enjeu économique majeur pour la sécurité alimentaire. International symposium, Douala, Cameroon, 10-14 November 1998. INIBAP, Montpellier, 797 p. https://agritrop.cirad.fr/300693/1/ID300693.pdf

Pierrot, J., Achard, R., Temple, L., Abadie, C., Fogain, R., 2002. Déterminants de la production de plantain dans le sud-ouest du Cameroun : intérêt d'un observatoire. Fruits 57, 75-86.

Quénéhervé, P., 2009. Integrated management of banana nematodes. In: Ciancio, A., Mukerji, K. (eds) Integrated management of fruit crops nematodes. Integrated management of plant pests and diseases, vol 4. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-9858-1_1

Quénéhervé, P., Barrière, V., Salmon, F., Houdin, F., Achard, R., Gertrude, J-C., Marie-Luce, S., Chabrier, C., Duyck, P.F., Tixier, P., 2011. Effect of banana crop mixtures on the plant-feeding nematode community. Appl. Soil Ecol. 49,40-45. https://doi.org/10.1016/j.apsoil.2011.07.003

R Core team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/

Reddy, G.V.P., Cruz, Z.T., Naz, F. and Muniappan, R. (2008). A pheromone-based trapping system for monitoring the population of *Cosmopolites sordidus* (germar) (Coleoptera: Curculionidae). J. Plant Prot. Res. 48, 515-527. https://doi.org/10.2478/v10045-009-0001-1

Rodriguez, S.A, Rodriguez J.L., 1999. Aspectos cocio económicos del cultivo del plátano en Colombia. Oficina Regional de Planeación-Corpoica, Regional Nueve. Manizales, 6-9.

Rodriguez, L., Suárez, J.C., Pulleman, M., Guaca, L., Rico, A., Romero, M., Quintero, M., Lavelle, P., 2021. Agroforestry systems in the Colombian Amazon improve the provision of soil ecosystem services, Appl. Soil Ecol. 164, 103933, https://doi.org/10.1016/j.apsoil.2021.103933

Sadom, L., Tomekpé, K., Folliot, M., Côte, F.X., 2010. Comparaison de l'efficacité de deux méthodes de multiplication rapide de plants de bananier à partir de l'étude des caractéristiques agronomiques d'un hybride de bananier plantain (*Musa* spp.). Fruits 65, 3-9. https://doi.org/10.1051/fruits/2009036

Sánchez-Moreno, S., Alonso-Prados, E., Alonso-Prados, J.L., García-Baudín, J.M., 2009. Multivariate analysis of toxicological and environmental properties of soil nematicides. Pest Manag. Sci. 65, 82-92. https://doi.org/10.1002/ps.1650

Sebasigari, K., 1990, les charançons et les nématodes du bananier dans les pays C.E.P, Burandi, Rwanda-Zaire, 80-81.

Sierra, J., Causeret, F., Diman, J.L., Publicol, M., Desfontaines, L., Cavalier, A., Chopin, P., 2015. Observed and predicted changes in soil carbon stocks under export and diversified agriculture in the Caribbean. The case study of Guadeloupe. Agric. Ecosyst. Environ. 213, 252-264. https://doi.org/10.1016/j.agee.2015.08.015

Sihi, D., Dari, B., Sharma, D.K., Pathak, H., Nain, L., Sharma, O.P., 2017. Evaluation of soil health in organic vs. conventional farming of basmati rice in North India. J. Plant Nutr. Soil Sc. 180, 389-406. https://doi.org/10.1002/jpln.201700128

Tabarant, P., Villenave, C., Risède J.M., Estrade, J.R., Thuriès, L., Dorel, M., 2011. Effects of four organic amendments on banana parasitic nematodes and soil nematode communities. Appl. Soil Ecol. 49, 59-67. https://doi.org/10.1016/j.apsoil.2011.07.001

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield, Sci. Adv. 6(45):eaba1715, https://doi.org/10.1126/sciadv.aba1715

Tchango Tchango, J., Bikoï, A., Achard, R., Escalan, J.V., Ngalani, J.A., 1999. Plantain: post-harvest operations. AGSI/FAO, 60 p.

