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Impact of agroecological management on plant diversity and soil-based ecosystem services in pasture and coffee systems in the Atlantic forest of Brazil

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ABSTRACT

The development of agroecosystems that can provide multiple ecosystem services with a reduced need of external inputs, requires management practices that foster ecological processes to enhance soil quality and crop productivity. We assessed the direct and indirect impacts of farmers' management practices on plant diversity, soil quality and crop productivity in coffee and pasture fields belonging to different types of farms: agroecological, conventional, and large-scale. The study was carried out in twelve farms in the Zona da Mata, Brazil. For each of the total of 24 fields (twelve pastures and twelve coffee) we recorded 41 variables associated with management practices, indicators of plant diversity (taxonomical, structural and functional diversity) and soil quality (biological, chemical and physical properties). The direct and indirect effects of management on plant diversity, soil quality and in the case of coffee, crop productivity, were assessed using structural equation models. In the case of pastures, we found that increased plant diversity due to agroecological management resulted in higher soil quality, probably due to higher soil litter cover and plant structural heterogeneity. Yet, practices presented in the agroecological farms also had a direct negative effect on soil quality, which indicates that increased plant diversity in pastures needs to be combined with other agroecological management practices than currently adopted. In the case of coffee, we show that despite the higher weeding intensity and higher use of external inputs in large-scale and conventional coffee farming systems, these practices did not result in increased soil quality or coffee productivity as compared to agroecological systems. In contrast, agroecological coffee management was associated with increased plant diversity, which, in turn, was positively associated with soil microbial biomass carbon. Our results highlight a causal pathway of agroecological management leading to increased plant diversity and, in turn, maintenance or increase in soil quality. While no causal link between agroecological coffee management and coffee productivity could be demonstrated, the biodiversity-mediated pathway resulted in similar coffee productivity in agroecological farms as compared to conventionally managed farms, which relied on pesticides and higher inputs of chemical fertilizers. We conclude that agroecological practices can be efficient to maintain satisfactory crop yields and soil fertility without the need of intensive use of external inputs and weeding.

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1. Introduction

The development of agroecosystems that can provide multiple ecosystem services with a reduced need of external inputs, requires management practices that foster ecological processes to enhance soil quality and crop productivity (Duru et al., 2015a; Nicholls and Altieri, 2017; Palomo-Campesino et al., 2018). Particularly in developing countries, the adoption of conservation management practices has been successful to maintain or increase crop yields while improving natural resource use efficiency (Pretty et al., 2006). Increasing plant diversity can enhance soil regulatory functions and the provision of other Ecosystem Services (ES), and therefore lies at heart of the transition to more sustainable systems (Duru et al., 2015b; Isbell et al., 2017). For instance, increased canopy cover can regulate air temperature and soil humidity, creating favourable conditions for the development of soil organisms (Gomes et al., 2016; Martius et al., 2004). In addition, plant leaf traits can influence litter decomposition, nutrient cycling and soil cover (Bakker et al., 2011; Mendonça and Stott, 2003). Therefore, the assessment of how a set of combined management practices can directly and indirectly influence plant diversity and ES provision can inform the development of more sustainable agroecosystems.

Among a variety of approaches that promote biodiversity-based systems, agroecology has been increasingly recognised by scientists and society due to its capacity to integrate practice, science and social movements (Wezel et al., 2009). The adoption of agroecological practices is a process based on general principles and experimentation, where different actors come together to share knowledge and find adaptive solutions for the local context and agricultural challenges (Bonaudo et al., 2014; Mccune et al., 2017). Research focusing on differences between agroecological and conventional farms suggest that agroecological systems can better provide food security, soil quality, resilience and habitat quality for biodiversity (Chavarria et al., 2018; Garibaldi et al., 2017; Holt-Giménez, 2002; Olimpi and Philpott, 2018; Souza et al., 2012b). Despite the advancements to understand the impact of agroecological management on biodiversity and ecosystem services (FAO, 2018; Liere et al., 2017; Palomo-Campesino et al., 2018), the interactions among multiple components of agroecosystems (i.e. management, plant diversity, soil quality and crop productivity) remain poorly understood, particularly in farming contexts where agroecological transitions are currently taking place. For example, very few studies have assessed the effect of taxonomical, structural and functional attributes of plant diversity on the ES provision in agricultural systems, although this approach has been used for carbon related ES in forested systems (Finegan et al., 2015; van der Sande et al., 2017).

The characterization of system components, such as management, plant diversity and soil quality should be based on a set of variables that capture the complexity of agroecosystems, which is especially relevant in realistic management scenarios (Birkhofer et al., 2015). The management component can have a direct and/or indirect effect on biodiversity and soil functioning, and consists of combined practices that are applied for different purposes (Jezeer et al., 2018; Mas and Dietsch, 2003; Rahn et al., 2018). For instance, weeding can be conducted with different intensities and methodologies (e.g. chemical herbicides, manual removal of weeds and mechanical weed control); fertilizer application may entail different doses of manure, chemical fertilizers and or other inputs; and pest management may involve application of different types and doses of pesticides (Jezeer et al., 2018; Rahn et al., 2018). Yet, a particular practice may have multiple purposes, such as the implementation of native and fruit trees in agricultural fields. Trees can contribute to a variety of functions and services, such as nutrient cycling, temperature regulation, provision of wood and fruits, carbon storage and pest control (Tscharntke et al., 2011). Therefore, focussing on just a single agroecosystem component or practice may be insufficient to capture the overarching impacts of applied management practices on agroecosystems (Mas and Dietsch, 2003).

Plant diversity can be measured in different ways and is an important component to be considered for the re-design of sustainable agroecosystems. The assessment of indicators of taxonomical, structural and functional diversity can be combined to better determine plant responses to management as well as the effect of plant components on ecosystem functioning (Balvanera et al., 2014; Díaz and Cabido, 2001). Taxonomical diversity can be used to assess the conservation value of land uses as well as the role of diversified systems to increase the complementary and efficient use of resources. The structural diversity of agroecosystems, typically defined as variance in vegetation height, can influence the efficiency to capture water, carbon and light, and, in turn, ecosystem functioning (Ali et al., 2016). Other components related to the structure of agroecosystems can also be relevant, such as canopy cover and total biomass (Gomes et al., 2016; Henry et al., 2009). Functional diversity is understood as “the value and range of functional traits of the organisms in a given ecosystem” (Tilman, 2001). Two main ecological mechanisms are suggested to explain the links between functional diversity and ecosystem functioning: the biomass ratio hypothesis and the niche complementarity hypothesis (Díaz et al., 2007). The biomass ratio hypothesis posits that functional traits of the dominant species, measured as the community weighted mean (CWM) of individual traits, are of overriding importance for determining ecosystem functioning (Finegan et al., 2015). On the other hand, the niche complementarity hypothesis postulates that the variation and distribution of species trait values can better explain niche occupation and complementary use of resources (Faucon et al., 2017). Therefore, functional diversity can be used to further assess the functional response and effect of diversity on ecosystem functioning based on trait dominance (e.g. community weighed means – CWM) and variance (e.g. functional richness; Faucon et al., 2017; Lavorel, 2013; Wood et al., 2015). For instance, CWM values of leaf nitrogen content can help to understand both the effects of nitrogen fertilization on plant nutrition (Buchanan et al., 2019) as well as the consequences of leaf nitrogen concentration on the efficiency of nutrient cycling and the associated soil fertility (Bakker et al., 2011).

Soil quality is influenced by the interplay of chemical, physical and biological soil factors (Karlen et al., 2003). Although soil chemical and physical indicators are commonly used by farmers and scientists to assess soil quality, biological indicators are often under-represented (Bünemann et al., 2018). Soil organisms are suggested to be very sensitive to ecosystem change and to play a central role in ecosystem functioning. Therefore, including biological indicators can help to better understand soil responses to aboveground biodiversity and management as well as the relationship between soil biology, chemistry and physics (Faucon et al., 2017).

The objective of this paper was to assess how a set of management practices used in coffee (*Coffea arabica* L.) and pastures influences plant diversity, soil quality and, in the case of coffee, crop productivity. First, the relationships between indicators for management, plant diversity and soil quality were explored using multivariate analysis. Then, structural equation models were used to assess the direct and indirect effects of management practices on plant diversity, soil quality and, in the case of coffee, crop productivity. The study was conducted in Zona da Mata, Minas Gerais, Brazil, where coffee is the main cash crop for farmers and pasture is the dominant land use, covering about 70 % of the landscape. The Zona da Mata is a suitable location for conducting this kind of research because of the ongoing process of agroecological transition that was initiated in the 1980′s as a joint initiative of farmers’ organisations, a local NGO (the Center for Alternative Technologies of Zona da Mata – CTA-ZM) and the Federal University of Viçosa (Cardoso et al., 2001). Moreover, previous studies in the region have established a farm typology that help to understand the local context and to select representative farms that configure a gradient of management strategies (Teixeira et al., 2018a).

2. Material and methods

2.1. Study site

The study was conducted in Araponga, Divino and Espera Feliz, which are three municipalities located in Zona da Mata, Minas Gerais, Brazil. These municipalities connect two important nature reserves (Caparaó National Park and Brigadeiro State Park; Fig. 1) and are part of the Atlantic forest biome, which is considered the fifth biodiversity hotspot in the world (Myers et al., 2000). The landscape in Zona da Mata can be understood as a dynamic mosaic of land uses (Vandermeer and Perfecto, 2007) predominated by pastures, coffee fields and secondary forest patches. The area is mountainous, leading to heterogeneous bio-physical conditions, limiting mechanization and predominance of family farmers (Valverde, 1958). The average temperature in the region is 19 °C and the average precipitation is 1300 mm (Golfari, 1975). The main soil type dominating the upper slopes is classified as Oxisol, which is highly weathered, deep, well-drained and acidic (Sarcinelli et al., 2009).

2.2. Selection of farms

Twelve farms were selected as case studies based on a farm typology previously developed in the region (Teixeira et al., 2018a). The typology helps to understand and take into account a diversity of management strategies and social-economic conditions faced by farmers. Three main farm types were considered for the present study: agroecological family farms, conventional family farms and large-scale farms (Teixeira et al., 2018a). In Zona da Mata the average farm size varies with farm type: 13.1 ha for family farms and 83.2 ha for non-family farms (IBGE, 2006). Agroecological family farms are characterized by the low use of external inputs and high crop and plant diversity, including trees. Many agroecological farmers also have a strong engagement in social networks and movements. For instance, agroecological farmers often play an active role in local cooperatives, family farmers unions, NGO`s, social collectives linked to the church, and specific societal groups (e.g. women and youth movements; Teixeira et al., 2018a). Conventional family farms typically have a limited number of crops in monocultures, rely on the high use of external inputs and have a strong focus on coffee production. Large-scale farms also tend to focus on specialized and input based systems, but have large farm area and depend on contracted labour. Large-scale farmers have more financial resources than family farmers, which facilitates the access to external inputs as well as fertile land, which is often more expensive than degraded land. Conventional and large-scale farmers use chemical pesticides, including the herbicide Glyphosate and fungicides and insecticides based on Flutriafol, Epoxiconazole, Imidacloprid, Cyproconazole and Thiamethoxam. Conventional family farmers in the region recognise a stronger negative impact of pesticides on ecosystem services than large-scale farmers, most likely because conventional family farmers often apply pesticides themselves, while these applications are conducted by contracted laborers on large-scale farms (Teixeira et al., 2018b). The main type of chemical fertilizer used was the NPK formulation 20−05-20, although other types of fertilizers were also reported. In all farm types, calcitic limestone was used in the case of liming. Agroecological farmers did not apply compost on their coffee fields or pastures, although compost was sometimes used in other land uses (e.g. home gardens and maize fields).

Four farms per farm type were identified and selected based on their structural characteristics (i.e. farm size, type of labour), suitability for the study (i.e. presence of coffee or pasture based on selection criteria provided below), and willingness of farmers to participate in the study.

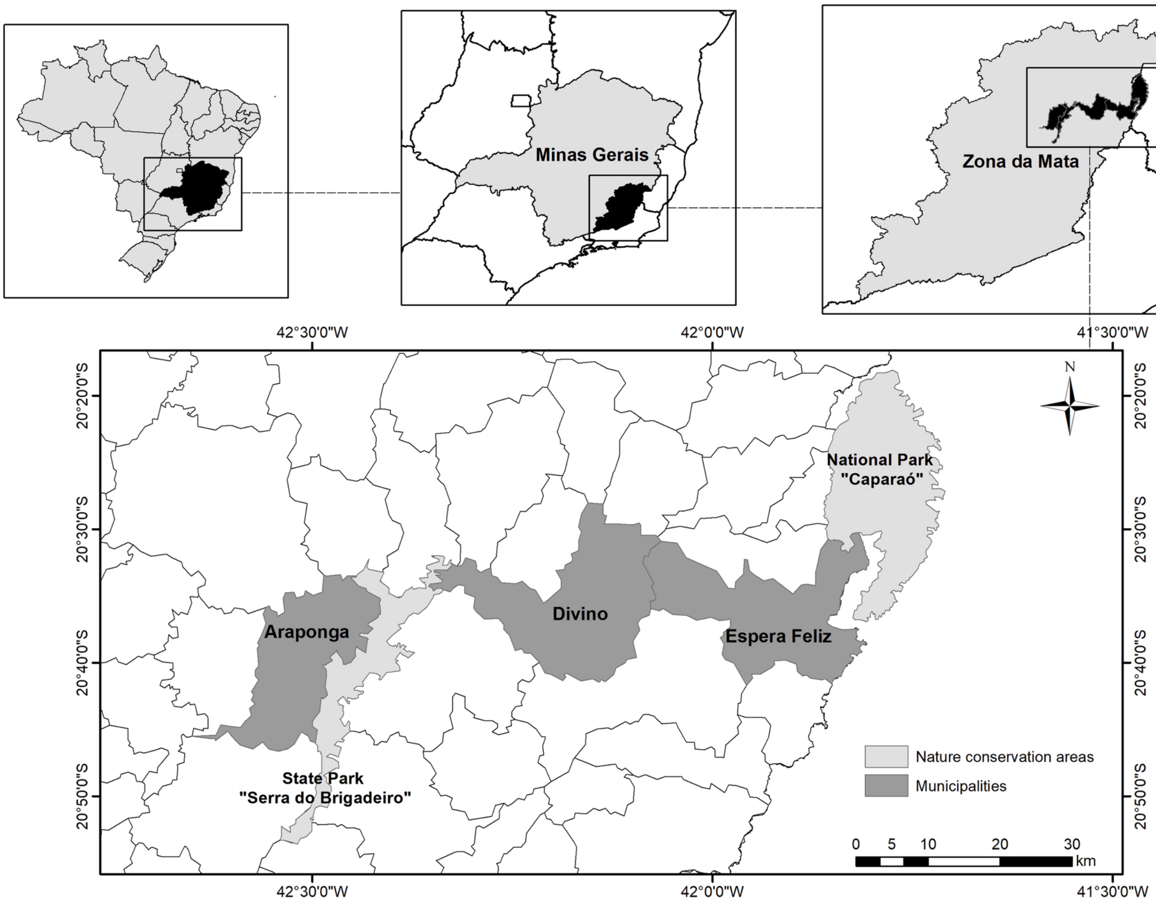

Fig. 1. Map highlighting the three studied municipalities in Zona da Mata, Minas Gerais, Brazil. Two important nature conservation areas are also shown.