Tixier, P., Salmon, F., Chabrier, C., Quénéhervé, P., 2008. Modelling pest dynamics of new crop cultivars: the FB920 banana with the *Helicotylenchus multicinctus* - *Radopholus similis* nematode complex in Martinique. Crop Prot. 27, 1427-1431. https://doi.org/10.1016/j.cropro.2008.06.004

Turbé, A., Toni, A., Benito, P., Lavelle, P., Ruiz, N., Van der Putten, W.H., Labouze, E., Mudgal, S., 2010. Soil biodiversity: functions, threats and tools for policy makers. Bio Intelligence Service, IRD, and NIOO, Report for European Commission (DG Environment).

Velasquez E., Lavelle, P., Andrade, M., 2007a. GISQ, a multifunctional indicator of soil quality. Soil Biol. Biochem. 39, 3066-3080. https://doi.org/10.1016/j.soilbio.2007.06.013

Velasquez, E., Pelosi, C., Brunet, D., Grimaldi, M., Martins, M., Rendeiro, A.C., Barrios, E., Lavelle, P., 2007b. This ped is my ped: Visual separation and near infrared spectra allow determination of the origins of soil macroaggregates. Pedobiologia 51, 75-87. https://doi.org/10.1016/j.pedobi.2007.01.002

Velasquez, E., Lavelle, P., 2019. Soil macrofauna as an indicator for evaluating soil based ecosystem services in agricultural landscapes. Acta Oecol. 100, 103446. https://doi.org/10.1016/j.actao.2019.103446

Zulu, S.G., Motsa, N.M., Sithole, N.J., Magwaza, L.S., Ncama, K., Soil macrofauna abundance and taxonomic richness under long-term no-till conservation agriculture in a semi-arid environment of South Africa. Agronomy 12, 722. https://doi.org/10.3390/agronomy12030722

Table 1

Description of the four groups of plantain plots identified in the hierarchical analysis and described as different cropping systems. Number into brackets following pesticide, herbicide and fertilizer levels are the mean number of applications during the plantation cycle observed in the plots of these groups.

	Group 1	Group 2	Group 3	Group 4
Cropping system name	Intensive	Intermediate	Low input	Integrated
Origin of plant material	Sucker	Sucker	Sucker	Tissue culture
Plot longevity	Annual	Annual	Annual	Perennial†
Pesticide application‡	High (2)	Moderate (1)	Moderate (1)	None (0)
Herbicide application§	High (3-5)	High (3-5)	None	Low (0-2)
Fertilization	Mineral# (4-8)	Mineral# (2-3)	Mineral# (2-3)	Organic
Tillage	Annual	Annual	Annual	None (0)

† 3 to 10 cycles

‡ 1 application of Nemathorin® (active ingredient Fosthiazate) at the plantation or 2 applications of Nemathorin® at the plantation and 6 months after the plantation.

§ application of Basta ® (active ingredient Glufosinate)

1 application of Diammonium phosphate (DAP) at the plantation, then application of a complete N20-P20-K20 fertilizer

Table 2

Plant parasitic nematode communities in 4 types of plantain cropping systems in Guadeloupe. Values are means of 5 samples (± SE). For each nematode species, means with different upper script letter are significantly different based on HSD test ($P \leq 0.05$).

	Intensive	Intermediate	Low Input	Agroecological	P
R. similis	2093 ± 2017 [a]	18294 ± 12630 [ab]	39758 ± 16102 [b]	0 ± 0 [a]	0.003
P. coffeae	116769 ± 34910 [a]	137516 ± 80124 [a]	85987 ± 29217 [a]	37527 ± 32568 [a]	0.621
H. multicinctus	320 ± 255 [ab]	21690 ± 21603 [ab]	19 ± 19 [a]	20776 ± 16780 [b]	0.031
Meloidogyne sp.	3171 ± 1964 [a]	2666 ± 1611 [a]	1378 ± 1105 [a]	2471 ± 1444 [a]	0.556
R. reniformis	80 ± 46 [a]	0 ± 0 [a]	135 ± 85 [a]	18 ± 10 [a]	0.271
Hoplolaimus sp.	70 ± 53 [a]	0 ± 0 [a]	0 ± 0 [a]	17 ± 12 [a]	0.120

Figure captions

Fig. 1. Distribution of plots and groups in the F1F2 factorial plane of the MCA. G1: “intensive”, G2: “intermediate”, G3: “low input” and G4: “agroecological” cropping system.

Fig. 2. Projection of (a) plots and groups and (b) variables in the factorial plane F1F2 of a PCA analysis of a matrix of chemical characteristics in plantain cropping systems. c) Soil Chemical Index in plantain cropping systems. 1: “intensive”, 2: “intermediate”, 3: “low input” and 4: “agroecological” cropping systems. Means with different upper script letter are significantly different based on HSD test.