In each farm, one coffee field and one pasture were selected for the study, for a total of 24 fields (2 land uses x 3 farm types x 4 farms = 24 fields). Only coffee plantations that were older than 7 years were selected to standardize the size of coffee plants, and we included only pastures that were actively managed during the sampling period. Furthermore, only fields located on the convex upper slopes were selected to minimize variation in soil conditions. None of the pastures and coffee fields were irrigated, reflecting standard practices in Zona da Mata. When both coffee plantations and pastures that met our selection criteria were not available on the same farm, a nearby representative field with comparable management practices was selected. This was the case in five different farms.

2.3. Field management and productivity

Field management and productivity in coffee and pasture were assessed by conducting interviews with farmers and land owners. The following information was collected for each field: age of the field (years), mowing intensity (hours/ha/year), weeding intensity (hours/ha/year), pesticide input (g/ha/year), nutrient input through chemical fertilizers (kg/ha/year; N, P, K and Ca), nutrient input through organic fertilizers (kg/ha/year; N, P, K) and use of manure (kg/ha/year). Coffee productivity (kg/ha/year) was assessed based on the average yields of the previous two years. Information on cattle stocking density (#/ha) and cattle grazing intensity (days/year) was obtained for pastures.

2.4. Plant diversity assessment

Plant diversity in each of the 24 fields was assessed along a 90-m linear transect, starting at the bottom edge of the field in the uphill direction. The starting point of the transect at the bottom edge was randomly drawn using the Random Number Generator App (RandomAppsInc, 2017). In the case of coffee, the transect was perpendicular to the coffee plant rows, starting in between coffee plants located in the same row, with the first two coffee rows being skipped to reduce edge effects.

The survey was conducted by assessing the vegetation at 5 m on both sides along the linear transect, covering an area of 900 m2 (90 × 10 m). All trees, palms, shrubs, giant herbs and treelets with diameter at 1.3 m height (DBH) $\geq$ 5 cm were recorded. The crown area of each individual was estimated based on the average of crown diameter measured in two perpendicular directions. Tree crown cover and tree density were calculated for each plot. DBH and height was assessed for 20 coffee plants. For this purpose, we divided the plot in ten equally sized subplots and randomly selected two coffee plants in each subplot.

The linear transect was also used for the point interception method, which allowed to assess taxonomical, structural and functional diversity of plant species regardless of their size, as well as soil cover and litter depth along the transect. In coffee plantations and pastures we sampled the vegetation at 2 and 1 m intervals, respectively. At each sampling point, we placed a stick with a diameter of 2.5 mm and the plant species and height of each individual whose leaves touched the stick was recorded. In case that the plant species could not be identified in the field, samples were taken and stored as exsiccates (dried and flattened plant material) for further identification with the help of botanical manuals (Lorenzi, 2016, 2008), experts and the herbarium collection of the Federal University of Viçosa, Minas Gerais, Brazil. For the assessment of grasses, we applied two rules. First, we did not take into account inflorescences for the vegetation height measurements because inflorescences are only present during part of the season, and are often taller than the rest of the plant. In this way we avoided overestimation of plant height. Second, tussocks were considered as separate individuals when they were separated at the base, even when they might have had the same root system. The standard deviation of height was used as a proxy of structural diversity. Number of plant species found in each transect and Shannon-Weaver index (Shannon and Weaver, 1949) were used as proxies of taxonomical diversity. Soil cover and litter thickness (of every plant material covering the soil) were assessed at each sampling point. Soil cover was recorded as presence/absence data and litter depth was measured with a ruler.

For the functional diversity assessment, we measured ten leaf traits that are associated to plant responses to light and fertilization, as well as plant effects on ecosystem productivity, litter production and nutrient cycling. In total, we assessed 64 plant species representing on average 92.35 % (range 84–100 %) of the vegetation cover in each transect according to the point interception method. Five mature, healthy, vigorous and sun-lit individuals of each species in each plot were sampled to provide plant material for assessing functional leaf traits following standard protocols (Pérez-Harguindeguy et al., 2013). The leaf petiole was included in the assessment, and in the case of compound leaves, the leaflet was considered as the unit of analysis. A hand-held chlorophyll meter (SPAD – Soil-Plant Analysis Development; Minolta, 1990) was used to obtain leaf chlorophyll content (Chlo). Leaves were flattened and photographed, and leaf area (LA) calculated with the software ImageJ, based on pixel counting. Leaf thickness (LT) was obtained using a digital micrometer. Leaf fresh mass was measured using a precise scale of five decimal places. Then leaves were dried in the oven at 65 °C until constant weight to obtain leaf dry mass. Leaf dry matter content (LDMC) was calculated dividing dry mass (mg) by fresh mass (g). Specific leaf area (SLA) was calculated as leaf area (cm^2) divided by leaf dry mass (g). We used a penetrometer built with a flat-end nail attached to a syringe and a water-basin on top to punch fresh leaf laminas. The total weight necessary to punch the leave was converted to Newton and divided by the nail surface to obtain values of specific force to punch (FtP, N/cm^2). Leaf nitrogen (leaf_N) was determined using the sulfuric digestion method (Carmo et al., 2000). Leaf phosphorus (leaf_P), potassium (leaf_K) and calcium (leaf_Ca) content were measured using Nitric-Perchloric Digestion (Carmo et al., 2000). For leaf nutrient content we had three replicates per species per plot. All leaf trait analyses were performed at the laboratory of Soil Fertility and the laboratory of Soil Organic Matter and Plant Residues, both at Federal University of Viçosa. As we expected intraspecific variation in leaf traits among fields, we used the species average trait values separately for each transect. Functional trait data at species level was scaled to the community level using indices of functional diversity and functional composition. As an indicator of functional diversity, the multi-trait index functional richness (Fric) was calculated based on the volume filled by the community in the trait space (Cornwell et al., 2006). For functional composition the aggregate value of leaf traits in each plot was measured using community weighed mean (CWM) for each leaf trait (Lavorel et al., 2008). All diversity indices were calculate using the FDiversity software and FD package in R 3.3.3.

2.5. Soil quality assessment

For the soil quality assessment, the transect lines were subdivided in three segments, each 30 m long. In each segment we collected three disturbed soil sub-samples from the 0−15 cm soil layer. The three soil sub-samples were mixed thoroughly and stored in closed plastic bags to form one composite sample per segment. All soil samples were collected during the dry season (June-August 2017). Soil clay content was determined using the pipette method with sodium hydroxide as a dispersant (Embrapa, 2011). Soil organic matter (SOM) was determined using the Walkley-Black chromic acid wet oxidation method (Walkley and Black, 1933). Soil pH was measured in water (Embrapa, 2011). Soil phosphorus and potassium were determined using Melich-1 extract (Mehlich, 1953), while soil calcium and magnesium using KCl extract (Embrapa, 2011). Acidic cations content (H + Al) was obtained using calcium acetate as extract (Embrapa, 2011). Soil total nitrogen was determined by automated combustion (Yeomans and Bremner, 1991). Soil base saturation (V) was calculated as the percentage of the soil exchange sites (CEC) occupied by the basic cations, potassium (K), magnesium (Mg) and calcium (Ca) (V= [100 x (Ca + Mg + K)] / (Ca + Mg + K+H + Al)).

An identical sampling design was applied to collect soil samples for the assessment of microbiota. However, for the microbiological analysis, soil samples were taken from the 0−5 cm layer in each segment, and samples were immediately stored in a cooler box at 4 °C. In the laboratory, the carbon of the microbial biomass was assessed using the fumigation-extraction method (Vance et al., 1987).

2.6. Data analysis

All the variables included in the study were grouped in three categories: management, plant diversity and soil quality (Table 1). A separate multivariate principal component analysis (PCA) was performed for each category (management, plant diversity and soil quality) and for each land use (coffee and pasture). The PCAs allowed to reduce the dimensionality of the data and to generate non-correlated principal components (Appendix A) that conceptually represent gradients of management, plant diversity and soil quality. The coordinates of each sample unit (field) according to the principal components were used as indicator values in the following analysis.

The first axes (PC1) of the PCAs for management and plant diversity, and the first two axes (PC1 and PC2) of the soil quality PCA were used to determine the direct and indirect effects of management on plant diversity and soils using structural equation models. The first two axes of the soil quality PCAs were selected instead of just PC1 because of the relatively low variance explained of PC1 for coffee systems, and because PC1 was associated with soil fertility and PC2 with carbon, potassium and phosphorus. In the case of pastures, PC1 was associated with soil biological and chemical quality and PC2 with soil texture (Appendix B). Separate structural equation models were developed for pastures and coffee fields. In each model, we tested direct effects of management on plant diversity, direct effects of plant diversity on soil quality, direct and indirect effects of management on soil quality, and in the case of coffee, direct and indirect effects of management, plant diversity and soil quality on coffee productivity. Coffee productivity was the only variable which was not included in the previous multivariate analysis because it was our final response variable. The comparative fit indexes (CFI) of the models for coffee and pasture were 1.0, exceeding the criterion of CFI > 0.95, indicating that the models were acceptable (Appendix C; Schreiber et al., 2006). The strength of causal relationships between variables was assessed using standardized parameter values, and relationships were considered significant when the p-value was $\leq$0.05 (Appendix D; Gana and Broc, 2018). The residuals of the correlational units obtained by subtracting the observed and model-implied matrices were checked to confirm that the model was not over or under-predicting the association between variables ($|res>0.1|$) (Appendix E; Gana and Broc, 2018). We used simple linear regressions to assess the bivariate relationship among variables. All analyses were conducted in R 3.3.3.

3. Results

The principal component analyses revealed how twelve pasture and twelve coffee fields belonging to three different farm types (conventional, agroecological and large-scale) are positioned in a gradient of management, plant diversity and soil quality. We only report correlation coefficients between the variables and the principal components (PCA loadings) if larger than 0.45 or lower than -0.45 (Appendix B).

3.1. Management

In the case of coffee, the management gradient was captured by the first principal component (PC1), which explained 47.8 % of the variance (Fig. 2A). The variables pesticide use (-0.83), N, K and Ca input from chemical fertilizers (-0.8; -0.72 and -0.71, respectively), weeding intensity (-0.65) and age of the field (-0.63) were negatively correlated with the first component (PC1), while tree density (+0.91), mowing intensity (+0.86), N and P input from organic fertilizers (+0.74 and +0.71, respectively) and total manure (+0.47) were positively correlated with PC1. All agroecological coffee fields were positively associated with PC1 whereas all conventional and large-scale fields were negatively associated (Fig. 2A). Therefore, PC1 can be understood as a gradient of agroecological management practices, ranging from more conventional to ecologically-based management. In the case of pastures, PC1 explained 49.8 % of the variability and can also be interpreted as a gradient of agroecological management practices. The variables tree density (+0.95) and mowing intensity (+0.88) were strongly positively correlated with PC1 and grazing intensity (-0.87) was strongly negatively correlated. Agroecological fields were positively associated with PC1, whereas conventional and large-scale fields were negatively associated with PC1 (Fig. 2B).

3.2. Plant diversity

For both coffee and pastures, PC1 was interpreted as a gradient of increased plant diversity explaining 45.8 % and 34.9 % of the variation, respectively. In coffee and pastures, species richness (+0.97; +0.93), Shannon index (+0.92; +0.84), tree cover (+0.86; +0.77), variance in height (+0.83; +0.87) and litter thickness (+0.53; +0.77) were positively correlated with PC1, whereas bare soil was negatively correlated (-0.69; -0.5) (Fig. 2C and 4D). However, different patterns were observed for coffee and pastures in terms of functional diversity and composition. In coffee systems, functional richness (+0.85), leaf area CWM (+0.78) and leaf phosphorus CWM (+0.51) were positively correlated with PC1, while leaf chlorophyll CWM (-0.88), leaf dry matter content CWM (-0.84) and leaf calcium CWM (-0.58) were negatively correlated (Fig. 2C). In the case of pastures, leaf nitrogen CWM (+0.83), leaf thickness CWM (+0.54), leaf dry matter content CWM (+0.53) and leaf calcium CWM (+0.52) were positively correlated with PC1 (Fig. 2D). In both coffee and pastures, all agroecological fields were positively associated with PC1, which was not the case for conventional and large-scale fields.

3.3. Soil quality

In the case of coffee, the first two PCA axes (PC1 and PC2) account together for 59.4 % of the variability in the data set. Soil PC1 can be interpreted as a soil chemical quality gradient, as it was positively correlated with soil pH (+0.95), base saturation (+0.95), soil calcium (+0.55) and soil phosphorus (+0.46), and negatively correlated with soil organic matter (-0.51) and soil nitrogen (-0.51). In contrast, PC2 can be interpreted as a soil biological quality gradient, as it was strongly positively correlated with carbon of the microbial biomass (+0.86). PC2 was also positively correlated to soil phosphorus (+0.64), soil potassium (+0.60) and soil organic matter (+0.46). There was no clear separation among farm types considering their position in PC1 (soil chemical quality gradient). Regarding the position along the PC2 axis (soil biological quality gradient), agroecological fields tended to have high score values in contrast to conventional fields. Large-scale fields do not show a clear tendency.

In the case of pastures, PC1 and PC2 explained together 74.4 % of the variance. Soil PC1 can be interpreted as a biological and chemical soil quality gradient, as it was positively correlated with soil calcium (+0.92), base saturation (+0.90), soil pH (+0.84), carbon of the microbial biomass (+0.81), soil organic matter (+0.80), soil phosphorus (+0.65) and soil potassium (+0.62). In contrast, soil PC2 was more strongly positively correlated with soil clay content (+0.94), and can be interpreted as a soil textural gradient. Conventional fields are positioned in the left lower part of the graph (low score values for PC 1 and 2), whereas agroecological and large-scale fields did not show a clear pattern.

Table 1
Overview of management, pant diversity and soil quality variables for coffee and pasture systems on conventional family, agroecological and large-scale farms in Zona da Mata, Minas Gerais, Brazil. Mean ± standard deviation values are reported.