Fig. 3. Projection of (a) plots and groups and (b) variables in the factorial plane F1F2 of a PCA analysis of a matrix of morphological characteristics in plantain cropping systems. AB: Biogenic aggregates, AR: Root aggregates, AP: Physical aggregates, NA: non macroaggregated soil. c) Soil Morphological Index in plantain cropping systems. 1: “intensive”, 2: “intermediate”, 3: “low input” and 4: “agroecological” cropping systems. Means with different upper script letter are significantly different based on HSD test.

Fig. 4. Projection of (a) plots and groups and (b) variables in the factorial plane F1F2 of a PCA analysis of a matrix of macroinvertebrates communities in plantain cropping systems. OLI: Earthworms, ISO: Isopoda, DIPL: Diplopoda, CHI: Chilopoda, DER: Dermaptera, FOR: Formicidae, TER: Termites, COL: Coleoptera, RTAX: Taxonomic richness. c) Soil Macrofauna Index in plantain cropping systems. 1: “intensive”, 2: “intermediate”, 3: “low input” and 4: “agroecological” cropping systems. Means with different upper script letter are significantly different based on HSD test.

Fig. 5. Projection of (a) plots and (b) variables grouped into plantain cropping systems of decreasing intensity from 1 (Intensive) to 4 (Agroecological) in the factorial plane F1F2 of a PCA analysis of a matrix of soil indexes.