Variable	Code	Unit	coffee			pasture		
			conventional	agroecological	large-scale	conventional	agroecological	large-scale
Management								
Age of the field	field_age	years	38.3 ± 20.0	15.0 ± 7.1	33.8 ± 25.3	31.3 ± 10.3	33.3 ± 22.3	29.3 ± 25.3
Mowing intensity	mowing	hours/ha/year	15.5 ± 5.0	83.6 ± 56.0	23.1 ± 16.7	13.1 ± 15.1	82.0 ± 65.4	18.0 ± 23.7
Uproot weeding intensity	weeding	hours/ha/year	31.2 ± 28.7	0.0 ± 0.0	77.2 ± 97.2	NA	NA	NA
Pesticide input	pesticide	g/ha/year	2514.0 ± 1238.6	0.0 ± 0.0	3116.5 ± 1664.6	NA	NA	NA
Nitrogen input (chemical fertilizer)	Nmin	Kg/ha/year	306.4 ± 118.1	27.0 ± 54.0	329.6 ± 150.0	NA	NA	NA
Phosphorus input (chemical fertilizer)	Pmin	Kg/ha/year	49.1 ± 37.8	6.8 ± 13.5	58.8 ± 54.9	NA	NA	NA
Potassium input (chemical fertilizer)	Kmin	Kg/ha/year	223.7 ± 122.3	27.0 ± 54.0	294.0 ± 178.4	NA	NA	NA
Calcium input (chemical fertilizer)	Camin	Kg/ha/year	799.3 ± 533.3	67.9 ± 135.8	501.9 ± 779.6	NA	NA	NA
Nitrogen input (organic fertilizer)	Norg	Kg/ha/year	24.3 ± 48.6	187.6 ± 121.4	52.5 ± 105.0	NA	NA	NA
Phosphorus input (organic fertilizer)	Porg	Kg/ha/year	8.7 ± 17.4	57.5 ± 32.4	18.8 ± 37.5	NA	NA	NA
Potassium input (organic fertilizer)	Korg	Kg/ha/year	36.5 ± 72.9	137.2 ± 63.0	78.8 ± 157.5	NA	NA	NA
Total manure	manure	Kg/ha/year	1736.3 ± 3472.5	7116.0 ± 2574.1	3750.0 ± 7500.0	NA	NA	NA
Tree density	tree_density	#/ha	0.0 ± 0.0	202.8 ± 68.7	0.0 ± 0.0	0.0 ± 0.0	158.3 ± 71.1	0.0 ± 0.0
Animal density	animal_density	#/ha	NA	NA	NA	2.4 ± 0.6	3.5 ± 1.0	5.3 ± 7.6
Grazing intensity	grazing_intensity	days/year	NA	NA	NA	285.0 ± 90.0	135.0 ± 30.0	360.0 ± 0.0
Coffee density	coffee_density	plants/ha	3638.2 ± 678.2	2966.3 ± 262.0	3513.9 ± 1293.7	NA	NA	NA
Coffee productivity	coffee_prod	Kg/ha/year	2144.5 ± 773.2	1401.6 ± 666.9	1742.3 ± 913.0	NA	NA	NA
Plant diversity								
Structural diversity								
Height standard deviation	sd_height	m	79.3 ± 18.0	220.8 ± 27.7	67.1 ± 21.4	9.5 ± 4.9	217.6 ± 83.9	8.6 ± 4.4
Litter thickness	litter_thickness	cm	1.2 ± 0.6	2.5 ± 2.3	0.9 ± 0.9	0.3 ± 0.2	1.0 ± 0.6	0.4 ± 0.3
Bare soil	bare_soil	%	19.6 ± 13.6	4.3 ± 2.5	42.4 ± 20.1	22.5 ± 8.3	6.6 ± 6.2	32.1 ± 25.1
Tree cover	tree_cover	m^2	0.0 ± 0.0	265.0 ± 71.0	0.0 ± 0.0	0.0 ± 0.0	197.2 ± 148.9	0.0 ± 0.0
Taxonomical diversity								
Number of plant species	total_species	#	7.5 ± 3.5	18.8 ± 3.4	6.0 ± 6.2	5.0 ± 2.0	23.0 ± 3.5	5.5 ± 3.7
Shannon-Weaver index	shannon	–	0.8 ± 0.5	2.1 ± 0.2	0.7 ± 1.0	0.7 ± 0.4	2.1 ± 0.3	0.6 ± 0.6
Functional diversity								
Leaf Area - CWM	CWM.LA	cm^2	42.2 ± 7.7	1267.1 ± 900.8	35.9 ± 11.8	24.4 ± 9.0	26.8 ± 10.5	18.9 ± 3.9
Chlorophyll content - CWM	CWM.Clo	SPAD units	60.2 ± 3.8	53.5 ± 3.2	64.5 ± 8.0	78.8 ± 80.2	41.2 ± 4.3	40.0 ± 3.0
Leaf dry matter content - CWM	CWM.LDMC	mg/g	308.3 ± 32.1	264.5 ± 4.7	307.9 ± 35.9	268.3 ± 40.1	284.1 ± 32.4	263.5 ± 26.4
Specific Leaf Area - CWM	CWM.SLA	m^2/Kg	164.8 ± 50.2	177.7 ± 28.3	149.6 ± 43.5	137.2 ± 38.3	176.4 ± 16.6	189.6 ± 31.7
Leaf thickness - CWM	CWM.LT	mm	0.3 ± 0.05	0.4 ± 0.1	0.3 ± 0.1	0.7 ± 0.3	2.3 ± 3.8	0.4 ± 0.0
Leaf force to punch - CWM	CWM.FtP	N/cm^2	0.3 ± 0.05	0.3 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.0	0.2 ± 0.0
Leaf nitrogen - CWM	CWM.N	%	3.1 ± 0.6	3.0 ± 0.5	3.1 ± 0.3	1.4 ± 0.5	2.2 ± 0.1	1.7 ± 0.3
Leaf phosphorus - CWM	CWM.P	%	0.2 ± 0.05	0.2 ± 0.0	0.2 ± 0.0	0.3 ± 0.4	0.1 ± 0.0	0.1 ± 0.0
Leaf potassium - CWM	CWM.K	%	1.8 ± 0.6	1.7 ± 0.5	2.3 ± 0.3	1.2 ± 0.6	1.4 ± 0.4	1.6 ± 0.5
Leaf calcium - CWM	CWM.Ca	%	2.2 ± 0.7	1.4 ± 0.5	1.6 ± 0.3	0.4 ± 0.1	0.5 ± 0.2	0.4 ± 0.1
Functional richness	Fric	–	2.9 ± 3.8	4082.8 ± 2394.1	0.5 ± 0.8	2.5 ± 4.7	3.5 ± 4.4	3.2 ± 4.3
Soil properties								
Clay content	Clay	%	0.6 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	0.6 ± 0.1
Soil Organic Matter	SOM	%	4.0 ± 0.5	5.8 ± 1.6	4.4 ± 2.1	4.4 ± 0.3	5.8 ± 1.8	6.0 ± 2.1
pH	pH	–	5.7 ± 0.7	5.7 ± 0.6	5.8 ± 0.5	5.0 ± 0.4	4.5 ± 0.8	4.9 ± 0.5
Nitrogen	N_soil	%	0.4 ± 0.3	0.3 ± 0.1	0.4 ± 0.3	0.2 ± 0.0	0.6 ± 0.5	0.5 ± 0.3
Phosphorus	P_soil	mg/dm^3	11.1 ± 8.4	62.1 ± 80.6	14.1 ± 9.6	1.8 ± 0.7	1.7 ± 0.3	2.8 ± 1.3
Potassium	K_soil	mg/dm^3	116.0 ± 54.5	186.0 ± 110.1	219.8 ± 49.8	63.7 ± 44.7	39.1 ± 18.6	179.9 ± 223.1
Calcium	Ca_soil	$cmolc/dm^3$	4.9 ± 1.5	5.1 ± 1.3	5.1 ± 1.1	1.6 ± 1.3	2.5 ± 3.6	2.8 ± 1.2
Base saturation	V	%	65.5 ± 15.0	68.0 ± 19.4	70.4 ± 16.4	28.7 ± 21.0	27.1 ± 31.2	36.1 ± 8.3
Carbon of the microbial biomass	CMB	μg/g	319.3 ± 60.8	444.1 ± 87.5	394.6 ± 84.3	419.6 ± 82.0	426.7 ± 192.7	552.7 ± 27.6

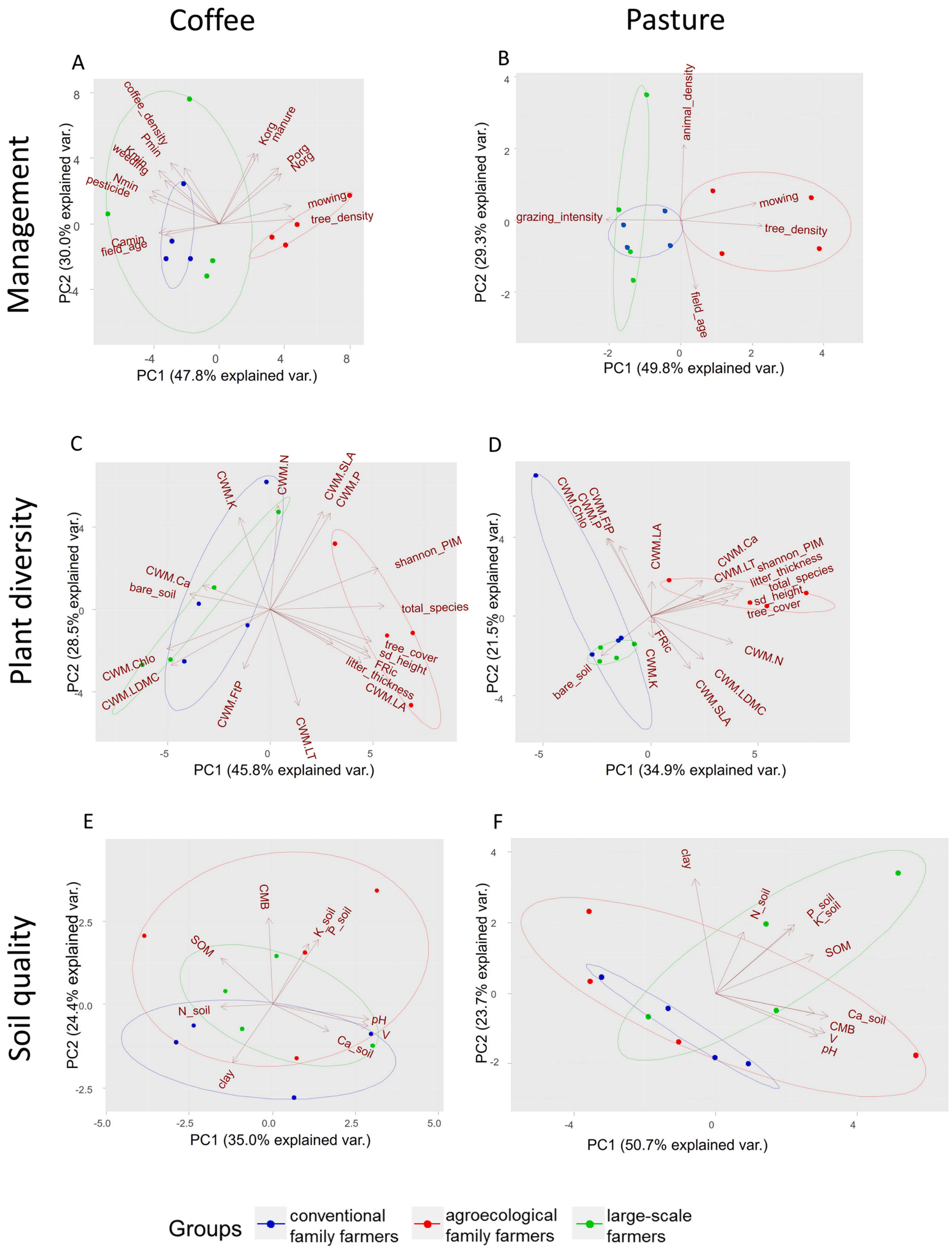

Fig. 2. Results of Principal Component Analyses for variables associated with management, plant diversity and soil quality. Separate analyses were performed for coffee (n = 12) and pastures (n = 12).

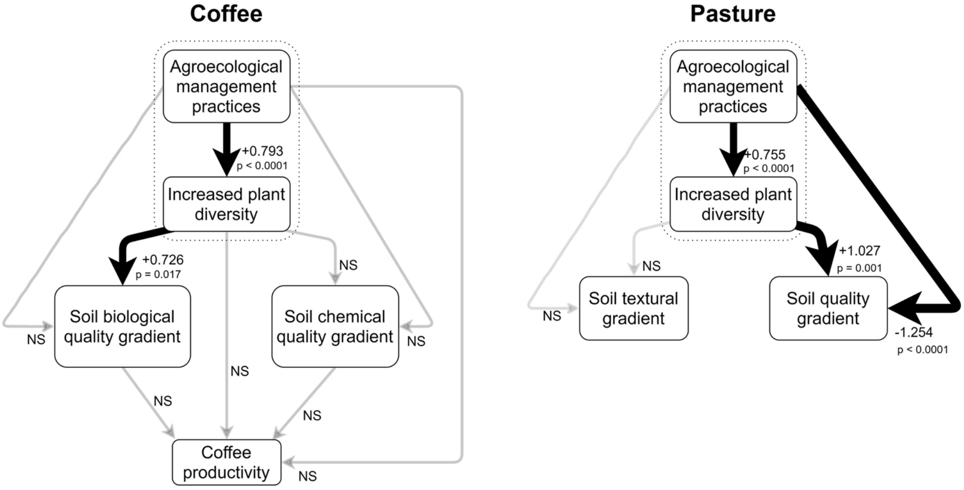

Fig. 3. Structural equation models showing the direct and indirect effects of management on plant diversity and soil quality for coffee and pasture. In the case of coffee, coffee productivity is included as a final response variable. Standardized coefficients and significant p-values ($p < 0.05$) generated by the model are displayed for each significant association. Non-significant associations are represented by grey arrows.

3.4. *Direct and indirect effects of management on plant diversity, soil quality and coffee productivity*

The structural equation model for coffee indicated that agroecological management had a positive effect on plant diversity (+0.793), which in turn had a positive effect on soil biological quality (soil PC 2) (+0.726; Fig. 3). All other tested relationships were non-significant. In the case of pastures, agroecological management had a positive effect on plant diversity (+0.755), which in turn had a positive effect on soil biological and chemical quality (soil PC 1) (+1.027; Fig. 3). At the same time, agroecological management with lower grazing intensity had a direct negative effect on soil biological and chemical quality (-1.254).