Fig. 1

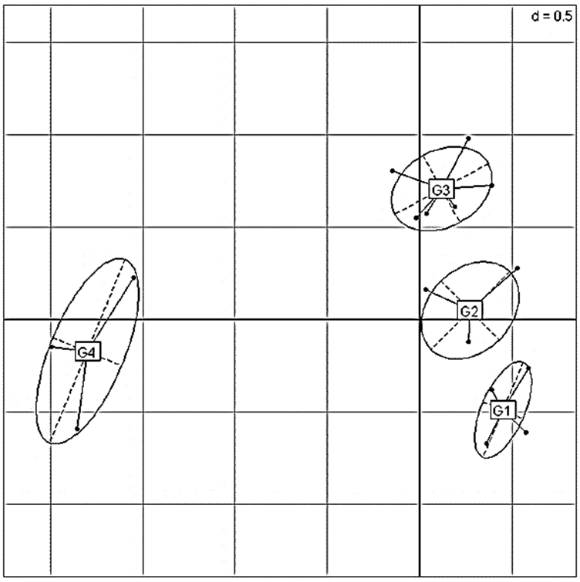


Fig. 2

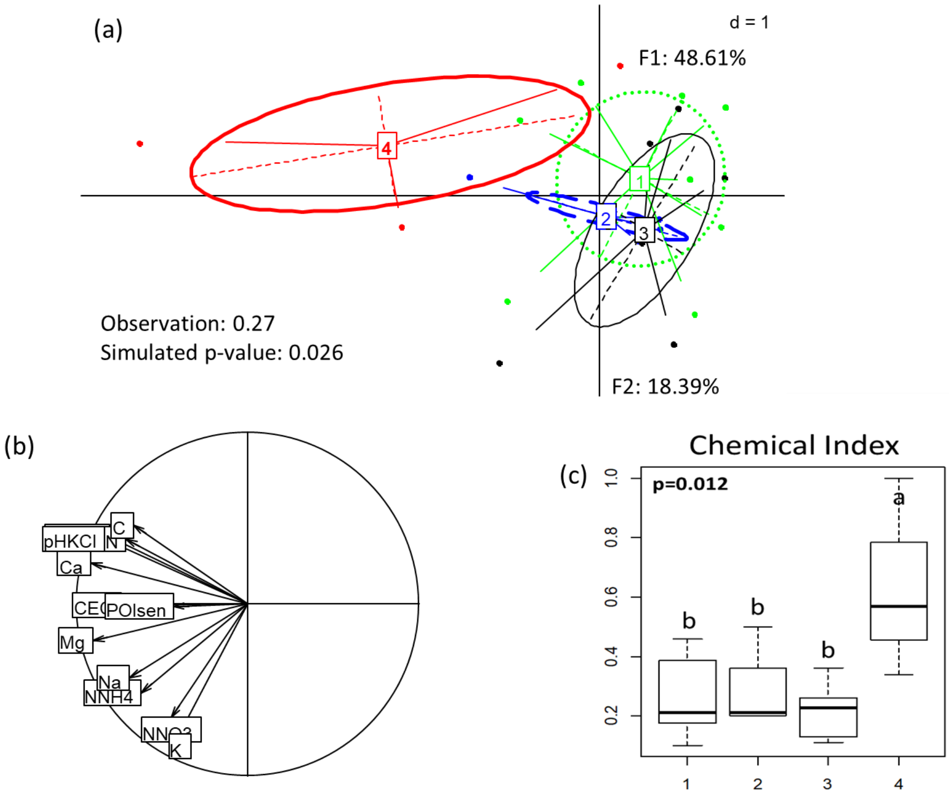

(a)
d = 1
F1: 48.61%
F2: 18.39%
Observation: 0.27
Simulated p-value: 0.026
1
2
3
4
(b)
C
pHKCl
N
Ca
CEC
POlsen
Mg
Na
NNH4
NNO3
K
(c)
Chemical Index
p=0.012
1.0
0.8
0.6
0.4
0.2
b
b
b
a
1
2
3
4

Fig. 3

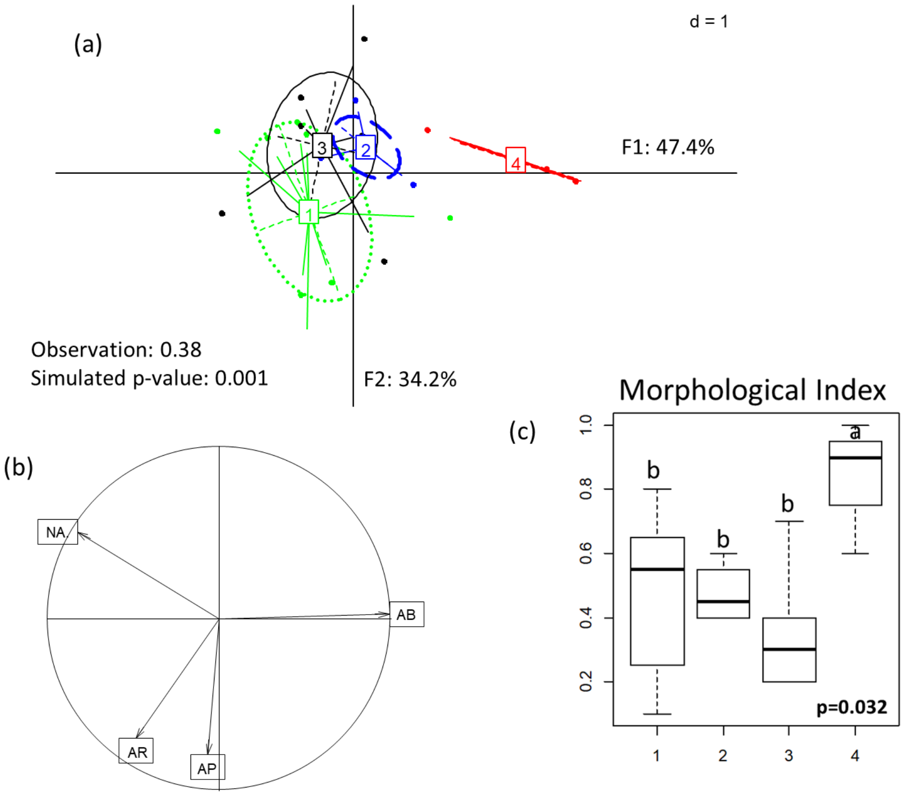

(a)
d = 1
F1: 47.4%
F2: 34.2%
Observation: 0.38
Simulated p-value: 0.001
1
2
3
4
(b)
NA
AB
AR
AP
(c)
Morphological Index
1.0
0.8
0.6
0.4
0.2
a
b
b
b
p=0.032
1
2
3
4