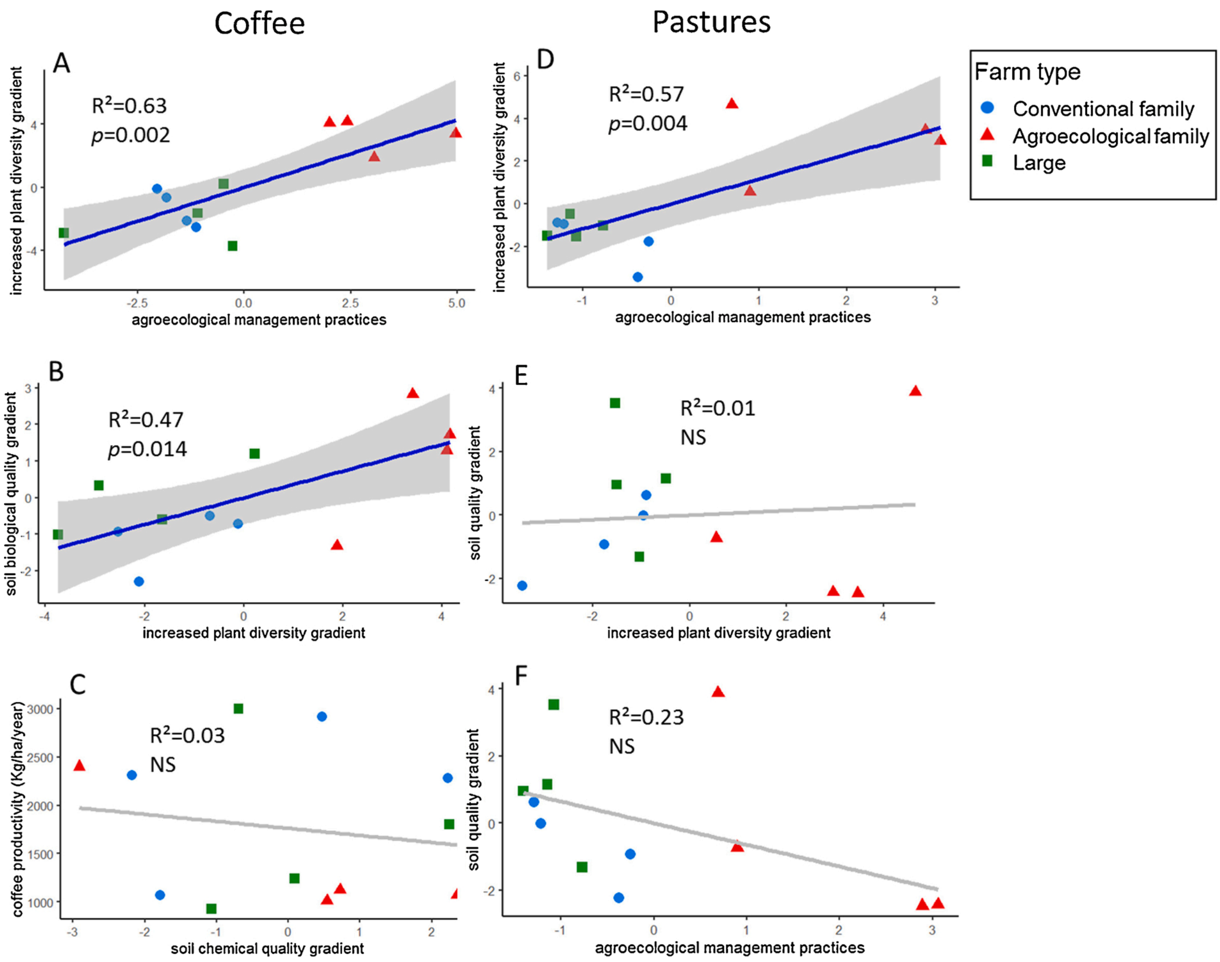

Fig. 4. Bivariate relationships to illustrate the patterns found in the structural equation models for coffee and pasture (see Fig. 3 for the complete model).

Linear regressions indicated that agroecological management practices were positively associated with plant diversity in coffee ($p = 0.002$) and pastures ($p = 0.004$) (Fig. 4A and D). In the case of coffee, plant diversity was positively associated with soil biological quality ($p = 0.014$), but soil chemical quality was not significantly associated with coffee productivity (Figs. 4B and C). In the case of pastures, there was no significant bivariate association between plant diversity and soil quality, and between agroecological management practices and soil quality.

4. Discussion

In this paper we assessed the direct and indirect impacts of farmers' management practices on plant diversity, soil quality and crop productivity in coffee and pasture fields belonging to different types of farms: agroecological, conventional, and large-scale. Our findings indicate that the higher weeding intensity and use of external inputs in large-scale and conventional coffee farming systems did not result in higher soil chemical quality or coffee productivity than in agroecological systems. In contrast, agroecological coffee management had a positive effect on plant diversity, which increased soil microbial biomass carbon in coffee fields (Figs. 3 and 4). Although in our model we assess plant diversity metrics as a response of management, agroecological farmers often consider biodiversity as a pillar for the sustainability and functioning of the system (FAO, 2018; Cardoso et al., 2001). Therefore, increasing plant diversity is also part of agroecological farmers management strategy, as they deliberately let natural vegetation, including trees, grow in their fields (Fig. 2A and B; Souza et al., 2010; Cardoso et al., 2001).

Even though pastures in Zona da Mata may be considered as a "neglected land use", as these are often extensively managed and farmers invest very little in their management (i.e. no use of inputs), we found a clear gradient of management practices from conventional and large-scale to agroecological farms (Fig. 2B). Agroecological management practices were positively associated with plant diversity, which entails increased tree cover, litter thickness and structural and taxonomical plant diversity (Fig. 3). In turn, the higher plant diversity in pastures resulted in increased soil chemical and biological quality. Yet, management practices at the agroecological farms also had a direct negative association with soil quality (Fig. 3), which indicates that increased plant diversity in pastures needs to be combined with other management practices than currently adopted. For instance, management practices such as rotational grazing and terracing have been pointed out as potential alternatives in previous meetings with farmers in Zona da Mata and research (Dogliotti et al., 2014; Ermgassen et al., 2018). However, there is little available resources, infrastructure and incentives from public policies to apply those practices, which limits the scope of adoption.

4.1. Direct and indirect effects of management on plant diversity, soil quality and crop yield

We found no effect of management practices on soil chemical fertility or coffee productivity (Fig. 3). Our results suggest that despite the higher weeding intensity and more intensive use of external inputs in large-scale and conventional coffee systems, this did not result in increased soil chemical quality nor coffee productivity (Fig. 2A and 3). In contrast, agroecological management relied more strongly on biodiversity to maintain similar levels of coffee production and soil nutrients, and even higher levels of soil biological quality (Fig. 3). This is probably because the higher species diversity was associated with higher soil cover, structural heterogeneity and functional diversity (Fig. 2C), creating favourable conditions for macro and microorganisms to recycle nutrients and carbon (Duru et al., 2015b; Faucon et al., 2017; Lange et al., 2015; Lemanceau et al., 2015). For example, the higher species richness in coffee systems was positively associated with microbial biomass carbon, and litter thickness was positively associated with soil organic matter (Appendix F). These findings challenge the current role of industrial inputs and intensive weeding for obtaining a successful agricultural production (Catarino et al., 2019; Hassanali et al., 2008; Lechenet et al., 2017). Even in cases when yield is reduced in agroecological systems, reduced costs of external inputs and machinery can compensate the profitability gap (Jezeer et al., 2018; Uphoff, 2017). Furthermore, agroforestry and diversified coffee systems can provide additional income from other products rather than coffee, such as fruits and wood (Souza et al., 2010). Beyond economic costs, reducing the dependency on pesticides is urgent to reduce impacts on the environment and human health (Chaza et al., 2018; Dromard et al., 2018; Müller et al., 2017; Rodríguez et al., 2017). Especially in developing countries, our findings are confirmed by large-scale studies, which reinforce that sustainable and agroecological practices can not only increase or maintain similar yields as conventional practices, but also improve the natural, human and social capital of the farms (Pretty, 2008; Schutter, 2010; Tully and Ryals, 2017).

In the case of pastures, management practices such as reduced grazing, increased mowing and increased tree density were associated with pastures located in agroecological farms. Reduced grazing intensity (days of grazing/year) was observed in agroecological farms probably because agroecological farmers tend to keep their animals in the stable during the dry season, when additional alternative feed is provided (Furtado, 2016). Besides, as pastures in agroecological farms are more diverse, farmers may need to spend more time with (selective) mowing than in conventional and large-scale farms. Management practices as selective mowing and increased tree density resulted in higher plant structural heterogeneity and soil litter cover, which in turn, increased soil quality (Fig. 3, Appendix F; Cardozo Junior et al., 2018). Yet, the current management practices adopted at the agroecological farms also had a direct negative effect on soil fertility (Fig. 3). The negative relationship between agroecological management practices and soil chemical and biological indicators in pastures may be explained in different ways. First, the lower grazing intensity associated with agroecological management may result in lower carbon and nutrient input from animal manure and urine, as well as lower below ground input of organic matter due to lower root turnover (Sato et al., 2019). Second, conventional and large-scale systems often had a high cover of exotic grasses such as *Brachiaria spp*. These exotic grasses have a short but dense root system, which can result in increased soil nutrient concentrations and soil microbial biomass in the superficial soil layer (Gichangi et al., 2016). Third, agroecological farmers reported that their pastures were very degraded when they started managing them 5–15 years ago, while large-scale farmers often have more land and resources to establish their pastures in areas with a higher soil fertility and soil organic matter. Nevertheless, soil physical indicators, such as water infiltration rate, compaction, density and porosity are expected to be negatively correlated with more intensive grazing and should be further explored in future studies (Bonetti et al., 2019; Vandandorj et al., 2017). Water was identified by farmers in Zona da Mata as one of the most important ES (Teixeira et al., 2018b) and the soil physical indicators listed above are crucial to understand water dynamics in pastures, which is of major importance for avoiding problems such as soil erosion and water run-off in mountainous areas (Roesch et al., 2019). Our results indicate that increased plant diversity in pastures can be a good strategy to enhance ecosystem services, but it needs to be combined with other management practices than currently adopted. Therefore, more action-oriented research is needed to inform sustainable pasture management considering the provision of multiple ecosystem services as this has been a largely overlooked aspect in Zona de Mata.

4.2. Contrasting plant diversity attributes

Agroecological systems displayed higher plant species richness, which was positively associated with structural diversity (i.e. variance in height), soil cover and litter thickness in both pastures and coffee systems (Figs. 2C and D). Agroecological farmers adopt practices aiming to increase local plant diversity, such as planting or regenerating trees and mowing the spontaneous vegetation (Fig. 2A–D). Previous studies in Zona da Mata show various benefits of tree canopy cover, such as temperature regulation (Gomes et al., 2016), biological control (Moreira et al., 2019; Rezende et al., 2014), environmental filter against exotic weeds (Ramos et al., 2015), production diversification (Souza et al., 2012b) and soil quality (Cardoso et al., 2003b). In addition to trees, agroecological farmers also allowed the spontaneous vegetation to grow, and controlling it with mowing instead of intensive uproot weeding or herbicides (Fig. 2A). In contrast to uproot weeding and herbicide use, mowing can increase plant diversity (Fig. 3) and associated ecosystems services. For instance, less intensive weeding strategies can lead to diversified plant communities, which may support pollinators and natural enemies of pests (Kovács-Hostyánszki et al., 2017). Therefore, as a cascade effect, higher planned biodiversity could result in more associated biodiversity, as new species can be attracted to the area, generating higher multi-trophic diversity both above and below ground (Duru et al., 2015b; Scherber et al., 2010). Previous studies show that higher plant taxonomic diversity was positively associated with diversity of birds, insects, and soil microorganisms (Naeem et al., 2012), including mycorrhiza fungi (Cardoso et al., 2003a). Furthermore, taxonomical diversity was positively associated with variation in vegetation structure, which can play an important role for ecosystem functioning as diversified agroecosystems with high structural heterogeneity may efficiently capture and recycle resources, such as water and light, due to niche differentiation (Nair, 2017; Yachi and Loreau, 2007). Furthermore, as diversified systems were associated with higher soil litter cover (Fig. 2C and D), they may have good potential to provide associated soil functions, such as water infiltration and erosion control (Liu et al., 2018; Lohbeck et al., 2017; Nzeyimana et al., 2017).

In the case of coffee, taxonomic and structural diversity were also strongly positively correlated to functional richness (Fig. 2C), suggesting high occupation of the niche space and limited niche overlap among species (Díaz and Cabido, 2001). This was not the case for pastures (Fig. 2D), which indicates that an increase in the number of plant species was not strongly associated with an increase in functional richness. This can be explained by the high cover of different grass species that have similar leaf functional traits, suggesting that the observed grass species can perform similar functions in the system. For both coffee and pastures, differences in functional composition (i.e. CWM's) among systems were mostly observed in plant diversity PC2, which explained 28.5 % and 21.5 % of the variance in coffee and pastures, respectively. In both cases, PC2 was not useful to detect differences among farm types. In the case of coffee, the variation in CWM values reflects the leaf economic spectrum (Salguero-Gómez et al., 2016; Wright et al., 2004), ranging from systems dominated by soft and nutrient rich leaves (high SLA and N, P and K content) to systems dominated by more conservative species, with tougher leaves (high FtP, LT and LDMC). In the case of pastures, no clear pattern could be detected, which might be related to the similarity of functional trait values among grass species. In addition, other factors than farm diversity (e.g. geographic location) may be influencing changes in functional composition (Sandel et al., 2016), which is beyond the scope of the present study.

4.3. *Soil quality indicators*

Differences in soil quality among the three farm types was less prominent than differences in management and plant diversity for both pastures and coffee fields (Figs. 2E and F). The limited contrast in soil quality between farm types may be explained by the fact that most of the indicators that we used were associated with soil chemical quality. Agroecological practices, such as tree intercropping, abandon or reduce the use of agrochemicals, mowing instead of intensive weeding, and use of manure (Fig. 2A) are aimed not only to provide nutrients for the soil, but can also enhance nutrient cycling (Duarte et al., 2013), improve water infiltration (Meylan et al., 2017; Pires et al., 2017), increase soil cover and organic matter, and enable favourable conditions for the development and activity of soil microbiota (Rigal et al., 2019; Tully and Ryals, 2017). For instance, the practice of mowing allow weed roots to remain in the soil and the mown aboveground plant material to serve as mulch to cover the soil. The decomposition of roots and higher soil cover can lead to higher soil organic matter (Appendix F) and nutrient mineralisation (Matos et al., 2011), and therefore enhance soil quality.

When focusing on the relationship among soil variables in coffee systems, the soil PC1 shows that systems with higher soil pH, base saturation and calcium content have less organic matter and nitrogen. These results indicate that the application of limestone can increase pH and calcium availability, but it does not result in higher organic matter. Therefore, liming as a standalone practice may not be sustainable, since organic matter is a crucial component to guarantee soil quality in the long-term. Furthermore, overuse of limestone to regulate soil pH can have detrimental effects for soil organic carbon stocks in the top soil due to increased biological activity and mineralisation of soil organic matter (Haynes and Naidu, 1998; Paradelo et al., 2015). On contrary, when appropriate doses are applied, long-term net effects of liming on soil organic matter are expected to be positive due to increased microbial activity, which is expected to improve soil structure, especially if carbon inputs are high (Haynes and Naidu, 1998; Paradelo et al., 2015). However, this seems not to be the case in Zona da Mata, suggesting that farmers need to apply more accurate doses of limestone when necessary, as well as increase soil carbon input. The application of adequate doses of limestone in coffee fields is especially relevant for large-scale and conventional family farms, as the use of limestone in these farm types tend to be much higher than in agroecological farms (Table 1; Fig. 2A). Soil PC2 shows the positive correlation between phosphorus, potassium, soil organic matter and microbial carbon biomass, indicating the role of microorganisms to cycle P and K and make these nutrients available for plants (Kaur et al., 2018; Meena et al., 2016). In the case of pastures, soil quality PC1 indicated a positive correlation among all variables, except for clay content, which is more strongly correlated with soil PC2. The contrast between soil pH and organic matter that occur in coffee systems may not have been observed in pastures because farmers did not apply any kind of inputs to regulate pH or to add nutrients. Therefore, the positive correlation among biological and chemical soil variables in pastures reinforces the role of carbon and microorganisms to cycle nutrients and improve soil fertility.

5. Conclusions

This is the first study to our knowledge that empirically tests the direct and indirect effects of changes in management (from conventional to agroecological) on plant diversity, soil quality and crop productivity. The approach allowed us to explore the complex management of agroecosystems by combining a multiple set of indicators. This is especially important when assessing realistic management scenarios, which involve multiple practices that may impact different aspects of the agroecosystem. Our findings indicate that the positive effect of agroecological management on soil quality is mediated by increased plant diversity, highlighting the role of biodiversity for the sustainability of agroecological systems. Besides, the reduced use of industrial inputs and reduced weeding intensity in agroecological coffee fields did not significantly reduce soil fertility and crop yield. Therefore, we suggest that agroecological practices that promote biodiversity, soil quality and farmers` autonomy can be efficient to maintain satisfactory crop yields and soil fertility without the need of intensive use of external inputs and weeding. Future studies are needed to further understand the direct and indirect impact of agroecological management on multiple ecosystem services, considering other regions, countries and cropping systems. For that, it is necessary to combine efforts of researchers from different disciplines to capture the complex provision of interconnected ecosystem services that occur at field, farm and landscape levels.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.107171.

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