Fig. 4

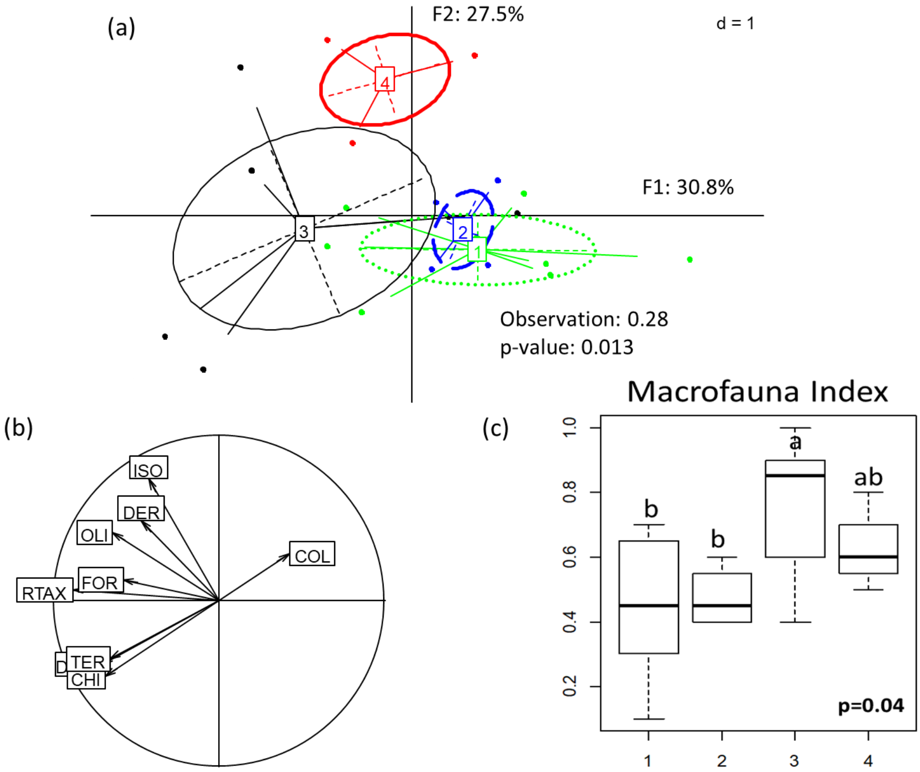
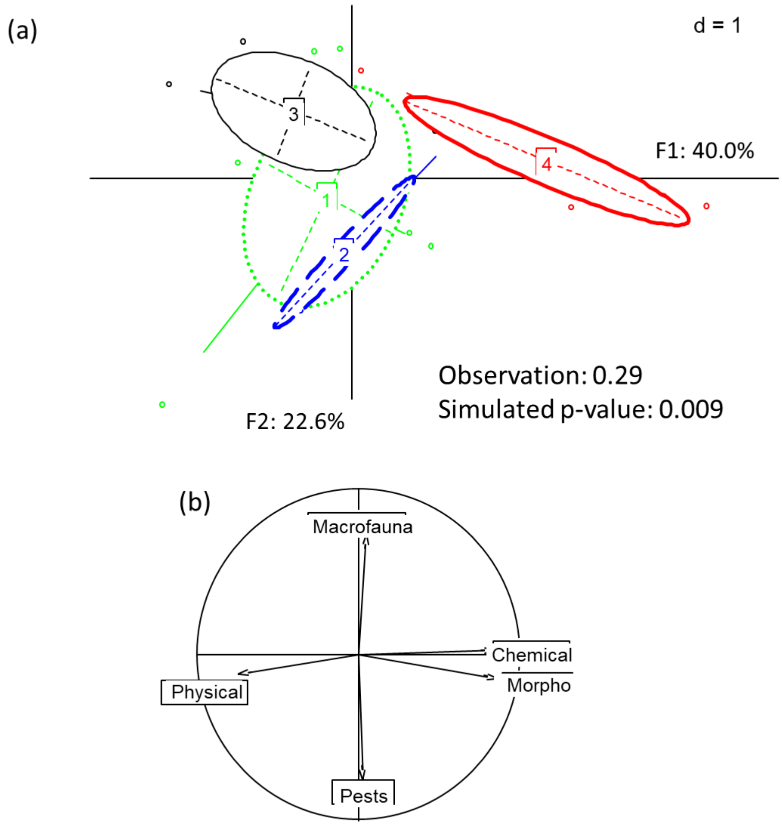

(a)
F2: 27.5%
d = 1
F1: 30.8%
4
3
2
1
Observation: 0.28
p-value: 0.013
(b)
ISO
DER
OLI
FOR
RTAX
COL
TER
CHI
(c)
Macrofauna Index
1.0
0.8
0.6
0.4
0.2
b
b
a
ab
p=0.04
1
2
3
4

Fig. 5


(a)
d = 1
3
4
1
2
F1: 40.0%
F2: 22.6%
Observation: 0.29
Simulated p-value: 0.009
(b)
Macrofauna
Chemical
Morpho
Physical
Pests